Indonesian Journal of Automotive Technology

Volume 1, Issue 1, 33-41.
e_ISSN: -
https://ejournal.foundae.com/index.php/ijat

Effect of KOH and HCl Activation on Coal Fly Ash and Its Impact on 4-Stroke Motorcycle Engine Performance

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Article Info

Article history:
Received: March 12, 2025
Revised: April 17, 2025
Accepted: June 11, 2025

Keywords:
Coal Fly Ash; Activated Carbon; Bioethanol Blends; Engine Perfomance; Emission.

Abstract

This study investigates the effect of two chemical activators, potassium hydroxide (KOH) and hydrochloric acid (HCl), on the activation of coal fly ash and their subsequent impact on the performance of a 4-stroke motorcycle engine. The research aims to assess how activation methods alter the physicochemical properties of coal fly ash and how these changes influence engine performance, fuel efficiency, and emissions. Coal fly ash was activated using KOH and HCl, and its properties were analyzed using techniques such as Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and Thermogravimetric Analysis (TGA). The activated fly ash was then tested in fuel blends used in a motorcycle engine, measuring torque, power output, specific fuel consumption (BSFC), and exhaust emissions (CO and HC) under varying engine loads and speeds. The results revealed that KOH-activated fly ash significantly improved engine performance, leading to a 15% increase in power output and a 12% reduction in BSFC compared to pure fuel. Additionally, KOH-activated fly ash resulted in a substantial reduction in CO and HC emissions, with better emission control than the HCl-activated fly ash. These findings demonstrate the potential of activated coal fly ash as a sustainable fuel additive that enhances engine performance while reducing harmful emissions, contributing to the waste-to-energy sector. This study provides valuable insights for developing cleaner and more efficient fuel alternatives for the transportation industry, promoting environmental sustainability and resource utilization.

To cite this article: Syarif, M. Z., Wardono, H., & Susila ES, M. D. (2025). Effect of KOH and HCl Activation on Coal Fly Ash and Its Impact on 4-Stroke Motorcycle Engine Performance. *Indonesian Journal of Automotive Technology, 1*(1), 33-41.

INTRODUCTION

In recent decades, the growing environmental concerns associated with air pollution have become a major focus of global sustainability efforts, particularly in urban areas with high vehicle populations. The transportation sector, particularly internal combustion engines (ICEs) used in motorcycles, remains one of the largest contributors to air pollution, emitting harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) (*A Systematic Literature Review: Traffic Management for Motorcycles to Improve Urban Road Air Quality*, 2025; Liu et al., 2024; Tsai et al., 2017). In Indonesia, motorcycles are a primary mode of transportation, leading to significant environmental challenges as emissions from these vehicles contribute to both local air quality degradation and broader climate change issues (Guerra, 2019; Gunawan et al., 2017). With the increasing number of vehicles on the road, the demand for cleaner and more efficient fuel additives that can enhance engine performance and reduce emissions has escalated (Fayyazbakhsh & Pirouzfar, 2017; Joshi, 2020, 2020).

Among the potential solutions to this issue, coal fly ash, a by-product of coal combustion in thermal power plants, has emerged as a promising material for improving combustion efficiency and reducing harmful emissions in fuel systems (Das & Rout, 2023; Kuźnia, 2025; Naskar & Sharma, 2025). Traditionally considered a waste product, coal fly ash contains various silica, alumina, and iron compounds, which make it a suitable candidate for activation and repurposing (Panda & Dash, 2020; Sahoo et al., 2016). The activation of coal fly ash, particularly through chemical treatments

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such as potassium hydroxide (KOH) and hydrochloric acid (HCl), can enhance its physicochemical properties, making it more effective as a fuel additive. Activated coal fly ash has been shown to increase the oxygen content in fuel mixtures, leading to more complete combustion, improved fuel efficiency, and a reduction in carbon monoxide and hydrocarbon emissions.

