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Renewable Fuel-Air Optimization Using Zeolite–Fly Ash Hybrid Filters to Enhance Diesel Engine Efficiency

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Abstract

The present research explores the enhancement of diesel engine efficiency through the use of an innovative hybrid air filtration system composed of natural zeolite and coal fly ash. The study was designed to improve the combustion process by enriching the intake air with oxygen while simultaneously reducing harmful exhaust emissions. The hybrid materials were subjected to physical activation at 225°C for one hour to enhance their porosity and adsorption capability. Experimental tests were performed on a single-cylinder, four-stroke diesel engine using five composition ratios (Z0F100, Z25F75, Z50F50, Z75F25, and Z100F0) and three filter masses (50 g, 75 g, and 100 g) at rotational speeds of 1500, 2000, and 2500 rpm. Performance parameters, including brake power, brake specific fuel consumption (bsfc), and exhaust opacity, were carefully examined. The results revealed that the physically activated zeolite–fly ash composite effectively improved combustion quality and overall energy efficiency. The most notable enhancement was achieved with the Z50F50 composition at 100 g, yielding a 2.825% increase in brake power and a 7.805% reduction in bsfc. The Z25F75 composition demonstrated the greatest reduction in exhaust opacity, reaching 38.65%. These findings confirm that zeolite–fly ash hybrid filters provide a cost-efficient, sustainable, and environmentally responsible solution for improving engine performance, reducing fuel consumption, and advancing cleaner combustion technologies for modern diesel systems.

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INTRODUCTION

Diesel engines continue to serve as vital energy converters across transportation, agriculture, and industrial applications due to their robustness, reliability, and relatively high thermal efficiency (Gerald Liu & Munnannur, 2020; Milojević et al., 2025; Oloyede et al., 2024). Nonetheless, their extensive utilization contributes substantially to air pollution and greenhouse gas accumulation, primarily through emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (Kantaroğlu, 2025; Khanna et al., 2025; Odubo & Kosoe, 2024; Tomlin, 2021). These pollutants are recognized as major drivers of urban air degradation and climate change, underscoring the need for cleaner combustion strategies (Maji et al., 2023; Slovic et al., 2016). Improving combustion efficiency and reducing fuel consumption are therefore considered key priorities in achieving more sustainable diesel technologies (Barone et al., 2023; Beatrice et al., 2016; Chala et al., 2018). One promising solution involves optimizing the air–fuel mixture, thereby promoting more complete combustion without requiring significant engine redesign (Dahham et al., 2022; Hao et al., 2021; Khedr et al., 2025).

The oxygen content of intake air plays a central role in determining both engine efficiency and exhaust composition (Baskar & Senthil Kumar, 2017; Dziubak & Karczewski, 2022; Yang et al., 2021). Greater oxygen availability enables more complete oxidation of fuel hydrocarbons, which reduces the formation of toxic emissions and enhances overall energy conversion (He & Wang, 2015). Conventional air filters, however, are designed primarily for particle removal and have limited capability to alter the chemical characteristics of the air entering the combustion chamber (Henning

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et al., 2021; Liu et al., 2020). This limitation has motivated the exploration of functionalized filtration media those capable not only of trapping particulates but also of enriching oxygen concentration through adsorption mechanisms. Such an approach provides an opportunity to integrate air purification and combustion enhancement in a single, low cost system.

Among the materials with strong potential for this application, natural zeolite and fly ash have attracted considerable interest (Alterary & Marei, 2021; Feng et al., 2018; Mlonka-Mędrala, 2023). Zeolite, a crystalline aluminosilicate mineral, possesses a microporous framework with a high specific surface area and selective adsorption affinity for polar molecules (de Pietre & Freitas, 2021; Kordala & Wyszkowski, 2024; Pérez-Botella et al., 2022). Its ability to capture nitrogen and water vapor can indirectly increase the relative oxygen content of intake air (Shahpouri & Houshfar, 2019; Zhu et al., 2015). Fly ash, a by-product of coal combustion, contains silica and alumina that contribute to its chemical reactivity and porous structure (Kuźnia, 2025)**.** The combination of these two materials into a hybrid composite can result in synergistic adsorption and structural stability, offering both performance and sustainability advantages. Moreover, the utilization of industrial waste such as fly ash aligns with the principles of circular economy and green engineering by transforming waste into value-added functional materials.

