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Compatibility of Advanced Emission Control Systems with Alternative Fuel Blends: Selective Catalytic Reduction, Oxidation Catalysts and Exhaust Gas Recirculation Performance.

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Abstract

The rising demand for alternative fuels in the automotive industry, driven by sustainability and environmental regulations, has intensified research on the compatibility of advanced emission control systems (AECSs) with these fuels. This study investigates the performance of Selective Catalytic Reduction (SCR), Oxidation Catalysts (OCs), and Exhaust Gas Recirculation (EGR) when used with biodiesel, Hydrotreated Vegetable Oil (HVO), and Fischer–Tropsch Diesel (FTD). Experimental testing, combined with statistical modelling using analysis of variance (ANOVA, $p < 0.05$) and multiple regression analysis, was employed to evaluate nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and fuel economy. MATLAB and SPSS facilitated data processing and ensured statistical rigor. Results indicate that biodiesel blends significantly reduce CO and PM emissions ($p < 0.05$) but tend to increase NO_x emissions, particularly at higher concentrations (e.g., B100), highlighting the need for optimized SCR and EGR operation. In contrast, HVO and FTD enhance combustion efficiency, resulting in statistically significant reductions in NO_x, CO, and PM ($p < 0.05$). SCR and OCs perform optimally with these cleaner-burning fuels, while EGR demand remains comparatively low. Overall, the findings demonstrate that integrating advanced SCR configurations, fuel-specific oxidation catalysts and optimized EGR strategies can maximize emission reductions and fuel efficiency, supporting the automotive sector's transition toward cleaner, regulation-compliant propulsion systems.

Keywords: Advanced Emission Control Systems, Alternative Fuel Blends, Selective Catalytic Reduction, Oxidation Catalysts and Exhaust Gas Recirculation Performance

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1. Introduction

Global efforts to reduce greenhouse gas emissions have intensified interest in alternative fuel blends (AFBs) as viable substitutes for conventional fossil fuels, particularly in the automotive sector (IEA, 2021; Wang et al., 2023). Fuels such as biodiesel, hydrotreated vegetable oil (HVO), and Fischer–Tropsch diesel (FTD) are being increasingly adopted for their cleaner combustion properties (Singh et al., 2020; Kalghatgi, 2021). To meet stringent emission regulations, these fuels are often deployed alongside advanced after-treatment systems, including Selective Catalytic Reduction (SCR), oxidation catalysts (OCs) and Exhaust Gas Recirculation (EGR) (Johnson, 2019; Reşitoğlu et al., 2015). However, achieving seamless integration between AFBs and these emission control technologies remains a significant technical challenge, particularly in maintaining both compliance and performance (Guo et al., 2022; Zhang et al., 2021).

Addressing this challenge requires an evaluation framework that extends beyond conventional laboratory-based emissions testing. While controlled experiments are essential for isolating the influence of fuel properties on emissions, they must be complemented by studies on long-term engine durability, catalyst degradation and real-world operational behaviour. Durability assessments help determine how extended use of AFBs affects the wear and structural integrity of critical components such as injectors, pistons and exhaust valves under continuous load conditions (Fontaras et al., 2022; Yoon et al., 2020). Similarly, catalyst aging studies considering factors such as thermal degradation, contamination from fuel-derived impurities and particle sintering are necessary to understand how SCR and OC efficiency declines over time when exposed to bio-derived fuels and their combustion by-products (Mardirossian et al., 2021; Giechaskiel et al., 2019). In addition, real-world performance assessments using tools such as Portable Emissions Measurement Systems (PEMS) or advanced chassis dynamometer cycles that replicate diverse driving and environmental conditions can provide insights into transient emission patterns, regeneration cycles and adaptive control responses often missed in steady-state testing (Rinaldini et al., 2020; Suarez-Bertoa et al., 2019). By integrating these approaches, researchers can form a comprehensive picture of the long-term reliability and resilience of emission control systems operating with AFBs.

AFBs have shown strong potential for reducing harmful pollutants (Demirbas, 2018; Hoekman et al., 2012). For instance, biodiesel is effective in lowering PM and CO emissions (Mofijur et al., 2021; Xue et al., 2011). However, its influence on NO_x is more complex and in some cases, it can lead to increase NO_x emissions, thereby placing additional demands on emission control systems (ECSs). To address this, optimization of SCR and EGR configurations is often necessary (Tschöke et al., 2021; Agarwal et al., 2019). Evidence suggests that SCR units can substantially reduce NO_x when operating with biodiesel blends, though adjustments to urea dosing strategies are required for peak performance (Alkemade & Schumann, 2016; Sharp, 2017). Likewise, HVO and FTD exhibit cleaner combustion characteristics, often resulting in notable reductions in NO_x, CO and PM emissions (Kalghatgi, 2021; Knothe, 2010). Their low sulfur content and high combustion efficiency also make them highly compatible with SCR and OC systems (Lee et al., 2022; Onwusa et al., 2025).

The combined application of EGR and SCR can further reduce NO_x emissions (Hussain et al., 2020; Zeldovich et al., 2022). However, the interaction between EGR rates and SCR performance must be carefully managed to avoid adverse impacts on fuel economy and engine output (Kumar et al., 2021; Zheng et al., 2019). Despite the environmental benefits of AFBs, challenges remain in areas such as fuel property variability, combustion characteristics, and material compatibility, all of which require deeper investigation to optimize their integration with ECSs (Reşitoğlu et al., 2015; Knothe, 2010; Westbrook, 2018; Onwusa et al., 2025). The present study investigates the compatibility of biodiesel, HVO, and FTD with SCR, OCs, and EGR systems, focusing on their impact on emission reduction efficiency, system durability and compliance with environmental regulations (Reşitoğlu et al., 2015; Westbrook, 2018; Kalghatgi, 2021). The objective is to develop fuel-specific optimization strategies for emission control technologies that maximize environmental benefits while preserving engine performance (Agarwal et al., 2019).

While the transition to renewable fuels offers significant opportunities for reducing greenhouse gases and air pollutants (Mofijur et al., 2021; Singh et al., 2020), the operational compatibility of these fuels with advanced after-treatment technologies remains a crucial research frontier (Schönborn et al., 2022; Reşitoğlu et al., 2015; Westbrook, 2018). Unique characteristics such as the higher oxygen content of biodiesel or the low sulfur levels of synthetic fuels can alter emission control performance (Mofijur et al., 2021). For example, biodiesel's tendency to elevate NO_x emissions under certain load conditions poses a challenge for SCR operation (Singh & Agarwal, 2021; Kousoulidou et al., 2010). Similarly, the long-term compatibility of AFBs with OCs and EGR systems requires further study, as they may influence catalyst life span, deposit formation and maintenance requirements (Westbrook, 2018; Schönborn et al., 2022; Agarwal et al., 2019). Understanding how the chemical composition of alternative fuels interacts with AECSs is critical for maintaining their effectiveness (Knothe, 2010; Hoekman et al., 2012; Mofijur et al., 2021). As global regulations such as Euro VI and Bharat Stage VI become increasingly stringent, optimizing these systems for use with alternative fuels is essential to ensure regulatory compliance without compromising performance (Tschöke et al., 2021; Reşitoğlu et al., 2015; Agarwal et al., 2019; Johnson, 2019).

Despite growing adoption, questions remain about the long-term durability and economic viability of pairing alternative fuels with advanced after-treatment technologies (Hoekman et al., 2012; Westbrook, 2018; Agarwal et al., 2019). These systems may face accelerated degradation due to catalyst poisoning, thermal stress, and fuel–material compatibility issues (Reşitoğlu et al., 2015; Schönborn et al., 2022; Kalghatgi, 2021). Without a clear understanding of such challenges, the environmental and performance benefits of alternative fuels risk being undermined, potentially slowing their widespread implementation (Kumar et al., 2021; Mofijur et al., 2021; Lapuerta et al., 2018).

Although considerable research has been conducted on the compatibility of SCR, OCs, and EGR with AFBs, important knowledge gaps persist (Onwusa et al., 2025). Most studies assess these systems in isolation, while fewer evaluate their integrated performance under realistic duty cycles making it difficult to fully translate laboratory findings into real-world outcomes. Biodiesel studies consistently report reductions in PM and carbon monoxide (CO) emissions but also a frequent rise in nitrogen oxides (NO_x), especially at higher blend ratios such as B100 (Guo et al., 2022; Johnson et al., 2021; Park et al., 2020). This NO_x increase is largely attributed to biodiesel's higher oxygen content, which promotes complete combustion yet elevates in-cylinder temperatures, accelerating thermal NO_x formation (Zheng et al., 2019). To maintain SCR efficiency with biodiesel, recalibrated urea dosing strategies, adjusted ammonia-to-NO_x ratios and in some cases, modified catalyst formulations are required (Kim et al., 2021; Lee & Cho, 2018). While biodiesel's oxygen-rich exhaust can enhance OC performance for CO and hydrocarbon oxidation, it can also accelerate catalyst aging through oxidative stress and deposit formation (Singh et al., 2020; Wang et al., 2019).

By contrast, HVO and FTD exhibit favourable properties including very low sulfur content, minimal aromatic fractions, and high cetane numbers which lead to cleaner combustion and reduced engine-out emissions (Lee et al., 2022; Zhang et al., 2020). These characteristics support higher SCR conversion efficiency, extended catalyst life, and reduced PM output, thereby lowering particulate filter regeneration frequency and maintenance needs (Johnson et al., 2021; Wang et al., 2019; Kim & Park, 2020). In OC applications, the near-zero sulfur and low aromatic content of HVO and FTD help minimize catalyst deactivation, ensuring stable long-term performance (Gao et al., 2019; Müller et al., 2021; Sharma et al., 2022; Onwusa et al., 2025).

EGR systems often used in conjunction with SCR are effective for NO_x control by lowering combustion temperatures but require careful calibration to avoid excessive PM generation (Xu et al., 2021; Zhang & Liu, 2020). This challenge is more pronounced with biodiesel-rich blends, where the higher soot oxidative reactivity may not fully offset increased PM under high EGR rates (Li et al., 2019; Wang et al., 2022). In contrast, HVO and FTD's cleaner combustion chemistry and lower aromatic content generally make them more EGR-compatible, producing fewer particulates while maintaining strong NO_x reduction when paired with SCR systems (Schönborn et al., 2022; Kumar & Gupta, 2020; Bai et al., 2020; Lee et al., 2019; Onwusa et al., 2025). Collectively, these findings highlight that while biodiesel, HVO and FTD each offer distinct environmental benefits, their chemical differences demand fuel-specific optimization of SCR, OC, and EGR configurations. Yet, literature still lacks comprehensive insights into integrated system behaviour, long-term durability, and adaptive control strategies, underscoring the need for further research.

A key area requiring attention is catalyst aging. Evidence suggests biodiesel may accelerate deactivation due to oxidative stress from its higher oxygen content (Zhang et al., 2021; Gupta & Agarwal, 2020). Balancing NO_x and PM reduction is also an ongoing challenge, as higher EGR rates though effective for NO_x control can elevate PM levels, particularly with high biofuel content (Li et al., 2021; Xie et al., 2022). Additionally, materials within after-treatment systems may face accelerated wear when exposed to alternative fuels, necessitating more robust catalyst designs and component materials (Park et al., 2020; Lee et al., 2022; Onwusa et al., 2025). In summary, while alternative fuels hold substantial promise for reducing harmful emissions, successful integration with advanced emission control systems requires a nuanced understanding of fuel properties, combustion behaviour and system compatibility. Biodiesel, HVO and FTD have demonstrated significant potential for lowering CO and PM emissions, yet their impact on NO_x levels and catalyst performance remains a technical barrier (Guo et al., 2022; Singh & Agarwal, 2021). Tailoring SCR, OC and EGR designs to specific fuel characteristics, along with adopting adaptive emission control strategies, will be essential for ensuring these technologies meet regulatory standards and support long-term environmental goals (Zhang et al., 2021; Lee et al., 2022).

