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Original Article

Eco-Friendly Catalytic Converters: Synthesis, Testing, and Engine Performance Evaluation of Rice Husk Waste-Derived Activated Carbon

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ABSTRACT

Catalytic converters (CCs) play a crucial role in mitigating exhaust emissions from motor vehicles. This study presents a sustainable methodology by utilizing rice husk waste (RHW) to produce activated carbon, subsequently fashioned into honeycomb-shaped catalytic converters with varying thicknesses of 10 mm, 15 mm, 20 mm, and 25 mm. Notably, the 15 mm-thick converter (CC15) exhibited the highest efficacy in emission reduction, achieving a 78.33% decrease in hydrocarbons (HC) and a 48.23% reduction in carbon monoxide (CO). To assess its impact on engine performance, dynamometer tests were conducted, revealing that the installation of CC15 resulted in less than a 6% reduction in both power and torque, which is considered acceptable for routine vehicle operation. Furthermore, the air–fuel ratio (AFR) shifted from an average of 13.38 under standard conditions to 14.19 with CC15, indicating stable combustion. Sound level measurements also confirmed that the CC did not function as a noise suppressor, resulting in no significant alterations in engine Sound levels. Overall, the CC15 effectively balances environmental performance with engine efficiency, offering a practical emission control solution derived from locally sourced agricultural waste.

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1. Introduction

National economic growth has a direct impact on population mobility and the increasing demand for transportation, particularly motorcycles, which are widely used in developing countries such as Indonesia because of their affordability and efficiency [1,2]. However, the rapid growth in motorcycle usage has led to escalating environmental concerns, particularly air pollution resulting from the exhaust gas emissions. These emissions typically consist of harmful components, such as hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter [3]. On a broader scale, motorcycle emissions contribute substantially to global warming and the greenhouse effect [4,5]. Indonesia ranks as the sixth-largest emitter of vehicular exhaust gases, contributing approximately 4.47% of global emissions [6].

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To address the adverse environmental impacts of vehicle emissions, the Indonesian government has implemented a series of regulatory measures, including the Ministry of Environment Regulations No. 05 of 2006 and No. 08 of 2023, which are designed to control and reduce exhaust emissions [7,8]. In response, the motorcycle manufacturing sector has adopted various technological advancements—most notably, the integration of catalytic converters (CCs) into modern vehicles—to meet these stricter emission standard [9]. CCs are typically installed in exhaust systems to catalyze redox reactions that convert harmful gases into less toxic compounds [10]. Conventional CCs often employ precious or transition metal-based catalysts, such as copper (Cu), copper–zinc (CuZn), and copper–chromium (CuCr) alloys, as illustrated in Figure 1 [11]. Although these materials exhibit high catalytic efficiency, their broad implementation is hindered by high costs, limited resource availability, and complex processing requirements, which challenge their long-term sustainability.

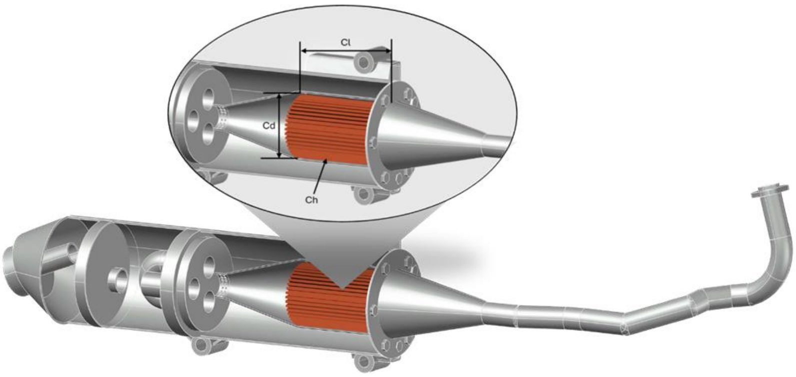

Figure 1. Schematic construction of an MCC, as reported in [11].

As a more economical and sustainable alternative, numerous studies have proposed the use of activated carbon (AC) derived from locally available biomass to replace precious-metal catalysts [12]. Research has demonstrated the viability of various agricultural waste as precursors for AC-based CCs. Gunawan et al. [13] fabricated a CCs from corn cobs and reported HC and CO emission reductions of 75.87% and 0.24%, respectively. Wagino et al. [14] utilized banana peels for AC synthesis, achieving an 11% reduction in CO emissions. Fajri et al. [15] further demonstrated that AC-based CCs could reduce HC and CO by 85.63% and 52.23%, respectively. Their findings underscore the potential of biomass-derived AC as an effective and affordable emission reduction medium, owing to its high porosity and adsorption capacity [16]. However, existing studies often face limitations related to feedstock availability, consistency, and scalability.

