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(Research Article)

Effect of oxygen flow rate on temperature and pressure distribution in a motorcycle exhaust system with activated candlenut shell adsorbent

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Abstract

This study investigates the thermofluid behavior of a motorcycle exhaust gas treatment system incorporating activated charcoal derived from candlenut (*Aleurites moluccanus*) shells, with and without supplementary oxygen injection. A modified exhaust casing was designed to house the adsorbent and was equipped with pressure and temperature sensors at multiple points. The system's performance was evaluated under varying oxygen flow rates (0, 1, 2, and 3 L/min), focusing on pressure differentials and temperature distributions during steady-state engine operation. Results showed that the inclusion of activated charcoal significantly increased the pressure drop across the adsorbent bed, indicating effective interaction between the exhaust gases and the porous medium. However, as the oxygen flow rate increased, the pressure differential decreased, suggesting improved flow permeability and reduced adsorbent clogging. Simultaneously, the internal temperature of the casing rose with higher oxygen levels due to exothermic oxidation reactions, particularly in the middle and rear sections of the adsorbent. These findings highlight the dual role of oxygen in enhancing pollutant removal and maintaining optimal thermal and flow conditions within the adsorbent system. The study contributes critical insights for the design and optimization of low-cost, biomass-based emission control technologies for small-displacement engines in resource-limited settings.

Keywords: Activated carbon adsorbent; Candlenut shell biomass; Motorcycle exhaust emissions; Thermal and pressure distribution

1. Introduction

Air pollution resulting from vehicle emissions remains a pressing environmental and public health concern, especially in rapidly developing countries where the use of small, fuel-efficient motorcycles dominates the transportation sector. In Southeast Asia, and particularly Indonesia, motorcycles represent the most affordable and practical mode of transport for millions of people. However, the majority of these vehicles are not equipped with advanced emission control technologies such as three-way catalytic converters. As a result, they contribute disproportionately to the release of hazardous exhaust pollutants, including carbon monoxide (CO), unburned hydrocarbons (HC), and carbon dioxide (CO_2) [1–3]. These gases not only degrade air quality but also pose direct threats to human health and exacerbate climate change.

The standard approach to reduce emissions in gasoline-powered vehicles involves the use of noble metal-based catalytic converters. Despite their effectiveness, these systems are often prohibitively expensive due to their reliance on platinum group metals. Consequently, there has been a growing interest in developing alternative, cost-effective emission control solutions that are accessible to low-income users and adaptable to existing motorcycle platforms. In this context, the use of agricultural waste as a source of activated carbon (AC) has garnered significant attention due to its environmental sustainability, local availability, and functional performance in gas purification applications [4–6].

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Candlenut shell (*Aleurites moluccanus*), a common agricultural byproduct in Indonesia, has been previously identified as a promising raw material for producing activated carbon with high surface area and adsorption capacity [7]. When activated using chemical and thermal processes, candlenut shell charcoal can effectively remove various pollutants through physical adsorption and, to some extent, catalytic surface reactions. A prior study demonstrated the efficacy of such material in reducing CO, HC, and CO_2 emissions from motorcycle exhaust when installed as a filtering medium within a modified exhaust chamber [8]. Furthermore, the introduction of oxygen into the system was shown to enhance the performance of the adsorbent by facilitating additional oxidation reactions [9].

Nevertheless, while the emission-reducing capability of the activated charcoal system has been established, there remains a significant gap in understanding the internal dynamics—namely, the distribution of temperature and pressure—within the adsorbent casing during operation. These parameters are critical because they govern not only the thermochemical behavior of the gas-adsorbent interaction but also influence the mechanical performance of the system. For instance, excessive temperature gradients may lead to thermal fatigue or structural failure, while elevated backpressure could impair engine performance and fuel efficiency [10,11]. Moreover, understanding how oxygen injection influences these internal conditions is essential for optimizing the design and operation of such systems.

