

Performance of a Rotary-Blade Real-Time Emulsification System on Diesel Vehicle Exhaust Emissions

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ABSTRACT

The use of water-in-diesel emulsion fuel has been widely investigated as a strategy to mitigate harmful diesel exhaust emissions, particularly nitrogen oxides (NO_x) and particulate-related smoke. However, practical implementation is often limited by emulsion instability, surfactant dependency, and storage-related challenges. This study aims to investigate the effects of surfactant-free, water-in-diesel emulsion fuel on harmful emissions from a common-rail diesel vehicle, using a rotary blade real-time emulsification system. Two fuels were employed: standard Euro 2 diesel and a 10% water-in-diesel emulsion prepared in real time by the rotary-blade system. Emission measurements were carried out at four idle engine speeds, namely 800, 1000, 1500, and 2000 revolutions per minute. Data was collected under steady-state conditions and compared against baseline diesel performance. The emissions measured during the tests included nitrogen oxides (NO_x), carbon monoxide (CO), and smoke opacity. The results showed that the rotary-blade emulsification system consistently reduced nitrogen oxide emissions, with decreases ranging from 9.4% at low idle to nearly 40% at higher idle speeds. Smoke opacity was also significantly reduced at lower speeds, achieving reductions of more than 50%. However, at higher speeds, smoke benefits diminished and even reversed, showing an 8.9% increase at 2000 revolutions per minute. Carbon monoxide emissions, by contrast, increased across all operating conditions, with penalties as high as 50.6% at high idle. These results confirm that the rotary-blade system delivers the expected benefits of water-in-diesel combustion, such as improved atomization and lower flame temperatures, but also highlight the consistent drawback of incomplete carbon monoxide oxidation under cooler combustion conditions.

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INTRODUCTION

Air pollution from diesel engine exhaust remains a major environmental concern, contributing significantly to urban smog, greenhouse gas emissions, and public health issues. Reducing harmful pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter is therefore critical in advancing cleaner transportation technologies. The growing concerns over air pollution and stringent emission regulations have intensified the search for cleaner alternative fuels for diesel engines. Among the various strategies, water-in-diesel emulsion fuel has gained attention due to its potential to reduce harmful exhaust emissions without requiring major engine modifications (Jayson et al., 2018; Nnadozie et al., 2025). The primary purpose of adding water is to reduce in-cylinder combustion temperature through heat absorption and charge cooling effects. Lower combustion temperatures directly suppress thermal NO_x formation; however, they may also influence other emission species, such as CO and smoke, by altering oxidation kinetics and combustion completeness. By introducing water into the fuel in the form of fine droplets, emulsion fuels can enhance combustion efficiency through secondary atomization and micro-explosions, in which volatile water rapidly expands during combustion, fragmenting surrounding fuel into finer droplets and improving air–fuel mixing. This mechanism has been shown to reduce NO_x formation and smoke opacity, while maintaining acceptable thermal efficiency (Huo et al., 2014; Jhalani et al., 2019; Sukra et al., 2026; Wang et al., 2018; Yonguep et al., 2022).

However, conventional pre-mixed emulsion methods face significant drawbacks. Stored emulsions are prone to phase separation over time, particularly in the absence of stabilizing surfactants (Ramlan et al., 2016; Mohd Tamam et al., 2023a). The use of surfactants can add cost, alter combustion chemistry, and in some cases produce undesirable residues. Moreover, large-scale storage of water–fuel blends raises logistical challenges, as emulsion stability is sensitive to temperature variations, handling conditions, and storage duration (Rahman et al., 2022). These drawbacks have restricted the adoption of emulsified fuel technology in practical, long-term diesel engine applications.

To address these limitations, a Real-Time Emulsion Fuel Supply System (RTES) is employed. The RTES generates stable fuel–water emulsions on demand, immediately before combustion, thereby eliminating storage-related stability issues and reducing dependence on additives (Abd Razak et al., 2020; Abdul Rashid et al., 2024; Wan Mahdi et al., 2020; Mazlan et al., 2018; Mohd Tamam et al., 2023b; Ramlan et al., 2020). The system integrates precision-controlled fuel and water supply circuits, a mixing chamber, and a closed-loop control unit capable of adjusting the water-to-fuel ratio in real time according to engine operating conditions. This approach ensures consistent emulsion quality, optimizes combustion, and has demonstrated notable reductions in NO_x emissions and smoke opacity, while maintaining or improving engine performance.