Rice husk waste (RHW) is a particularly promising and underutilized biomass resource. Indonesia generates approximately 15.02 million tons of RHW annually; however, a significant portion of this by-product remains unmanaged and unused [17]. Chemically, RHW contains approximately 35% cellulose, 25% hemicellulose, 20% lignin, and 17% inorganic compounds, such as silica, making it an ideal carbon-rich precursor for AC production [18,19]. Previous work by Febryanti et al. [20] showed that RHW possesses favorable properties for gas adsorption, indicating its potential application in environmental remediation technologies. Nevertheless, its integration into engineered catalytic systems, specifically honeycomb-structured CCs for vehicular exhaust treatment, remains largely unexplored in both academic literature and industrial practice.

Although RHW has been explored for general adsorption applications, its practical implementation in CCs systems remains underexplored, particularly in geometrically optimized configurations that have been tested under real engine operating conditions. Therefore, this study aimed to develop a catalytic converter using activated carbon derived from rice husk waste (RHW) engineered in a honeycomb configuration to enhance the surface area and promote laminar gas flow for more effective exhaust emission reduction. The activated carbon material was characterized using X-ray Diffraction (XRD) to analyze its crystalline structure and phase composition, as well as Fourier-Transform Infrared Spectroscopy (FTIR) to identify functional groups relevant to adsorption mechanisms. Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM-EDS) was employed to examine the surface morphology and elemental distribution. In a unique element of this study, all CC samples were subjected to emission testing in accordance with the Ministry of Environment and Forestry Regulation No. 8 of 2023 to assess their effectiveness in reducing hydrocarbon (HC) and carbon monoxide (CO) emissions. Furthermore, the most effective CC configuration was subjected to engine dynamometer testing to assess its influence on torque, power, and air–fuel ratio (AFR), ensuring that the emission reduction performance did not compromise the engine output. This integrative approach, combining local waste-derived materials, material characterization, structural optimization, and real-engine validation, represents a novel contribution toward sustainable emission control technologies aligned with SDG No. 7 on affordable and clean energy.

2. Materials and Methods

2.1. *Preparation of activated carbon from rice husk waste (RHW)*

The extraction and activation of carbon from rice husk waste (RHW) were adapted with modifications from the method developed by Labato-Peralta et al. [21]. The process began with a pretreatment step involving soaking the RHW in clean water to eliminate impurities and foreign particles. Floating husks, which are typically indicative of lower density and poor carbon yield, were discarded. The remaining RHW was sun-dried for approximately 5 h to reduce its moisture content. Following drying, the RHW underwent a pre-carbonization process in a furnace at 400 °C for 2 h, resulting in crude carbon. The carbon was manually ground using a mortar and pestle to obtain a fine carbon powder, which was then sieved through a 200-mesh sieve to ensure particle size uniformity and prevent agglomeration.

The sieved carbon powder was chemically activated using hydrochloric acid (HCl) at a 1:2 weight-to-volume ratio (100 g carbon: 200 mL HCl). The activation process involved continuous stirring of the carbon–acid mixture with a magnetic stirrer for 2 h, followed by a 48-h resting period at room temperature to enhance pore development. After activation, the carbon–acid mixture was filtered and rinsed repeatedly with distilled water until a neutral pH was reached, ensuring the removal of residual acid and soluble impurities. The cleaned carbon was then oven-dried at 100 °C for one hour and subjected to a final carbonization process at 650 °C for six hours in a controlled furnace to improve structural integrity and adsorption capability. The resulting activated carbon was characterized using XRD to determine its crystalline structure and phase composition, FTIR to identify surface functional groups, and Scanning Electron Microscopy with SEM-EDS to analyze surface morphology and elemental composition. These techniques provided a comprehensive understanding of the microstructure of activated carbon and its suitability for catalytic converter applications.

2.2. *Fabrication of catalytic converters (CCs) structures*

The CCs were fabricated using a composite mixture of activated carbon, polyvinyl acetate (PVA) as a binder, distilled water, and starch. The specific proportions of each component are listed in Table 1. All the ingredients were carefully weighed using a digital scale and thoroughly mixed in a clean container until a homogeneous paste was formed. The resulting mixture was cast into cylindrical stainless-steel molds with a fixed diameter of 22 mm and varying lengths of 10 mm (CC10), 15 mm (CC15), 20 mm (CC20), and 25 mm (CC25), as shown in Figure 2. These geometric variations were designed to investigate the influence of converter dimensions on the emission reduction performance. The molded samples were initially subjected to natural drying under direct sunlight for approximately two days. Prior to complete drying, each sample was perforated longitudinally using an iron rod with a diameter of 1.55 mm to form a honeycomb-like internal structure. This design was intended to maximize the surface area and promote the laminar flow of exhaust gases through the converter, thereby enhancing its adsorption and filtration efficiency.