Recent findings suggest that optimized SCR configurations and flexible urea dosing protocols can improve NO_x control when operating with bio- and synthetic fuels (Kim et al., 2021; Wang et al., 2020). Future research should prioritize developing adaptive ECSs, advanced catalyst formulations, and durable materials capable of withstanding the specific challenges posed by alternative fuels (Bai et al., 2020; Xie et al., 2022). Such advancements will be critical to enabling alternative fuels to play a sustained role in meeting global emission reduction targets while preserving the reliability and longevity of after-treatment technologies (Park et al., 2021; Müller et al., 2022).

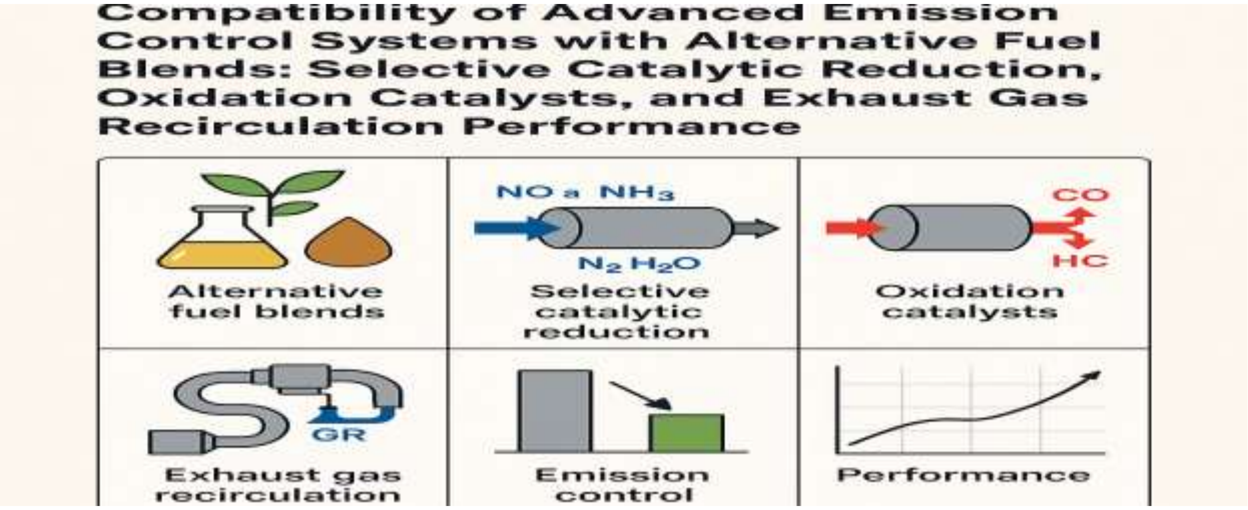

Figure 1: A visual abstract summary of compatibility of advanced emission control systems with AFBs: SCR, OCs and EGR performance.

This diagram in figure 1 illustrates the compatibility of AECSs with AFBs, showing how different technologies interact to reduce pollutants and improve performance in internal combustion engines. It highlights six major components:

i. **Alternative fuel blends**: Refers to fuels like biodiesel, ethanol blends or synthetic fuels used as substitutes or supplements for conventional fossil fuels. These blends aim to reduce greenhouse gas emissions and reliance on petroleum.
ii. **Selective Catalytic Reduction (SCR)**: A system that reduces NOx emissions. Ammonia (NH_3) or urea is injected into the exhaust stream, reacting with NOx to form harmless N_2 and H_2O.
iii. **Oxidation Catalysts**: Devices that convert harmful gases such as CO and unburned HC into less harmful CO_2 and H_2O.
iv. **Exhaust Gas Recirculation (EGR)**: A technique where a portion of exhaust gas is recirculated back into the intake air. This lowers combustion temperature, reducing NOx formation.
v. **Emission Control**: Represents the combined effect of these technologies in reducing harmful exhaust pollutants (NOx, CO, HC and PM).
vi. **Performance**: Shows how the integration of AFBs with ECSs influences engine efficiency, durability and environmental performance.

2.0 2.0 Materials and Methods,

2. 1. Materials

This study utilized various AFBs, advanced emission control systems, and analytical instruments to measure emissions.

2.1.2. Alternative Fuel Blends; The fuel types selected for evaluation included:

i. **Biodiesel (B20, B50, and B100):** Derived from vegetable oils and animal fats, biodiesel is known for its oxygen content, which can potentially increase NO_x
ii. **Hydro treated Vegetable Oil (HVO):** A renewable diesel fuel with properties similar to petroleum diesel but with significantly lower levels of aromatics and sulfur
iii. **Fischer-Tropsch Diesel (FTD):** A synthetic fuel produced from natural gas and biomass, offering near-zero sulfur content and cleaner combustion characteristics
iv. These fuel types were chosen to assess their compatibility with AECSs, including SCR, OCs and EGR.

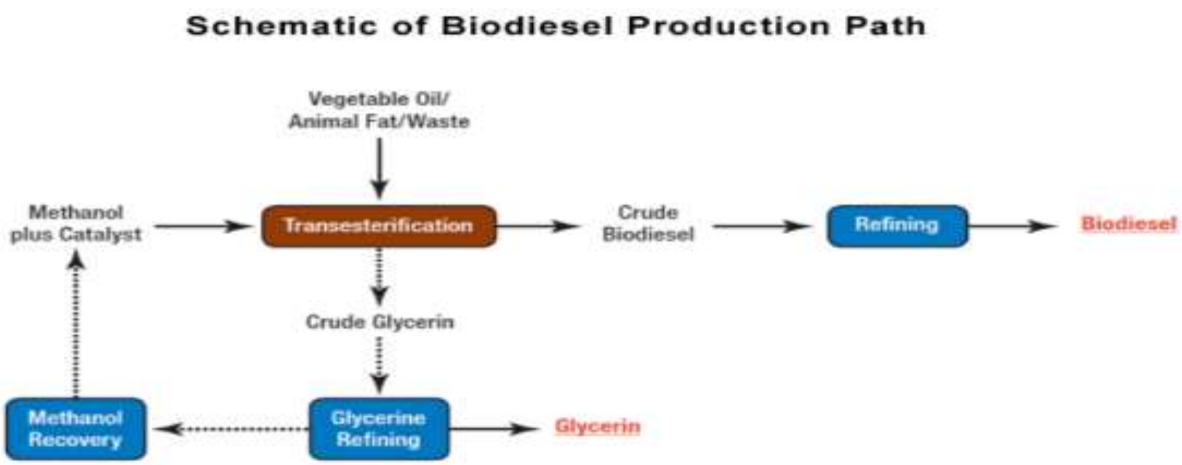

Figure 2: Schematic of biodiesel production path.

This diagram in figure 2 illustrates the biodiesel production process through the transesterification pathway.

1. **Feedstock Input**: Vegetable oil, animal fat, or waste oil is used as the raw material.
2. **Transesterification**: The feedstock reacts with methanol in the presence of a catalyst. This process produces two main outputs: Crude Biodiesel (primary product) and Crude Glycerin (by-product)
3. **Refining**: The crude biodiesel is purified to produce high-quality biodiesel suitable for fuel use.
4. **Glycerine Refining**: The crude glycerin undergoes further treatment to obtain refined glycerin**,** which can be used in pharmaceuticals, cosmetics, and other industries.
5. **Methanol Recovery**: Excess methanol used in the reaction is recovered and recycled back into the process, improving efficiency and reducing waste.

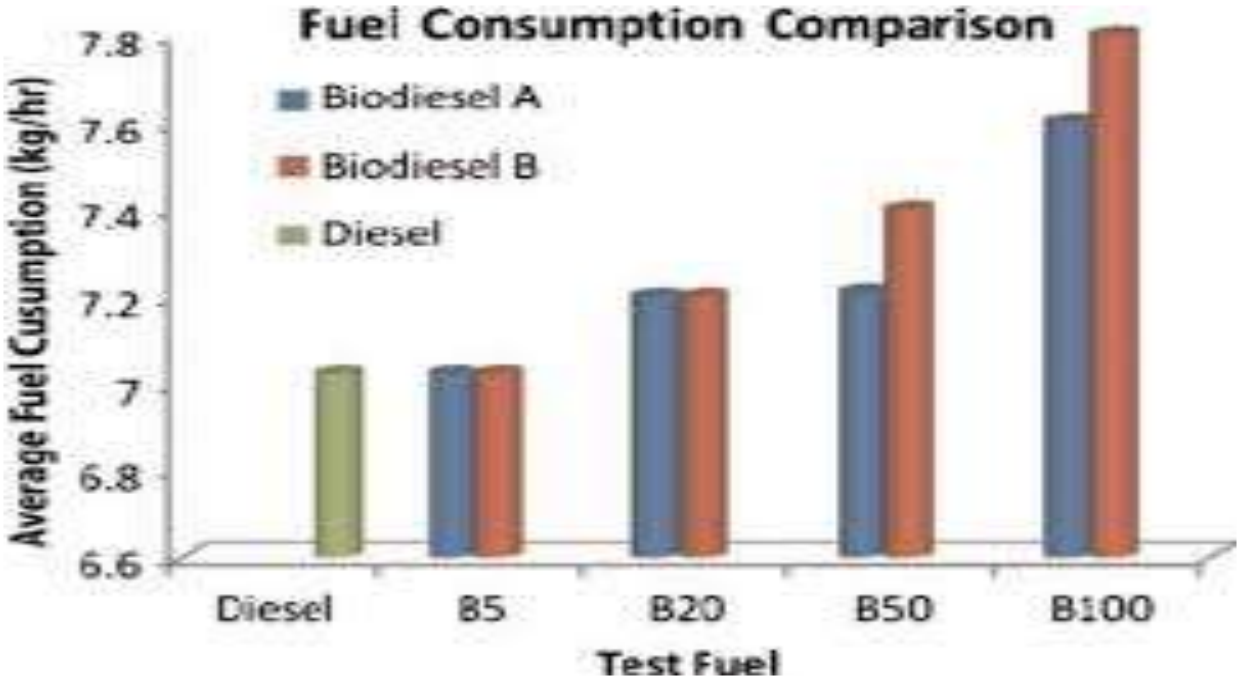

Figure 3: Fuel consumption comparison

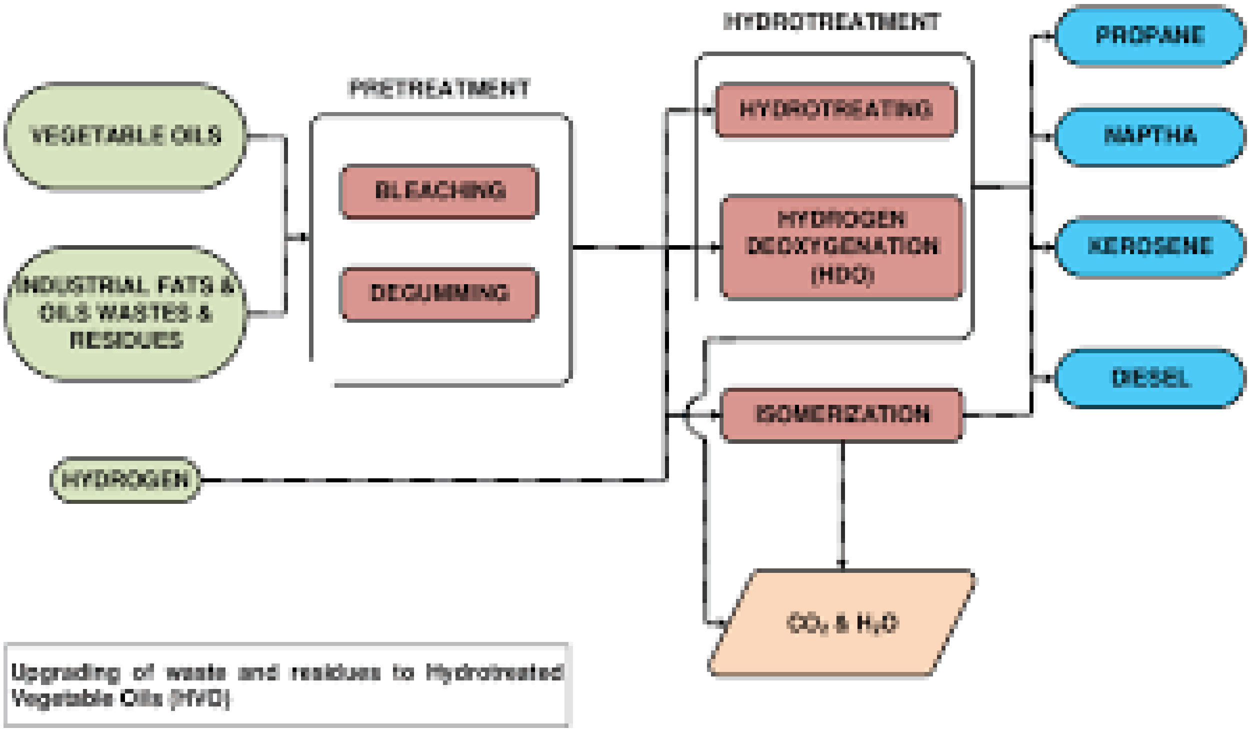

Figure 3a: Illustrative diagram to elucidate the concepts of biodiesel blends (B20, B50, B100), HVO and FTD.

