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Original Article

Nanotechnology-Assisted Performance, Combustion and Emission Control: A Study on Al_2O_3-Enriched GABME B20 in CI Engines

C.S. Abdul Favas[1], M. Ramarao[1], S. Prakash[2], S. Nallusamy[3]

[1]*Department of Mechanical Engineering, Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India.*
[2]*Department of Mechanical Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation, Deemed to be University, Tamil Nadu, India*
[3]*Department of Adult, Continuing Education and Extension, Jadavpur University, Kolkata, India.*

[1]*Corresponding Author : Prakash.mech94@gmail.com*

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Abstract - *This research work investigates the green algal biomass induced by Aluminum Oxide (Al_2O_3) nanoparticles on the performance, combustion, and emission characteristics of a diesel engine fueled with neat Diesel and a Green Algae Biofuel Methyl Ester (GABME20) biodiesel blend. The concentration of Al_2O_3 nanoparticles with pure diesel and biodiesel blend, with enhancement in combustion efficiency and emission reduction compared to base diesel. For diesel, the Brake Thermal Efficiency (BTE) increased from 28.2% to 30% which increased to around 6.38%, while BSFC decreased from 0.693 to 0.662 kg/kWh, which decreased to around 4.47%. When Al_2O_3 was added to GABME B20, BTE improved from 27.5% to 29.1% increasing by 3.19% and BSFC was reduced from 0.71 to 0.678 kg/kWh, decreasing around 2.16%. The Heat Release Rate (HRR) reached a maximum of 75 J/°CA for GABME + Al_2O_3 compared to 68 J/°CA for Diesel, indicating enhanced combustion due to improved atomization and catalytic oxidation. Emission analysis revealed significant improvements with Al_2O_3 addition. CO emissions were reduced by 20% for Diesel + Al_2O_3 and 30.86% for GABME + Al_2O_3 relative to Diesel. HC emissions decreased by 11.92% and 8.46% respectively, while NOx increased by 9.57% and 40.43% due to higher in-cylinder temperature and oxygen availability. Smoke opacity showed a marked reduction: 20.31% for Diesel + Al_2O_3, 25% for GABME (B20) and 35.94% for GABME + Al_2O_3 compared to Diesel.*

Keywords - *Green Algae Biodiesel, Chlorella vulgaris, (Al_2O_3) nanoparticles, Wastewater Derived Fuel.*