The previous RTES mixing method, such as using high-shear mechanical or ultrasonic mixing, can be complex, costly, or energy-intensive. These approaches often face challenges in maintaining stable droplet size distribution under varying engine loads and during long-term operation. There is limited research exploring alternative, simpler mixing mechanisms that could provide efficient emulsification, reduced system complexity, and improved reliability.

Therefore, this study explores the application of surfactant-free emulsified diesel fuel with 10% water content, generated using a rotary blade RTES. The experimental work focuses on a common-rail diesel engine in an SUV platform, operating under idling conditions between 800 and 2000 rpm. Emission parameters measured include NO_x, CO, and smoke opacity, and these results were compared with the conventional diesel, offering insight into the environmental impact and practical viability of emulsified fuels for modern diesel-powered vehicles. The present study focuses on a single water fraction (10%) to isolate the performance of the rotary-blade RTES under practical conditions. At the same time, investigation of varying water contents will be considered in future work to optimize emission trade-offs further.

While the fundamental advantages of water-in-diesel emulsions in terms of the reduction of NO_x and particulate matter through micro-explosions are well-documented, their practical application has been historically stalled by the stability-cost trade-off. Conventional methods require either expensive surfactants that may leave chemical residues or energy-intensive ultrasonic mixing that adds significant mechanical complexity to the vehicle. The rotary-blade Real-Time Emulsification System (RTES) utilized in this study addresses these limitations by providing a mechanically simplified, surfactant-free solution that generates the emulsion immediately before combustion. By focusing on a common-rail SUV platform under varying idle speeds, this research evaluates whether such a streamlined system can maintain the critical balance between emission reduction and combustion stability in real-world urban driving scenarios.

EXPERIMENTAL SETUP

Test vehicle

The experimental investigation was conducted using a standardized test platform comprising a sport utility vehicle (SUV) equipped with a common-rail fuel injection diesel engine. The engine conforms to Euro 2 emission standards and features a four-stroke, four-cylinder, turbocharged configuration. A comprehensive summary of the vehicle's technical specifications is provided in Table 1.

Table 1. Technical specification of the test vehicle

Parameter	Specification
Model	Hyundai Santa Fe
Power	150 Hp @ 4000 rpm
Power per liter	68.6 Hp/l
Torque	335 Nm @ 1800 rpm
Engine displacement	2188 cm ³
Number of cylinders	4
Position of cylinders	Inline
Cylinder Bore	87 mm
Piston Stroke	92 mm
Compression ratio	17.3
No. of valves per cylinder	4
Fuel System	Diesel Common rail
Engine aspiration	Turbocharger, Intercooler

Test fuel

The baseline fuel utilized in this study is commercially available conventional diesel, commonly distributed at public fueling stations. This fuel was selected to ensure the relevance and practicality of the findings, as it reflects the standard fuel type used in everyday diesel-powered vehicles. The properties of the diesel fuel are shown in Table 2. This fuel contains a high cetane index fuel designed for low and high-speed self-ignited compression engines to provide efficient, dependable, and smooth operation.

In addition to the baseline fuel, emulsified diesel fuel containing 10% water content by volume was utilized for comparative analysis. This emulsified fuel was generated without the use of surfactants, using a rotary blade real-time emulsification system (RTES).

Table 2. Diesel fuel properties

Parameter	Specification
Cetene Index	45
Density @ 15 °C, kg/m ³	815
Sulphur, % m/m	0.5
Distillation, recovery @ 300 °C, % vol	40
Pour Point, °C	18
Flash Point, °C	60
Total Acid No., mg KOH/g	0.6

Real-time emulsification system (RTES)

The key innovation of this study lies in the use of a rotary-blade real-time emulsification system (RTES) to generate surfactant-free water-in-diesel emulsions on demand. The RTES operates on a mechanical shear principle, where controlled rotational motion of internal blades induces intense shear forces within a compact mixing chamber. Diesel fuel and water are supplied through separate metered lines and introduced simultaneously into the chamber, where rapid blade rotation fragments the water phase into fine droplets dispersed within the diesel fuel.