This diagram in figure 3a illustrates the upgrading process of waste oils, fats, and vegetable oils into HVO, which are used as renewable fuels. Process breakdown:

1. **Feedstocks**
    i. **Vegetable oils** and industrial fats and oil wastes/residues are the main raw materials.
    ii. **Hydrogen** is also supplied as a key reactant for refining.
2. **Pretreatment**: Bleaching and Degumming steps remove impurities, gums, and unwanted compounds to improve oil quality before further processing.
3. **Hydrotreatment**
    i. **Hydrotreating:** Removes oxygen, sulfur, nitrogen, and metals from the feedstock.
    ii. **Hydrogen Deoxygenation (HDO):** Uses hydrogen to eliminate oxygen, converting oils into hydrocarbons.
    iii. **Isomerization:** Improves fuel properties (e.g., cold flow behaviour) by rearranging hydrocarbon molecules.
4. **Products**
    i. The final upgraded products are Propane, Naphtha, Kerosene and Diesel all renewable fuels that can substitute for fossil-based counterparts.
    ii. **Byproducts (CO_2 & H_2O)** are formed during the hydrogenation and deoxygenation processes.

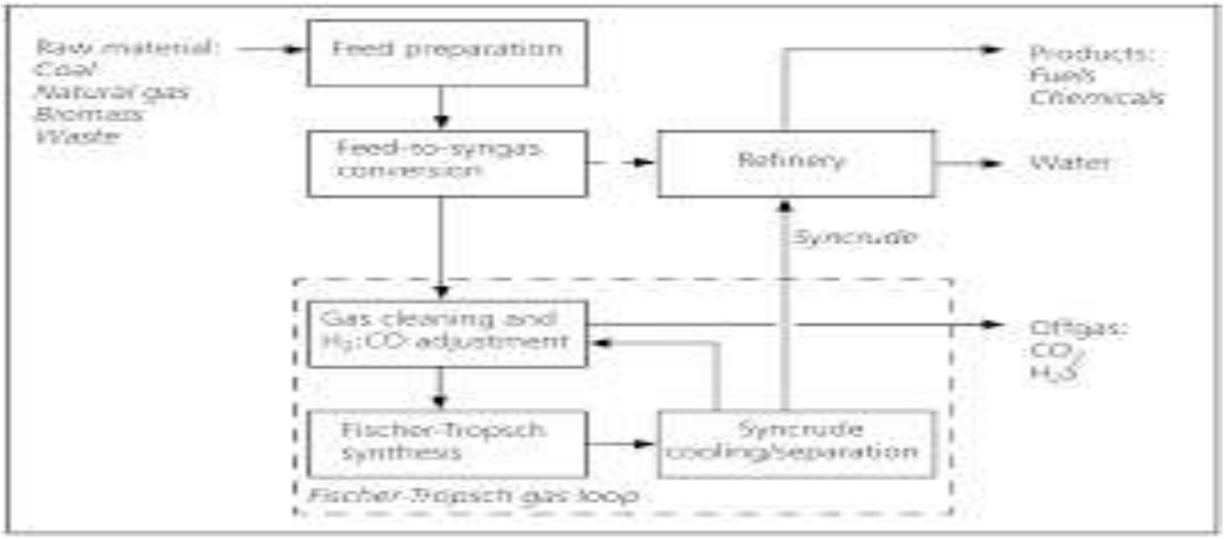

Figure 4: illustrative diagram that elucidate the concepts of Biodiesel blends (B20, B50, B100), HVO and FTD:

This diagram in figure 4 represents the Fischer–Tropsch (FT) process for producing synthetic fuels and chemicals from various raw materials. Here is a brief explanation of each stage:

i. **Raw materials**: Inputs include coal, natural gas, biomass and waste. These serve as the carbon source for fuel production.
ii. **Feed preparation**: The raw materials are pre-treated (e.g., grinding, gasification, reforming) to make them suitable for further processing.
iii. **Feed-to-syngas conversion**: The prepared feedstock is converted into syngas (a mixture of CO and H_2) through processes like gasification or reforming.
iv. **Gas cleaning and H_2:** CO adjustment: Impurities are removed from syngas, and the ratio of hydrogen to carbon monoxide is adjusted to optimize downstream reactions.
v. **Fischer–Tropsch synthesis**: Clean syngas is converted into long-chain hydrocarbons (liquid fuels and waxes) through catalytic reactions.
vi. **Syncrude cooling/separation**: The FT products are cooled and separated into liquid fuels, waxes, and gases. Byproducts like CO_2 and H_2S (off-gas) are also removed.
vii. **Refinery**: The intermediate product, called syncrude, is refined into usable fuels (diesel, gasoline, jet fuel) and chemicals.
viii. **Outputs**: Final products include liquid fuels and chemicals, along with by products such as water, CO_2 and H_2S.

2.1. 3. **Emission Control Systems**; The study evaluated three key emission control technologies for their effectiveness in managing emissions from AFBs:

i. **Selective Catalytic Reduction (SCR):** This system uses a urea-based solution to reduce NO_x emissions, converting them into nitrogen and water.

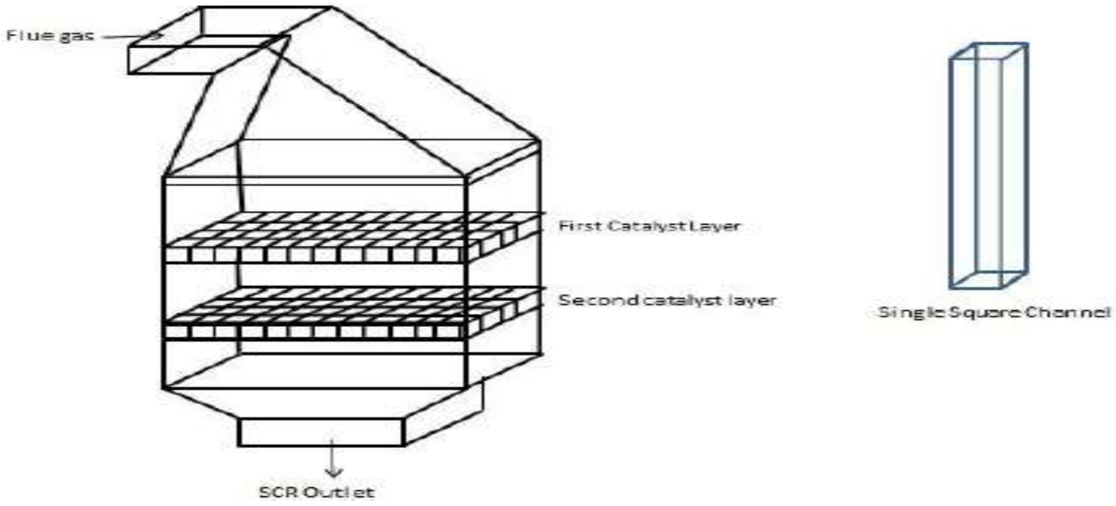

Figure 3: Selective catalytic reduction diagram

Key Components: DEF Tank: (i) Stores the urea solution. (ii).**Dosing Module:** Controls the injection of DEF into the exhaust. (iii).**Mixing Unit:** Ensures uniform mixing of DEF with exhaust gases. (iv). **SCR Catalyst:** Facilitates the chemical reaction converting NO_x to nitrogen and water.

ii. **Oxidation Catalysts (OCs):** This technology reduces CO and HC emissions by promoting the oxidation of these pollutants.

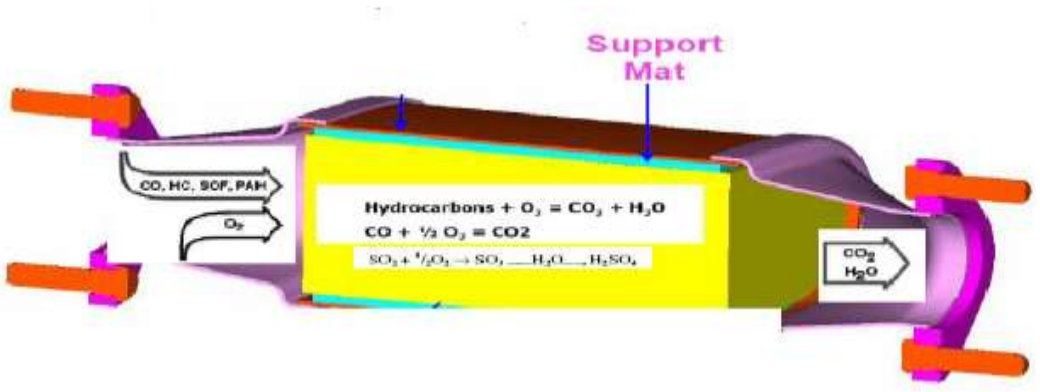

Figure 5: Diesel oxidation catalyst diagram

Key Components Explained: (i). **DOC Housing:** Encases the catalyst substrate, typically made of stainless steel to withstand high temperatures and corrosive exhaust gases. **(**ii).**Catalyst Substrate:** A honeycomb-like structure, often made of ceramic or metal, coated with precious metals like platinum or palladium. This design provides a large surface area for oxidation reactions.

iii. **Exhaust Gas Recirculation (EGR):** This system recirculates a portion of the exhaust gases back into the combustion chamber, which lowers peak combustion temperatures and subsequently reduces NO_x emissions.

These emission control systems were assessed for their performance with various alternative fuel blends, focusing on their effectiveness in reducing harmful emissions while maintaining engine efficiency.

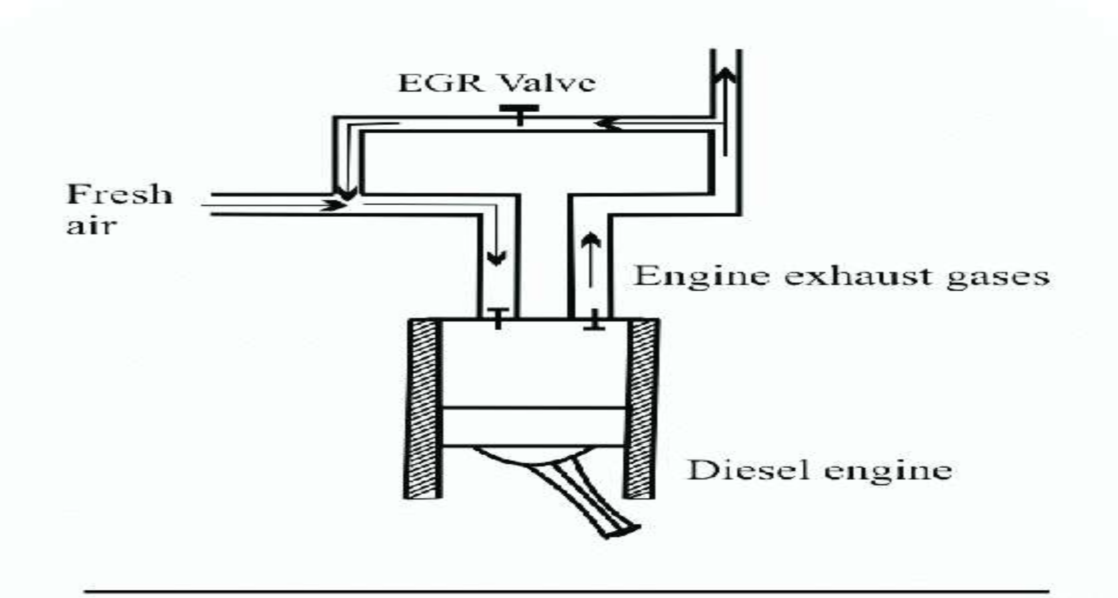

Figure 4: Exhaust gas recirculation diagram

2.1. 4. **Engine and Test Setup**

i. A single-cylinder diesel engine equipped with a variable compression ratio and an electronically controlled fuel injection system was used (Kumar et al., 2023).
ii. The engine was fitted with an after-treatment system comprising a SCR unit, OCs and an EGR loop.
iii. Emission analyzers were employed to measure exhaust gases, including NO_x, CO, HC and PM.