Table 1. Material composition for fabricating activated carbon-based catalytic converters.

Material	Activated Carbon	PVA	Distilled Water	Starch
Percentage (%)	60	15	10	15

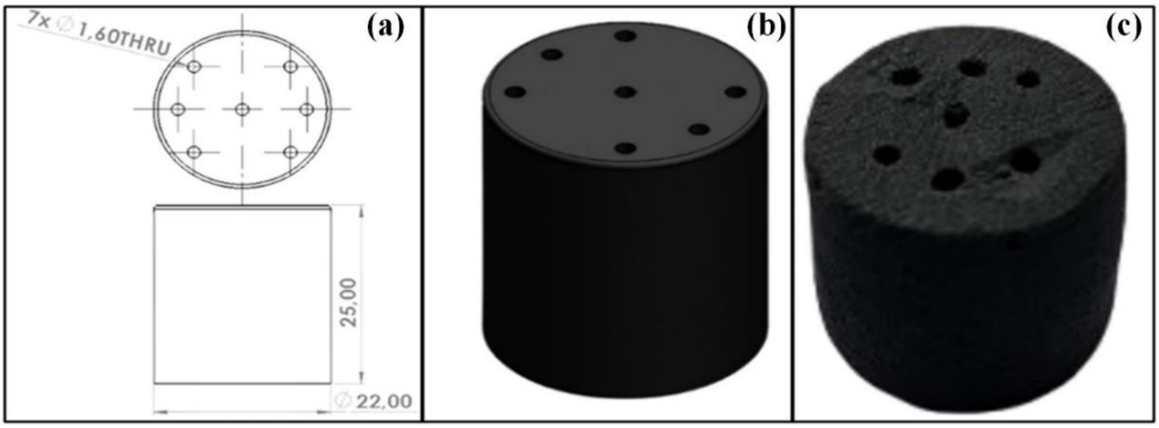

Figure 2. Illustration of the fabricated catalytic converter:(a) 2D-dimensions, (b) 3D-design, and (c) final product resulting from the fabrication process.

Following the demolding process, the catalytic converter samples were subjected to final drying in a convection oven at 100 °C for 30 min. This thermal treatment ensured the complete removal of residual moisture and facilitated the structural hardening of the CCs units. The finalized converters were subsequently prepared for characterization and performance testing to evaluate their effectiveness in reducing motorcycle exhaust emissions.

The installation of the CCs onto the motorcycle exhaust system began with the modification of the exhaust pipe, as shown in Figure 3. This process involved precisely cutting a 40 mm section from the original exhaust pipe to accommodate the insertion of the CC. The removed section was replaced with a custom-fabricated stainless-steel pipe segment designed to house the preinstalled CCs. The replacement pipe featured an inner diameter of 60 mm to match the dimensions of the converter and ensure an optimal fit within the exhaust stream. The CCs were securely fixed within the pipe using epoxy resin, which served as a bonding agent to ensure structural integrity and prevent gas leakage at the connection points. This installation method enables the seamless integration of the CC into the vehicle exhaust system while maintaining its mechanical stability under operating conditions.

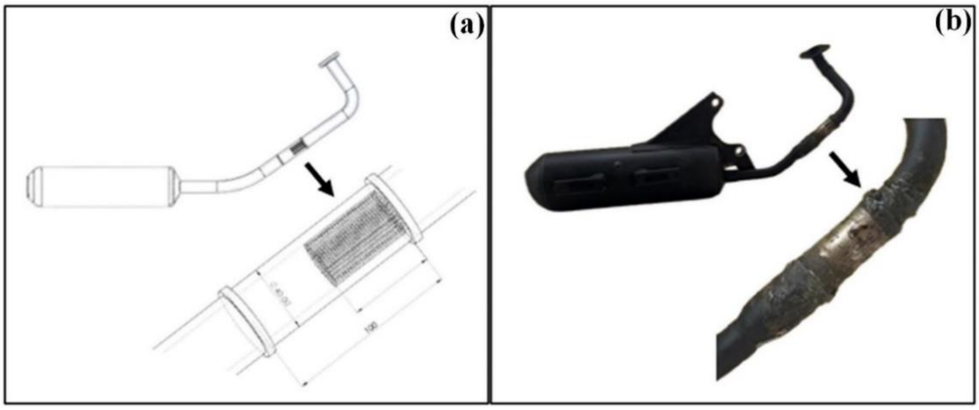

Figure 3. Modification process of the exhaust system with a catalytic converter: (a) CAD-based design layout of the CC placement and (b) photographic documentation of the installed system.