1. Introduction

Growing populations, growth in industry, and urban development have increased the demand for petroleum fuels, raising concerns about their potential extinction [1]. The ecosystem is now threatened by the hazardous gases emitted by petroleum fuels. The primary causes of greenhouse gas emissions, ozone layer deterioration, and climate change are emissions from internal combustion engines. Finding an alternative fuel that is not only clean and environmentally friendly but also economically feasible and lowers overall energy usage has therefore become imperative [2]. When magnesium oxide nanoparticles are added to jojoba oil-based biodiesel, it can be a beneficial strategy for marine diesel engines. Additionally, compared to diesel fuel with different nanoparticles, such as aluminum, titanium, and copper oxide, the measured CO emission value decreased by 32%, and HC emissions also decreased by approximately 20.2% [3]. The analysis of diesel engines using diesel fuel and neat jatropha methyl ester, showed that jatropha biodiesel had a higher BSFC, which means fuel consumption is higher and the value and a lower BTE, which means the performance is decreased when associated to diesel. In difference to diesel, the emission parameters, such as CO_2 and HC, were minimal [4, 5]. NOx emissions were shown to be negatively impacted. One noteworthy finding is that the introduction of aqueous nano-Al2O3 at low volume percentages has no discernible effect on BTE or BSFC [6]. In this case, the higher evaporation and improved water thermal capacity are responsible for the decrease in NOx concentration [7, 8]. It is clear that nano-Al2O3 induced nanoparticle to improve the heat transfer coefficients and combustion properties [9]. The average BSFC was impressively reduced by 35% when hydrogen was added to diesel. [10] examined how the performance of DI engines was affected by nanoparticle jatropha biodiesel diesel mixes infused with Zinc Oxide (ZnO) [11]. They employed nanoparticles with diameters between 10 and 30 nm and a concentration of different dosage. The outcomes of the experiment clearly demonstrate that engine performance and emissions are significantly influenced by the size of the nanoparticles [12]. When compared to traditional ZnO–ZnS, the results showed that using nanoparticles was equivalent to another biodiesel. The number of carboxylic acids in the contaminated water was reduced by 88% by using the bimetallic CNi-Al_2O_3 structure (AlCNi) as a catalyst and thermal conductivity [13]. By infusing as catalysts that promote more thorough fuel oxidation and lower emissions of CO and HC emissiopn, mixing biodiesel with Mo nanoparticles also helps to further expand combustion characteristics. [14] examined the combustion and emission characteristics of spirulina oil as clean energy substitutes with and without the inclusion of induced nanoparticles [15, 16]. Biodiesel blends B10 and B20 of different biodiesel and biodiesel with different nanoparticles were treated with nanoparticles varing from 25, 50, 75 and 100 ppm concentration, examined biodiesel mixtures containing nanoparticle and cerium oxide nanoparticles [17, 18]. Water jacinth biodiesel blends can improve cost-effectiveness and lessen environmental impact, according to experiments [19]. The ideal parameters were 32.68% biofuel blend, 77.58% engine load, 50 ppm NPC, 17.5 compression ratios and 178.44 bar IP [20]. By complementing the nanoparticle-enhanced biodiesel with microalgal-derived wastewater feedstock, there are opportunities for realizing both an environmental pollution reduction impact from cleaner combustion and sustainable feedstock utilization. Hence, this study addressed the gap in former and current research, as outlined in Table 1.

Table 1. Comparative evaluation of past studies and the present investigation

Author	**Functioning Parameters**	**Performance**	**Combustion**	**Emissions**	**Eco Focus**
Ge, Shengbo, et al (2022) [8]	Algae biodiesel (Chlorella, Nannochloropsis),	BTE ↑, BSFC ↓	CP ↑, HRR ↑	CO ↓, HC ↓, NOx ↑, Smoke	Algae + H_2
Gupta, et al. (2025) [9]	Algae biodiesel (B. braunii), nanoparticles, HHO	BTE ↑, BSFC ↓	CP ↑	CO ↓, HC ↓, NOx ↑, Smoke	Nano + HHO
Liu, et al. (2013) [14]	Algae–ethanol blend, H_2	BTE ↑	HRR ↑, Ignition delay ↓	CO ↓, HC ↓, NOx ↑, Smoke ↓	Ethanol + H_2
Prabhahar et al. (2019) [18]	H_2, water injection, pongamia biodiesel	BTE ↑, BSFC ↓	HRR ↑	CO ↓, HC ↓, NOx ↑, Smoke	Water + H_2
Kim et al. (2018) [11]	H_2–diesel, Dunaliella biodiesel, nozzle, CR	BTE ↑	CP ↑	CO ↓, HC ↓, NOx ↑, Smoke	Marine algae
Ramano et al. (2021) [21]	Injection pressure, timing, Jatropha biodiesel–H_2	BTE ↑, BSFC ↓	HRR ↑	CO ↓, HC ↓, NOx ↑, Smoke ↓	Optimized IP
Senthil, et al. (2017) [23]	EGR %, timing, nanoparticles, Nerium biodiesel	BTE ↑, BSFC ↓	CP ↑, HRR ↑	CO ↓, HC ↓, NOx ↑, Smoke ↓	EGR + Nano
Aravind et al. (2025) [3]	Injection pressure, EGR, spirogyra biodiesel	BTE ↑, BSFC ↓	CP ↑, HRR ↑	CO ↓, HC ↓, NOx ↑, Smoke ↓	EGR + Algae
Devan et al. (2009) [7]	Poon oil–ethanol blend, timing	BTE ↑	Ignition delay ↓	CO ↓, HC ↓, NOx ↑, Smoke ↓	Ethanol blend
Current Study	Chlorella biodiesel blend (GABME20) + Al_2O_3 nanoparticles, CR variation	BTE ↑, BSFC ↓	CP ↑, HRR ↑	CO ↓, HC ↓, NOx ↑, Smoke ↓	Wastewater Algae + Al_2O_3 Nano

