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Effect of Exhaust Gas Recirculation on the Performance and Emissions of Green Algae Methyl Ester (GAME).

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Abstract

This experimental work evaluates the effects of Green Algae Methyl Ester (GAME) biodiesel blends on diesel engine performance and emissions under different injection timings and EGR conditions. The highest Brake Thermal Efficiency of 31.15% was obtained at 27° bTDC for GAME20, which is moderate lower than diesel 31.7%. The minimum BSFC was 0.26 kg/kWh at 23° bTDC, which is compared to 0.24 kg/kWh for diesel. The investigation of GAME20 exhibited reduced NOx emissions is achieved 720 ppm with 30% EGR compare to 972 ppm for diesel and reasonable CO emissions which is compare to 0.165% and Diesel 0.132%. Smoke opacity for GAME20 was recorded at 67.5%, so, it is lower than diesel 69%. The investigation of GAME biodiesel with EGR focusing the NOx emission reduction to suggestions a cleaner and sustainable alternative to diesel with minimal changes.

Keywords: *Green Algae Methyl Ester (GAME), Exhaust Gas Recirculation (EGR), Engine Performance, Emission Characteristics, Affordable and Clean Energy (SDG 7).*

1. Introduction

Recent concerns about rising energy costs and the need for renewable, sustainable alternatives have fuelled global efforts to fulfil expanding energy demand [1], [2]. Because oil resources are concentrated in specific locations, meeting energy demands presents a number of issues, depending on the political stability of these countries. Furthermore, when reserves fall, the cost of extracting petroleum products rises, exacerbating the dilemma [3]. NOx emissions could be reduced by more than 42% when the EGR rate was 18%, and more than 81% when the EGR rate was 23%. Furthermore, larger EGR may result in higher PM and HC emissions [4]. Similar to that, an assessment of the impact of EGR rates on diesel engines that use blended fuels indicated that increasing the EGR rate reduces NOx emissions [5]. EGR works by recirculating a portion of the engine's EGR into the combustion chamber. This method reduces the amount of oxygen in the combustion area, which results in lower combustion temperatures [6]. Reducing the peak combustion temperature can effectively reduce NOx emissions because NOx generation is directly proportional to temperature [7].

Several research have looked into the usage of EGR in CI engines fuelled by biodiesel and diesel [8]. The study investigated the effect of EGR on CI engine feeding with diesel and found that diesel reduced BSFC by 7%-13% while increased BTE by 9-16.6% at minimum and highest loads. CO emissions fell by 11.4% to 43.2% at the lowest and highest loads, whereas HC emissions fell by 12.3% to 29.5%. However, introducing HHO increased NOx emissions by 2.62% at 75% load and 3.5% at full load when compared to a clean diesel operation [10]. They discovered that the single water injection method reduced NOx emissions by up to 22%, while the EGR technique lowered emissions by up to 27% [11]. The combination of EGR and hydrogen enrichment reduces NOx while stabilising combustion, allowing for thinner fuel blends and higher fuel economy [12]. The latest research finding is shown in table 1.

Table 1: Latest literatures of research findings

References	Fuel Type / Additive	Focus Area	Key Findings
[1], [5], [9]	Karanja Biodiesel	Influence of EGR on emission reduction	Applying EGR with Karanja biodiesel effectively lowered NOx emissions due to reduce in-cylinder temperatures, though slight increases in CO and HC levels were noted.
[2], [8], [14]	Biodiesel–Diesel Blends with EGR	Effect of additives with varying EGR rates	Moderate EGR levels (15–25%) used along with oxygen-enriched additives improved the NOx–smoke balance and helped maintain stable combustion.
[3], [10], [17]	Soybean Biodiesel (30–45% cooled EGR)	Impact of cooled EGR on combustion and emissions	Higher cooled-EGR percentages significantly decreased NOx but led to increases in soot and BSFC; around 30% EGR was identified as the optimal point balancing emissions and efficiency.
[4], [11], [16]	B20 Jatropha Biodiesel	Combined effect of biodiesel and EGR	The B20 blend required comparatively higher EGR levels to achieve low-temperature combustion, resulting in reduced NOx and more uniform combustion behaviour.
[6], [12], [19]	Mahua Biodiesel	EGR–SCR hybrid emission control	Using a combined EGR and SCR approach brought substantial reductions in NOx and smoke, making Mahua biodiesel highly suitable for agricultural and rural diesel engines.
[7], [13], [18]	General Biodiesel Fuels	Review of EGR and fuel modification strategies	Research indicated that moderate EGR lowers NOx for most biodiesels, while nano-additives help compensate for the BTE losses resulting from oxygen dilution.
[9], [15], [20], [21], [22]	Palm Biodiesel + TiO_2 Nanoparticles	EGR synergy with nanoparticles	TiO_2 nano-additives enhanced combustion quality and further reduced NOx when used in conjunction with EGR.
[1], [8], [17]	Neem Biodiesel + TiO_2	Effect of nanoparticles under EGR	The combination of TiO_2 nanoparticles with controlled EGR improved oxidation, lowered CO and smoke emissions, and preserved adequate engine performance.
[2], [10], [14]	Rapeseed Methyl Ester (RME)	Particle size behaviour under EGR	EGR modified particle size distribution without significantly affecting the total particle count; fine particulate emissions decreased at moderate EGR levels.