Unlike ultrasonic or high-pressure homogenization techniques, the rotary-blade system offers a mechanically simple and energy-efficient emulsification process with minimal auxiliary power demand. The absence of surfactants eliminates potential chemical interference with combustion while avoiding long-term storage instability issues. The RTES is positioned near the engine intake, ensuring a smooth flow of the emulsion fuel into the engine and minimizing residence time between emulsification and combustion, ensuring that the emulsion remains stable until injection. This positioning allows for efficient mixing of the emulsified fuel with air, optimizing combustion and enhancing the overall effectiveness of the system. The proximity to the engine intake enables a seamless transfer of the emulsion fuel, minimizing any potential disruptions or flow restrictions, thereby supporting consistent combustion behavior under varying engine speeds. For clarity and consistency throughout the study, the conventional diesel fuel is denoted as D, while the emulsified fuel with 10% water content is referred to as E10.

Test setup

To evaluate exhaust emissions, tests were conducted under realistic engine operating conditions across various idle speeds, specifically from 800 to 2000 revolutions per minute (RPM). These conditions were selected to simulate typical low-load engine behavior and to assess the impact of different fuel types on emission characteristics. The emission testing was performed at the G3 Laboratory, Universiti Teknologi Malaysia (UTM), Kuala Lumpur. Exhaust gases were analyzed using a Sauermann Sica 130 KIT 3BS gas analyzer, which accurately measures key regulated pollutants, including NO_x and CO, providing reliable data on combustion efficiency and emission trends. To measure smoke density, a HORIBA MEXA-600S smoke meter was employed. This device operates as a light-transmitting opacimeter, determining the opacity of exhaust gases by analyzing the absorption and scattering of light as it passes through the exhaust stream. A schematic diagram for the idling testing setup is provided in Fig. 1.

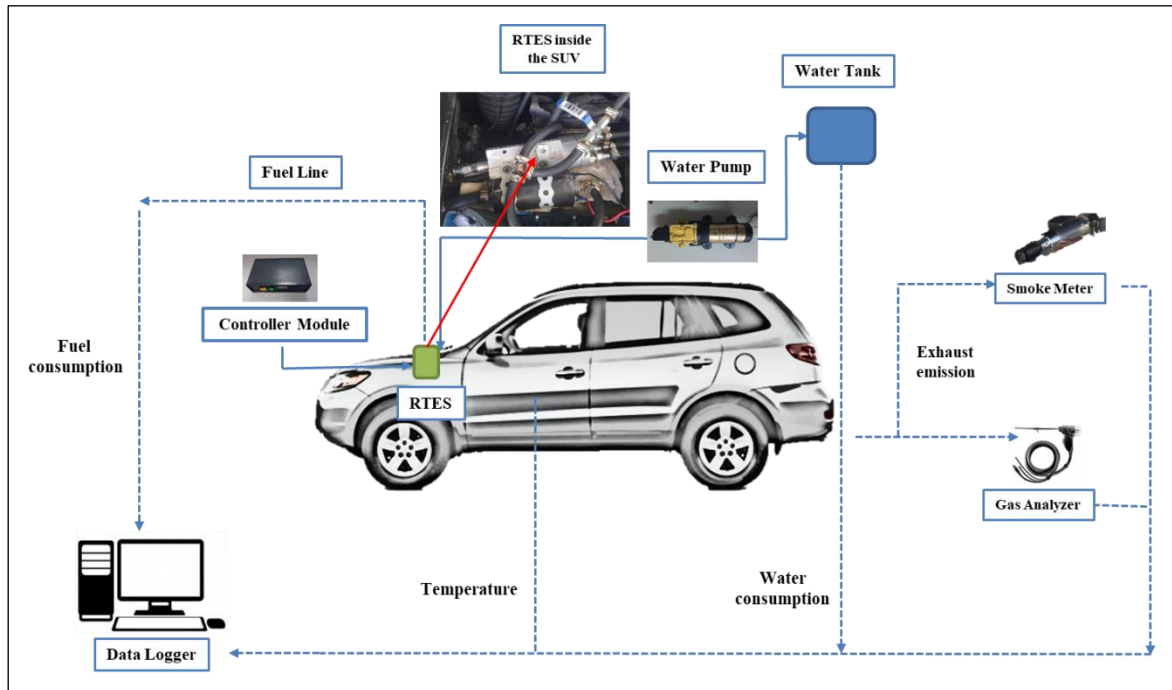


Fig. 1. Schematic diagram of the idling testing setup.