The research focuses on the cultivation of Chlorella vulgaris in synthetic wastewater with human urine inputs, extraction of biodiesel and biofuels and modification of improvised Edible Filtration biodiesel using Al_2O_3 nanoparticles. Engine testing was conducted using 10%, 20% blends of CVA biodiesel + diesel and 30% edit using the GABME20 (20% algae biodiesel + 50 ppm Al_2O_3) nanoparticle modified fuel in both high and low compression ratios.

The engine performance, the emissions and the combustion traits were analyzed for evaluation of algae biodiesel fuels. This method is useful for tackling the general issues with algae biodiesel (lower BTE and increased NOx) by using aluminum oxide nanoparticles to improve the combustion and emissions profile.

2. Materials and Methods

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

Microalgae have recently been recognised as a feedstock for renewable energy due to their capacity to use nutrients and sunshine to produce biomass that is rich in lipids. Chlorella vulgaris is the most studied microalgae because of its quick growth, environmental tolerance and oil-enhanced productivity [22]. These qualities make C. vulgaris a viable feedstock for the manufacture of biofuel on a commercial scale, not only as a substitute for traditional fossil fuels but also in terms of environmental considerations like waste treatment and carbon capture. Therefore, this study will look at using a base-catalyzed transesterification method to produce GABME20, a 20% biodiesel blend made of Chlorella vulgaris. The transesterification process was optimized in terms of reaching a high rate of conversion while complying with quality expectations for the biodiesel fuel category used in engines. Further economic benefits of using C. vulgaris as feedstock stem from its known uses in nutrition and pharmaceuticals, further supporting the feasibility of an integrated algal biorefinery.

2.2. Algal Biomass Cultivation and Oil Extraction

The C. vulgaris was grown in open canal ponds in a regulated manner to allow for constant biomass. Centrifugation was used to harvest the biomass from the culture medium during the ideal growth stage of the culture. In order to remove moisture, the slurry was subsequently desiccated in a hot-air oven at 40°C until a steady weight was achieved. To maximise surface area during the extraction stage, the biomass was crushed into a fine powder after drying. Using a Soxhlet device and n-hexane as the solvent, lipids were extracted. To help the oils in the cells enter the extraction solution, the dried powder was put in the extraction chamber, and reflux was carried out for a few hours. The lipids in the extraction solution were then filtered off, and to create crude algal oil, the flush was removed under vacuum using a rotary evaporator. The oil was stored under airtight conditions in amber-colored bottles to protect against oxidation until further use [24].

2.3. Biodiesel Conversion via Transesterification

Transesterification occurred using a laboratory-scale reactor setup, which consisted of a magnetic stirrer, heating mantle, and a reflux condenser. Potassium Hydroxide (KOH) was designated as the alkaline catalyst due to its high catalytic activity and broad application in biodiesel production.

A One-Variable-At-a-Time (OVAT) experimental method design was used to find the most favorable operating conditions for biodiesel yield [25]. The following factors were varied systematically:

- Catalyst concentration (KOH, % w/v): 0.5, 1.0, 1.5
- Reaction temp (°C): 40, 50, 60
- Methanol to oil molar ratio: 8:1, 10:1, 12:1
- Reaction time (min): 60, 120, 180