The CCs were evaluated using a 110 cubic centimeter (cc) motorcycle to assess their effectiveness in reducing exhaust emissions. The initial phase of testing focused on measuring the emission levels before and after the CCs installation, adhering to the standardized protocol outlined in the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 8 of 2023 [22]. Emission analyses were performed on all CCs variants produced in this study. The results demonstrated that each CCs sample contributed to a measurable reduction in exhaust gas pollutants, indicating the potential efficacy of RHW-based activated carbon as a functional emission-reducing material.

Subsequently, the most effective CCs configuration was subjected to further performance assessments, including a dynamometer test and noise level measurement. A dynamometer test was conducted to evaluate engine performance indicators, such as torque, power output, and air–fuel ratio (AFR), to confirm that the integration of the CCs did not adversely affect engine functionality. In addition, a noise level test was performed to assess the sound level output using a sound level meter positioned 50 cm behind the exhaust outlet and 20 cm above the ground level. This test ensured that the CC installation did not excessively suppress the engine sound, which could otherwise affect the backpressure and overall performance efficiency.

3. Results and Discussion

3.1. *Characterization of activated carbon derived from rice husk waste*

The effectiveness of activated carbon synthesized from rice husk waste (RHW) was evaluated using XRD. As shown in Figure 4(a), the XRD analysis revealed a broad peak centered at 21.98°, which fell within the 2θ range of 10°–30°. This range is typically associated with amorphous carbon structures, as reported by Neme et al. [23]. The amorphous nature of carbon is known to enhance its adsorption properties because of the increased availability of active surfaces [24, 25]. In parallel, FTIR analysis was performed in the 500–4000 cm^{-1} wavenumber range to identify the surface functional groups present. The results, presented in Figure 4 (b) and Table 2, reveal the presence of O–H (3200–3500 cm^{-1}), C–O (1050–1150 cm^{-1}), and C–H (800–860 cm^{-1}) stretching vibrations [26]. These functional groups play a crucial role in adsorbing gaseous pollutants, and their presence supports the use of activated carbon as an effective adsorbent material in CCs applications. This aligns with the findings of Li [27], who reported that the presence of hydroxyl groups on activated carbon surfaces significantly improved pollutant adsorption in vehicular exhaust gas treatment.

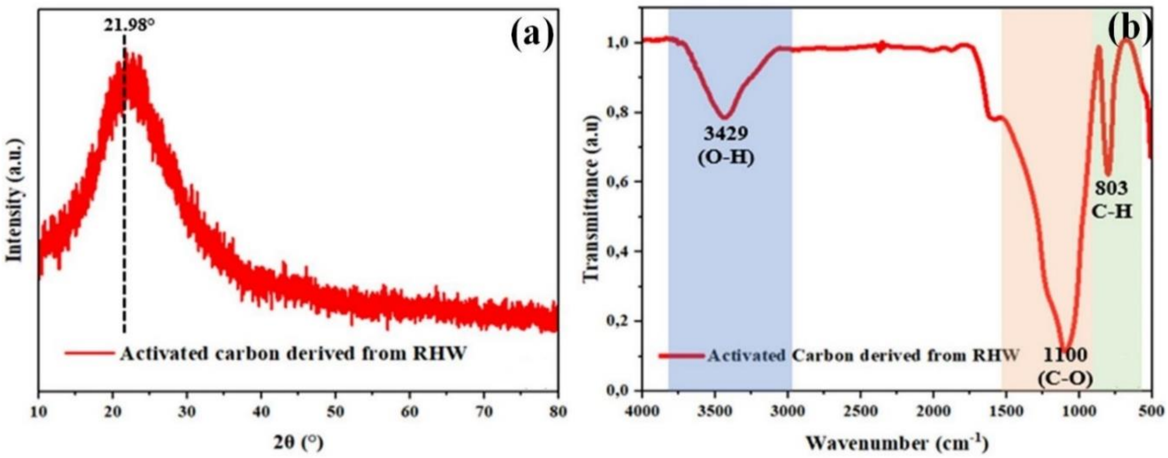

Figure 4. Characterization of activated carbon derived from RHW: (a) XRD pattern and (b) FTIR spectrum.

Table 2. The functional groups of the activated carbon derived from RHW were successfully identified in this study.