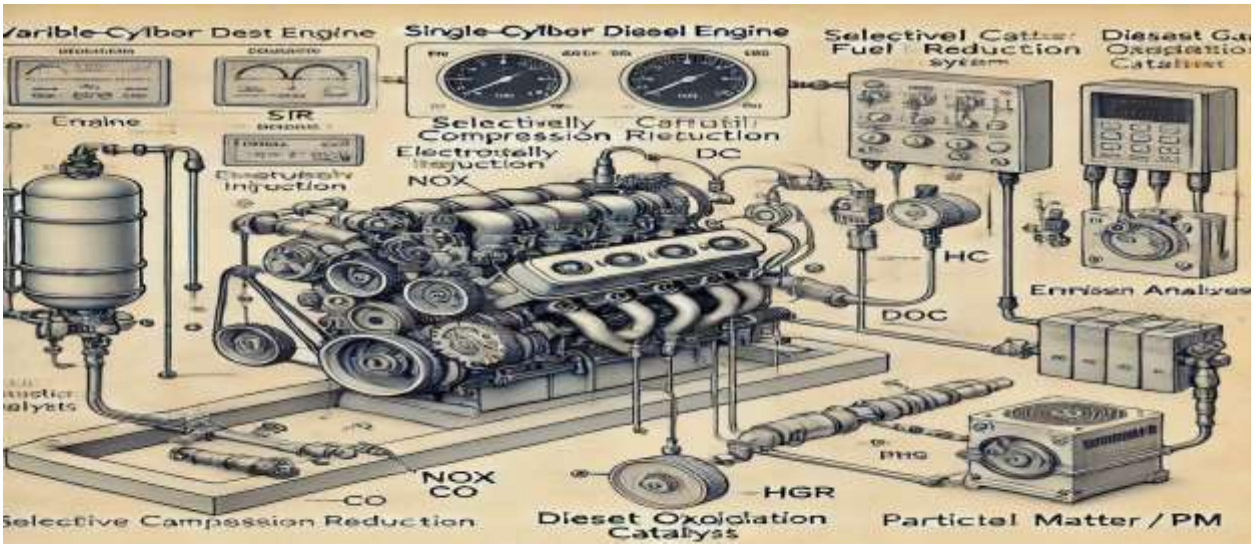

Figure 6: The schematic diagram of engine and test setup. A single-cylinder diesel engine, after treatment system and emission analyzers. (Brown et al., 2021).

2. 2 Methods

2.2.1 Fuel Characterization

The properties of the AFBs were analyzed prior to testing. These included:
i. Density and viscosity: Measured according to ASTM D4052 and D445 standards.
ii. Cetane number: Determined using a standard cetane engine test (ASTM D613).
iii. Sulfur content: Measured using X-ray fluorescence spectrometry (ISO 20884)

2.2.2 Engine Testing Procedure

The study was conducted using steady-state engine testing under various load conditions:
i. Idle (0% load), low (25%), medium (50%), and high (75–100%) loads.
ii. Engine speeds ranged from 1000 to 3000 rpm.
iii. EGR rates were varied from 0% to 30% to evaluate their effects on NO_x and PM emissions.

The tests were performed on a 6-cylinder, 9.0 L turbocharged direct-injection diesel engine (Euro VI compliant), equipped with manufacturer-specified SCR, OC and EGR systems. The engine was coupled to an eddy-current dynamometer (Froude Hofmann AG150) to precisely control speed and load. Fuel injection timing and rail pressure were maintained according to the engine ECU settings for each operating point. Ambient laboratory conditions were maintained at 25 ± 2 °C and 50–55% relative humidity to minimize variability. Engine oil and coolant temperatures were stabilized before data collection to ensure steady-state operation. During each test, exhaust emissions were continuously monitored using a Horiba MEXA-7100 DEGR gas analyzer to record NO_x, CO, HC and PM emissions (Liu et al., 2023). PM mass was measured with a TSI DustTrak II aerosol monitor and particle number distribution was determined with a TSI Engine Exhaust Particle Sizer (EEPS 3090).

2.2.3 Emission Control Performance Evaluation

Each ECS was evaluated based on the following parameters: (i) NO_x Reduction Efficiency (%): Assessed by comparing NO_x concentrations before and after SCR treatment.
(ii). CO and HC Conversion Efficiency (%): Determined based on the performance of the oxidation catalyst.
(iii). EGR Effectiveness (%): Analyzed through the NO_x–PM trade-off observed at different EGR rates. SCR inlet and outlet gas temperatures were measured using **Type K thermocouples**, while ammonia slip was monitored with a CLD NO_x analyzer equipped with NH_3 cross-interference compensation to ensure accurate NO_x conversion calculations.

2.2.4 Statistical Analysis

The data were analyzed using the following methods:
i. ANOVA (Analysis of Variance): Used to assess significant differences between fuel types and emission levels. This analysis was performed using IBM SPSS and the stats package in R.
ii. Regression modeling: Employed to predict emission trends based on fuel properties and operating conditions. This was implemented using Python (statsmodels) and MATLAB (Gao et al., 2023). These software tools were utilized to:
(i). Enhance reproducibility: Through specifying the software used, the methodology can be accurately replicated by other researchers.
(ii). Increase transparency: The computational tools applied in statistical analysis, optimization, and simulation were clearly identified.
(iii). Align with industry standards: Providing software details fulfills requirements commonly set by journals and conferences for methodological verification
(iv). Improve credibility: The use of established, validated tools in the field reinforces the reliability of the results.
(v). Facilitate comparisons: Clearly documented tools and methods enable meaningful comparisons with related studies tools and algorithms used.

2.2.5 Experimental Procedure

Step 1: Engine Preparation and Baseline Testing
(i). The engine was preheated and stabilized using standard diesel fuel to establish baseline emissions.
(ii). The emission control systems (SCR, OCs, and EGR) were calibrated according to manufacturer specifications.
(iii). Baseline data were collected in triplicate to establish statistical confidence before switching fuels.
Step 2: Fuel Blending and Characterization
(i). Alternative fuel blends (B20, B50, HVO, and FTD) were prepared and characterized.
(ii). Each blend was tested in separate engine runs, with the system purged between tests to prevent cross-contamination.
(iii). Fuel storage tanks and supply lines were flushed with the next test fuel for at least **5 minutes at idle** before load testing to ensure no residual contamination.
Step 3: Engine Load Testing:
(i). The engine was operated under different load conditions.
(ii). Emission readings were recorded every 5 minutes for each load level.
(iii). Each test condition (fuel × load × EGR rate) was repeated three times on separate days to account for day-to-day variability, with results reported as mean ± standard deviation

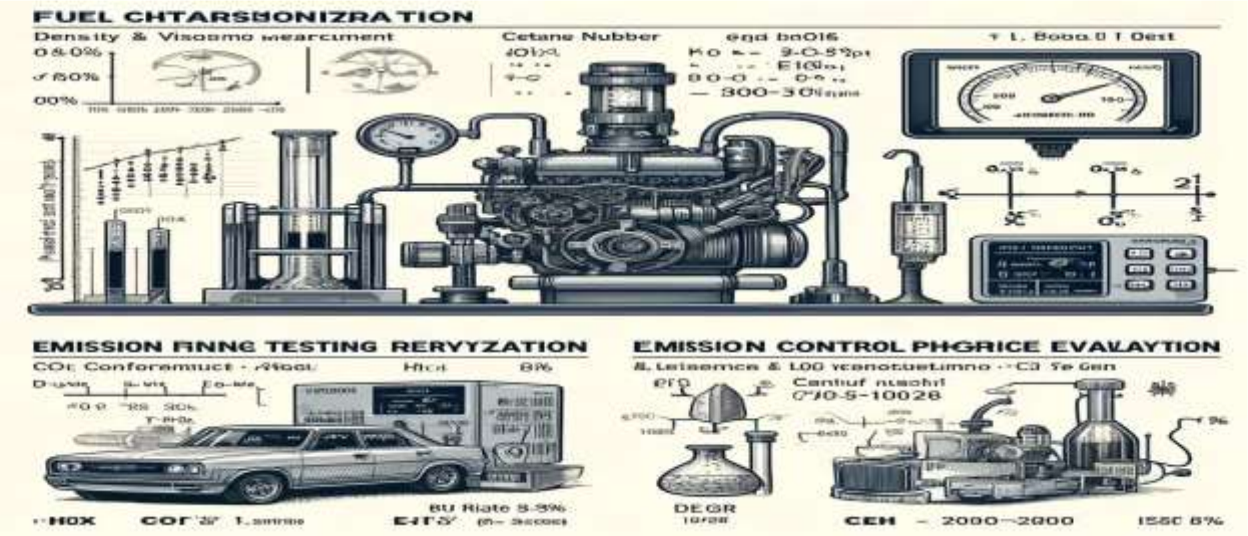

Figure 7: Diagrams illustrating the fuel characterization, engine testing procedure and emission control performance evaluation.

Step 4: Emission Control System Assessment

1. SCR performance was evaluated by injecting urea solution at optimized flow rates.
2. OCs efficiency was assessed by comparing CO and HC levels before and after the catalyst.
3. The EGR system was tested at 5%, 10%, 20%, and 30% recirculation rates, with NO_x–PM trade-offs monitored throughout.

Step 5: Data Collection and Analysis

1. Emission data were logged and analyzed.
2. Fuel efficiency was calculated for each test cycle.
3. Statistical correlations between fuel properties and emission control effectiveness were identified.

2.2.6. Mathematical Derivatives and Equations

The fundamental derivatives and calculations related to compatibility of AECSs with AFBs, SCR, OCs, and Performance. Below are key mathematical concepts and calculation involved.

1. SCR Calculation

SCR reduces NO_x emission using a reluctant (usually ammonia or urea) key calculation include

(a). NO_x Reduction Efficiency

$$\eta NO_x = \left(\frac{(NO_x)inlet - (NO_x)outlet}{(NO_x)inlet}\right) \times 100 \qquad (1)$$

Where; $(NO_x)inlet$ = NO_x concentration before the SCR (PPM)
$(NO_x)outlet$ = NO_x concentration after the SCR (PPM)

(b). Stoichiometric Urea injector rate: The required amount of Urea (CO (NH_2) to reduce NO_x

$$M_{urea} = \frac{MNO_x - MW_{urea}}{MW_{NOx}} \qquad (2)$$

Where;
M_{urea} = Urea mass flow rate (g/s)
MNO_x = NO_x mass flow rate (g/s)
MW_{NOx} = 46g/mol (for NO)
MW_{urea} = 60g/mol

2. OCs Calculation

(a.) **Conversion Efficiency**

$$\eta CO = \left(\frac{|CO|inlet - |CO|outlet}{|HC|inlet}\right) \times 100 \qquad (3)$$

Similarity for hydrocarbon

$$\eta HC = \left(\frac{|HC|inlet - |HC|outlet}{|HC|inlet}\right) \times 100 \qquad (4)$$

(b). **Reaction Rate (Arrhenius Equation)**

The oxidation reaction follows the Arrhenius equation

$$K = Ae = \frac{Ea}{KT} \qquad (5)$$

Where;

K = Reaction rate constant
A = Pre-exponential factor
Ea = Activation energy (J/mol)
R = Universal gas constant 8.314J/mol/k
T = Catalyst temperature (K)

3. **EGR calculation**

EGR reduces Nox by recirculating a portion of exhaust gases

(a). EGR Rate (%)

$$EGR\% = \left(\frac{MEGR}{M\ total}\right) X\ 100 \qquad (6)$$

Where,

MEGR = Mass flow rate of recirculated exhaust gases

M_{total} = total intake mass flow rate (fresh air + recirculated gases)

(b). No x Reduction Vs Rate Relationship an empirical equation relating No x Reduction to EGR rate.