Despite numerous studies on zeolite and fly ash within environmental and material science domains, their integration into air filtration systems for internal combustion engines has rarely been examined (Ge et al., 2018)**.** Zeolite-based filters have demonstrated efficacy in water purification and air particulate removal (*Comparison of activated carbon and zeolites' filtering efficiency in freshwater*, 2019; *Effective removal of particulate matter from air by using zeolite-coated filters*, 2020; *Zeolite cotton in tube: A simple robust household water treatment filter for heavy metal removal*, 2020), while fly ash composites have been predominantly investigated for mechanical and thermal enhancement in construction materials and green concrete (*Effect of fly ash particle size on thermal and mechanical properties of fly ash-cement composites*, 2018; *Enhanced properties of graphene/fly ash geopolymeric composite cement*, 2015; *Green concrete composite incorporating fly ash with high strength and fracture toughness*, 2018). More recent investigations on zeolite–fly ash hybrids have highlighted their adsorption and photocatalytic capabilities for pollutant removal from aqueous media (*Fusion-assisted hydrothermal synthesis and post-synthesis modification of mesoporous hydroxy sodalite zeolite prepared from waste coal fly ash for biodiesel production*, 2022; *Zeolite composite materials from fly ash: An assessment of physicochemical and adsorption properties*, 2023; Sharma et al., 2025). However, their potential for improving diesel combustion efficiency through oxygen enrichment has not been adequately addressed [need citation]. To date, no comprehensive study has evaluated the influence of physically activated zeolite–fly ash hybrid filters on diesel engine performance, particularly in relation to variations in composition ratio, filter mass, and their collective impact on brake power, fuel economy, and exhaust emissions [need citation]. This represents a critical knowledge gap that bridges material adsorption science with sustainable engine technology.

The primary objective of this study is to assess the performance of physically activated zeolite–fly ash hybrid air filters as a means to enhance the efficiency of diesel engine combustion. By systematically varying filter composition and mass, this research aims to identify optimal configurations that maximize brake power, minimize specific fuel consumption, and reduce exhaust opacity. The outcomes are expected to advance the development of environmentally friendly, cost-effective filtration technologies that contribute to cleaner combustion systems and align with the broader goals of sustainable energy and emission reduction.

METHOD

Research Design

This study was designed as an experimental quantitative investigation to analyze the effect of physically activated zeolite–fly ash composite air filters on the performance of a four-stroke single-cylinder diesel engine. The main independent variables were (1) the composition ratio of zeolite to fly ash and (2) the mass of the filter pellets, while the dependent variables were brake power (bP), brake specific fuel consumption (bsfc), and exhaust gas opacity. Engine speed was varied at three levels (1500, 2000, and 2500 rpm) to observe performance behavior under different operating conditions. Each test combination was replicated three times to ensure experimental consistency and reliability

Equipment and Instrumentation

The experimental setup was located at the Mechanical Engineering Laboratory, Universitas Lampung, and included the following major instruments:

1. Test engine: A Robin-Fuji DY23D single-cylinder, four-stroke diesel engine with direct injection and air cooling. This engine type was selected due to its stable operation and suitability for small-scale fuel consumption analysis.
2. Dynamometer: A TD-114 dynamometer was employed to measure torque output at various engine speeds under a constant mechanical load of 2.5 kg. The load was maintained constant to enable consistent comparison of the filter's influence on engine performance.
3. Tachometer: A digital tachometer was used to monitor and verify the accuracy of engine speed during each experimental run.
4. Fuel consumption measurement unit: A graduated burette (8 mL capacity) coupled with a stopwatch was used to measure the time required for the engine to consume a specific volume of fuel, allowing the determination of fuel mass flow rate (mf).
5. Temperature measurement: Two mercury thermometers were installed at the air inlet and exhaust outlet to monitor temperature variations that could influence combustion efficiency.
6. Emission measurement: A StarGas 898 smokemeter was used to quantify exhaust gas opacity, expressed in parts per million (ppm) and percentage (%). This device detects the degree of light absorption in the exhaust stream, indicating particulate concentration.
7. Auxiliary tools: Additional tools included a pellet mold, electric stove, digital scale, ampia (pellet flattener), 100-mesh sieve, and wire mesh packaging material to fabricate and secure the hybrid filters.

Materials

Two primary adsorbents were used in the fabrication of hybrid filters:

- Natural zeolite (clinoptilolite type), sourced from CV. Minatama, Lampung. Zeolite was chosen for its high porosity, cation exchange capacity, and strong affinity for polar molecules such as nitrogen and water vapor.
- Fly ash, obtained as a by-product of coal combustion from a local thermal power plant. It contained aluminosilicate compounds that enhance structural stability and adsorptive properties.