This study aims to investigate the temperature and pressure distribution in a motorcycle exhaust system equipped with an activated charcoal adsorbent made from candlenut shell, under varying oxygen flow rates. By conducting real-time measurements at multiple locations inside and around the adsorbent casing, the study seeks to provide a comprehensive thermofluid characterization of the system. The resulting insights will help to bridge the knowledge gap between emission reduction effectiveness and the internal physical behavior of low-cost adsorbent systems. Ultimately, this work contributes to the broader effort to develop scalable, affordable, and environmentally sustainable emission control technologies for the transportation sector in developing regions

2. Material and methods

2.1. Experimental Setup

The experimental investigation was conducted using a 100 cc four-stroke gasoline motorcycle (Honda Supra), which was modified at the exhaust section to accommodate a custom-made adsorbent casing [12]. The system was designed to analyze the influence of activated charcoal derived from candlenut shells on the internal pressure and temperature distribution during engine operation under steady-state conditions. A schematic of the test configuration is presented in Figure 1.

The exhaust system was retrofitted with a stainless-steel casing of 15 cm in length and 4.4 cm in internal diameter to house the adsorbent material. The casing was positioned approximately 35 cm downstream from the exhaust valve, ensuring consistent exposure to exhaust gases while minimizing thermal degradation of the adsorbent. The adsorbent chamber was filled with chemically and thermally activated candlenut shell charcoal, and oxygen was injected at the inlet side of the casing at varying flow rates (0, 1, 2, and 3 L/min) using a controlled flow regulator.

2.2. Pressure and Temperature Measurement

To capture the dynamic behavior of gas flow and thermal conditions within the adsorbent casing, pressure and temperature sensors were installed at key locations throughout the system. Two pressure taps, designated as P1 (before the adsorbent casing) and P2 (after the casing), were used to record the differential pressure across the adsorbent bed. These measurements were obtained using calibrated piezoresistive pressure sensors with a resolution of 0.01 kPa.

For thermal mapping, four K-type thermocouples were installed at specific points: T1 (reference point, approximately 35 cm after the exhaust valve), T2 (inlet of the adsorbent casing), T3 (middle section of the adsorbent bed), and T4 (outlet of the casing). An additional thermocouple was placed in the ambient environment to record T.ling (ambient temperature). All thermocouples were connected to a digital data logger (labelled as component 5 in Figure 1) with a sampling rate of 1 Hz and an accuracy of ±0.5°C.

2.3. Oxygen Injection and Flow Control

An auxiliary oxygen injection system was introduced upstream of the adsorbent casing via a microflow regulator connected to a pressurized oxygen cylinder. The injection port was positioned immediately before the entry point of the adsorbent chamber (component 1), allowing homogeneous mixing between the oxygen and exhaust gases. Flow rates were adjusted to 0 (control), 1, 2, and 3 L/min using a calibrated rotameter, with flow verification conducted using a secondary bubble-type flowmeter for accuracy.

2.4. Operating Conditions and Data Acquisition

During testing, the motorcycle was operated under no-load conditions with the engine running at a constant idle speed. All measurements were initiated after the system reached thermal equilibrium, indicated by a stable engine temperature and exhaust gas flow. Each trial was conducted for a continuous duration of 60 seconds, and the experimental parameters (pressure and temperature) were logged continuously throughout the duration.

2.5. Preparation of the Adsorbent

The activated charcoal used in this study was produced from locally sourced candlenut (*Aleurites moluccanus*) shells. The shells were first sun-dried and then carbonized in a closed chamber. Chemical activation was carried out using a $ZnCl_2$ solution with a 1:1 impregnation ratio, followed by physical activation in a muffle furnace at 400°C for 4 hours. The resulting activated charcoal was sieved to uniform granule sizes and stored in a dry container prior to use. This activation process aimed to enhance the adsorbent's porosity and surface area, thereby improving its capacity to interact with gas-phase pollutants and thermal energy.

2.6. Schematic Overview

Figure 1 illustrates the schematic layout of the experimental system, including sensor positions, oxygen injection line, and the modified exhaust with the integrated adsorbent casing. The numbered parts in the figure are described as follows: 1. Front section of the modified exhaust pipe, 2. Middle section of the exhaust pipe, 3. Rear section of the exhaust pipe, 4. Activated charcoal adsorbent made from candlenut shell, 5. Thermocouple (temperature sensor), 6. U-tube manometer, 7. Pressure sensor tubing, 8. Temperature sensor tubing, 9. Oxygen supply line, 10. Automotive emission analyzer.