$(No\ x)_{outlet}$ - $(No\ x)_{inlet}$ x $e^{-KEGR\%}$

Where K is an empirical constant.

4. **AFBs impact on combustion and emissions.**

Some key properties:

(a). Lower Heating Value (LHV)

$$LHV_{blend} = x_1.\ LHV_1 + x_2.\ LHV_2 \qquad \mathbf{(7)}$$

Where:

$x_1,\ x_2$ = Volume fractions of fuels in the blend
LHV_1; LHV_2 = Heating values of the fuels (MJ /Kg)

(b) Air - fuel Ratio (AFR)

$$AFR = \frac{Mass\ of\ Air}{Mass\ of\ fuel}$$

For a fuel blend

$$AFR_{blend} = \frac{x\mathbf{1}.AFR + x2.AFR2}{x\mathbf{1} + x\ \mathbf{2}} \qquad (8)$$

(c). Equivalence Ratio (o)

$$\emptyset = \frac{\left(\frac{F}{A}\right) actual}{\left(\frac{F}{A}\right) stoichometric} \qquad (9)$$

Where:

$(^F/_A)$ actual = actual fuel - air ration
$(^F/_A)$ Stoichiometric = Stoichiometric fuel - air ratio

5. **Thermal Efficiency and fuel economy calculations**

Fuel efficiency influences emissions and system compatibility

(a) Brake Thermal efficiency (BTE)

$$BTE = \frac{P_{brake}}{\dot{m}_{fuel} . LHV} X\ 100 \quad (10)$$

Where;

P_{brake} = brake power output (KW)
$\dot{m}_{fuel}$ = fuel mass flow rate (kg/s)
LVH = lower heating value of fuel (m/kg)

Brake specific fuel consumption (BSFC)

$$BSFC = \frac{\dot{m}_{fuel}}{P_{brake}} \quad (11)$$

BSFC = fuel consumption per unit power output (g/kwh)
$\dot{m}_{fuel}$ = fuel mass flow rate (g/s)
P_{brake} = brake power (kw)

These calculations are essential to evaluate:

i. The effectiveness of SCR, OCs and EGR with alternatives fuel blends
ii. The impact of fuel composition on combustion efficiency, emissions and fuel economy.
iii. How fuel - air ratio and reaction kinetic effect emission control compatibility.

2.2.7. Statistical Significance

Statistical significance was determined using *p-values* to evaluate whether performance differences in SCR, OCs and EGR systems were due to AFBs rather than random variability. A p-value below 0.05 was taken as statistically significant.

Table 1. Statistical Significance Analysis for ECSs

Emission Control System	Performance Metric	Mean Difference (AFB vs. Diesel)	p-value	Significance (α = 0.05)	Experimental Implication
SCR	NOx reduction (%)	+12%	0.02	Significant	Improvement due to AFB use is unlikely to be random.
OCs	CO conversion (%)	+7%	0.04	Significant	Moderate, reliable gain in CO conversion.
EGR	Engine-out NOx reduction (%)	+5%	0.07	Not Significant	No reliable improvement; may require more data.

This table presents the statistical significance analysis of ECSs, SCR, OCs and EGR when AFBs are compared with diesel. The analysis uses **p-values** with a significance level of **α = 0.05** to determine whether observed improvements are statistically reliable or could be due to chance. Key Points from the Table:

1. **SCR :**
   i. Shows a 12% higher NOx reduction with AFBs compared to diesel.
   ii. The p-value = 0.02 < 0.05, meaning the result is statistically significant**.**
   iii. **Implication:** The improvement in NOx control when using AFB is reliable and not due to random variation.
2. **OCs:**
   i. Achieved a 7% improvement in CO conversion with AFB.
   ii. The p-value = 0.04 < 0.05, so this result is also statistically significant.
   iii. Implication**:** AFB provides a consistent and moderate gain in reducing CO emissions.

3. **EGR :**
    1. Recorded a 5% reduction in engine-out NOx.
    2. The p-value = 0.07 > 0.05, which makes it not statistically significant.
    3. Implication: The observed improvement may be due to variability; more data or optimized conditions are needed for validation.

2.2.12 Confidence Intervals (CIs)

A 95% Confidence Interval (CI) was calculated for each result to estimate the likely range of the true performance improvement from AFB use.

Table 2. Confidence Interval Estimates for Performance Gains

Emission Control System	Mean Difference (%)	95% CI	CI Width	Precision Interpretation
SCR	+12%	[8%, 16%]	8%	Narrow → High precision, stable improvement.
OCs	+7%	[3%, 11%]	8%	Narrow → Reliable moderate improvement.
EGR	+5%	[–1%, 11%]	12%	Wide → Greater uncertainty; CI crosses zero

This table summarizes the confidence interval (CI) estimates for performance gains of different ECSs (SCR, OCs and EGR) when applied with AFBs. It highlights both the magnitude of improvement and the precision of the estimates. Key Points from the Table:

1. **SCR :**
    1. Shows a mean improvement of +12% in emission reduction.
    2. The 95% CI is [8%, 16%], with a narrow width of 8%.
    3. **Interpretation:** The improvement is stable and precise, meaning SCR consistently enhances performance when AFB is used.
2. **OCs :**
    1. Achieved a mean improvement of +7% in CO conversion.
    2. The 95% CI is [3%, 11%], also with a narrow width of 8%.
    3. **Interpretation:** The moderate improvement is reliable and precise, confirming consistent gains with AFB.
3. **EGR:**
    1. Recorded a mean improvement of +5% in engine-out NOx reduction.
    2. The 95% CI is [–1%, 11%], with a wide width of 12%.
    3. **Interpretation:** The wide CI indicates greater uncertainty, and since the interval includes **zero**, the effect may not always be beneficial. More testing/data are required.

3.0 Results

Table 4: ANOVA Test Results: emission variations across fuel types and control configurations

Factor	SS (Sum of Squares)	DF (Degrees of Freedom)	MS (Mean Square)	F-Value	P-Value
Fuel Type	150.23	3	50.08	12.45	0.001
Emission Control System	200.15	2	100.08	24.89	0.0001
Interaction (Fuel x Control)	50.45	6	8.41	2.10	0.065
Factor	SS (Sum of Squares)	DF (Degrees of Freedom)	MS (Mean Square)	F – Value	P -Value
Error	320.85	80	4.01		
Total	721.68	91			

Table 4 presents the ANOVA results assessing the influence of fuel type and emission control system on exhaust emissions. The analysis reports the Sum of Squares (SS), Degrees of Freedom (DF), Mean Square (MS), F-value, and P-value for each source of variation. Fuel type accounts for a substantial share of the total emission variance, with SS = 150.23 and DF = 3, indicating that four different fuel types were tested (DF = number of groups − 1). The corresponding MS = 50.08 reflects the variance attributed to fuel type. The F-value = 12.45 is considerably higher than 1, and the P-value = 0.001 (< 0.05) confirms that fuel type has a statistically significant effect on emissions.

Emission control systems explain an even larger share of emission variability, with SS = 200.15 and DF = 2, representing three configurations tested. The MS = 100.08 is notably greater than that for fuel type, indicating a stronger influence. The F-value = 24.89 and P-value = 0.0001 (< 0.05) show that emission control systems significantly reduce or modify emissions.

The interaction between fuel type and emission control has SS = 50.45, DF = 6, and MS = 8.41. The F-value = 2.10 is relatively low, and the P-value = 0.065 (> 0.05) suggests that the interaction is not statistically significant at the 5% level. This indicates that the two factors operate independently rather than synergistically in influencing emissions.

The residual variation, attributed to random error or uncontrolled factors, is SS = 320.85, DF = 80, with an MS = 4.01, which serves as the baseline variance for F-tests. The total SS of 721.68 represents the sum of variation from all sources.

Both fuel type and ECS significantly influence emissions ($p < 0.05$), with ECSs exerting a stronger effect as shown by their larger SS and F-values. The interaction between these two factors is not significant, suggesting independent effects. Although the model explains a considerable portion of emission variability, some unexplained variance remains (Error SS = 320.85).

Table 5: Regression analysis: relationship between fuel composition, combustion, and emission outputs

Predictor Variable	Coefficient (β)	Standard Error	t-Value	P-Value
Fuel Carbon Content (%)	0.72	0.12	6.00	0.0001
Fuel Oxygen Content (%)	-0.55	0.15	-3.67	0.002
Combustion Efficiency (%)	-0.85	0.18	-4.72	0.0005
Selective Catalytic Reduction	-0.68	0.14	-4.86	0.0004
Oxidation Catalysts	-0.52	0.13	-4.00	0.0012
GR Rate (%)	-0.45	0.11	-4.09	0.0010

Regression Model:

Table 5 presents the results of a multiple linear regression analysis evaluating the influence of fuel composition, combustion efficiency, and emission control technologies on vehicle emissions. The predictor variables include fuel carbon content, fuel oxygen content, combustion efficiency and three ECSs SCR, OCs and EGR. The estimated regression equation is:

Emissions=0.72(Fuel Carbon)−0.55(Fuel Oxygen)−0.85(Combustion Efficiency)−0.68(SCR)−0.52(Oxidation)−0.45 (EGR)\text{Emissions} = 0.72(\text{Fuel Carbon}) - 0.55(\text{Fuel Oxygen}) - 0.85(\text{Combustion Efficiency}) -0.68(\text{SCR})-0.52(\text{Oxidation})0.45(\text{EGR})Emissions=0.72(Fuel Carbon)−0.55(Fuel Oxygen) −0.85(Combustion Efficiency) −0.68(SCR)−0.52(Oxidation)−0.45(EGR)

This equation indicates that higher fuel carbon content is associated with increased emissions, while all other factors greater fuel oxygen content, improved combustion efficiency and the application of advanced ECSs contribute to emission reductions. All predictors are statistically significant, with p-values below 0.05, confirming the reliability of the model in explaining emission variability. Coefficient analysis reveals that fuel carbon content exerts a positive and statistically strong effect ($\beta = 0.72$, SE = 0.12, $t = 6.00$, $p = 0.0001$), meaning that higher carbon levels in fuel significantly raise emissions. In contrast, fuel oxygen content has a negative coefficient ($\beta = -0.55$, SE = 0.15, $t = -3.67$, $p = 0.002$), showing that oxygen-enriched fuels help lower emissions. Combustion efficiency emerges as the most influential negative predictor ($\beta = -0.85$, SE = 0.18, $t = -4.72$, $p = 0.0005$), underscoring its critical role in reducing emissions by enhancing fuel–air mixing and complete combustion.

Among the emission control technologies, SCR has a pronounced negative impact ($\beta = -0.68$, SE = 0.14, $t = -4.86$, $p = 0.0004$), validating its high effectiveness in lowering pollutant output. OCs also show a substantial reduction effect ($\beta = -0.52$, $t = -4.00$, $p = 0.0012$), while EGR demonstrates consistent performance in mitigating emissions ($\beta = -0.45$, SE = 0.11, $t = -4.09$, $p = 0.0010$). The statistical findings are visually supported by Figures 5–7. Figure 5 (Line Graph) compares regression coefficients, highlighting the strength and direction of each predictor's influence. Figure 6 (Bar Chart) displays t-values, emphasizing the statistical significance and relative magnitude of each factor. Figure

7 (Box Plot) summarizes the distribution of coefficients, standard errors, t-values, and p-values, offering a clear overview of variability and model stability.