Wavenumber (cm^{-1})	Vibration Type	Functional Group	Ref.
803	C–H bending (out-of-plane)	Aromatic	[28]
1100	C-O stretching	Ether, ester, and phenol	[12]
3429	O-H stretching	Hydroxyl (alcohol, phenol)	[12]

Further morphological analysis using SEM demonstrated that the activated carbon possessed a porous structure characterized by voids and cavities distributed across its surface, as shown in Figure 5(a). A detailed pore analysis conducted using ImageJ software, as illustrated in Figure 5(b), revealed an average pore size of 3.55 µm with a distribution range of 1–9 µm, as shown in Figure 5(c). These pore characteristics are deemed optimal for adsorption applications, particularly concerning gas-phase pollutants, and align with the findings of Saban [24], who reported that activated carbon with a pore size of 3–7 µm is well suited for emission control systems. The porous nature of the surface enhances the specific surface area available for adsorption and facilitates the diffusion of exhaust gases into the active sites of the CCs material.

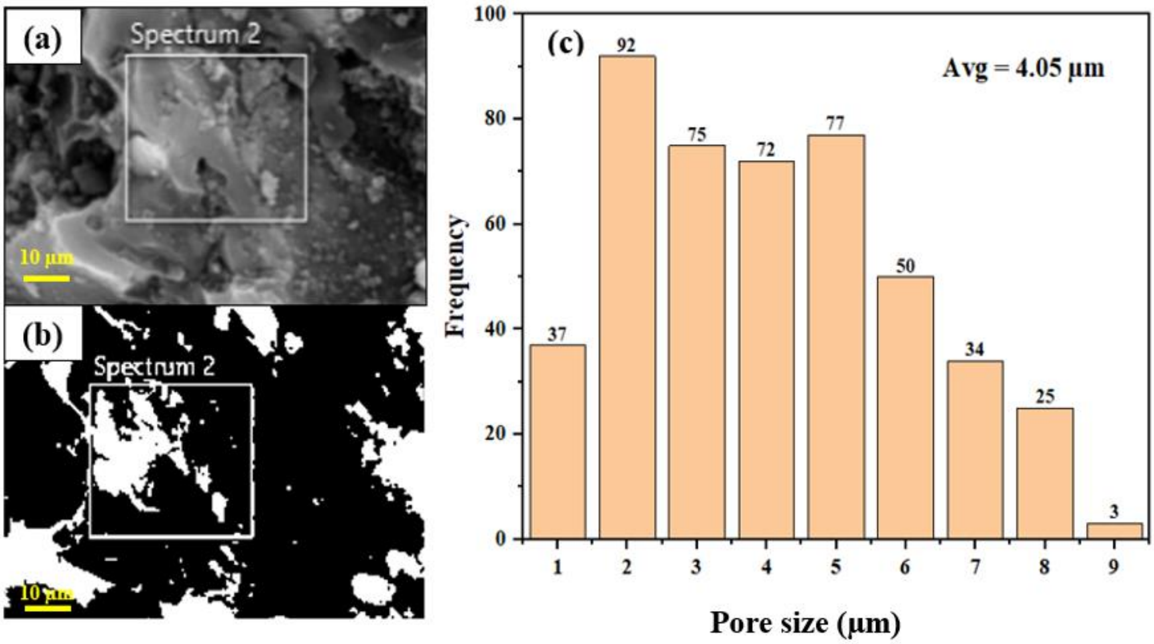

Figure 5. SEM characterization results: (a) micrograph of the activated carbon, (b) image processed using ImageJ software, and (c) pore size distribution of the activated carbon.

Finally, the elemental composition of the activated carbon was determined using energy-dispersive EDS, and the results are summarized in Table 3. The carbon content was 65.29%, indicating a successful carbonization process [29]. The oxygen content of 19.23% reflects the formation of oxygen-containing functional groups, such as hydroxyls, during activation, while the silica content of 15.48% is inherent to the RHW precursor material. These findings are consistent with those of previous studies by Agung et al. [30] and Riyanto et al. [31], who reported that RHW-derived activated carbon is typically composed of carbon, oxygen, and silica. Overall, the combination of the amorphous structure, abundant functional groups, porous morphology, and favorable elemental composition confirms that RHW-based activated carbon is well-suited for application in catalytic converter systems designed to reduce vehicular exhaust emissions. The chemical composition analysis of activated carbon from RHW provides insights into its structure and applications. The high carbon content of 65.29% demonstrates effective carbonization, which is crucial for developing materials with strong adsorptive properties. The presence of oxygen-containing functional groups, indicated by a 19.23% oxygen content, enhances the surface reactivity and interaction with pollutants in vehicular exhaust. These functional groups, such as hydroxyls, facilitate the adsorption and catalytic conversion of harmful emissions. The silica content of 15.48% inherent to RHW contributes to thermal stability and mechanical strength, which are essential characteristics for withstanding harsh conditions in catalytic converter systems.