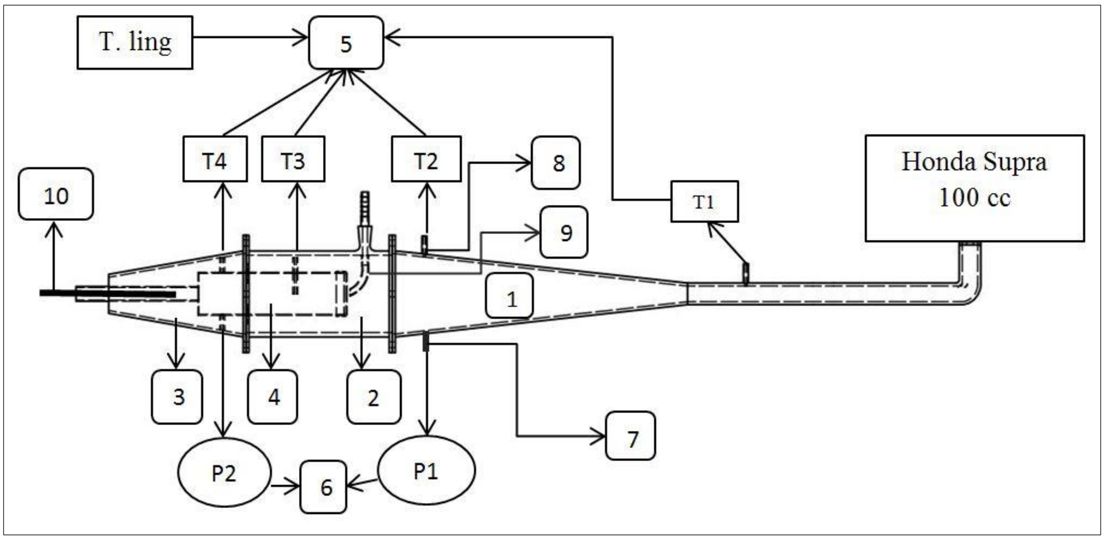

Figure 1 Schematic diagram of the experimental setup showing the modified exhaust system with activated charcoal adsorbent casing

3. Results and discussion

This study evaluated the effect of activated candlenut shell charcoal adsorbents, combined with varying oxygen injection rates, on the pressure and temperature distribution within the exhaust gas treatment system of a gasoline motorcycle. The results are presented in two sets of data: pressure differential profiles before and after the adsorbent casing, and thermal distribution profiles at selected positions along the exhaust system, particularly within the adsorbent housing.