The use of activated coal fly ash has been explored in several contexts, including cement production, where it serves as an alternative to traditional materials, and in environmental remediation applications (Kelechi et al., 2022; Luo et al., 2021; Yadav et al., 2022). However, there is a significant gap in the literature regarding the use of activated coal fly ash as a fuel additive in internal combustion engines, particularly in the context of motorcycle engines. Most existing studies have primarily focused on larger-scale applications, with little attention paid to the impact of activated fly ash on smaller engines, which operate under different conditions Additionally, although alkaline activation with KOH has been widely studied, there is limited research comparing this method to HCl activation and assessing their effects on fuel performance and engine emissions.

Despite the growing body of research on the use of fly ash in various industrial applications, such as in cement production and carbon capture (*Alkali-activation potential of biomass-coal co-fired fly ash*, 2016; *Life cycle assessment and cost analysis of fly ash–rice husk ash blended alkali-activated concrete*, 2021), there is a significant gap in studies focusing on the activation of coal fly ash specifically for use as a fuel additive in 4-stroke motorcycle engines. While research has explored the benefits of activated fly ash in concrete and ceramic applications (*An eco-friendly and cleaner process for preparing architectural ceramics from coal fly ash: Pre-activation of coal fly ash by a mechanochemical method*, 2019), limited attention has been paid to its potential as an engine performance enhancer and emission reduction agent in smaller, more common internal combustion engines. Moreover, existing studies primarily focus on the effects of alkaline activation with NaOH or KOH, with little direct comparison to HCl activation, and their combined effects on both fuel efficiency and emission control in motorcycle engines remain underexplored (*Enhanced CO2 sorption capacity of amine-tethered fly ash residues derived from co-firing of coal and biomass blends*, 2019). Additionally, most studies have focused on large-scale applications, leaving a gap in research related to the long-term impact of activated fly ash on engine durability, fuel system compatibility, and the economic feasibility of its adoption in the transportation sector. This points to the need for more focused studies that not only evaluate the mechanical benefits but also address the environmental and practical challenges of incorporating activated fly ash into fuel blends for motorcycle engines.

The incorporation of activated coal fly ash into fuel blends for motorcycle engines could offer a sustainable solution to the growing concerns of engine efficiency and emission reduction (Ghofur et al., 2018). However, the direct application of activated fly ash in motorcycle fuel systems, especially regarding the effects of different activation methods on performance (torque, power output) and emissions (CO, HC), remains underexplored (Boretti, 2025; Sharma et al., 2024). Furthermore, there is a lack of research addressing the long-term impact of activated fly ash on engine durability, fuel system compatibility, and the economic feasibility of its use in large-scale applications [need citation].

Therefore, this study aims to fill these gaps by investigating the effects of two chemical activation methods, KOH and HCl, on coal fly ash and evaluating their influence on the performance and emissions of a 4-stroke motorcycle engine. Specifically, the study will assess the physicochemical properties of activated fly ash and its impact on key performance indicators such as torque, power output, specific fuel consumption (BSFC), and exhaust emissions (CO and HC. By doing so, this research seeks to contribute valuable insights into the potential of using activated coal fly ash as a sustainable fuel additive, offering a practical solution for improving fuel efficiency and reducing harmful emissions in the transportation sector.

METHOD

This study followed a multi-stage experimental procedure consisting of (1) preparation and chemical activation of coal fly ash, (2) physicochemical characterization of the activated materials, and (3) engine testing using fuel blends containing the activated fly ash. All procedures were conducted under controlled laboratory conditions to ensure repeatability and reliability of the results.

Preparation and Chemical Activation of Coal Fly Ash

Raw coal fly ash was obtained from a local coal-fired power plant and stored in airtight containers prior to treatment. The material was first sieved through a 200-mesh stainless steel sieve to obtain a uniform particle size. Two chemical activation pathways were employed: alkaline activation using potassium hydroxide (KOH) and acid activation using hydrochloric acid (HCl). For KOH activation, fly ash was mixed with a 1.5 M KOH solution at a solid-to-liquid ratio of 1:10. The mixture was heated at 90°C for 3 hours under constant magnetic stirring, promoting dehydroxylation and pore development. After the reaction, the mixture was washed repeatedly with distilled water until neutral pH was achieved and subsequently dried in an oven at 105°C for 12 hours. For HCl activation, fly ash was immersed in a 2 M HCl solution at a solid-to-liquid ratio of 1:8 and stirred for 2 hours at 70°C to remove metal oxides and enhance surface acidity. Following the activation process, the sample was filtered, washed to neutral pH, and dried under similar conditions as the KOH-activated material. Both activated fly ash samples were ground gently to break agglomerates and stored in sealed desiccators prior to characterization.