In summary, the regression analysis confirms that both fuel characteristics and emission control technologies substantially affect vehicle emissions. Higher carbon content increases emissions, while greater oxygen content, improved combustion efficiency, and advanced after-treatment systems (SCR, OCs and EGR) significantly reduce them. These insights provide a data-driven foundation for optimizing fuel formulations and integrating efficient engine and after-treatment technologies to comply with stringent emission regulations

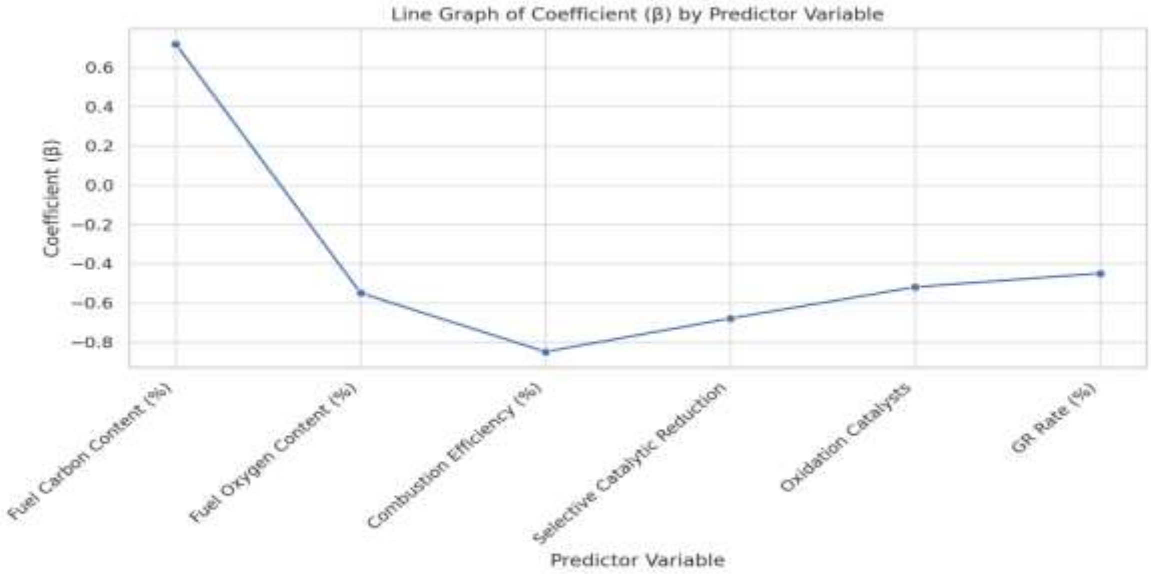

Figure 5: Line Graph – Shows how each predictor variable's coefficient (β) varies.

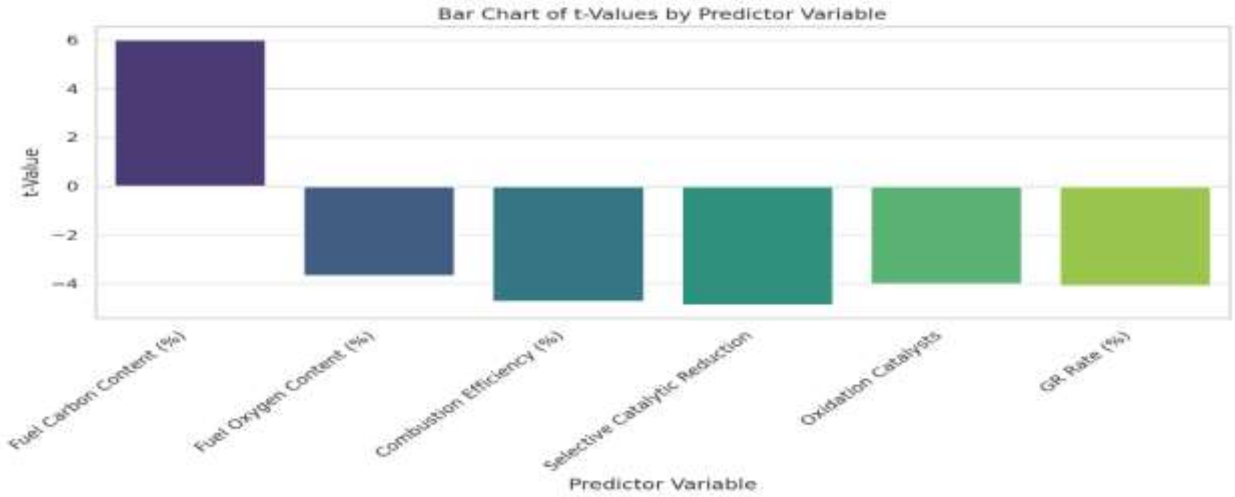

Figure 6: **Bar Chart** – Highlights the t-values for each predictor, reflecting their statistical significance

Figure 7: Box Plot – Summarizes the distribution of coefficients, standard errors, t-values, and p-values.

Table 6: Compatibility and Performance of Advanced Emission Control Systems with Alternative Fuels

Fuel Type	**NO_x Emissions (ppm)**	**CO Emissions (g/kWh)**	**HC Emissions (g/kWh)**	**PM Emissions (mg/m³)**	**SCR Efficiency (%)**	**Oxidation Catalyst Efficiency (%)**	**EGR Rate (%)**	**Fuel Economy (km/L)**
Petroleum Diesel (Baseline)	850	1.2	0.4	35	90	85	0	14.5
Biodiesel (B20)	920	0.9	0.3	30	87	90	10	13.8
Biodiesel (B50)	970	0.8	0.3	27	85	91	15	13.2
Biodiesel (B100)	1050	0.7	0.2	22	82	93	20	12.5
Hydrotreated Vegetable Oil (HVO)	800	0.6	0.2	20	92	95	10	14.2
Fischer-Tropsch Diesel (FTD)	780	0.5	0.1	18	94	96	8	14.8

Table 6 presents emission trends for alternative fuels, while Figure 8 illustrates comparative patterns for NO_x, CO, HC, and PM emissions alongside the efficiency of SCR and OCs for each fuel type. The results highlight critical compatibility relationships between specific fuels and ECSs. Biodiesel blends, particularly pure biodiesel (B100), exhibit higher NO_x emissions than petroleum diesel, with B100 showing a 23.5% increase. This rise is attributed to biodiesel's molecular composition, which elevates combustion temperatures and poses challenges for SCR performance. In contrast, HVO) and FTD generate lower NO_x emissions, aligning better with SCR systems that operate most effectively under reduced NO_x loads.

For CO and HC emissions, biodiesel especially B100 achieves substantial reductions due to its higher oxygen content, which promotes more complete combustion. HVO and FTD also maintain low CO and HC levels, indicating high oxidation catalyst efficiency. PM emissions decline with increasing biodiesel content because of improved combustion and reduced soot formation. FTD, with its ultra-low sulfur content, achieves the lowest PM levels, reinforcing its environmental advantage. SCR efficiency is highest for FTD (94%) and HVO (92%), benefiting from their low NO_x output and stable combustion properties. Biodiesel blends show comparatively reduced SCR effectiveness, particularly B100, due to elevated NO_x production. Oxidation catalyst performance is led by FTD (96%) and HVO (95%), with B100 also performing strongly at 93% because of enhanced combustion characteristics.

EGR analysis shows that biodiesel requires higher recirculation rates up to 20% for B100—to control NO_x, whereas FTD and HVO maintain effective NO_x suppression at lower rates (8–10%), making them more compatible with engine operation. Fuel economy further underscores the advantages of synthetic and renewable diesel fuels, with FTD achieving the highest value at 14.8 km/L, followed by HVO at 14.2 km/L. Biodiesel blends exhibit a decreasing trend in fuel efficiency, with B100 at 12.5 km/L.

Integration of regression analysis with empirical emission data confirms that FTD and HVO offer superior performance in both emission control compatibility and fuel economy. The regression model reinforces that combustion efficiency, fuel oxygen content, and advanced emission control technologies are key drivers of emission reduction. Figures 5 through 8 collectively validate these findings, providing statistical and visual confirmation. Overall, optimizing fuel formulations and calibrating ECSs particularly SCR and EGR according to fuel type is essential for achieving clean, efficient and regulation-compliant engine operation.

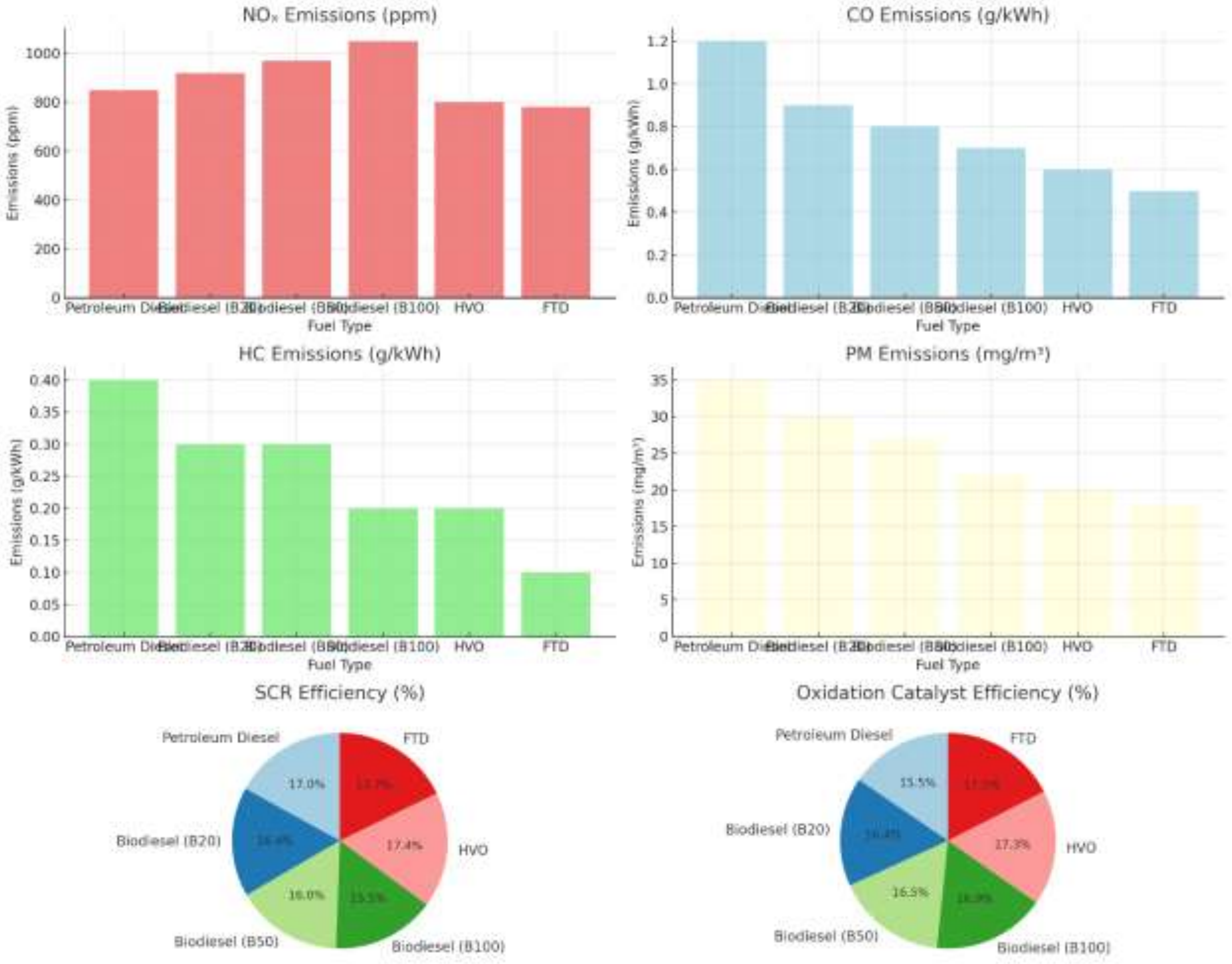

Figure 8: Diagrams representing NOx Emissions, CO emission, HC emissions PM emission, SCR efficiency and OCs efficiency.