The amorphous structure, abundant functional groups, porous morphology, and favorable elemental composition make RHW-based activated carbon excellent for catalytic converter applications. The amorphous structure provides a high surface area for adsorption and catalysis, while the porous morphology enables efficient gas flow and contact between exhaust pollutants and active sites. Oxygen-containing functional groups and silica enhance the ability of the material to support metal catalysts used in catalytic converters for reduction and oxidation reactions. These characteristics contribute to the potential of RHW-based activated carbon to reduce vehicular emissions, offering a sustainable solution for environmental protection in automotive applications.

Table 3. Chemical composition of activated carbon derived from RHW.

Element	Carbon (C)	Oxygen (O)	Silika (S)	Total
Weight (%)	65.29	19.23	15.48	100

3.2. *Performance evaluation of the catalytic converter*

The successfully synthesized activated carbon was used to fabricate CCs, which were subsequently subjected to performance evaluation through exhaust-gas emission testing. The primary focus of this assessment was to quantify the levels of hydrocarbon (HC) and carbon monoxide (CO), both of which are key pollutants resulting from incomplete combustion in internal combustion engines, as represented by the combustion reaction shown in Eq. 1 [32]. Emission testing was conducted in accordance with Indonesian Ministry of Environment and Forestry Regulation No. 8 of 2023 [22], and the emission data for each CCs sample are presented in Table 4. Among all the variants tested, the CC15 sample demonstrated the highest effectiveness, achieving reductions of 78.33% and 48.23% in HC and CO emissions, respectively. These trends are depicted in Figure 6.

$$C_{10}H_{24} + O_2 + N_2 \rightarrow CO + CO_2 + HC + NO_x \quad (1)$$

Table 4. Exhaust gas emission test results.

Emission Type	Samples				
	Standard	CC10	CC15	CC20	CC25
HC (ppm)	674	193	146	178	195
CO (%)	2.84	1.82	1.47	1.56	1.60

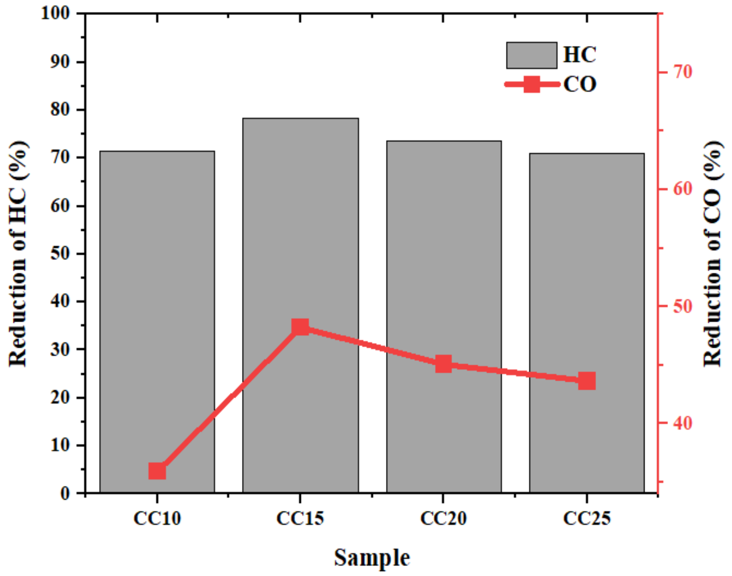

Figure 6. Reduction in HC and CO levels (%) across the samples.

The superior performance of the CC15 unit can be attributed to the optimal geometry and high adsorptive capacity of the activated carbon, which features a porous morphology conducive to pollutant entrapment. The porous carbon matrix facilitates the adsorption and retention of oxygen (O_2) molecules, enabling surface-level redox reactions between O_2 and gaseous pollutants [33]. Specifically, HC compounds react with O_2 to form water vapor (H_2O), whereas CO undergoes oxidation to produce carbon dioxide (CO_2) [34]. These reactions effectively reduce the concentration of harmful emissions in the exhaust stream, thereby enhancing the environmental sustainability of engine systems. The emission reduction performance observed validates the practical applicability of RHW-derived activated carbon as an efficient and eco-friendly material for catalytic converter development. The effectiveness of the CC15 unit extends beyond its adsorptive properties, as it also demonstrates catalytic activity that further enhances the conversion of pollutants. This dual functionality allows for a more comprehensive treatment of exhaust gases, addressing a wider range of pollutants than that of traditional catalytic converters. Moreover, the use of RHW-derived activated carbon in the CC15 unit represents a sustainable approach to automotive emission control, as it repurposes agricultural waste into high-value materials for environmental protection.

