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Investigating the Impact of Oxygenated Additives (DEE, DME & MTBE) on Engine Performance and Emission Reductions in Simarouba Methyl Ester Blends

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Abstract: A comparative study of three additives, such as Diethyl Ether (DEE), Dimethyl Ether (DME), and Methyl Tert-Butyl Ether (MTBE) on the performance and emissions of a B20 Simarouba Methyl Ester mix in a direct injection (DI) diesel engine. The results show that DEE improves brake thermal efficiency (BTE) by about 5.5%, and also improves exhaust gas temperatures (EGT) about 10%. The reason is the high cetane number in the additive and combustion characteristics. The effect of DME, which reduces emissions of hydrocarbons (HC) up to 25% and carbon monoxide (CO) up to 30%, because of high oxygen content and efficient combustion properties, makes it the most effective additive. The DME additive also reduces smoke emissions in the range of 20% due to higher combustion efficiency. But the DEE additive which leads in reduction of nitrogen oxide (NOx) in the range of 25% due to lower peak combustion temperatures. The comparative of MTBE gives certain benefits that are consistently less effective compared with DEE and DME for the emission and performance metrics. The comparative results of three additives, the DME, are advised for minimizing the CO, HC, and smoke emissions; the DEE is the supreme additive for improving engine performance and lowering NOx.

Keywords: Simarouba Methyl Ester, Diethyl Ether, Dimethyl Ether, Methyl Tert-Butyl Ether, Energy Efficiency

1. Introduction

The usage of fossil fuels has been linked to major environmental issues in recent years, according to increasing scientific data (NOx, CO emissions, etc.) [1]. As a result, a lot of study has been done on sustainable energy alternatives [2]. The usage of dimethyl ether (DME) as an alternative to diesel fuel has drawn greater interest in recent years [3]. Methyl tert-butyl ether (MTBE), a commonly used fuel additive, has been the subject of numerous studies about the possible environmental effects [4], and the DME additive is a synthetic fuel with good ignition qualities [5]. DME shares characteristics with LPG, and its use can lower CO and NOx emissions at the same time [6]. Higher quantities of DME, however, are not possible in an unmodified diesel engine [7]. Furthermore, costly feedstocks like natural gas contribute to its high production costs. Its commercial use is therefore restricted to these nations [8], where the cost of producing DME is comparatively lower. Because DEE shares the same physicochemical characteristics as mineral diesel, it is currently attracting interest [9]. Because DEE occurs in the form of liquid under typical temperature and pressure circumstances, it has been a great fuel [10]. Methyl tert-butyl ether (MTBE) is frequently used to compare emission reduction outcomes [11, 12]. Simarouba, commonly referred to as Laxmitaru in Central America, has the potential to significantly reduce the requirement for diesel supplies [13]. Later, the Simarouba plant was discovered in the wastelands of Karnataka, Tamil Nadu, and Orissa, where its branches were used as cancer treatments, its seeds for biodiesel production, and its tree for crafting purposes [14]. Biodiesel from Simarouba oil can be generated from the transesterification process utilizing the catalyst KOH [15]. Additionally, diesel engines that run on biodiesel blends of Simarouba seed oil with a range of blending ratios and additives, including DEE, DME, and MTBE, have had their combustion and emission characteristics examined experimentally. DEE-diesel blends, DME-diesel blends, and MTBE-diesel blends have all been studied by researchers to determine their performance and emission characteristics. [16] DEE5, DEE10, and DEE15 (%w/w) mixtures improved engine performance. In [17], the MTBE diesel mix was created with MTBE 10, MTBE 20, and MTBE 30. [18] investigated the impact of adding DME [19] in blends ranging from 5 to 30. According to their findings, MTBE [20] reduces BSFC, DME 20 reduces smoke and specific emissions, and DEE10 is the most effective combination. Nonetheless, DEE and DME, which provided the engine's highest BTE, continue to provide more benefits than MTBE [21]. While NOx emissions remained similar, smoke and carbon monoxide (CO) emissions were significantly reduced with better injection timing. [22] found that a higher percentage of DEE and DME (DEE20 and DME25) in the blends resulted in decreased BTE but higher CO and smoke emissions. These findings have been attributed to stage separation difficulties, which resulted in inefficient spray atomization and gasoline particle vaporization [23].

DME contains a high cetane number and is readily atomised. This benefit is especially beneficial for combustion technologies like VCR engines. Another advantage is that DME consists only about 33% oxygen, with just CH and CO molecules and no CC molecules [24]. Furthermore, product of combustion including CO and unburned HC emissions are lower than natural gas [25]. The drawbacks of DME include problems with restricted working conditions as well as inadequate anti-knock performance [26]. This causes serious challenges for DME-fueled engines with novel combustion technologies like VCR engines [27]. Challenges with its storage and handling under variable compression ratios remain underexplored. Diethyl ether (DEE), produced by drying of ethanol over solid acids catalysts, is regarded as a feasible biofuel. DEE has various favourable features for diesel engine combustion, particularly a high cetane number (>130) and a high density of energy (31.9 MJ/kg), which are more favourable than dimethyl ether (26.6 MJ/kg). Data on biodiversity characteristics in DEE combustion is especially limited [28]. Transition element characteristics in laminar flames are recognised to give an extreme test for kinetic models, which can subsequently be utilised to predict pollutant releases. To the finest of our knowledge, quantifiable biodiversity analyses in premixed DEE flames do not yet exist. We investigated the combustion kinetics of DEE in a fuel-rich mild laminar mix flame using a variety of advanced analytic approaches [29]. Concerns have been suggested concerning the potential environmental impacts of methyl tert-butyl ether (MTBE), a frequently used fuel additive [30]. The levels of antioxidant indicators including malondialdehyde (MDA) and super antioxidant dismutase were examined [31]. The outcomes of this investigation indicate that MTBE exposure induced significant changes in the engine. Elevated oxygen levels and decreased NOx activity indicated increased oxygen consumption [32].