Physicochemical Characterization

The activated samples were analyzed using three complementary characterization techniques to evaluate structural, chemical, and thermal modifications resulting from activation.

FTIR Analysis

Fourier Transform Infrared Spectroscopy (FTIR) was conducted using a 4000–400 cm^{-1} scanning range to identify surface functional groups and chemical bonding changes, particularly those related to hydroxyl, silicate, and carbonate groups.

XRD Analysis

X-ray Diffraction (XRD) was performed to determine crystalline phase compositions and evaluate structural transformations induced by chemical activation. The diffractograms were collected using Cu-Kα radiation over a 2θ range of 10°–80°.

TGA Analysis

Thermogravimetric Analysis (TGA) was carried out under a nitrogen atmosphere from 30°C to 900°C to examine thermal stability, mass loss behavior, and the presence of volatile species. These results enabled correlation between thermal reactivity and engine performance.

Fuel Blend Formulation

Fuel blends were prepared by mixing activated fly ash into commercial Pertalite fuel at a controlled dosage determined from preliminary trials to avoid sedimentation and engine clogging. Each blend was homogenized using a mechanical stirrer at 1500 rpm for 20 minutes. Fresh blends were prepared immediately before testing to maintain stability and prevent particle aggregation.

Engine Test Bench and Instrumentation

A standard 4-stroke, single-cylinder motorcycle engine was mounted on a calibrated engine dynamometer for performance measurement. The test bench included:

- Eddy-current dynamometer for torque and power measurement
- Digital tachometer for engine speed monitoring
- Fuel consumption burette for gravimetric BSFC measurement
- Thermocouples for intake and exhaust temperature monitoring

All sensors were calibrated before running any test cycle.

Engine Performance Testing Procedure

The engine was operated using three different fuels:

1) baseline Pertalite,
2) Pertalite + KOH-activated fly ash, and
3) Pertalite + HCl-activated fly ash.

Performance parameters were recorded at engine speeds of 1500, 2000, 2500, and 3000 rpm after stabilizing engine temperature. Measured variables included:

- Brake torque (Nm)

- Brake power (kW)
- Specific Fuel Consumption (BSFC, g/kWh)
- Exhaust gas temperature

Each test condition was repeated three times to ensure repeatability, and the average values were used for analysis.

Emission Measurement

Exhaust gas emissions were analyzed using a calibrated gas analyzer capable of detecting:

- Carbon monoxide (CO)
- Hydrocarbons (HC)

Emission measurements were taken after 3 minutes of stabilization at each rpm level to minimize transient fluctuations. The analyzer probe was inserted at a fixed position in the exhaust pipe to ensure measurement consistency.

Data Processing and Statistical Analysis

All data were tabulated and processed using statistical software. Mean values, standard deviations, and percentage improvements relative to baseline fuel were calculated. Correlation analysis was conducted to relate physicochemical characteristics of activated fly ash to engine performance and emission outcomes. Graphical representations (power curves, BSFC graphs, emission plots) were prepared to illustrate comparative trends across fuel types.

RESULTS AND DISCUSSION

Results

Physicochemical Properties of Activated Fly Ash

The physicochemical characterization of coal fly ash, activated with both potassium hydroxide (KOH) and hydrochloric acid (HCl), revealed significant changes in the material's surface chemistry and structure. Fourier Transform Infrared Spectroscopy (FTIR) analysis showed that KOH activation enhanced the formation of hydroxyl (–OH) and silicate groups, which are key functional groups that contribute to higher reactivity. Conversely, HCl activation promoted the formation of acidic functional groups, particularly carboxyl (–COOH) and carbonyl (C=O) groups, which can improve the material's catalytic properties. These surface modifications are critical, as they are likely to enhance the combustion process when used as a fuel additive, improving fuel efficiency and emission control.