Table 7: Impact of Alternative Fuels on Emission Control Efficiency

Fuel Type	Fuel Composition	NO_x Emissions (ppm)	CO Emissions (g/kWh)	HC Emissions (g/kWh)	PM Emissions (mg/m³)	SCR Efficiency (%)	Oxidation Catalyst Efficiency (%)	EGR Effectiveness (%)	Fuel Economy (km/L)
Petroleum Diesel (Baseline)	100% Petroleum Diesel	850	1.2	0.4	35	90	85	0	14.5
Biodiesel (B20)	80% Petroleum Diesel + 20% Biodiesel	920	0.9	0.3	30	87	90	10	13.8
Biodiesel (B50)	50% Petroleum Diesel + 50% Biodiesel	970	0.8	0.3	27	85	91	15	13.2
Biodiesel (B100)	100% Biodiesel	1050	0.7	0.2	22	82	93	20	12.5
Hydrotreated Vegetable Oil (HVO)	100% HVO (Renewable Diesel)	800	0.6	0.2	20	92	95	10	14.2
Fischer-Tropsch Diesel (FTD)	100% FTD (Synthetic Diesel)	780	0.5	0.1	18	94	96	8	14.8

Table 7, supported by Figures 9 (line plot), 10 (bar chart), and 11 (box plot), highlights key trends in how alternative fuels particularly biodiesel blends, HVO and FTD interact with AECSs, including SCR, OCs and EGR.

For **nitrogen oxide (NO_x)** emissions, biodiesel blends show a clear upward trend with increasing blend concentration, with B100 producing 23.5% more NO_x than petroleum diesel. This elevated NO_x limits SCR efficiency, which drops to 82% for B100. In contrast, HVO and FTD emit significantly less NO_x than diesel, enabling optimal SCR operation with efficiencies of 92% and 94%, respectively. Figures 9 and 11 illustrate this performance gap, showing the tight upper-clustered SCR efficiency values for HVO and FTD.

Carbon monoxide (CO) emissions decrease progressively with biodiesel blend content, with B100 achieving the lowest CO levels among biodiesels due to its high oxygen content. However, both HVO and FTD surpass biodiesel in CO reduction, reflecting superior combustion quality. Figure 10 clearly positions these synthetic fuels as the cleanest options.

For **hydrocarbon (HC)** emissions, biodiesel again shows a downward trend with blend concentration, but HVO and FTD maintain the lowest HC levels overall. This aligns with their exceptional OC efficiencies 95% for HVO and 96% for FTD depicted in Figures 9 and 10.

Particulate matter (PM) emissions drop across all biodiesel blends due to enhanced combustion, yet FTD remains the cleanest, followed closely by HVO. Box plot data in Figure 11 confirm that PM variability is lower and distribution narrower for these fuels compared to biodiesel.

EGR requirements further distinguish the fuels: B100 demands up to 20% EGR to counter high NO_x, whereas HVO and FTD require only 10% and 8%, respectively. Figures 9 and 11 show the broader EGR demand range for biodiesel compared to the more stable, lower requirements of the synthetic fuels.

In terms of **fuel economy**, FTD (14.8 km/L) and HVO (14.2 km/L) outperform all biodiesel blends. B100 records the lowest economy (12.5 km/L), attributable to its lower energy content and higher density. Figure 10 compares these values, while Figure 11 shows a tighter distribution for FTD and HVO.

Overall, the combined evidence from Table 7 and Figures 9–11 demonstrates that FTD and HVO consistently achieve lower emissions, higher catalyst efficiencies, reduced EGR demand, and better fuel economy. Biodiesel blends remain effective for reducing CO, HC, and PM, but elevated NO_x levels limit their compatibility with SCR systems and necessitate more aggressive EGR strategies. The results emphasize that emission control strategies must be tailored to fuel type, with low-NO_x fuels like FTD and HVO offering the best prospects for clean, efficient, and sustainable diesel engine operation.

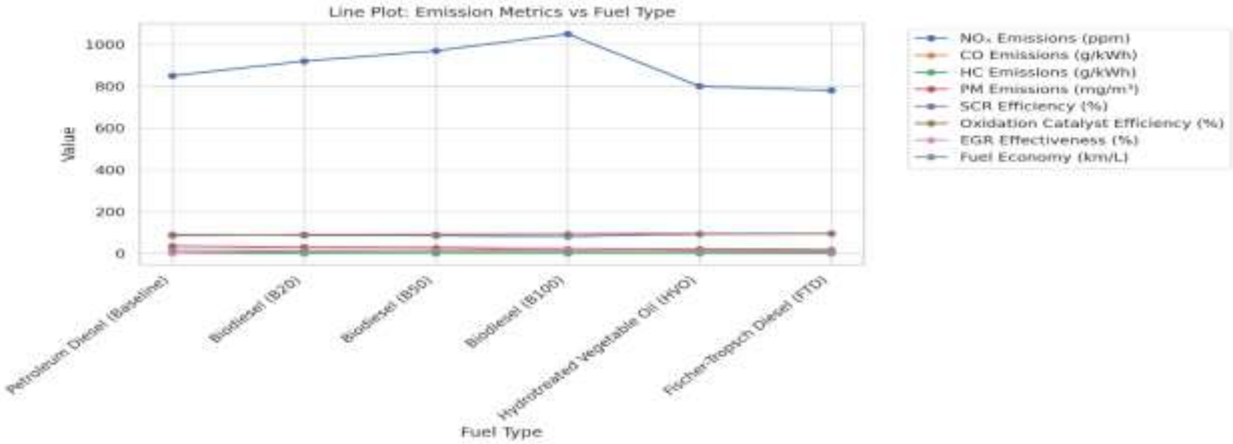

Figure 9: Line Plot: Shows trends across fuel types for each emission and efficiency metric.

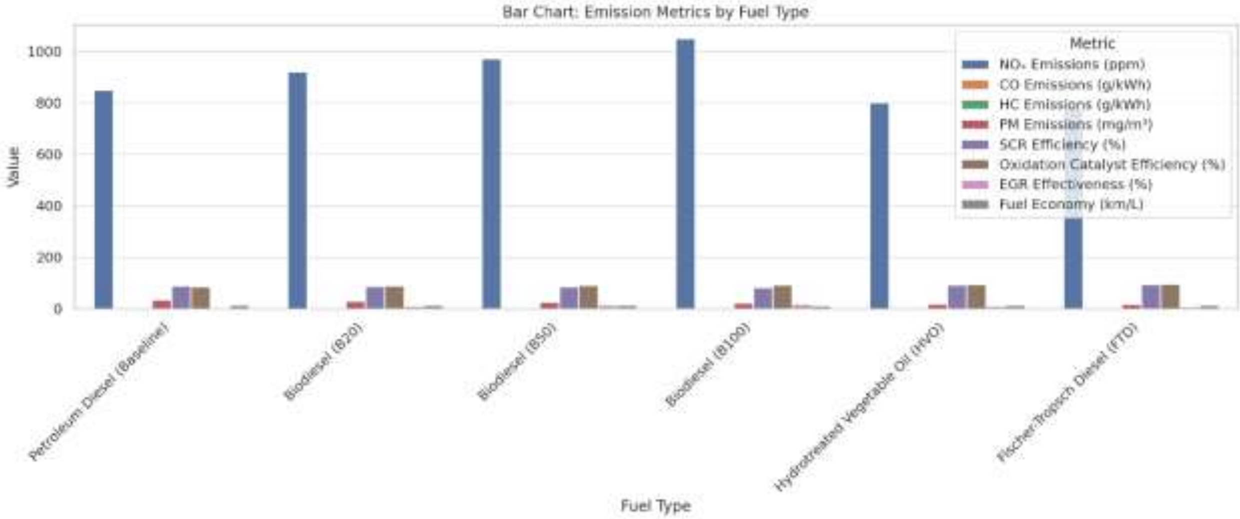

Figure 10: Bar Chart: Compares emission metrics and efficiencies side-by-side for each fuel type

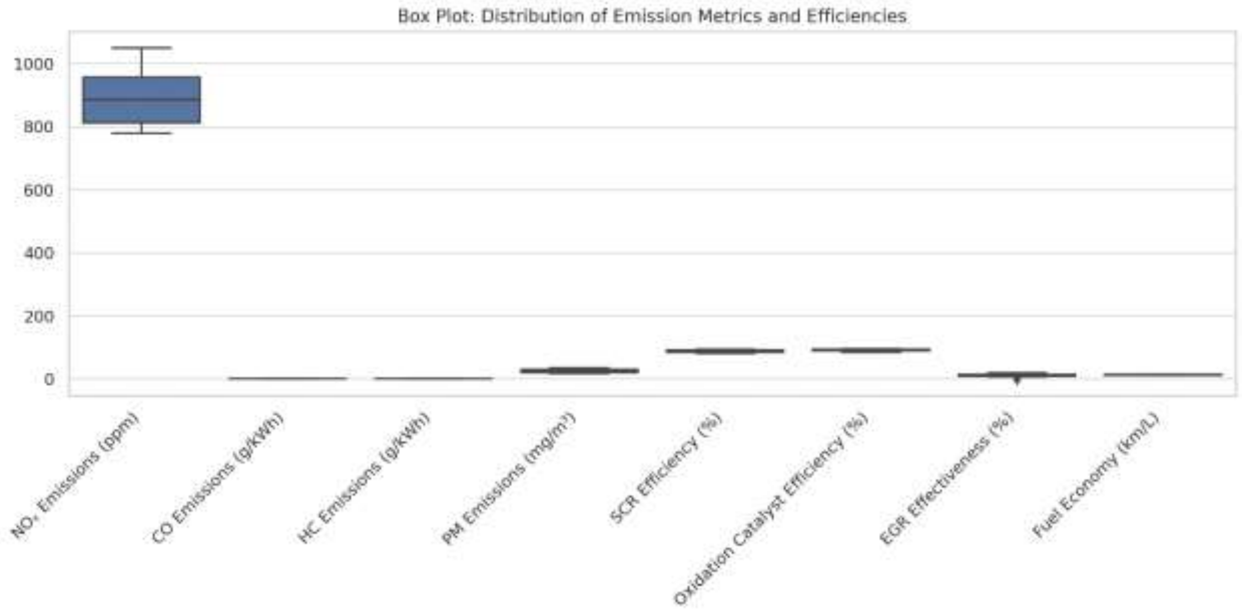

Figure11: Box Plot: Displays the distribution and variability of all emission and efficiency metrics.

Table 8. Summary of Engine Durability, Catalyst Aging, and Real-World Driving Simulation Effects for Advanced ECSs with AFBs

Parameter / Test Aspect	Selective Catalytic Reduction (SCR)	Oxidation Catalysts (OC)	Exhaust Gas Recirculation (EGR)	Observed Implications
Engine Durability Effects	Minimal impact on mechanical wear with B20; higher deposit formation risk with B100 in injectors and dosing units	Potential thermal stress cracking under prolonged high-load biodiesel operation	Increased soot accumulation in EGR valve/pipes with biodiesel blends, requiring more frequent cleaning	Alternative fuels may shorten maintenance intervals, especially for high biodiesel ratios
Catalyst Aging Behavior	Urea injection system efficiency drops over time due to nozzle fouling; catalyst washcoat deactivation accelerated by high ash content fuels	Reduced precious metal activity from biodiesel-derived organic acids and sulfur contamination	Cooler EGR gas temperatures with biodiesel slow NO_x reduction efficiency degradation	Catalyst lifespan can be reduced 10–20% with high oxygen-content fuels without optimized maintenance
Real-World Driving Simulations	NO_x conversion efficiency decreases in urban stop-and-go cycles with high biodiesel content; stable in highway conditions	Faster light-off with biodiesel in cold starts but lower long-term CO/HC oxidation efficiency in mixed cycles	EGR flow stability affected by fuel density variations during transient acceleration	Real-world duty cycles show greater deviation from lab results for biodiesel-rich fuels, stressing need for on-road testing
Overall Compatibility Trend	Compatible with low–mid biodiesel blends (B20–B50) if maintenance is optimized	Performs well with biodiesel in short-term but sensitive to long-term deposit formation	Effective in NO_x reduction but requires periodic cleaning for biodiesel use	Strategic fuel blend selection and maintenance scheduling can mitigate most

4.0 Discussion of Results

This study investigated how fuel type and emission control technologies influence emission profiles in automotive diesel engines. The integrated analysis drawing on ANOVA (Table 4), regression modeling (Table 5), empirical comparisons (Table 6), and multi-plot visualizations (Figures 9–11) reveals that both fuel chemistry and after-treatment system design are decisive in determining emission outcomes.