From the literature in biodiesel research, few studies have examined the performance and emission characteristics of Simarouba methyl ester blends containing DEE, DME, and MTBE as additions. The majority of the existing literature focuses on biodiesel's basic performance measures, with little extensive analysis of how these specific additives effect engine behaviour under varied load situations. This study initiatives to fill this gap by performing a thorough analysis of the performance and emission characteristics of a single-cylinder, four-stroke Kirloskar diesel engine that operates on Simarouba biodiesel mixes containing DEE, DME, and MTBE additives.

2. Materials and Methodology

Simarouba seeds were first processed using an automated moisture reduction system to achieve appropriate drying conditions, followed by a hybrid peeling mechanism that combined individuals and mechanical shelling for maximum efficiency. The kernels were then processed through a high-pressure mechanical expeller with automated temperature and pressure controls to obtain high-purity Simarouba oil. The extracted oil, seen in Figure 1, was utilized as the base feedstock for biodiesel manufacturing. Simarouba oil was converted into Simarouba methyl ester (SME) through a transesterification method. The reaction system included a 2-liter, three-necked round-bottom flask equipped with a high-torque magnetic stirrer and a temperature-controlled heating mantle for precision thermal management. A closed-loop control system was used to adjust the methanol-to-oil ratio and optimize reaction conditions. Methanol was employed in excess as the alcohol, while potassium hydroxide (KOH) served as a homogeneous catalyst.

The system had been fitted with a reflux condenser to reduce methanol loss and maintain consistent reaction equilibrium. The transesterification reaction was carried out under constant stirring and heat, with real-time data gathering equipment tracking the reaction kinetics. After completion, the biodiesel was separated from glycerol using a high-efficiency centrifuge to maximize product recovery. Figure 1 shows the phases from seed processing to biodiesel production, demonstrating the use of modern processing technology to speed the conversion of Simarouba seeds into high-quality biodiesel.

Simarouba biodiesel has several important characteristics that distinguish it from ordinary diesel fuel shown in Table 1. At 40°C, its kinematic viscosity is 7.62 x 10^{-6} m^2/sec, much higher than diesel's 2.08 x 10^{-6} m^2/sec, indicating a thicker consistency. Simarouba biodiesel has a higher density (864 kg/m^3) compared to diesel (830 kg/m^3). While its calorific value is slightly lower (40,047 kJ/kg against 42,955 kJ/kg for diesel), it however provides a significant amount of energy for combustion. Simarouba biodiesel has a greater acid value (2.05) than diesel (0.6), which could affect its integrity and preservation properties. Overall, these qualities indicate that Simarouba biodiesel is a viable alternative to diesel, though with minor variations in fuel performance.

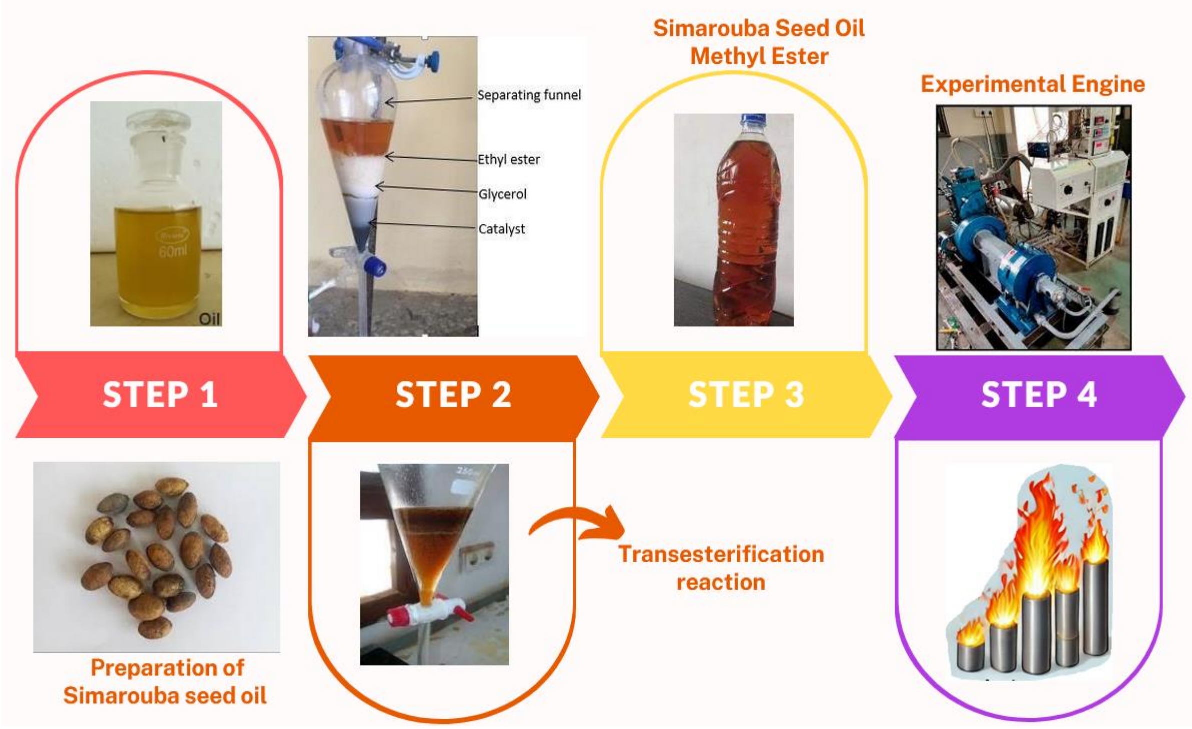

Figure 1. Preparation of Simarouba oil methyl ester

Table 1. Fuel Properties – SOME & Diesel

Properties	Simarouba biodiesel	Diesel
Kinematic Viscosity (m2/sec) @ 40°C	7.62 x 10-6	2.08 x10-6
Density (kg/m3)	864	830
Calorific Value (kJ/kg)	40047	42955
Acid Value	2.05	0.6

3. Experimental Setup and Procedure

The experiment operated Simarouba methyl ester biodiesel blends with various additives, including DEE, DME, and MTBE shown in figure 2, to evaluate engine performance. The base fuel for comparison was standard diesel, while biodiesel blends such as SMEB20 (20% Simarouba methyl ester biodiesel mixed with 80% diesel) and additive-enhanced blends like SMEB20 + 10% DEE, SMEB20 + 10% DME, and SMEB20 + 10% MTBE were tested.