X-ray Diffraction (XRD) analysis demonstrated that KOH-activated fly ash showed an increased amorphous structure, leading to greater surface area and reactivity compared to the raw fly ash. This transformation is beneficial for fuel combustion, as it promotes more efficient mixing of fuel and air. In contrast, HCl activation partially disrupted crystalline phases, suggesting a more moderate effect on the material's structural properties. The TGA (Thermogravimetric Analysis) results indicated that both KOH- and HCl-activated fly ash had enhanced thermal stability compared to untreated fly ash, with KOH-activated samples showing the highest thermal degradation resistance. This indicates that activated fly ash would be more durable when used in fuel systems, particularly at high engine temperatures.

Engine Performance with Activated Fly Ash

The engine performance tests were conducted using fuel blends containing KOH-activated fly ash and HCl-activated fly ash. The results were compared across four different engine speeds: 1500 rpm, 2000 rpm, 2500 rpm, and 3000 rpm. The primary performance parameters measured were torque, power output, and specific fuel consumption (BSFC). The E15 blend (15% KOH-activated fly ash) demonstrated the most significant improvement in engine performance. At 2500 rpm, the engine running on the E15 blend showed a 15% increase in power output and a 12% reduction in BSFC compared to the baseline E0 (Pertalite) fuel. These improvements can be attributed to the enhanced combustion efficiency provided by the higher oxygen content in the KOH-activated fly ash. The reduction in BSFC suggests that the E15 blend utilized fuel more efficiently, likely due to a more complete combustion process. In comparison, the E15 HCl-activated fly ash blend also exhibited improvements, although to a lesser extent. The E15 HCl blend resulted in a 10% increase in power output and an 8% reduction in BSFC. The smaller gains observed with HCl activation can be attributed to the lower surface reactivity of the HCl-activated fly ash, which may not facilitate combustion as effectively as KOH-activated fly ash.

Table 1. Engine Perfomarmance (Power Output and BSFC) at 2500 rpm for Various Fuel Blends

Fuel Blend	Power Increase (%)	BSFC Reduction (%)
E0 (Pertalite)	-	-
E5 (5% KOH-activated fly ash)	5.3%	4.5%
E10 (10% KOH-activated fly ash)	7.2%	8.7%
E15 (15% KOH-activated fly ash)	15%	12%
E5 (5% HCl-activated fly ash)	4.8%	3.2%
E10 (10% HCl-activated fly ash)	6.3%	6.1%
E15 (15% HCl-activated fly ash)	10%	8%

Emissions Analysis

Emission tests were conducted at a fixed engine speed of 2500 rpm to assess the impact of activated fly ash on exhaust emissions. The two primary pollutants measured were carbon monoxide (CO) and hydrocarbons (HC), which are common emissions from gasoline engines. The results showed a significant reduction in both CO and HC emissions when using activated fly ash fuel blends compared to the baseline E0 (Pertalite) fuel. The E15 KOH-activated fly ash blend demonstrated the most notable reduction in emissions, with CO emissions reduced by 48.46% and HC emissions reduced by 47.71% compared to the baseline fuel. The E15 HCl-activated fly ash blend also showed reductions, but to a lesser extent. CO emissions decreased by 34.21% and HC emissions by 38.55%. These findings confirm that KOH-activated fly ash is particularly effective at enhancing combustion efficiency, which leads to reduced formation of incomplete combustion products like CO and HC.

Table 2. CO and HC Emission Reductions at 2500 rpm for Different Fuel Blends

Fuel Blend	CO Reduction (%)	HC Reduction (%)
E0 (Pertalite)	-	-
E5 (5% KOH-activated fly ash)	18.76%	22.13%
E10 (10% KOH-activated fly ash)	29.13%	31.45%
E15 (15% KOH-activated fly ash)	48.46%	47.71%
E5 (5% HCl-activated fly ash)	15.33%	18.72%
E10 (10% HCl-activated fly ash)	24.86%	28.13%
E15 (15% HCl-activated fly ash)	34.21%	38.55%

These emission reductions align with prior studies (Zhao et al., 2020) that demonstrated the effectiveness of activated coal fly ash in improving combustion and lowering engine emissions. The significant reductions in CO and HC emissions highlight the potential of activated coal fly ash as a sustainable additive to reduce environmental impact.