[3], [6], [19]	Waste Cooking Oil Biodiesel + Metal Oxide Nanoparticles	Impact of nanoparticles and EGR	Using metal oxide nanoparticles along with EGR enabled simultaneous reduction of NOx and smoke while boosting combustion efficiency.

Although Exhaust Gas Recirculation (EGR) is a proven method for mitigating nitrogen oxide emissions [1, 4], the existing literature has disproportionately focused on conventional feedstocks like palm, jatropha, and mahua [7, 8, 20]. Consequently, the specific behaviour of GAME under EGR conditions; particularly at full load, remains largely unexplored. This creates a significant blind spot regarding the inevitable trade-offs in engine performance; while EGR typically reduces NOx, it often incurs penalties in Carbon Monoxide (CO), smoke opacity, and fuel consumption [2, 3]. It is currently unclear how the specific physicochemical properties of GAME might alter these established patterns. Furthermore, the fundamental combustion dynamics, including heat release rates and ignition delay periods, have not been adequately characterized for algal biodiesel subjected to high dilution rates [11, 13]. There is also significant uncertainty regarding how the intrinsic oxygen content of GAME interacts with EGR-induced oxygen deficiency [10, 17]. Lacking a comprehensive framework to balance these opposing factors, this study seeks to fill the void by experimentally investigating the effect of Exhaust Gas Recirculation on the performance and emissions of Green Algae Methyl Ester.

2. Materials And Methods

2.1. Preparation of Green Algae Biofuel Methyl Ester (GABME20)

Microalgae have lately gained recognition as a renewable energy feedstock due to their ability to absorb nutrients and sunlight to produce lipid-rich biomass.