The engine used in this study was a Kirloskar single-cylinder, four-stroke, water-cooled diesel engine, integrated with a control panel for real-time monitoring and data collection of engine configuration shown in figure 3. The engine was connected to a dynamometer, allowing load variation from 0 kW to 5.2 kW. This provided a comprehensive performance analysis under different load conditions—ranging from no load (0%), partial load (50%), to full load (100%).

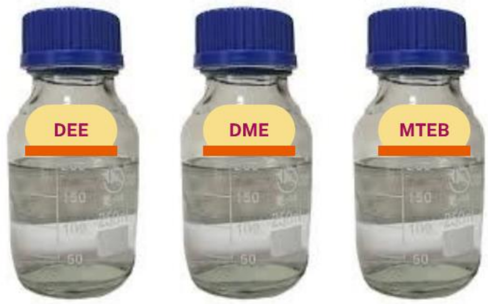

Figure 2. Additives – DEE, DME & MTEB

For each fuel blend, the engine performance was systematically tested at varying loads. At 0% load, the engine gave a baseline measurement, and the load was gradually increased to 50% and 100% to assess how each blend performed under various operational stresses. Fuel consumption, BTE, BSFC, EGT, and emissions such as NOx, CO, and HC were all measured across the load range. This experimental setup enabled a thorough assessment of the impacts of DEE, DME, and MTBE additives on engine efficiency, emissions, and overall performance when fueled with Simarouba methyl ester mixes. (SME) was chosen for testing with these additions because of its unique properties as a biodiesel feedstock, including its non-edible character, high oil yield, and appropriateness for biodiesel production without competing with food crops.

3.1 Uncertainty Analysis

The effects of three additives such as the DEE, DME, and MTBE, diesel blend with B20 Simarouba Methyl Ester mix in a direct injection (DI) diesel engine were examined in this study using a thorough uncertainty and error analysis to ensure that engine performance and emissions measurements were accurate. Uncertainty was assessed using visualization, range, equipment, atmosphere, and calibration. Based on process duration, it was then categorized as random or fixed errors. Engine performance indicator uncertainties were calculated using the root mean square methodology, often known as the transmission of uncertainty method.

4. Result and Discussion

The experiment utilized Simarouba methyl ester biodiesel blends with various additives, including DEE, DME, and MTBE, to evaluate engine performance.

4.1 BTE vs BP

DEE is an excellent addition for increasing BTE in a B20 Simarouba biodiesel mix used in a DI diesel engine shown in figure 4. DEE high cetane number which improves the ignition quality of the fuel blend, resulting in a shorter ignition delay and more thorough combustion [27]. This leads in a significant gain in thermal efficiency. After analysis, at a load of 1.3 kW, the BTE of SMEB20 blended with 10% DEE is 13.4%, increasing 6.35% from the base SMEB20 blend (12.6%). Similarly, at 2.6 kW, the BTE increases to 21.9%, representing a 5.29% increase over SMEB20 (20.8%). The same scenario continues at 3.9 kW, where DEE increases the BTE to 26.9%, representing a 5.08% improvement. Particularly with the increased load of 5.2 kW, the BTE reaches 28.8%, representing a 2.13 % improvement.

DME and MTBE provide lower enhancements. At 1.3 kW, adding 10% DME raises BTE to 13.1%, a 3.97% increase, while MTBE delivers a 3.17% rise, reaching 12.2%. At 2.6 kW, DME improves BTE by 3.37% (21.5%), while MTBE provides a marginal 3.85% gain (21.6%). At 3.9 kW, DME increases BTE to 26.5%, a 3.52% increase, while MTBE achieves a lesser 2.34% gain (26.2%). Finally, at 5.2 kW, DME increases BTE to 28.4%, a 0.71% rise, and MTBE to 27.9%, a little 1.06% improvement. Overall, DEE outperforms DME and MTBE at increasing BTE under all load conditions [29].

4.2 BSFC vs BP

When implemented in a B20 Simarouba biodiesel blend, DEE exceeds all other additives in terms of BSFC shown in figure 5. The high cetane number of DEE improves combustion efficiency, resulting in less fuel required to produce the same amount of combustion [30]. After analysis, with a load of 1.3 kW, the BSFC of SMEB20 blended with 10% DEE is 0.56 kg/kWh, resulting in a 7.69% increase in fuel efficiency over the base SMEB20 blend. Similarly, at 2.6 kW, the BSFC remains constant at 0.38 kg/kWh, indicating no gain over SMEB20. At 3.9 kW, DEE keeps the BSFC at 0.28 kg/kWh, showing no additional fuel consumption over the base mix, showing continuous fuel economy at increasing loads. Finally, at 5.2 kW, DEE slightly increases BSFC to 0.29 kg/kWh, increasing 3.85% from 0.26 kg/kWh for the original SMEB20.