RESULTS AND DISCUSSIONS

Carbon monoxide

The variation in CO emissions between conventional diesel and E10 at different engine speeds is presented in Fig. 2. At an engine speed of 800 rpm, CO emissions from E10 increased by approximately 29% compared to diesel. A similar trend was observed at 1000 rpm, where CO emissions rose by 8.7% relative to the baseline fuel. At 1500 rpm, the use of emulsified fuel resulted in an estimated 21% increase in CO emissions. Notably, at the highest tested engine speed of 2000 rpm, CO emissions exhibited a substantial rise of 50.6%, indicating a strong correlation between engine speed and incomplete combustion behavior associated with water content in the emulsion. Water content leads to a reduction in local flame temperature during combustion, which inhibits the oxidation process required to convert CO into carbon dioxide (CO₂). As a result, the combustion process remains incomplete under certain operating conditions, particularly at lower combustion temperatures, leading to elevated CO emissions. This phenomenon is proved in recent studies, which confirm that water-in-diesel emulsions often suppress peak temperatures, thereby limiting the thermal energy available to fully oxidize CO to CO₂ (Mi et al., 2024; Patel & Dhiman, 2022; Sugeng et al., 2020).

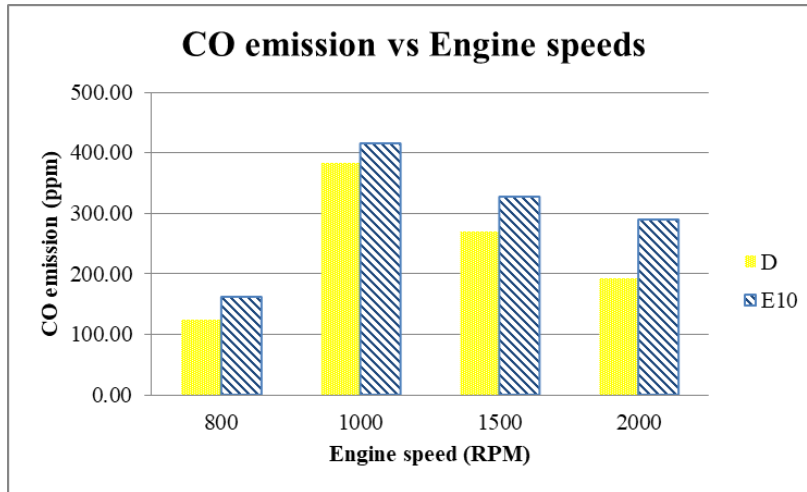


Fig. 2. CO emission of diesel and emulsion at various engine speeds.

Nitrogen oxide

Fig. 3 shows the trend of NO_x emissions for diesel and E10 at various engine speeds. In contrast to CO emissions, E10 demonstrated a notable reduction in NO_x output at all engine speeds. Specifically, NO_x emissions were reduced by 9.4% at 800 rpm, 14.0% at 1000 rpm, 15.8% at 1500 rpm, and a remarkable 39.5% at 2000 rpm compared to diesel. This reduction is largely attributed to the thermal characteristics of the emulsified fuel, particularly the water content, which acts as a thermal buffer during combustion (Rao et al., 2023). Water has a high specific heat capacity and absorbs a significant portion of the combustion heat, effectively reducing the peak in-cylinder temperatures. This cooling mechanism, widely referred to as the heat sink effect, suppresses the formation of thermal NO_x , which is highly dependent on combustion temperature. Lower combustion temperatures limit the thermal fixation of nitrogen, resulting in lower NO_x emissions (Ko et al., 2018; Pitale et al., 2026).

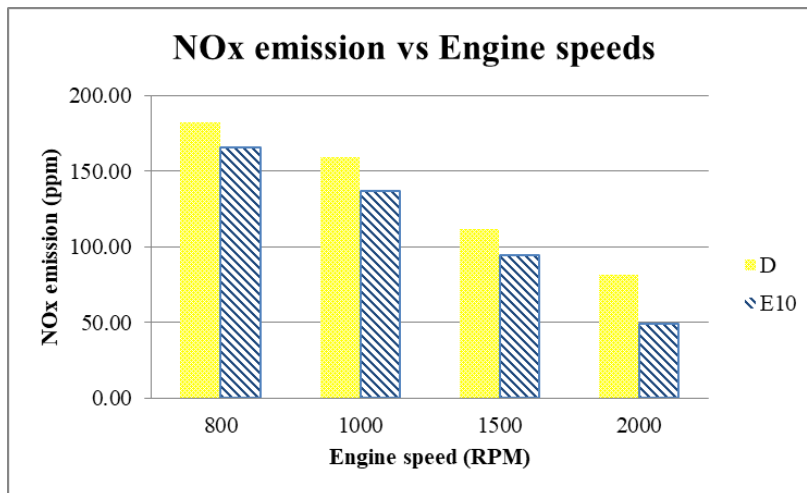


Fig. 3. NO_x emission of diesel and emulsion at various engine speeds.