3.1. Pressure Distribution Analysis

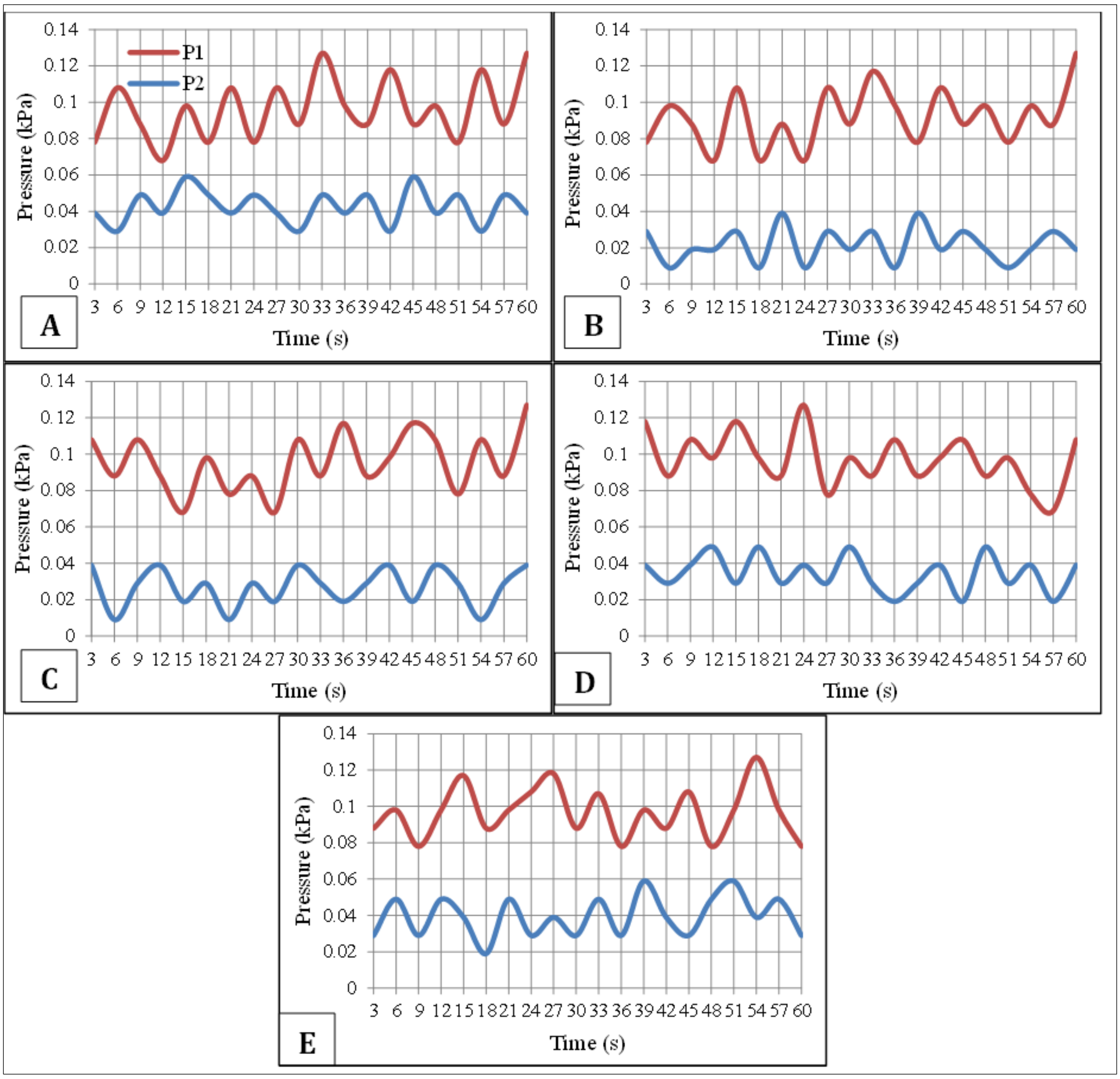

Figure 2 Pressure distribution: A. without AC, B. with AC, C. with AC + O_2 1 L/min, D. with AC + O_2 2 L/min, E. with AC + O_2 3 L/min

Figures 2. A to E depict the pressure profiles at two key positions: P1 (before the adsorbent casing) and P2 (after the adsorbent casing), over a 60-second observation period. Figure A serves as a baseline, where the motorcycle operated without the adsorbent. In this condition, the pressure difference (ΔP) between P1 and P2 remained minimal, indicating negligible flow resistance in the absence of any filtering medium.

In contrast, Figure B illustrates the condition with the insertion of activated charcoal adsorbent, without any oxygen injection. Here, a substantial increase in P1 was observed compared to P2, highlighting the presence of flow resistance across the adsorbent layer. This pressure drop is a clear indicator of the filtering activity, where the porous structure of the activated charcoal traps exhaust gas constituents such as CO, HC, and CO_2, resulting in energy loss in the flow stream. The existence of this pressure gradient confirms the physical adsorption process and flow obstruction due to particle deposition within the pores—phenomena corroborated by prior findings involving SEM and EDX analyses [13].

Figures 2.C to E demonstrate the effect of oxygen injection at increasing flow rates (1, 2, and 3 L/min, respectively). A noticeable trend of decreasing ΔP is recorded across these cases. The reduction in flow resistance suggests that oxygen assists in maintaining the cleanliness and functionality of the adsorbent pores by promoting oxidation of deposited hydrocarbons and CO, which would otherwise block the flow channels. This is consistent with earlier findings that indicate the addition of oxygen helps maintain the adsorbent's performance and ensures stable gas flow by preventing pore blockage and promoting the oxidation of residual pollutants [14,15].