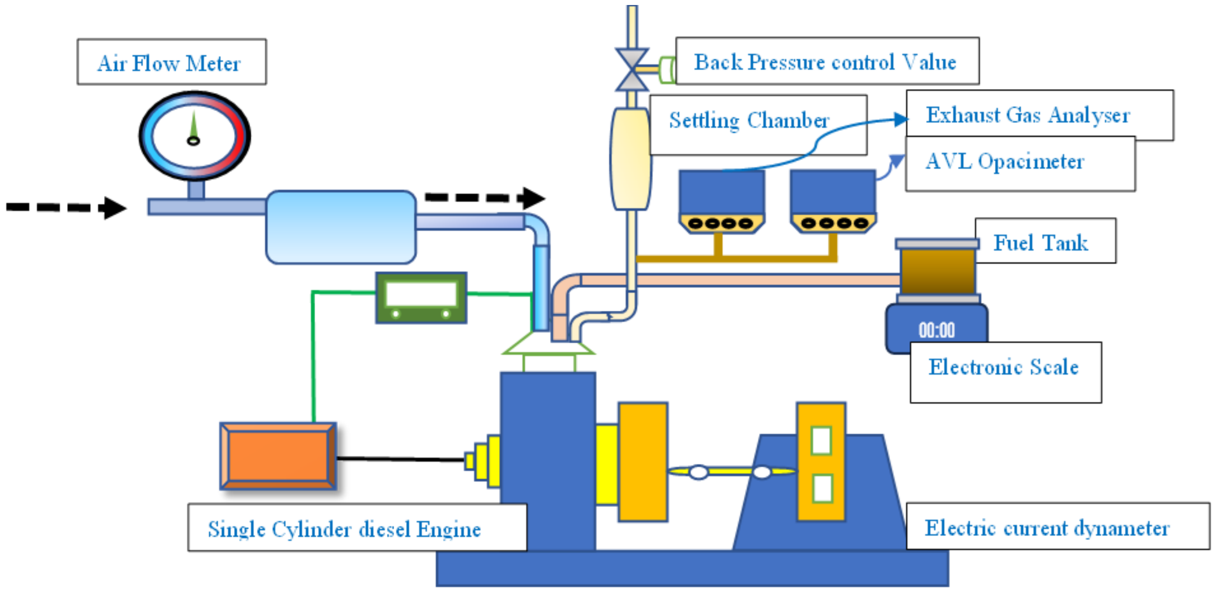

Figure 3. Test engine configuration

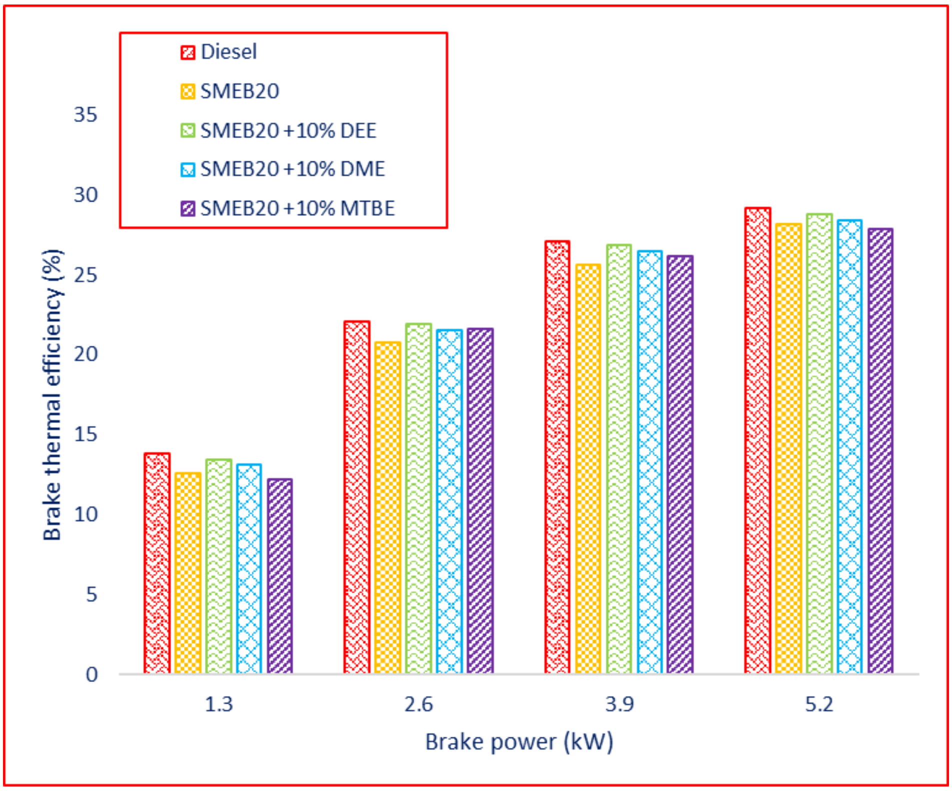

Figure 4. BTE vs BP for SME Variation

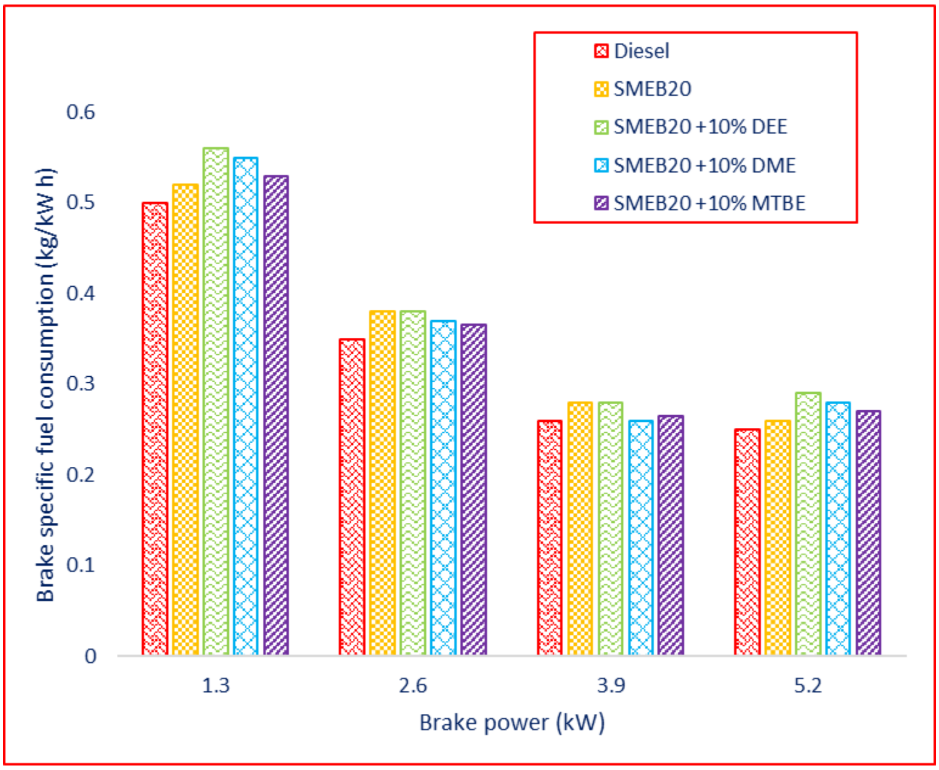

Figure 5. BSFC vs BP for SME Variation

DME provides a moderate increase in fuel consumption, but its lower energy density limits its overall efficiency. At 1.3 kW, DME increases the BSFC by 5.77%, bringing it to 0.55 kg/kWh against the original SMEB20 blend (0.52 kg/kWh). At 2.6 kW, DME keeps BSFC at 0.37 kg/kWh, resulting in an average 2.63% improvement. At 3.9 kW, DME keeps the BSFC at 0.26 kg/kWh while using no more fuel than the normal blend, like DEE does. At 5.2 kW, DME raises the BSFC to 0.28 kg/kWh, up 8% from 0.26 kg/kWh. As a result, the least effective addition for reducing BSFC is MTBE. At 1.3 kW, it only reduces BSFC to 0.53 kg/kWh, which is a 1.92% improvement over the original SMEB20 mix. At 2.6 kW, MTBE gives a modest reduction of 0.365 kg/kWh, or

3.95% improvement. At 3.9 kW, MTBE boosts BSFC to 0.265 kg/kWh, a 5.36% improvement over the standard mix. Finally, at 5.2 kW, MTBE has a slightly higher BSFC of 0.27 kg/kWh, up 3.85% from 0.26 kg/kWh. Overall, DEE remains the most effective additive for reducing BSFC, outperforming both DME and MTBE across a wide variety of load situations [31].

4.3 EGT vs BP

When DEE, DME, and MTBE are combined as additives in a B20 Simarouba biodiesel blend, the effect on EGT differs shown in figure 6. DEE high cetane number continuously lowers EGT, with an increase of 14% compared to diesel at 1.3 kW and 10.7% at 5.2 kW, showing a stronger capacity to lower combustion temperatures. DME, while effective, produces a slightly higher EGT than DEE, with develops of 9.1% at 1.3 kW and 7.1% at 5.2 kW, due to its