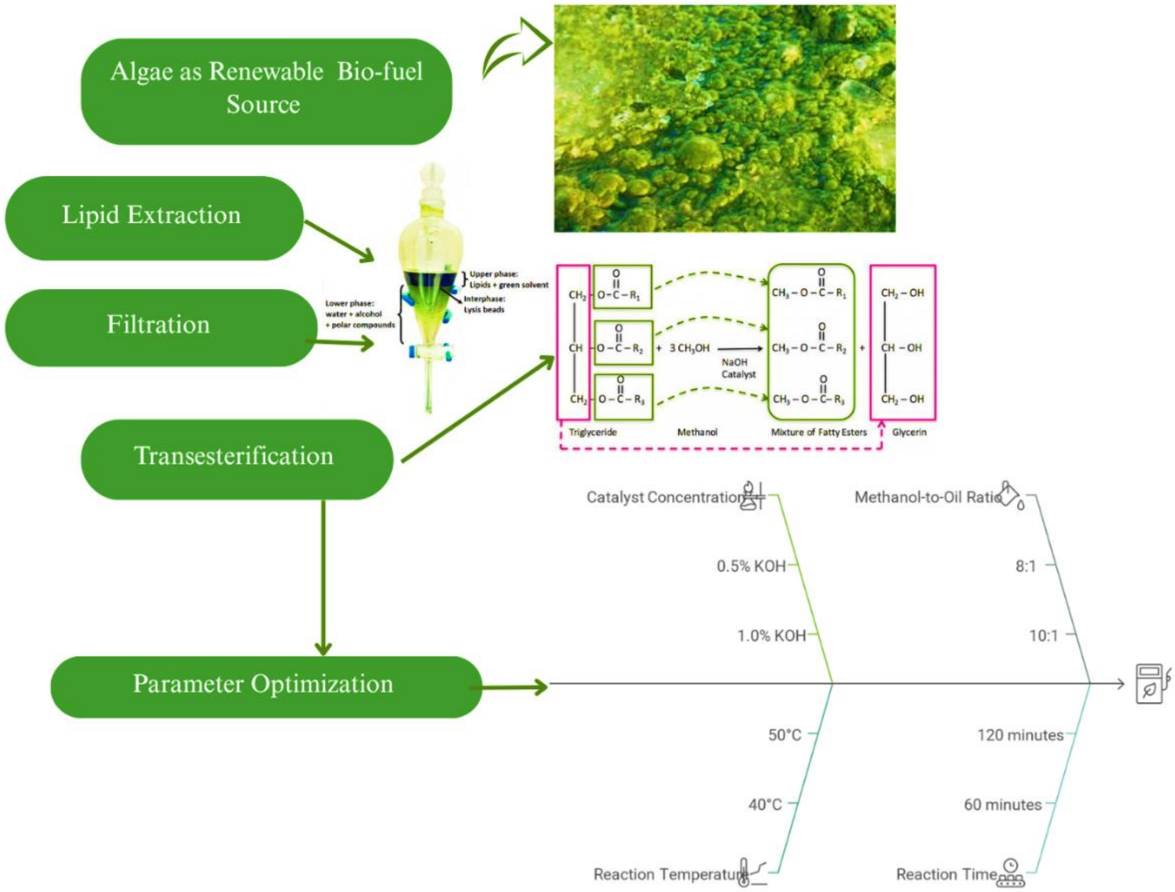

Figure 1. Optimization of biodiesel

Chlorella vulgaris is the most extensively studied microalgae because to its rapid growth, environmental tolerance, and oil-enhanced production [20-22]. These characteristics make C. vulgaris a feasible feedstock for commercial biofuel production, not just as a replacement for traditional fossil fuels, but also for environmental reasons like waste treatment and carbon capture. As a result, this study will explore into employing a base-catalyzed transesterification process to make GABME20, a 20% biodiesel mix derived from Chlorella vulgaris. The transesterification process was optimized to provide a high rate of conversion while meeting quality standards for the biodiesel fuel category used in engines. The economic benefits of using C. vulgaris as feedstock stem from its established usage in nutrition and pharmaceuticals, which adds to the practicality of an integrated algae biorefinery. Figure 1- GAME conversion efficiency is evident throughout the data presented in this figure.

3. Experimental Setup for GAME

The same experimental test rig is used for analyzing the performance of Green Algae Methyl Ester (GAME) biodiesel. Figure 2 shows the CI engine, equipped with an EGR setup and eddy current dynamometer, allows for accurate control of exhaust gas recirculation and engine loading. The DAQ system records in-cylinder pressure, crank angle, and exhaust temperature for combustion analysis. Emission measuring instruments such as the AVL smoke meter and multi-gas analyzer are employed to assess the concentration of pollutants. GAME blends are tested at different EGR rates and compression ratios to investigate their effects on BTE, BSFC, and emission reduction potential, providing a comparative assessment with conventional diesel fuel.