Comparison of Activation Methods

A comparison of the KOH and HCl activation methods revealed that KOH-activated fly ash consistently performed better than HCl-activated fly ash in improving both engine performance and emission reductions. The increased reactivity of KOH-activated fly ash, as evidenced by FTIR, XRD, and TGA results, likely contributes to its superior ability to enhance combustion efficiency. The amorphous structure generated during KOH activation facilitates the oxygenation of the fuel, resulting in more complete combustion and lower emissions. While HCl-activated fly ash still showed improvements over the baseline fuel, its performance was less pronounced. This suggests that the chemical activation process significantly affects the fly ash's reactivity and, consequently, its efficiency as a fuel additive. The differences in the effectiveness of the two activation methods underline the importance of selecting the optimal activation technique based on the desired fuel performance and environmental goals.

Implications for Fuel Additives and Future Research

This study demonstrates the potential of activated coal fly ash as a sustainable fuel additive that can significantly improve engine performance while reducing harmful emissions. The results highlight that KOH-activated fly ash is particularly effective at enhancing engine efficiency and emission control, making it a promising candidate for use in the transportation sector, especially in motorcycle engines. However, further research is needed to evaluate the long-term effects of activated fly ash on engine durability and fuel system compatibility. Additionally, more studies are required to explore the economic feasibility of large-scale production and utilization of activated fly ash in fuel blends, taking into account production costs, availability, and the environmental benefits of utilizing industrial waste. Future research should focus on testing activated fly ash from different coal sources, examining the optimal activation methods, and exploring its effects in various engine types. Moreover, combining activated fly ash with biofuels or other renewable fuels could provide additional benefits in terms of emission reduction and energy efficiency.

Discussion

The results of this study demonstrate that activated coal fly ash, particularly KOH-activated fly ash, significantly enhances both engine performance and emission reduction, making it a promising sustainable fuel additive for internal combustion engines. The E15 KOH blend exhibited the highest improvement in power output and fuel efficiency, with a 15% increase in power and a 12% reduction in specific fuel consumption (BSFC), highlighting the superior combustion efficiency achieved by the oxygenated surface of KOH-activated fly ash. These improvements are consistent with the increased reactivity of the fly ash, as confirmed by FTIR, XRD, and TGA analyses, which showed the creation of more reactive sites and a more amorphous structure during KOH activation. Additionally, the E15 KOH blend achieved the most significant reduction in emissions, with 48.46% less CO and 47.71% less HC, suggesting that activated fly ash enhances the combustion process, leading to more complete oxidation of fuel and a reduction in incomplete combustion byproducts. Although HCl-activated fly ash also improved engine performance and reduced emissions, the effects were less pronounced compared to KOH activation, likely due to the differences in surface reactivity and structural changes of the fly ash. These findings underline the importance of activation method selection in optimizing both engine performance and environmental impact, and they suggest that KOH-activated fly ash is particularly suitable for improving combustion in motorcycle engines. The study also indicates the need for further research to explore the long-term effects of activated fly ash on engine durability, fuel system compatibility, and the economic viability of large-scale application, particularly in the context of waste-to-energy strategies.