Both materials were ground and sieved to a 100-mesh particle size to ensure homogeneity. The zeolite–fly ash compositions were prepared in five ratios by mass:

- Z0F100 (100% fly ash)
- Z25F75
- Z50F50
- Z75F25
- Z100F0 (100% zeolite)

Each composition was further tested in three mass variations: 50 g, 75 g, and 100 g, resulting in a total of 15 experimental filter configurations

Filter Preparation and Physical Activation

The zeolite and fly ash powders were mixed thoroughly using an ampia (manual mixer) until homogeneous and cohesive. The mixture was then molded into pellets using a cylindrical press mold (diameter ≈ 3 cm, height ≈ 1.5 cm). The pellets were allowed to air-dry to remove surface moisture before being thermally activated.

- Activation process: Each pellet batch was placed in a convection oven at 225°C for one hour. This temperature was chosen based on preliminary testing to dehydrate the zeolite's internal pores and eliminate volatile matter from fly ash without altering the crystalline structure. The purpose of this activation was to enhance adsorption capacity and increase pore accessibility. After activation, the pellets were stored in airtight plastic containers to prevent rehydration prior to installation in the filter assembly.
- Filter assembly: Activated pellets were packed into a cylindrical wire mesh housing, forming the hybrid air filter. The wire mesh served as both a physical enclosure and a passage for air, ensuring minimal pressure drop while maintaining structural integrity during engine suction.

Testing Procedure

The experiment was conducted in two main phases:

1. Baseline testing: The diesel engine was first operated without any filter modification to establish reference values for brake power, fuel consumption, and exhaust opacity.
2. Filter performance testing: Each zeolite–fly ash filter (varying in mass and composition) was sequentially installed at the air intake manifold. The engine was operated at 1500, 2000, and 2500 rpm, maintaining a load of 2.5 kg on the dynamometer. The time required to consume 8 mL of diesel fuel was recorded for each condition, allowing for the calculation of fuel consumption rate. After each trial, the engine was allowed to rest for approximately 10 minutes to return to ambient temperature before proceeding to the next run.

During operation, intake and exhaust temperatures were recorded to monitor the thermal environment, and smokemeter readings were obtained under steady-state conditions to evaluate emission characteristics.

Data Analysis

The performance parameters were calculated using the following equations:

1. Brake Power (bP):

$$bP = \frac{2\pi NT}{60} \quad (1)$$

where N is the engine speed (rpm) and T is torque (Nm).

2. Brake Specific Fuel Consumption (bsfc):

$$bsfc = \frac{mf}{bP} \quad (2)$$

where mf is the fuel mass flow rate (kg/h).

3. Percentage Change:

$$\%change = \frac{(X1-X0)}{X0}\ x\ 100 \quad (3)$$

where X1 and X0 represent measurements with and without the filter, respectively.

Data were processed using Microsoft Excel for tabulation and visualization. Comparative analysis was performed to identify the filter configuration that yielded the highest brake power, lowest bsfc, and minimum exhaust opacity. The most effective combination was determined through the analysis of mean performance improvements across all test speeds, supported by statistical averaging from triplicate trials.

Reliability and Experimental Control

To minimize errors, all measuring instruments were calibrated before testing. Environmental conditions such as room temperature and humidity were recorded, as they could influence combustion efficiency and air density. Each measurement was repeated three times, and the mean values were used for interpretation. Random errors were estimated through standard deviation analysis. Furthermore, the activation temperature, pellet dimensions, and packing density were maintained constant across all samples to ensure that variations in results were solely attributed to the independent variables (composition ratio and mass).

RESULTS AND DISCUSSION

Overview of Experimental Findings

The experiment aimed to analyze the performance of a four-stroke, single-cylinder diesel engine using hybrid air filters composed of physically activated zeolite and fly ash. The tested variables included five filter composition ratios—Z0F100, Z25F75, Z50F50, Z75F25, and Z100F0—and three filter masses: 50 g, 75 g, and 100 g. Each configuration was tested under three engine speeds (1500, 2000, and 2500 rpm). The results revealed that the incorporation of zeolite–fly ash hybrid filters significantly influenced the combustion process, affecting brake power, brake specific fuel consumption (bsfc), and exhaust gas opacity. Among all variations, the Z50F50 composition with a mass of 100 g consistently provided the highest brake power, lowest bsfc, and a balanced emission reduction, indicating an optimal balance between adsorption activity and airflow resistance.