Smoke opacity

The comparison between diesel and E10 at various engine speeds in terms of the smoke number level is indicated in Fig. 4. The results indicate a generally favorable reduction in smoke emissions when using E10, particularly at lower engine speeds. At 800 rpm, E10 achieved a substantial reduction in smoke opacity by 53.9%, while a similarly significant reduction of 51.3% was observed at 1000 rpm. These reductions are attributed to the water content in the emulsion, which promotes secondary atomization through micro-explosions, leading to finer fuel droplets and more complete combustion. However, at 1500 rpm, the reduction in smoke emissions is comparatively modest, recorded at 8.7%. More notably, at 2000 rpm, E10 resulted in an 8.9% increase in smoke opacity relative to diesel. This reversal in trend can be explained by the interaction between increased combustion temperature and combustion dynamics at higher engine speeds. Although higher temperatures typically enhance the micro-explosion phenomenon and result in improved atomization, the overall combustion quality may decline due to reduced residence time and insufficient oxygen availability. This limits the oxidation of soot particles, thereby offsetting the beneficial effects of emulsification and resulting in elevated smoke emissions at the highest test speed (Kesharvani et al., 2023; Mohd Tamam et al., 2023b). These findings highlight that while emulsified fuel offers considerable benefits in reducing smoke emissions at lower and moderate engine speeds, its effectiveness may diminish under high-speed operating conditions where combustion becomes less complete.

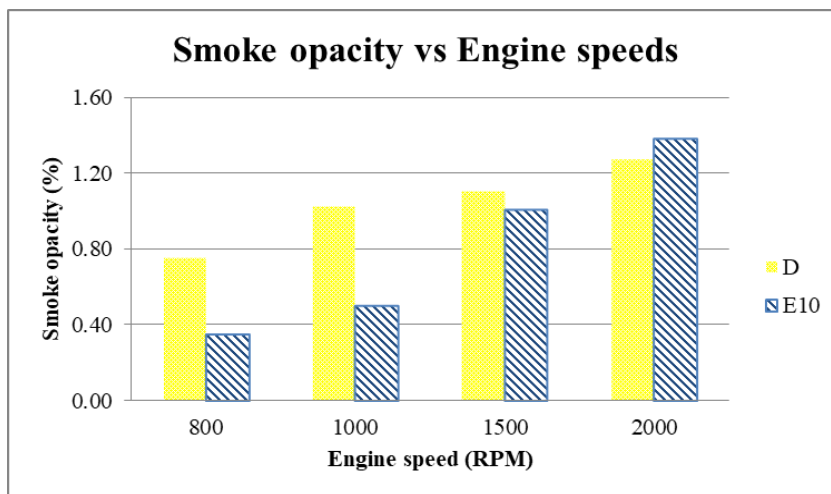


Fig. 4. Smoke opacity of diesel and emulsion at various engine speeds.

NO_x and smoke trade off

For all tested speeds, the NO_x emissions from E10 were consistently lower than those from diesel. This consistent downward trend is attributed to the strong thermal suppression effect introduced by the water content. The effect becomes more pronounced at higher idle speeds, where faster combustion promotes NO_x generation. Meanwhile, the smoke opacity trends show a contrasting pattern. At 800 rpm, smoke opacity for E10 decreased substantially with 53.9%, and at 1000 rpm, a similar strong reduction was recorded. At 1500 rpm, however, the reduction was modest, and at 2000 rpm, the smoke emissions from E10 exceeded diesel by 8.9%. These results confirm that the micro-explosion and secondary atomization effects dominate at low idle speeds, where longer residence times allow the finer droplets to mix more thoroughly with the available air, thereby reducing soot precursors. At high idle speeds, however, the shortened combustion duration, coupled with lower flame temperatures and oxygen dilution from water vapor, suppresses soot oxidation.