These results provide a critical insight: while the presence of an adsorbent inevitably introduces flow resistance, controlled oxygen supplementation mitigates this issue by restoring partial permeability to the adsorbent. As the oxygen flow increases, the adsorbent operates more effectively, with lower pressure losses, thereby sustaining both filtering and flow efficiency.

3.2. Temperature Distribution Analysis

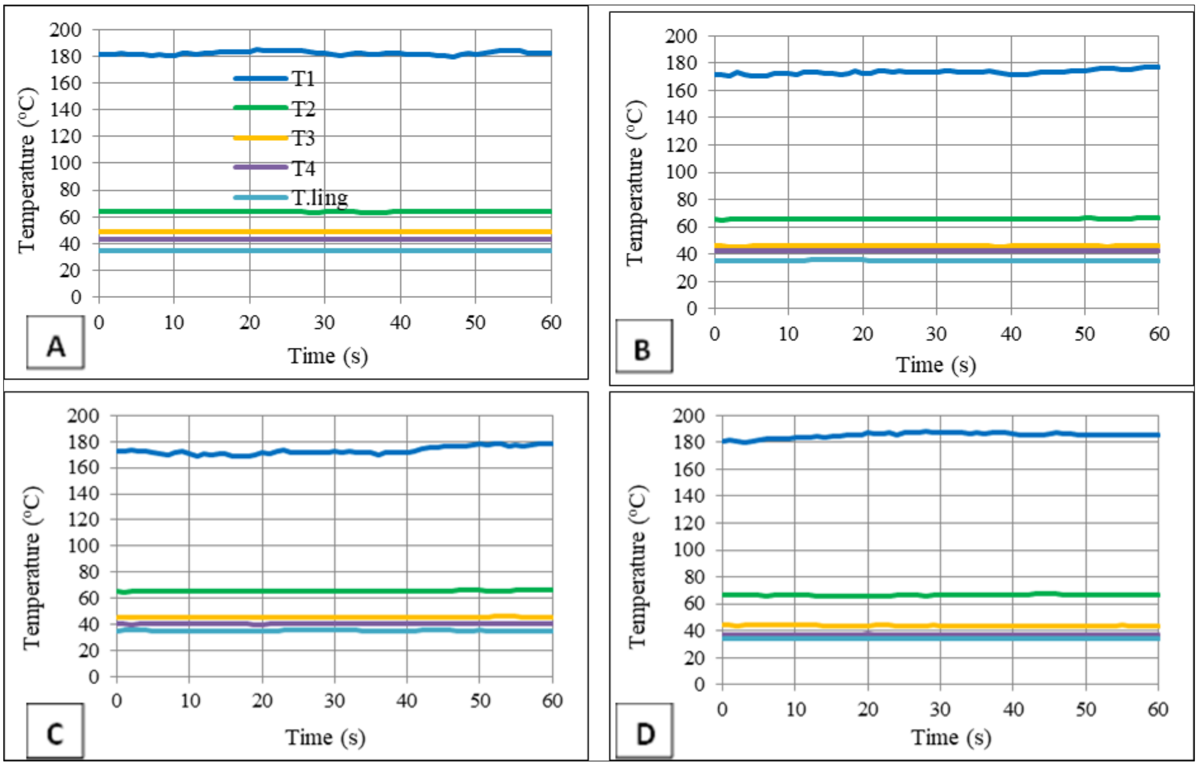

Figure 3 Temperature distribution: A. with candlenut shell AC adsorbent, B. AC + O_2 1 L/min, C. AC + O_2 2 L/min, D. AC + O_2 3 L/min

Figures 3.A to D show the temperature profiles at five specific points: T1 (post-exhaust valve, 35 cm downstream), T2 (pre-adsorbent casing), T3 (center of the casing), T4 (rear of the casing), and T.ling (ambient temperature). These profiles offer a comprehensive thermal characterization of the exhaust system under different oxygen injection scenarios.

In Figure 3.A (no oxygen), T1 consistently exhibits the highest temperature (~180°C), as expected from the immediate post-combustion zone. T2, T3, and T4 show progressively lower temperatures (~70°C to 50°C), indicating heat absorption and dissipation through the adsorbent material and casing wall. This pattern reflects the thermal buffering effect of the activated charcoal and suggests endothermic processes or thermal damping occurring within the filter medium.