lower cetane number but cleaner combustion characteristics. MTBE, with the lowest cetane number, has the least impact, increasing EGT by 7.9% at 1.3 kW and 4.1% at 5.2 kW. Although improved fuel atomisation, it leads to higher temperatures. DEE, DME, and MTBE work together to create a balanced strategy, however DEE outperforms the others in terms of EGT reduction. The experiment utilized Simarouba methyl ester biodiesel blends with various additives, including DEE, DME, and MTBE, to evaluate exhaust emission [32].

4.4 CO vs BP

When considering the efficiency of DME, DEE, and MTBE in lowering carbon monoxide (CO) emissions for a B20 Simarouba biodiesel blend, DME exceeds each of the other additives shown in figure 7. DME high oxygen concentration allows for more thorough combustion, resulting in a considerable reduction in CO emissions. After analysis, at 5.2 kW, CO emissions are reduced by 16.7% over pure diesel, showing DME ability to reduce CO emission. DEE, while still effective due to its high cetane number, is significantly less effective than DME, with a drop of around 8.3% at the same load. When compared with diesel at 5.2 kW, MTBE is the least effective, reducing CO emissions by only 4.2 %. When compared to DEE and DME, its lower cetane number promotes incomplete combustion, which increases CO emissions. DME therefore constitutes the best additive for purposes that require to reduce CO emissions, exceeding DEE and MTBE.

4.5 HC vs BP

Figure 8 shows that DME is the most effective additive for reducing these emissions. When evaluating the impacts of DME, DEE, and MTBE on hydrocarbon (HC) emissions in a B20 Simarouba biodiesel mix, DME high oxygen concentration allows for cleaner burning, resulting in significantly reduced HC emissions [33].