Taken together, the graph illustrates a classical NO_x –smoke trade-off that is typical in diesel combustion but altered by the presence of water emulsification. The addition of water reliably reduces NO_x across the entire speed range, but the smoke benefits are speed-dependent, which are strong at low idle, diminishing at medium idle, and reversing at high idle. This indicates that the combustion trend determines whether the cooling and dilution effects of water improve or impair soot oxidation. At low speed, mixing dominates and soot falls; at high speed, cooling and oxygen dilution dominate, causing soot to rise even as NO_x is suppressed. This observed trade-off trend is also consistent with previous studies (How et al., 2018; Maiboom & Tauzia, 2011), where reductions in NO_x were accompanied by variable smoke behavior depending on operating conditions, confirming that the fundamental balance between flame temperature suppression and fuel–air mixing governs the simultaneous formation of NO_x and smoke.

Overall emission performance and optimal operating conditions

While the individual trends of CO, NO_x , and smoke emissions provide insight into specific combustion phenomena, an overall assessment is necessary to identify operating conditions that offer the best compromise among all major emissions. At low idle speeds (800–1000 rpm), WD10 demonstrated substantial reductions in NO_x and smoke opacity, with moderate increases in CO emissions. These conditions benefit from longer residence time and enhance micro-explosion effects, which promote improved mixing and soot oxidation while maintaining sufficient combustion stability.

At higher idle speeds (1500–2000 rpm), although NO_x reduction remained significant, the penalties in CO and smoke emissions became more pronounced due to shortened combustion duration, reduced oxidation time, and increased cooling effects from water vapor. From an overall emission standpoint, idle speeds of 800–1000 rpm represent the most favourable operating range for WD10, providing a balanced reduction in NO_x and smoke with comparatively lower CO penalties. This trade-off analysis highlights the importance of operating-condition optimization when implementing water-in-diesel emulsification systems in practical applications.

In terms of an environmental and regulatory perspective, NO_x and smoke opacity are the most critical emissions for diesel engines due to their strong association with urban air quality degradation and respiratory health impacts. Although CO emissions increased with E10, CO is generally more manageable through oxidation catalysts and is less critical under idling conditions compared to NO_x and particulate-related emissions.

CONCLUSION

This study investigated the effects of water-in-diesel emulsified fuel with 10% water content (E10) on the emission characteristics of a common-rail diesel engine under idling conditions at engine speeds ranging from 800 to 2000 rpm. The key pollutants evaluated were carbon monoxide (CO), nitrogen oxides (NO_x), and smoke opacity, with results compared against a baseline of commercially available diesel fuel. The use of E10 demonstrated a significant reduction in NO_x emissions, with the highest reduction of 39.5% observed at 2000 rpm. This improvement is primarily attributed to the thermal dilution and heat absorption properties of water during combustion, which reduce peak flame temperatures and inhibit thermal NO_x formation. Similarly, notable reductions in smoke opacity were recorded at lower engine speeds, exceeding 50% at 800 and 1000 rpm. These reductions are credited to enhanced fuel atomization and the occurrence of micro-explosions, which promote more complete combustion. However, compared to diesel, E10 was associated with increased CO emissions across all engine speeds, with the most pronounced rise of 50.6% at 2000 rpm. This increase is attributed to the lower in-cylinder temperatures caused by the water content, which impedes the complete oxidation of CO-to- CO_2 . When considering the overall emission trade-off among CO, NO_x , and smoke, low idle speeds (800–1000 rpm) were identified as the optimal operating range,

offering the best compromise between emission reductions and penalties. These findings demonstrate the practical potential of rotary-blade RTES technology for urban driving conditions where idling is frequent, while also emphasizing the need for further optimization of water fraction or supplementary emission control strategies to achieve balanced emission performance.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: Study conception and design: Wira Jazair Yahya, Hasbullah Abdul Rahman; data collection: Nur Atiqah Ramlan, Mohamad Qayyum Mohd Tamam; analysis and interpretation of results: Nur Atiqah Ramlan, Hasbullah Abdul Rahman; draft manuscript preparation: Nur Atiqah Ramlan, Mohamad Qayyum Mohd Tamam. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the authors used generative AI and AI-assisted technologies to improve readability and ensure correct English grammar throughout the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

DATA AVAILABILITY/ SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA and Universiti Teknologi Malaysia.

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