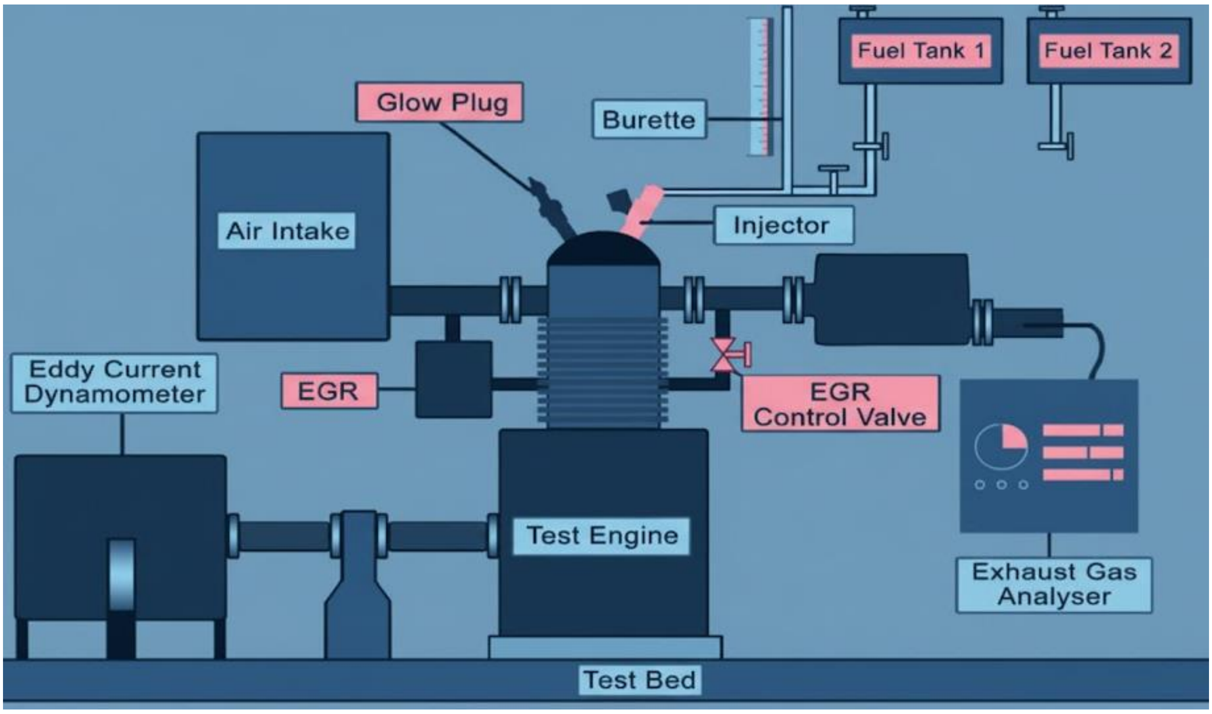

Figure 2. Experimental Setup

4. Result and Discussion

4.1 BTE vs BP

At full load, the GAME B20 has a BTE of 28.4%, which is lower than the 31.7% for diesel which shown in figure 3. The 3.3% loss is primarily due to GAME lower calorific value and higher viscosity, which result in less efficient atomisation and delayed burning. When EGR is utilised, the BTE decreases to 27.6% (10% EGR), 26.7% (20% EGR) and 25.9% (30% EGR) the oxygen available for combustion is reduced by the recirculated exhaust gases. GAME pure oxygen content enables partial oxidation, but it would fully compensate for the oxygen dilution caused by EGR. The EGR levels increase, total combustion efficiency and thermal conversion decrease, indicating to focus between lower NOx and lower efficiency.

4.2 BSFC vs BP

Figure 4 shows the BSFC at full load for diesel is 0.274 kg/kWh and GAME B20 displays a somewhat greater 0.280 kg/kWh, which indicates that more fuel must be used to provide the same power due to biodiesel lower energy content. The EGR setup and the amount of BSFC gradually increases: 0.295 kg/kWh (10% EGR), 0.310 kg/kWh (20% EGR), and 0.327 kg/kWh (30% EGR). The increase in BSFC is due to lower combustion temperatures and partial oxidation under higher EGR settings. Compared to diesel, GAME B20 +30% EGR needs approximately 19% more fuel, suggesting that both EGR and biodiesel lower heating value contribute to increased fuel consumption.

4.3 CO vs BP

Figure 5 shows the CO emissions for diesel are 0.162% at full load and compare to GAME B20 offers a lower value of 0.140% under normal conditions which is caused by the presence of oxygen molecules inside the biodiesel structure, which improves oxidation. The CO emissions rise with EGR setup upto 0.172% for EGR 10%) 0.189% for EGR 20% and 0.207% for EGR 30%, approaching diesel levels at higher EGR levels. Oxygen insufficient and lower combustion temperatures which prevent CO from being converted into CO_2, generating such increase. The GAME biodiesel itself improves CO emissions relative to diesel; its advantage decreases when EGR increases.

4.4 HC vs BP

At full load the HC emissions are 52 ppm for diesel and 56 ppm for GAME B20, including an incremental rise caused by biodiesel propensity to create unburned fuel deposits near cold zones in the cylinder. The presence of EGR increases HC levels to 59 ppm with 10% EGR, 62 ppm with 20% EGR and 66 ppm with 30% EGR so low oxygen and flame temperatures promote incomplete combustion. Compared to diesel, GAME B20 +30% EGR produces approximately 27% additional HC which indicating that EGR has a negative impact on hydrocarbon oxidation in biodiesel-based engines shown in figure 6.