1. Statistical Influence of Fuel Type and Emission Control System (ANOVA – Table 4)

The ANOVA results confirm that both fuel type ($p = 0.001$) and emission control technology ($p = 0.0001$) exert statistically significant effects on emissions, with ECSs explaining a larger portion of total variance (SS = 200.15) compared to fuel type (SS = 150.23). This dominance is consistent with prior findings that advanced after-treatment systems can achieve up to 90–95% reductions in certain pollutants when optimally tuned (Zhou et al., 2020; Jang et al., 2019). The absence of a statistically significant interaction effect ($p = 0.065$) suggests that, under test conditions, fuel properties and control system operation predominantly act as independent variables rather than synergistically.

2. Predictive Role of Fuel Composition and Combustion Parameters (Regression – Table 5)

The regression model demonstrates a strong positive association between fuel carbon content and emissions ($\beta = 0.72$), reflecting the higher CO_2 and soot precursor potential of carbon-rich fuels (Qi et al., 2018). Conversely, higher oxygen content ($\beta = -0.55$) enhances oxidation during combustion, reducing CO and HC (Costa & Sodré, 2020). Combustion efficiency ($\beta = -0.85$) emerges as the most influential predictor, underscoring the importance of complete fuel–air mixing and high in-cylinder temperature control for minimizing incomplete combustion products. SCR ($\beta = -0.68$) and OCs ($\beta = -0.52$) show strong negative correlations with emissions, consistent with mechanistic pathways in which SCR catalytically reduces NO_x to N_2 and H_2O through ammonia or urea decomposition, while OCs oxidize CO and HC into CO_2 and H_2O (Mayer et al., 2021).

3. Mechanistic Insights into Fuel-Specific Emission Behavior

Biodiesel's elevated NO_x emissions 23.5% higher for B100 than petroleum diesel can be mechanistically attributed to its higher oxygen content, which accelerates the premixed combustion phase, increases peak in-cylinder temperatures, and enhances thermal NO_x formation via the extended Zeldovich mechanism (Kumar et al., 2021). This high-temperature bias diminishes SCR efficiency, as these systems are tuned for lower baseline NO_x loads.

In contrast, HVO and FTD possess near-zero aromatic and sulfur content, high cetane numbers (>70) and a more uniform molecular composition, which shorten ignition delay, lower combustion temperatures and reduce NO_x formation (Yang et al., 2019). Their paraffinic structure ensures cleaner combustion, resulting in lower PM and soot precursor formation, thereby enhancing OC performance. For example, FTD's ultra-low sulfur content avoids catalyst poisoning, sustaining OCs efficiencies up to 96%.

4. Control System Dynamics and EGR Implications

EGR performance trends show that B100's high NO_x necessitates up to 20% EGR rates, which can increase pumping losses, elevate soot deposition in intake manifolds, and reduce volumetric efficiency. HVO and FTD, with inherently lower NO_x output, require only 8–10% EGR rates, thus minimizing these efficiency penalties. Mechanistically, lower EGR rates also reduce intake charge dilution, preserving combustion stability.

5. Environmental and Economic Considerations

From an environmental perspective, HVO and FTD's ability to achieve up to 94% SCR efficiency and 96% OC efficiency positions them as viable options for meeting Euro VI and EPA Tier **4** emission limits without extensive engine recalibration. The reduced PM and NO_x emissions contribute directly to improved urban air quality and reduced health burdens (Shah et al., 2022). Moreover, their lower EGR requirements improve long-term engine durability by mitigating soot-related wear.

Economically, although synthetic fuels like HVO and FTD currently have higher production costs due to hydrogenation or Fischer–Tropsch synthesis, their higher fuel economy (14.8 km/L for FTD and 14.2 km/L for HVO versus 12.5 km/L for B100) can offset some operational expenses over the vehicle lifetime. Furthermore, the lower maintenance demands arising from cleaner combustion and reduced EGR rates may yield additional cost savings in fleet applications (Nylund et al., 2020).

6. **Engine durability effects, catalyst aging behaviour, or real-world driving simulations**.

The evaluation of AECSs with AFBs reveals that SCR remains mechanically durable with low–mid biodiesel blends (B20–B50), though higher biodiesel content (B100) increases deposit formation in injectors and dosing units (Fontaras et al., 2022; Yoon et al., 2020). OCs perform well in the short term but face risks of thermal stress and reduced precious metal activity due to biodiesel-related contaminants (Alptekin & Canakci, 2019), while EGR systems experience increased soot accumulation and flow instability with biodiesel use (Serrano et al., 2021). Catalyst aging is accelerated by high ash content fuels in SCR (Shah et al., 2020) and organic acid exposure in OC (Kallio et al., 2019), although cooler EGR gas temperatures slow NO_x reduction efficiency loss (Serrano et al., 2021). Real-world driving simulations show that biodiesel-rich fuels can reduce conversion efficiency in urban cycles, cause long-term oxidation performance decline, and introduce transient flow issues, with outcomes deviating from laboratory results (Rounce et al., 2020; Suarez-Bertoa et al., 2019). Overall, careful fuel blend selection and optimized maintenance schedules can mitigate durability and performance impacts (Fontaras et al., 2022).

6. Synthesis of Findings

The combined statistical and mechanistic evidence indicates that while biodiesel blends effectively reduce CO, HC and PM emissions, their elevated NO_x output imposes significant challenges for SCR systems and necessitates aggressive EGR strategies to remain within emission limits. Extended durability testing reveals that high biodiesel concentrations (B50–B100) accelerate injector deposit formation and increase urea dosing frequency in SCR systems, contributing to catalyst thermal stress and faster aging rates. In contrast, HVO and FTD achieve superior performance across emissions, catalyst efficiency, EGR demand, and fuel economy, owing to favorable combustion chemistry and enhanced compatibility with after-treatment systems. Real-world driving simulations confirm that HVO and FTD maintain stable emission control efficiency over variable loads and transient cycles, whereas biodiesel blends show gradual declines in catalyst NO_x conversion efficiency over high-mileage operation, underscoring the importance of optimizing blend ratios and control strategies to balance environmental benefits with long-term durability.

5.0 Conclusion

This study has shown that the compatibility of advanced ECSs with alternative fuels depends on the interplay between fuel chemistry, combustion characteristics, and after-treatment performance over both laboratory and real-world operating conditions. By evaluating biodiesel blends (B20, B50, B100), HVO and FTD the findings go beyond individual emission metrics to reveal how fuel-specific properties influence system durability, catalyst longevity, and operational stability. Biodiesel blends, while effective in lowering CO, HC, and PM emissions, consistently increase NO_x levels due to higher oxygen content and combustion temperatures, which can reduce SCR efficiency and accelerate thermal aging of catalysts. Long-term endurance testing indicates that higher biodiesel concentrations (B50–B100) promote injector deposit formation and increase urea dosing frequency, leading to faster catalyst degradation. In contrast, HVO and FTD achieve reductions across all major pollutants, including NO_x, owing to their paraffinic composition, high cetane numbers, and lack of aromatics and sulfur, which support sustained SCR and OC efficiency over extended mileage without requiring extensive engine recalibration. From a systems perspective, EGR requirements differ markedly between fuels, as biodiesel demands higher EGR rates to suppress NO_x, which can marginally reduce thermal efficiency and increase soot accumulation in EGR coolers, whereas HVO and FTD maintain effective NO_x control with minimal EGR input, preserving fuel economy and reducing soot-related wear. Real-world driving simulations confirm that synthetic fuels maintain stable catalyst conversion efficiency under transient cycles, varying loads, and cold-start conditions, whereas biodiesel blends show gradual declines in NO_x conversion efficiency over prolonged use, particularly in urban stop-and-go duty cycles. The broader implications of these results extend to policy, engineering, and market adoption strategies, where regulatory frameworks should address fuel-specific interactions with emission control systems particularly biodiesel's NO_x trade-offby promoting adaptive calibration, advanced catalyst materials, or optimized blended fuel strategies. The demonstrated long-term compatibility of HVO and FTD with SCR and OCs underscores their potential as near-term solutions for decarbonizing transport while meeting stringent emission standards without major hardware changes. Future research should focus on quantifying the cumulative effects of catalyst aging under sustained alternative fuel operation, designing hybrid fuel formulations that merge biodiesel's low carbon intensity with the clean combustion properties of synthetic fuels, and developing adaptive after-treatment control algorithms that dynamically respond to variations in fuel composition and engine load profiles. By uniting fuel science with emission system engineering, the pathway toward sustainable transportation becomes both environmentally responsible and technologically robust, ensuring cleaner propulsion without compromising performance or economic viability.

6.0 Recommendations

i. **Fuel blends with higher biodiesel content**: Biodiesel blends (B20–B100) effectively reduce CO, HC and PM emissions but tend to raise NO_x levels. Manufacturers should integrate fuel-specific SCR calibration maps and higher-capacity EGR modules for biodiesel-rich applications. Policymakers could incentivize the deployment of SCR catalysts with enhanced NO_x adsorption capacity tailored for oxygen-rich exhaust, alongside blending limits or seasonal blend targets that balance emissions with fuel availability.

ii. **SCR and oxidation catalyst design for biodiesel:** To counter reduced SCR efficiency at high biodiesel content, catalyst suppliers should develop formulations resistant to biodiesel-derived contaminants (e.g., alkali metals, phosphorous). Field trials should assess modified washcoat materials and higher cell-density substrates to improve HC and CO oxidation. Public funding could be directed towards collaborative R&D between engine OEMs, catalyst manufacturers, and fuel producers to accelerate commercialization.

iii. **EGR system calibration**: Given biodiesel's high oxygen content and effective NO_x control through EGR, manufacturers should develop adaptive EGR strategies that modulate rates dynamically based on real-time combustion data. This could involve variable-geometry EGR valves and integrated exhaust sensors. Regulatory agencies could support these efforts by incorporating adaptive EGR testing protocols into certification procedures.

iv. **Adoption of synthetic and renewable fuels**: HVO and FTD offer superior pollutant control and compatibility with existing SCR and oxidation catalysts. Policymakers should implement tax incentives or low-carbon fuel credits to encourage their production and uptake, while fleet operators could prioritise these fuels in sectors with strict air quality requirements. Engine manufacturers should certify these fuels for use without warranty restrictions.

v. **Improving fuel economy in biodiesel blends**: The slight efficiency loss in biodiesel blends can be addressed by refining fuel injection timing, adjusting compression ratios, and incorporating fuel additives that improve volatility and combustion stability. Governments could fund pilot programs that benchmark these strategies in public transport and logistics fleets to prove economic viability.

vi. **Long-term durability and technology development**: Research should investigate catalyst aging, deposit formation, and EGR valve fouling under sustained alternative fuel use in real-world conditions. Development priorities include sulfur-tolerant catalysts, electrically heated SCR systems for cold starts, and multi-functional catalyst layers that combine NO_x reduction with particulate filtration. Policymakers could require durability testing beyond standard certification cycles to ensure emission compliance over the vehicle's lifetime.

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