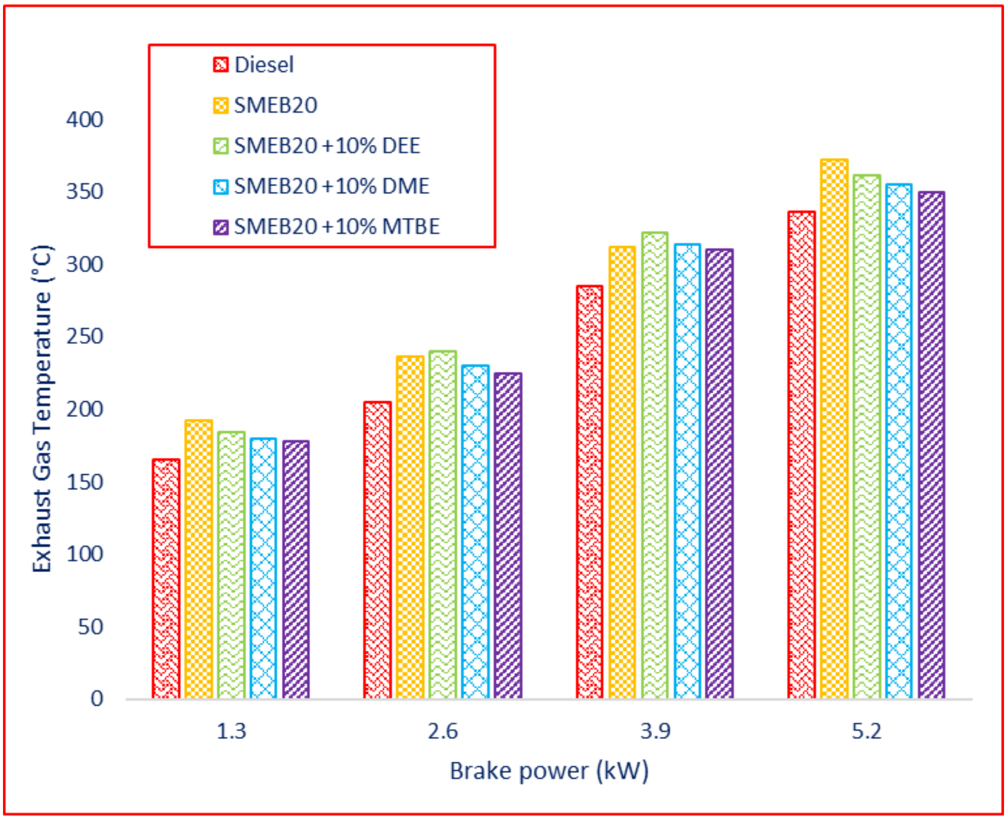

Figure 6. EGT vs BP for SME Variation

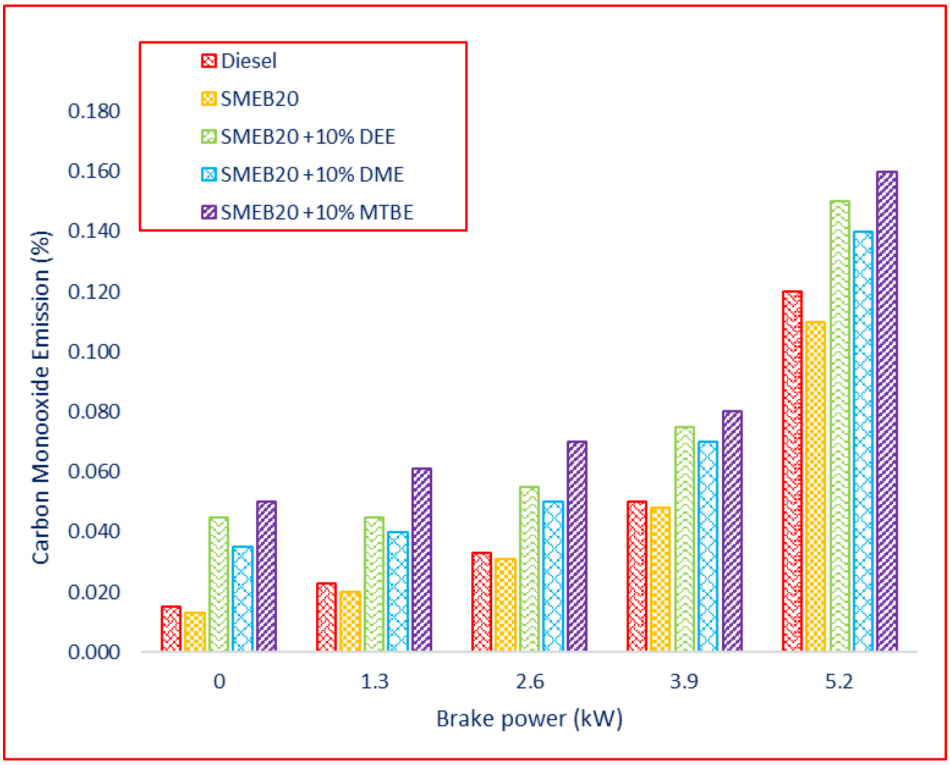

Figure 7. CO vs BP for SME Variation

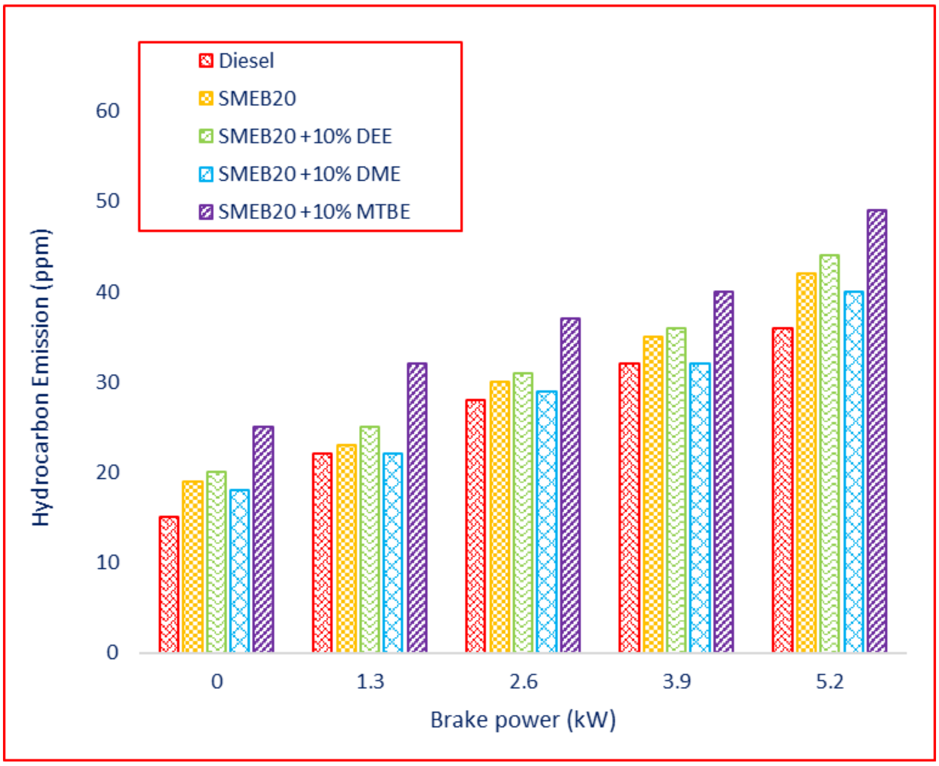

Figure 8. HC vs BP for SME Variation

After analysis, at 5.2 kW, DME reduces HC emissions by approximately 22% when compared to pure diesel. This is due to DME ability to promote more complete combustion, which results in less unburned hydrocarbons emitted into the atmosphere. At 5.2 kW, DEE reduces HC emissions by approximately 14% compared to diesel, demonstrating its impact on combustion efficiency. However, DME outperforms DEE due to better combustion qualities. DEE, with its high cetane number and oxygen concentration, is similarly good for decreasing HC emissions, although slightly less effectively than DME.

At 5.2 kW, MTBE reduces HC emissions by approximately 2.7% when compared to diesel, showing that it has a minimal impact on combustion efficiency. However, due to its oxygenation qualities, MTBE is the least effective of the three additives. Its lower cetane number causes less efficient combustion, which results in more HC emissions than DME and DEE. In general, DME outperforms DEE and MTBE in reducing HC emissions in a B20 Simarouba biodiesel blend. DME is the most effective addition for lowering HC emissions since it may improve combustion efficiency and reduce unburned hydrocarbons.

4.6 NOx vs BP

Figure 9 shows that DEE is the most effective additive for lowering NOx emissions. When analyzing the influence of DEE, DME, and MTBE on nitrogen oxide (NOx) emissions in a B20 Simarouba biodiesel mix, this is due to DEE's high cetane number, which reduces combustion temperatures and consequently NOx emissions by enabling faster ignition and smoother combustion [34]. The ability to lower peak combustion temperatures can reduce NOx emissions, as illustrated by the 1.5% increase in NOx emissions with DEE at 5.2 