4.5 NOx vs BP

Figure 7 shows the NOx emissions at full load for diesel are 972 ppm compare with GAME B20 produces 1054 ppm which is 8.5% greater. The reason is due to its oxygen-rich nature and higher combustion temperatures. When EGR is utilised the NOx emissions reduce significantly focusing of NOx reduction shows 910 ppm with 10% EGR, 810 ppm with 20% EGR and 720 ppm with 30% EGR. The reduction in temperature is due to reduced oxygen concentration and lower peak flame temperatures induced by exhaust gas recirculation. The instigation 30% EGR reduces NOx emissions by around 32% compared to the baseline GAME, lowering emissions much below diesel NOx level.

4.6 Smoke vs BP

Figure 8 shows the Smoke opacity results indicate 32% for diesel and 24% for GAME B20 which indicating the cleaner burning behaviour of algae-based biodiesel due to its higher oxygen content and lower aromatic proportion. The EGR setup of smoke emission levels gradually increase to 29% with 10% EGR, 31.2% with 20% EGR and 33.5% with 30% EGR. Because of oxygen deficits, incomplete combustion and soot generation become more prevalent at increasing EGR rates, and at 30% EGR, smoke exceeds diesel standards. The GAME B20 without EGR significantly reduces smoke, the advantage decreases at higher EGR rates due to loss of combustion quality.