Brake Power Characteristics

Brake power (bP) quantifies the actual mechanical power delivered by the engine and represents the efficiency with which the combustion process is converted into mechanical work. The measured results are summarized in Table 1.

Table 1. Brake power of diesel engine under different zeolite–fly ash filter compositions and masses.

Composition	Filter Mass (g)	1500 rpm (kW)	2000 rpm (kW)	2500 rpm (kW)
Z0F100	50	0.82	0.90	0.94
Z25F75	50	0.84	0.93	0.96
Z50F50	50	0.86	0.94	0.97
Z50F50	100	0.87	0.99	1.01
Z75F25	100	0.85	0.96	0.98
Z100F0	100	0.84	0.95	0.97

As shown in Figure 3, brake power increased proportionally with engine speed for all configurations. The highest recorded improvement—2.825% relative to the baseline—was achieved by the Z50F50 filter at 2000 rpm. This result demonstrates that a balanced zeolite–fly ash ratio optimized the airflow and oxygen concentration entering the combustion chamber. Zeolite's crystalline framework, dominated by microporous channels, effectively adsorbs nitrogen and water vapor, which in turn enriches the oxygen composition of intake air. Fly ash, on the other hand, acts as a fine particulate filter, stabilizing turbulence and preventing dust interference in the air–fuel mixture. Consequently, the improved air composition results in a more stable flame front, higher combustion pressure, and increased power output. The enhanced performance at 2000 rpm indicates that the hybrid filter improves volumetric efficiency and combustion completeness without introducing excessive flow resistance. These findings are consistent with previous studies by Singh et al. (2022), who reported that modified air filters enriched with oxygen-adsorbing materials increased engine torque by 2–4% under similar operational conditions.

Brake Specific Fuel Consumption (bsfc)

Brake specific fuel consumption (bsfc) represents the mass of fuel consumed per unit of power output and serves as a primary indicator of fuel efficiency. The results are presented in Table 2.

Table 2. Brake specific fuel consumption (bsfc) for various zeolite–fly ash filter compositions and engine speeds.

Composition	Filter Mass (g)	1500 rpm (kg/kWh)	2000 rpm (kg/kWh)	2500 rpm (kg/kWh)
Z0F100	50	0.355	0.340	0.325
Z25F75	75	0.340	0.330	0.318
Z50F50	100	0.325	0.312	0.310
Z75F25	100	0.330	0.315	0.312
Z100F0	100	0.335	0.320	
Composition	Filter Mass (g)	1500 rpm (kg/kWh)	2000 rpm (kg/kWh)	2500 rpm (kg/kWh)

The bsfc values exhibited a consistent decline across all hybrid filters compared with the unfiltered baseline, indicating more efficient fuel utilization. The minimum bsfc value (0.312 kg/kWh) was obtained with the Z50F50 filter at 2000 rpm—corresponding to a 7.805% reduction relative to the baseline.

The improvement in bsfc can be attributed to the enhanced oxygen density in the intake air, which supports complete oxidation of fuel molecules and minimizes unburned hydrocarbons. At lower filter masses (50 g), limited adsorption and airflow stabilization reduced the efficiency improvement. Conversely, excessive mass (>100 g) could restrict intake airflow and reduce power, confirming that 100 g represents the optimal mass for achieving an ideal balance between permeability and adsorption. These findings are corroborated by Sharma et al. (2025), who demonstrated that porous mineral composites can enhance combustion stability and reduce fuel consumption by 6–9% through controlled air–fuel homogenization.

Exhaust Gas Opacity

Exhaust opacity serves as a direct measure of soot and particulate emissions. Table 3 and Figure 5 show the results for various filter configurations.

Table 3. Exhaust gas opacity under different zeolite–fly ash filter compositions and engine speeds.

Composition	Filter Mass (g)	1500 rpm (%)	2000 rpm (%)	2500 rpm (%)
Z0F100	50	59.42	54.38	52.16
Z25F75	75	42.54	38.65	41.20
Z50F50	100	45.10	40.22	43.65
Z75F25	100	48.73	43.19	44.10
Z100F0	100	50.12	45.80	46.00

The exhaust opacity decreased significantly for all hybrid filters, confirming improved combustion quality and reduced particulate formation. The Z25F75 filter achieved the lowest opacity (38.65%), corresponding to a 35% reduction compared with the baseline. This composition, which has higher fly ash content, provides more surface sites for particle adsorption and neutralization of hydrocarbon radicals, leading to cleaner combustion.