Upon oxygen injection (Figures 3.B–D), particularly at 1 to 3 L/min, temperatures at T3 and T4 exhibit a clear upward trend. This increase can be attributed to exothermic oxidation reactions catalyzed by the additional oxygen, notably:

$$2CO+O_2 \rightarrow 2CO_2 \qquad (\Delta H<0)$$

$$C_xH_y+O_2 \rightarrow CO_2+H_2O \qquad \text{(exothermic)}$$

Such reactions not only improve gas emission profiles, as demonstrated in the previous work, but also raise the local temperature within the adsorbent bed. This effect is beneficial in facilitating continued oxidation and desorption of retained gases, effectively regenerating the adsorbent in situ. Nevertheless, the accumulation of excessive heat must be carefully controlled, as sustained high temperatures can potentially reduce the structural integrity and adsorption efficiency of biomass-based filter materials over extended periods of use [16,17].

The narrowing temperature differential between T2, T3, and T4 observed in Figure 3.D (oxygen 3 L/min) indicates a more uniform thermal distribution throughout the adsorbent casing. This thermal homogeneity implies a higher degree of oxidative reactivity across the adsorbent volume, improving gas treatment efficiency. Nevertheless, it also underscores the importance of selecting thermally robust casing materials and ensuring appropriate insulation to withstand the thermal stress induced by exothermic reactions.

3.3. **Integrated Interpretation and Design Implications**

The combined pressure and temperature analyses reinforce the critical role of oxygen in enhancing the dual performance of the adsorbent system. From a fluid dynamic perspective, oxygen reduces pressure drop across the adsorbent bed, ensuring smoother flow. Thermodynamically, oxygen increases internal temperatures through oxidation, thereby boosting adsorptive and catalytic reactions within the media. This synergy results in an overall improvement in emission reduction capacity while maintaining operational stability.

Therefore, the design of biomass-based emission control systems should incorporate:

- Optimization of oxygen injection rate to balance thermal reactivity and structural integrity,
- Monitoring of pressure differentials to assess filter saturation and clogging tendencies,
- Thermal mapping to prevent localized overheating and material fatigue.

These findings advocate for the expanded application of oxygen-assisted activated carbon filters in low-cost, decentralized emission control solutions, particularly for small-displacement internal combustion engines common in developing countries.

4. Conclusion

This experimental study has demonstrated the critical impact of oxygen-assisted adsorption on the pressure and temperature dynamics within a motorcycle exhaust system equipped with activated candlenut shell charcoal. The key findings are as follows:

- Pressure Analysis: The introduction of activated charcoal adsorbents led to a noticeable pressure drop across the casing, confirming flow resistance due to adsorption and particle accumulation. However, incremental increases in oxygen flow (1–3 L/min) consistently reduced the pressure differential (ΔP), indicating improved internal permeability and the restoration of adsorptive function through oxidative cleaning.
- Temperature Behavior: Internal temperature measurements revealed that oxygen injection elevated the thermal profile of the adsorbent bed. The temperature increase was most prominent at the center and outlet sections, attributed to exothermic oxidation reactions. These thermal effects are beneficial for enhancing reaction kinetics but must be managed to avoid thermal degradation of the adsorbent material.
- System Performance: The combined effect of pressure normalization and thermal activation suggests that controlled oxygen injection significantly improves the operational efficiency of the biomass-based emission control system.

In conclusion, the integration of activated charcoal with regulated oxygen injection offers a viable, low-cost strategy for reducing emissions and maintaining system performance in small-engine vehicles. Future research should explore long-term durability, optimal oxygen flow rates under dynamic engine loads, and integration strategies for commercial-scale applications

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial, personal, or professional relationships with individuals or organizations have influenced the outcome or content of this manuscript.

References

[1] Odunlami OA, Oderinde OK, Akeredolu FA, Sonibare JA, Obanla OR, Ojewumi ME. (2022). The effect of air-fuel ratio on tailpipe exhaust emission of motorcycles. Fuel Communications, 11, 100040.

[2] Pechout M, Jindra P, Hart J, Vojtisek-Lom M. (2022). Regulated and unregulated emissions and exhaust flow measurement of four in-use high performance motorcycles. Atmospheric Environment, X, 14, 100170.