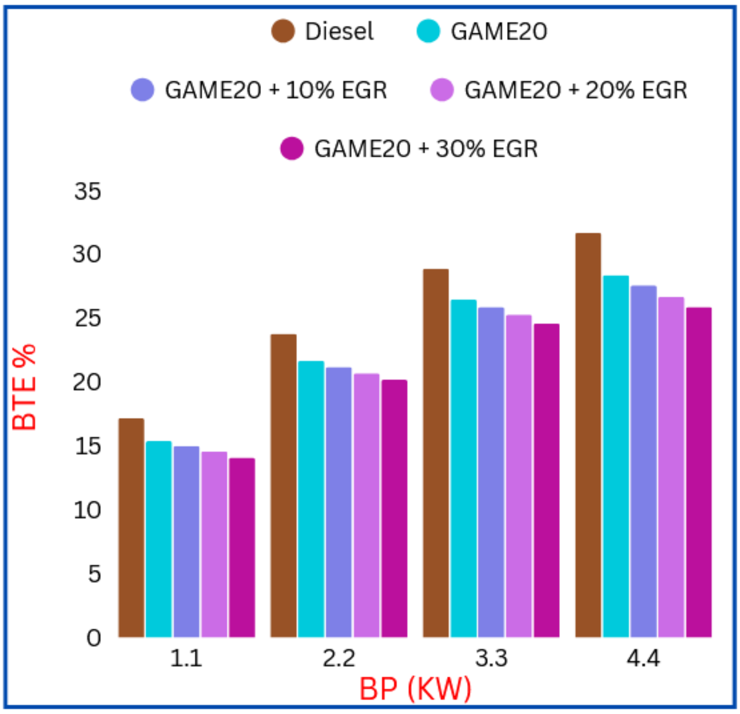

Figure 3. BTE vs BP

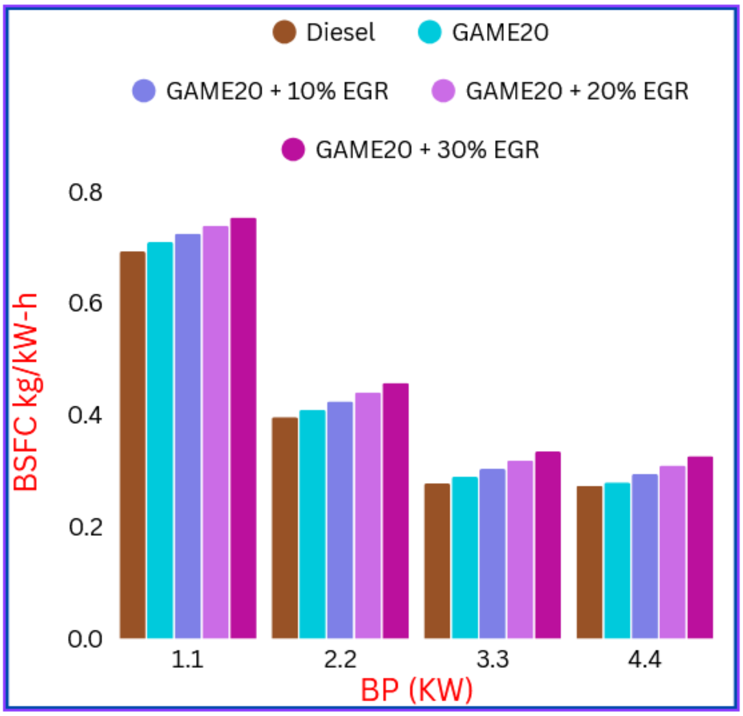

Figure 4. BSFC vs BP

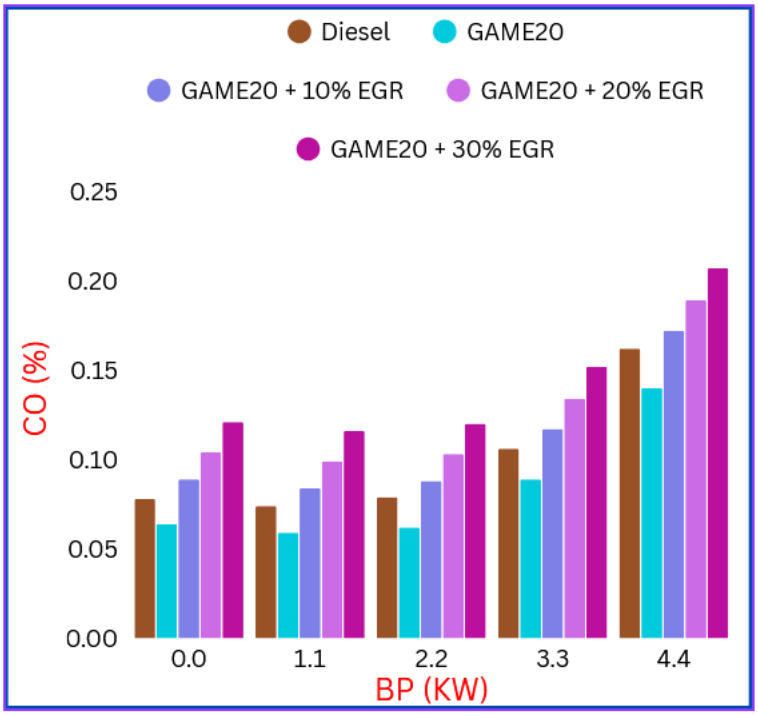

Figure 5. CO vs BP

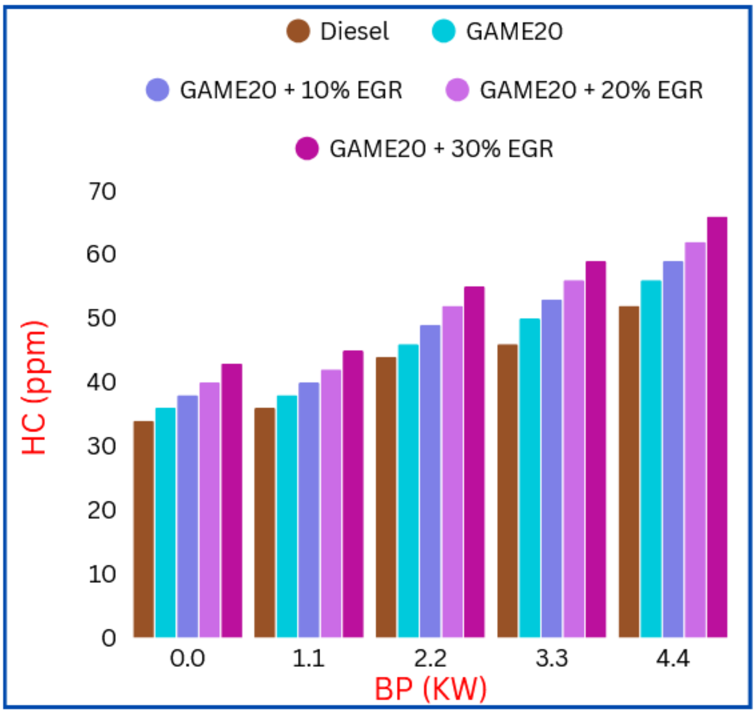

Figure 6. HC vs BP

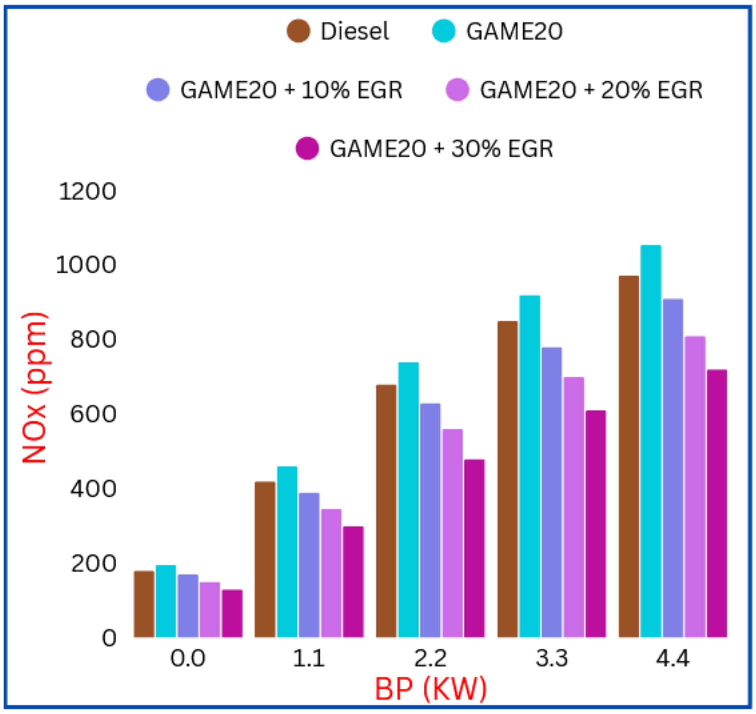

Figure 7. NOx vs BP

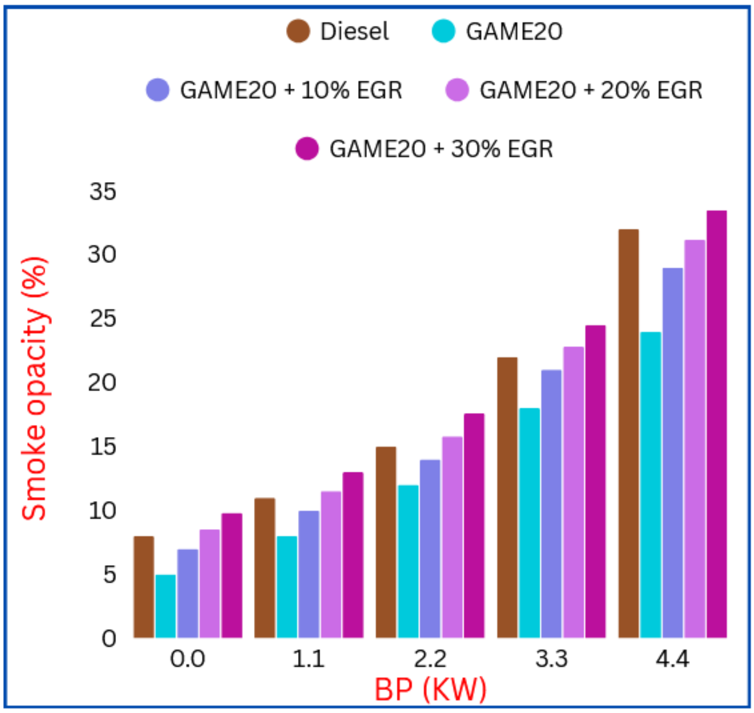

Figure 8. Smoke vs BP

5. Conclusion

The comparative analysis of Diesel, GAME B20 and GAME B20 with EGR shows the performance and emissions in biodiesel and powered engines. GAME B20 has a lower BTE 28.4% than diesel (31.7%) due to lower calorific value and higher viscosity, which lowers further with increasing EGR due to oxygen dilution. BSFC increases for GAME B20 and gradually increases under EGR due to partial combustion and lower flame temperatures. Emission investigation shows that GAME B20 decreases CO and smoke opacity more effectively than diesel due to its natural oxygen content, but these benefits diminish with higher EGR levels. HC emissions also higher for GAME B20 and increase with EGR which indicating incomplete combustion in oxygen and deficient conditions. GAME B20 initially generates higher levels of NOx than diesel, but the NOx decreases considerably with EGR, with 30% EGR achieving a reduction of around 32% relative to baseline GAME B20. The GAME B20 has cleaner combustion characteristics than diesel which integrating EGR demands an appropriate balance to achieve reduced NOx without significantly lowering efficiency and fuel economy.

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