3.3. *Dynamometer test and combustion analysis*

After conducting the emission tests, the CCs performance was further assessed using a dynamometer, focusing on the most effective sample, CC15. This evaluation aimed to determine the impact of integrating CC15 on torque and power output, which are two critical indicators of engine performance. As depicted in Figure 7(a), the maximum torque achieved by the standard engine and the engine equipped with CC15 was 9.38 Nm and 9.24 Nm, respectively, indicating a slight reduction of 5.26%. Despite this decrease, the torque at higher engine speeds demonstrated greater stability with CC15, suggesting improved retention of the engine performance beyond the peak. Similarly, the power output, shown in Figure 7(b), reached a maximum of 8.19 HP for the standard engine and 8.45 HP for the engine with CC15, representing a 5.06% increase in power output. This finding implies that the use of CC15 did not impair the engine power; instead, it contributed to smoother combustion and potentially enhanced performance at higher revolutions. Although a minor decline in torque and power was observed at lower RPMs, likely due to initial backpressure and AFR compensation, the engine performance remained within acceptable ranges, confirming the practical viability of CC15 for vehicle applications.

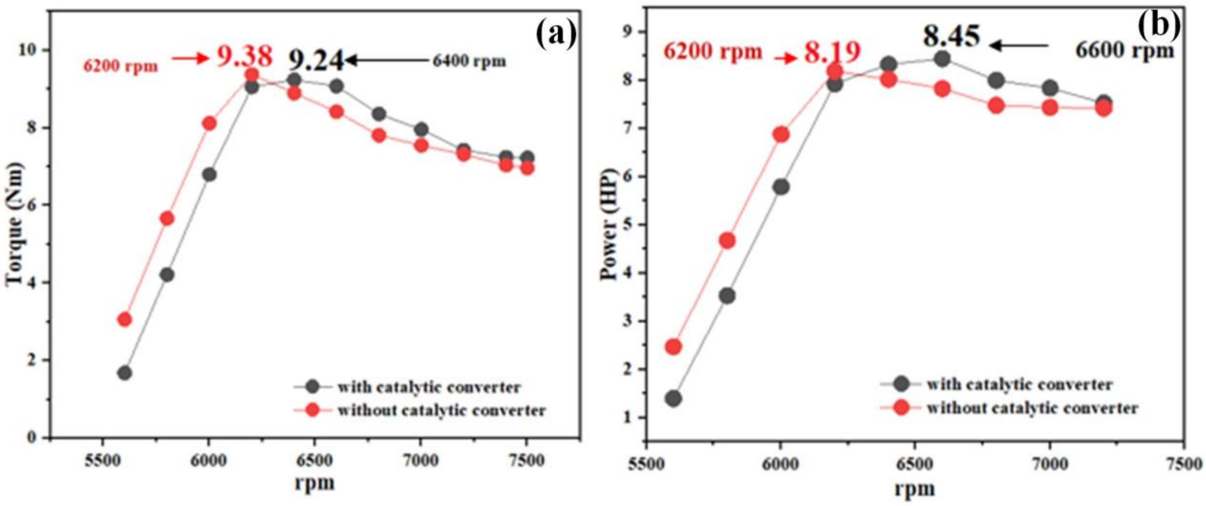

Figure 7. Dynamometer test results: (a) torque output and (b) power output of the engine before and after CC15 integration.

3.4. *Combustion behavior: AFR and lambda analysis*

Further combustion analysis was conducted to examine the air–fuel dynamics before and after CC15 integration. As shown in Figure 8(a), the average air–fuel ratio (AFR) increased from 13.38 under standard conditions to 14.19 with CC15, indicating a shift toward a leaner mixture. Figure 8(b) shows an increase in the lambda value from 0.91 to 0.96, further confirming this trend. A leaner mixture can slightly reduce power at low RPMs but generally improves fuel efficiency and enhances the oxidation of unburnt hydrocarbons and carbon monoxide. This aligns with the findings of Kurniawan et al. [35], who demonstrated that an increased AFR promotes more complete combustion and reduces emissions. Therefore, CC15 not only reduced HC and CO emissions but also contributed to combustion optimization without significantly compromising performance. The integration of CC15 thus presents a balanced enhancement in both emission control and engine efficiency, underscoring its potential for use in environmentally responsible transportation technologies.