Zeolite further contributes to this effect by promoting oxygen enrichment and supporting complete oxidation of carbonaceous matter. Together, these materials create a dual mechanism of filtration and catalytic enhancement, ensuring that fewer incomplete combustion residues are emitted. These results agree with the findings of Alam and Yadav (2023), who demonstrated that aluminosilicate-based hybrid filters can reduce soot emissions by over 30% in small diesel engines.

Comparative Performance Evaluation

A comparison of the relative improvements in performance and emission parameters is summarized in Table 4.

Table 4. Percentage improvement of performance parameters compared with baseline conditions.

Composition	Filter Mass (g)	ΔBrake Power (%)	Δbsfc (%)	ΔSmoke Opacity (%)
Z0F100	50	+1.35	−4.20	−18.5
Z25F75	75	+2.11	−6.50	−35.0
Z50F50	100	+2.825	−7.805	−32.3
Z75F25	100	+1.98	−6.10	−27.4
Z100F0	100	+1.62	−5.30	−25.2

Figure 6 presents the comparative analysis of brake power, bsfc, and smoke opacity across all configurations. The Z50F50 filter exhibits the most balanced performance enhancement, with significant gains in power and fuel economy while maintaining low emissions. Although Z25F75 achieves the lowest opacity, the higher fly ash content slightly increases flow resistance, reducing engine output marginally.

Mechanistic Interpretation

The improvement in engine performance can be explained by the synergistic mechanism of the zeolite–fly ash hybrid system, illustrated conceptually in Figure 7.

1. Adsorptive Regulation of Air Composition: Zeolite selectively adsorbs nitrogen and water vapor molecules, enriching the oxygen fraction of intake air. This process creates a localized oxygen-enriched zone, improving flame propagation and reducing ignition delay.
2. Particulate and Radical Filtration: Fly ash, composed of spherical aluminosilicate micro-particles, provides extensive active sites for the adsorption of hydrocarbons and soot precursors. Its fine structure traps dust and unburned carbon, preventing their entry into the combustion chamber.
3. Thermal Activation Enhancement: Heating at 225°C expands pore networks and increases the specific surface area, improving adsorption–desorption kinetics during suction and compression cycles.
4. Combustion Optimization: The combined adsorption and filtration effects produce a cleaner and oxygen-rich air charge, increasing combustion pressure and reducing incomplete oxidation.

Influence of Composition, Filter Mass, and Engine Speed

The relationship between filter composition, mass, and engine speed exhibits an interdependent effect on overall engine performance, visualized in Figure 8. At low engine speed (1500 rpm), incomplete fuel atomization results in reduced efficiency despite improved air filtration. The optimal condition occurs at 2000 rpm, where turbulence and air–fuel mixing are well-balanced, ensuring near-complete combustion. At 2500 rpm, although oxygen availability remains sufficient, shortened residence time and high exhaust temperature slightly reduce combustion efficiency. A zeolite fraction of 50% offers the best trade-off between oxygen enrichment and airflow permeability, while the remaining 50% fly ash ensures adequate particulate capture. The 100 g filter mass provides sufficient adsorptive capacity without creating significant intake restriction.

Discussion

The integration of a physically activated zeolite–fly ash hybrid filter into the diesel engine air intake system has been shown to substantially enhance combustion quality, energy efficiency, and emission control through synergistic physicochemical mechanisms. The hybrid material operates as an active oxygen-enriching medium in which zeolite, with its crystalline microporous framework, selectively adsorbs nitrogen and water vapor, while fly ash, composed primarily of amorphous aluminosilicate particles, captures residual moisture and fine particulates, thereby increasing the relative concentration of oxygen in the intake air. This process facilitates more complete fuel oxidation, resulting in improved combustion thermodynamics and cleaner exhaust output. The physical activation of both materials at 225°C significantly enhances pore structure, surface roughness, and gas adsorption kinetics, enabling greater oxygen diffusion into the combustion chamber. Experimentally, the optimal configuration—Z50F50 at 100 g—produced the highest brake power with a 2.825% increase over the baseline, while the Z25F75 configuration achieved the lowest brake specific fuel consumption, decreasing by 7.805%, and exhibited the lowest exhaust opacity at 38.65%, confirming reduced soot and hydrocarbon residues. These outcomes affirm that the oxygen-enriched combustion environment generated by the hybrid filter improves thermal efficiency, stabilizes in-cylinder pressure, and minimizes incomplete oxidation reactions responsible for pollutant formation. The significant reduction in exhaust opacity and fuel consumption collectively underscores the hybrid filter's capacity to transform conventional diesel engines into more energy-efficient and environmentally sustainable systems, offering a low-cost, scalable innovation for future clean combustion technologies.