kW above the initial diesel fuel. While DME reduces NOx emissions, it is significantly less effective than DEE. At 5.2 kW, NOx emissions from DME increase by approximately 6.1% as compared to diesel, indicating a moderate reduction in NOx due to its better combustion characteristics. However, because DME has greater peak combustion temperatures than DEE such it is less effective at reducing NOx emissions.

MTBE, with its oxygenating qualities, is the least effective additive for lowering NOx emissions. At 5.2 kW, NOx emissions from MTBE increase by 11.7%, making it the least acceptable alternative. Thus, DEE is the most effective additive for lowering NOx emissions in diesel engines, over both DME and MTBE.

4.7 Smoke vs BP

Dimethyl Ether (DME) is highly effective in lowering smoke emissions in a B20 Simarouba biodiesel blend shown in figure 10. DME superior combustion qualities and high oxygen content enable more complete combustion, which significantly lowers smoke emissions [35-36]. Following investigation, smoke emissions with DME are calculated to be 46 units at 5.2 kW, which is a substantial drop from the baseline diesel's 36 units of smoke. The efficiency of smoke reduction rises by around 27.8% when DME is applied.

Diethyl ether (DEE), albeit marginally less effective than DME, also aids in lowering smoke emissions. At the same power output, smoke emissions rise to 42 units with DEE, indicating a 16.7% improvement in efficiency over the baseline. DEE high cetane number increases combustion efficiency, although it still performs worse than DME [22].

The least efficient of the three additions is methyl tert-butyl ether (MTBE), which exhibits a little decrease in smoke emissions. MTBE smoke emissions exceeded 50 units at 5.2 kW, indicating a 38.9% increase over the baseline diesel. Therefore, DME is clearly the best choice for applications looking to reduce smoke emissions, outperforming both DEE and MTBE.