[3] Nguyen YL, Le AT, Duc KN, Duy VN, Nguyen CD. (2021). A study on emission and fuel consumption of motorcycles in idle mode and the impacts on air quality in Hanoi, Vietnam. International Journal of Urban Sciences, 25(4), 522–541.

[4] Zhang J, Duan C, Huang X, Meng M, Li Y, Huang H, Wang H, Yan M, Tang X. (2024). A review on research progress and prospects of agricultural waste-based activated carbon: preparation, application, and source of raw materials. Journal of Materials Science, 59(13), 5271–5292.

[5] Yunus ZM, Al-Gheethi A, Othman N, Hamdan R, Ruslan NN. (2022). Advanced methods for activated carbon from agriculture wastes; a comprehensive review. International Journal of Environmental Analytical Chemistry, 102(1), 134–158.

[6] Saleh TS, Badawi AK, Salama RS, Mostafa MM. (2023). Design and development of novel composites containing nickel ferrites supported on activated carbon derived from agricultural wastes and its application in water remediation. Materials, 16(6), 2170.

[7] Hidayat S, Mudaim S. (2022). Study of chemical structure and electrical properties of nitrogen-doped activated carbon from candlenut shell (Aleurites moluccana). JIIF (Jurnal Ilmu dan Inovasi Fisika), 6(2), 166–173.

[8] Maniarasu R, Rathore SK, Murugan S. (2022). Preparation, characterization, and performance of activated carbon for CO_2 adsorption from CI engine exhaust. Greenhouse Gases: Science and Technology, 12(2), 284–304.

[9] Karimi M, Wang X, Hamilton J, Negnevitsky M. (2022). Numerical investigation on hydrogen-diesel dual-fuel engine improvements by oxygen enrichment. International Journal of Hydrogen Energy, 47(60), 25418–25432.

[10] Ma Z, Zhang K, Xiang H, Gu J, Yang M, Deng K. (2023). Experimental study on influence of high exhaust backpressure on diesel engine performance via energy and exergy analysis. Energy, 263, 125788.

[11] Murali R, Shahriman AB, Razlan ZM, Ahmad WK, Azizul AI, Rojan MA, Ma'arof MI, Radzuan MA, Hassan MA, Ibrahim Z. (2021). A review on the correlation between exhaust backpressure and the performance of IC engine. In Journal of Physics: Conference Series, 2051(1), 012044. IOP Publishing.

[12] Tira HS, Wirawan M, Zulkarnaen WK. (2023). The use of activated charcoal of candlenut shell (Aleurites moluccana) as adsorbent to reduce motorcycle emissions. In AIP Conference Proceedings, 2609(1). AIP Publishing.

[13] Usman F, Zeb B, Alam K, Huang Z, Shah A, Ahmad I, Ullah S. (2022). In-depth analysis of physicochemical properties of particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) and its characterization through FTIR, XRD and SEM–EDX Techniques in the Foothills of the Hindu Kush Region of Northern Pakistan. Atmosphere, 13(1), 124.

[14] Hamilton FW, Gregson FK, Arnold DT, Sheikh S, Ward K, Brown J, Moran E, White C, Morley AJ, Bzdek BR, Reid JP. (2022). Aerosol emission from the respiratory tract: an analysis of aerosol generation from oxygen delivery systems. Thorax, 77(3), 276–282.

[15] Elnajjar E, Al-Omari SA, Selim MY, Purayil ST. (2022). CI engine performance and emissions with waste cooking oil biodiesel boosted with hydrogen supplement under different load and engine parameters. Alexandria Engineering Journal, 61(6), 4793–4805.

[16] Lee H, Choi K, Jang YC, Cho H, Baek C, Herlintama SA, Lee S, Lee J, Park I, Jeong G. (2025). Study on Filter Manufacturing Using Lignocellulosic Biomass and Greenhouse Gas Reduction Assessment. New & Renewable Energy, 21(1), 46–55.

[17] Raj R, Singh DK, Tirkey JV. (2022). Co-gasification of Low-grade coal with Madhuca longifolia (Mahua) biomass and dual-fuelled mode engine performance: Effect of biomass blend and engine operating condition. Energy Conversion and Management, 269, 116150.