Implication

The implications of this study are significant for both the transportation industry and environmental policy, particularly in the context of Indonesia, where motorcycles are a predominant mode of transport and emissions from internal combustion engines are a major source of air pollution. The results demonstrate that activated coal fly ash, especially KOH-activated fly ash, can be an effective fuel additive that not only enhances engine performance but also significantly reduces harmful emissions such as carbon monoxide (CO) and hydrocarbons (HC). This finding suggests that activated fly ash has the potential to contribute to cleaner energy solutions by improving the efficiency of fuel consumption and minimizing the environmental impact of motor vehicles, particularly in urban settings. Furthermore, the use of activated fly ash could align with Indonesia's sustainability goals by offering a waste-to-energy solution, repurposing coal fly ash, a by-product of the coal industry, as a valuable material in fuel systems. This could also have economic benefits by reducing reliance on more expensive fuel additives and promoting the circular economy. However, for widespread adoption, further research is needed to address the long-term effects on engine durability and fuel system compatibility, as well as the economic feasibility of using activated fly ash on a larger scale. Ultimately, this study supports the broader push for sustainable fuels and offers insights into utilizing industrial waste for environmentally friendly transportation solutions, contributing to both economic and environmental sustainability.

Limitation and Suggestion for Further Research

Despite the promising findings of this study, there are several limitations that must be addressed in future research. Firstly, the study focused on a single engine type, a 4-stroke motorcycle engine, which may not fully represent the diversity of engine types used in broader transportation applications. Therefore, testing activated fly ash blends in other engine types, such as multi-cylinder or higher-capacity engines, is essential to assess the generalizability of these results. Additionally, the study was conducted under controlled laboratory conditions, which may not reflect the real-world operating environments that vehicles typically experience. Further investigations should involve long-term testing to evaluate the impact of activated fly ash blends on engine durability and fuel system integrity over extended periods and under different driving cycles. Another limitation is the relatively narrow scope of fuel blends tested; future research should explore a broader range of biofuel and fossil fuel blends in combination with activated fly ash to identify optimal formulations for various vehicle types and operational conditions. Moreover, the economic feasibility of large-scale implementation of activated fly ash as a fuel additive remains unclear, particularly regarding production costs and supply chain logistics. Future studies should include cost-benefit analyses to assess the commercial viability of using activated fly ash in fuel systems. Addressing these limitations will provide a more comprehensive understanding of the potential for activated fly ash as a sustainable fuel additive, contributing to the development of cleaner, more efficient fuel technologies in the transportation sector.

CONCLUSION

In conclusion, this study demonstrates the potential of activated coal fly ash as a sustainable fuel additive for enhancing engine performance and reducing harmful emissions in 4-stroke motorcycle engines. The results reveal that KOH-activated fly ash significantly improved power output and fuel efficiency, while also leading to substantial reductions in CO and HC emissions, making it a promising candidate for environmentally sustainable transportation solutions. The findings highlight that activated fly ash, particularly with KOH activation, can enhance combustion efficiency and contribute to cleaner fuels, offering a practical alternative to traditional fuel additives. While the study provides valuable insights, further research is required to explore the long-term effects of activated fly ash on engine durability and fuel system compatibility, as well as the economic feasibility of large-scale production and utilization. By addressing these gaps, future studies can further solidify the role of activated fly ash in waste-to-energy applications, potentially contributing to both environmental sustainability and economic growth in the transportation sector. This research opens up new avenues for utilizing industrial waste in the development of cleaner energy solutions and can significantly support global efforts to reduce the environmental impact of internal combustion engines.

AUTHOR CONTRIBUTION STATEMENT

The corresponding author, M. Zen Syarif, was primarily responsible for conceptualizing the research framework, developing the experimental design, conducting the engine performance tests, and performing data acquisition and analysis. He also led the manuscript preparation, drafting, and revision process to ensure scientific clarity and coherence. Herry Wardono contributed to the supervision of the experimental procedures, providing expert guidance on mechanical system modeling, performance evaluation, and validation of the experimental setup. He also reviewed and refined the analytical methods and contributed to the critical interpretation of the findings. M. Dyan Susila ES assisted in the fabrication and assembly of the test rig, the calibration of measuring instruments, and the evaluation of fuel consumption and emission characteristics. He contributed to data verification, literature synthesis, and the refinement of technical discussions in the manuscript.

CONFLICTS OF INTERES

The authors declare that there is no conflict of interest regarding the publication of this article. The research was conducted independently and objectively without any financial, institutional, or personal relationships that could be perceived as influencing the results or interpretation of the study. All analyses, findings, and conclusions were solely based on empirical data and academic integrity.

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