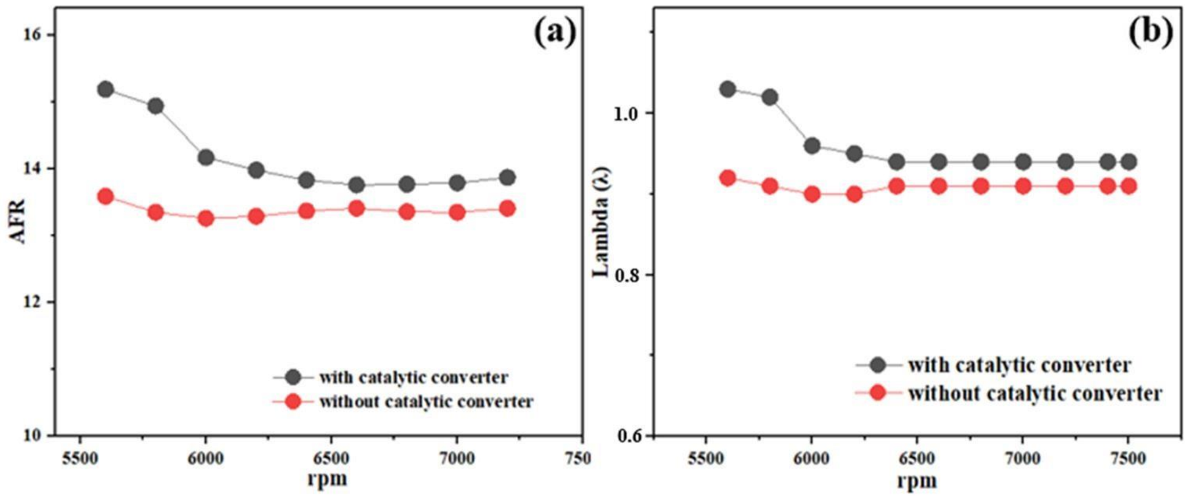

Figure 8. Results of combustion analysis: (a) air–fuel ratio (AFR) measurements and (b) lambda value evaluation before and after CC15 integration.

To assess the sound-level impact of the CC15 installation, noise-level testing was conducted. The measured noise intensities, as shown in Table 5, remained within the permissible threshold of 80 dB, as regulated by the Minister of Environment and Forestry No. 56 of 2009 for motorcycles with engine capacities between 80 and 175 cc. No significant differences were observed in the noise levels before and after the CC15 installation, suggesting that the catalytic converter neither suppressed the engine sound nor introduced additional noise. These findings confirm that the CC15 complies with regulatory standards, not only in terms of emission control but also in terms of sound level performance, further demonstrating its potential for sustainable transportation technologies.

Table 5. Noise level measurements before and after post-CC15 installation.

Samples	Noise Level (dB)
Standard (no CCs)	80.1 ±1
CC15	79.2 ±1

4. Conclusions

This study successfully demonstrated the synthesis of activated carbon derived from rice husk waste (RHW) and its functional integration into catalytic converter (CC) systems for internal combustion engine applications. Structural characterization using XRD confirmed the amorphous nature of the carbon material, as evidenced by broad diffraction peaks within the 2θ range of 10–30°, with the most prominent peak observed at 2θ = 21.98°. Complementary FTIR analysis identified key functional groups (O–H, C–O, and C–H) that are critical for adsorption, while SEM-EDX revealed a porous morphology and a carbon content of 65.29 wt%, indicating successful carbonization and activation. Among all tested configurations, the catalytic converter with a thickness of 15 mm (CC15) exhibited superior emission-reduction performance, lowering hydrocarbon (HC) and carbon monoxide (CO) emissions by 78.33% and 48.23%, respectively, without significantly impairing torque or power output. Dynamometer tests showed that the engine performance remained stable, and noise-level assessments confirmed compliance with regulatory limits without any muffling effect. These results highlight the potential of RHW-derived activated carbon as a low-cost, sustainable, and effective material for emission control in small-engine vehicles. Future investigations should focus on optimizing the activation parameters, evaluating the long-term durability under dynamic engine loads, and benchmarking the performance against conventional catalytic substrates to support industrial adoption.

Author Declaration

Author contributions and responsibilities

Imam Mandriyanto was responsible for conducting the literature review, drafting the original manuscript, and collecting the data. **Amir Amir** oversaw the writing process and reviewed the manuscript. **Sukarman Sukarman** contributed to the review process, supervised the research, and edited the original manuscript. **Agus Supriyanto** provided methodological suggestions during the study. **Rizki Aulia Nanda** validated the data collection and addressed the reviewers' comments. **Muchammad Chusnan Aprianto** reviewed the manuscript and managed the submission process.

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Data and materials availability

All data are available from the corresponding author upon request.

Competing Interests

The authors declare no competing interests.

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