The implications of this study extend beyond the scope of engine performance optimization, highlighting the potential of zeolite–fly ash hybrid filters as a sustainable and economically viable pathway toward cleaner combustion technologies. The demonstrated improvements in brake power, fuel efficiency, and emission reduction indicate that the integration of physically activated mineral-based filters can effectively address two major challenges in diesel engine operation—energy efficiency and environmental pollution—without requiring significant modifications to existing engine architecture. From an environmental perspective, the ability of the hybrid filter to lower exhaust opacity and reduce unburned hydrocarbons and carbon monoxide directly contributes to the mitigation of urban air pollution and supports compliance with stricter emission regulations. In terms of resource management, the use of fly ash, a by-product of coal combustion, and naturally abundant zeolite offers a form of circular economy innovation by repurposing industrial waste into value-added engineering materials. Furthermore, the findings provide a scientific foundation for developing next-generation filtration systems that integrate adsorption, catalytic, and oxygen-enrichment functions for internal combustion engines. This innovation aligns with global sustainability frameworks such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action), positioning the zeolite–fly ash hybrid filter as a practical solution for reducing the carbon footprint of diesel-powered systems while enhancing energy conversion efficiency in the transportation and industrial sectors.

This study acknowledges several limitations that provide valuable direction for further research in optimizing the performance of zeolite–fly ash hybrid filters for diesel engine applications. The experimental design was restricted to a single physical activation temperature of 225°C, which may not represent the optimum condition for maximizing the adsorptive capacity and surface reactivity of the composite materials. Future studies should investigate a wider range of activation temperatures to determine the thermal threshold that yields the highest pore uniformity and oxygen adsorption efficiency. Additionally, the pellets used in this study were limited to a single shape and size, which may have constrained airflow characteristics and the contact surface area available for adsorption; thus, variations in pellet geometry, porosity, and packing density should be explored to enhance filtration performance. The current research also employed only zeolite and fly ash as adsorptive materials, without incorporating other potential biomass-based adsorbents such as rice husk charcoal or coconut shell biochar, which could further improve water vapor adsorption and oxygen enrichment. Moreover, the investigation focused primarily on brake power, fuel consumption, and exhaust opacity, while other critical emission parameters such as nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter were not analyzed. Future work should include these parameters and assess the long-term durability, regeneration potential, and economic feasibility of the hybrid filter under real-world operating conditions. Addressing these limitations would significantly advance the development of a more efficient, sustainable, and scalable air filtration technology for cleaner diesel combustion systems.

CONCLUSION

In conclusion, the findings of this study confirm that the integration of a physically activated zeolite–fly ash hybrid filter into the air intake system of a diesel engine effectively enhances combustion efficiency, mechanical performance, and environmental sustainability. The synergistic interaction between zeolite's oxygen enrichment capability and fly ash's particulate adsorption properties resulted in measurable improvements in engine output and emission quality. The optimal configuration, consisting of a 50:50 zeolite-to-fly ash ratio with a 100 g filter mass, achieved a 2.825% increase in brake power, a 7.805% reduction in brake specific fuel consumption, and a significant decrease in exhaust opacity by 38.65%, indicating more complete combustion and lower soot generation. These outcomes demonstrate that the hybrid filter provides an efficient means of improving air quality in the combustion chamber without the need for major mechanical modifications. Moreover, by utilizing abundant and low-cost materials such as natural zeolite and coal fly ash, this innovation promotes the circular economy through the valorization of industrial waste. Overall, the study establishes the zeolite–fly ash hybrid filter as a promising, low-cost, and scalable solution for enhancing the energy efficiency of diesel engines while substantially reducing their environmental footprint, thereby contributing to the broader goals of sustainable energy utilization and cleaner transportation technologies.

AUTHOR CONTRIBUTIONS STATEMENT

Andika Sofyan Amarullah, as the corresponding author, was primarily responsible for conceptualizing the research framework, developing the experimental design, conducting the diesel 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. A. Yudi Eka Risano 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.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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