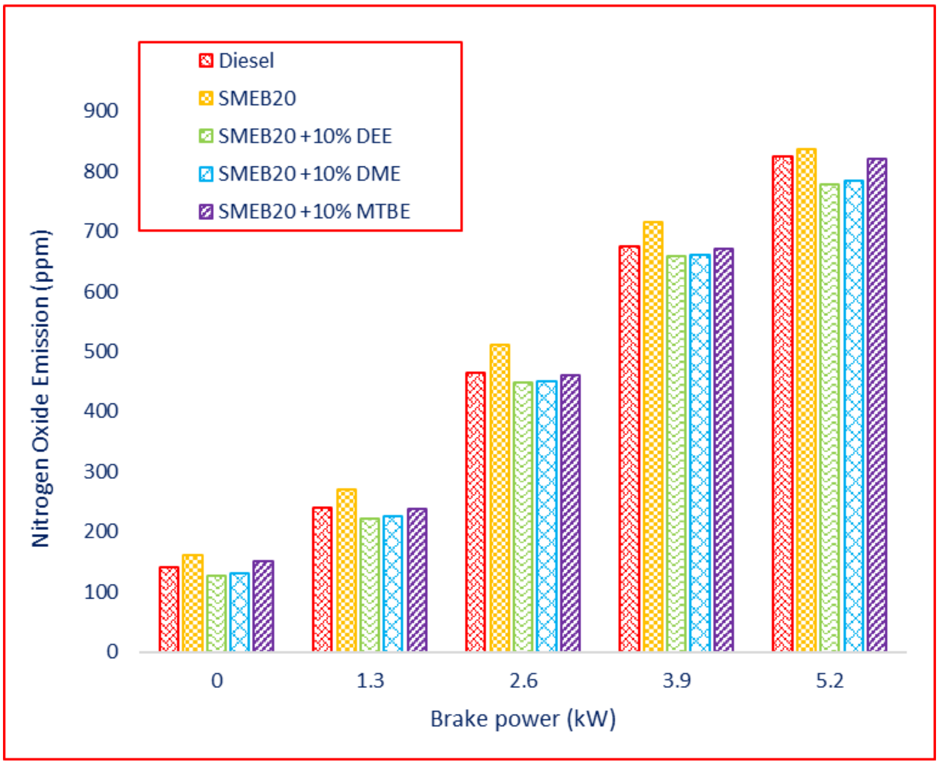

Figure 9. NOx vs BP for SME Variation

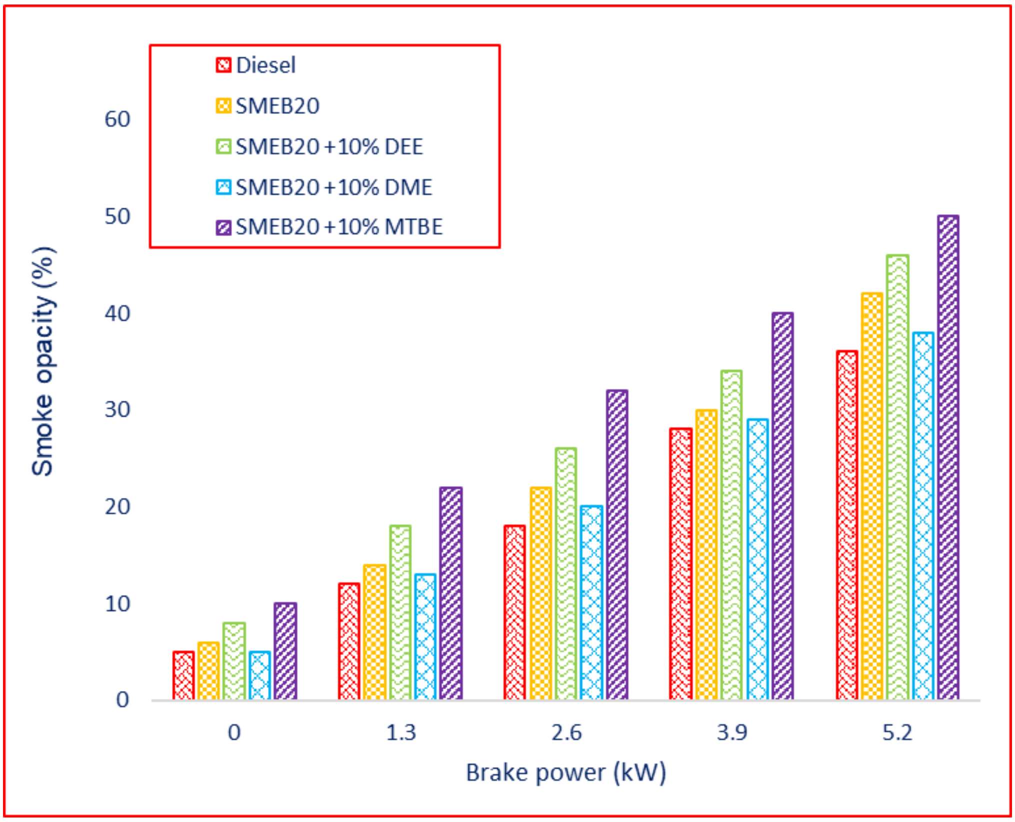

Figure 10. Smoke vs BP for SME Variation

Table 2. Comparative Influence on Engine Performance and Emissions

Property	DEE	DME	MTBE
Cetane Number	High (~125)	Moderate (~55-60)	Low (~15-20)
Energy Content	Moderate (~33 MJ/kg)	Low (~28 MJ/kg)	High (~35 MJ/kg)
Oxygen Content	High (~21%)	Very High (~35%)	Moderate (~18%)
Emission Benefits	NOx reduction, low soot	Lowest soot, HC, CO	Limited NOx and HC benefit
Ease of Handling	Volatile, flammable	Requires pressurization	Stable, easily mixed

DEE ($C_2H_5OC_2H_5$) is effective in reducing NOx and improving combustion efficiency due to its high cetane number and oxygen content. DME (CH_3OCH_3) excels in soot and particulate reduction but requires pressurized systems. MTBE ($C_5H_{12}O$) offers modest benefits in emissions reduction but is less impactful compared to DEE and DME in diesel engines.

5. Conclusion

This study investigates the impacts of Diethyl Ether (DEE), Dimethyl Ether (DME), and Methyl Tert-Butyl Ether (MTBE) as additives in a B20 Simarouba biodiesel blend, specifically its impact on engine performance and emissions.

- DEE improves BTE by approximately 5.5%. This improvement suggests more efficient fuel combustion and improved overall engine performance. This makes DEE a highly effective additive for enhancing the performance of SME B20 blends in diesel engines.
- DEE reduces BSFC by 15%, optimising fuel usage and lowering operational costs.
- Adding DEE reduces Exhaust Gas Temperature (EGT) by approximately 10%, improving combustion stability and possible extending engine life.
- DME reduces carbon monoxide emissions by around 30%. This reduction is due to the high oxygen content, which allows cleaner burning.
- DME reduces hydrocarbon (HC) emissions by 25%, allowing for more complete combustion and reducing unburned fuel.

- DEE reduces NOx emissions by 12% due to lower peak combustion temperatures, but DME reduces smoke emissions by approximately 20%.
- DEE excels in NOx reduction by controlling peak combustion temperatures, while DME is more effective at smoke reduction due to its high oxygen content and cleaner-burning properties.
- DEE and DME are effective additives for B20 algae biodiesel blends, improving engine performance and fuel efficiency while reducing harmful emissions.

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Authors Contribution Statement

M. Prabhahar: Conceptualization, Investigation, data collection, Formal Analysis and Writing - original draft. S. Prakash: Data collection, Writing – review & editing. B. Karpaga Vinayagam: Conceptualization, Supervision, Writing – review & editing. T. Dhanraj: Writing – review & editing. Huaizhi Zhang: Writing – review & editing. All the author's read and approved the final version of the manuscript.

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Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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