The transesterification reaction was started for each trial by adding a predetermined volume of algal oil to the reactor and then adding methanol with the appropriate proportion of dissolved KOH [26]. In order to establish a constant environment and a uniform phase for the transesterification reaction, the algal oil and methanol were aggressively swirled at a set speed. The reactor's temperature was closely and continually monitored. Two immiscible phases were created by this settling, with the methyl ester phase biodiesel at the top and the solider glycerol phase at the bottom [26]. To get rid of any leftover catalyst, soaps, and other pollutants, the upper phase (biodiesel) was decanted and repeatedly cleaned with warm distilled water. The washed biodiesel was then dried with anhydrous sodium sulfate to remove any trace water and subsequently filtered for clarity. B20 was produced by blending the purified biodiesel with commercial diesel in a ratio of 25% biodiesel to 75% diesel by volume and was used for engine testing in subsequent experiments. The effect of various transesterification variables on biodiesel yield is summarized in Figure 1 the optimum conditions for maximum conversion efficiency are evident throughout the data presented in this figure.

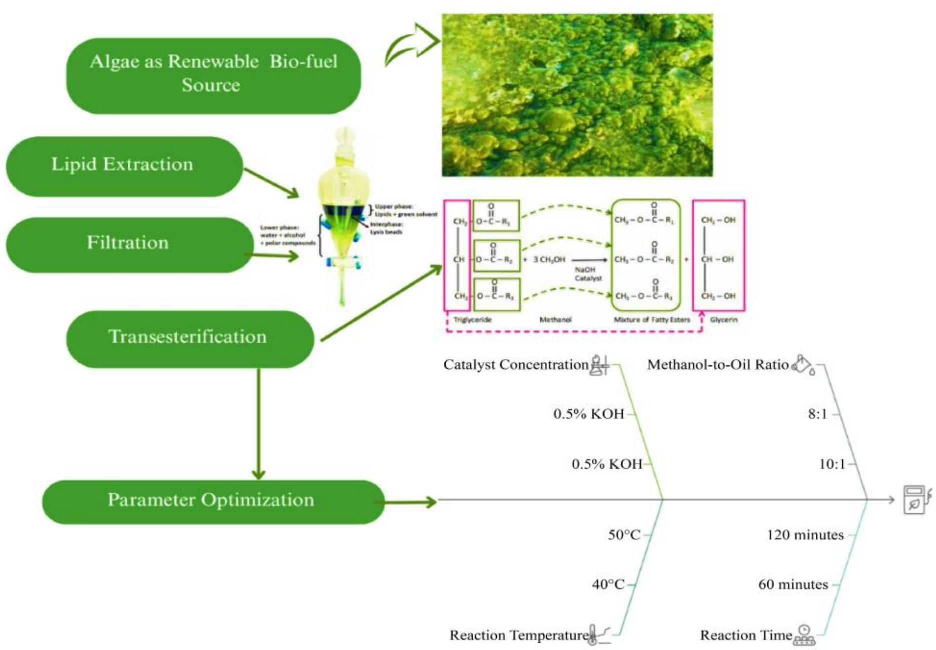

Fig. 1 Optimization of biodiesel yield

2.4. Physicochemical Characterization

The physicochemical characteristics of the manufactured GABME20 product were in agreement with ASTM methods to verify that the fuel met established quality standards. The properties examined included specification as Gravity, viscosity, boiling range, cetane number, flash point and calorific value. Each physicochemical property was measured three times for accuracy, and average values were reported. The characteristics of produced GABME20 were compared to neat diesel fuel and ASTM limits, which are summarized in Table 2.

Table 2. Comparative fuel properties of diesel, GABME20 and GABME20 + Al_2O_3 Nanoparticles

Property	Diesel	GABME20	GABME20 + Al_2O_3
Physical state	Liquid	Liquid	Liquid
Specific gravity @ 16 °C	0.86	0.90	0.91
Stoichiometric air–fuel ratio	14.5	13.2	13.0
Kinematic viscosity @ 40 °C (mm²/s)	2.42	4.1	4.3
Boiling range (°C)	160–366	185–365	185–368
Cetane number	51	55	56
Flash point (°C)	59	162	168
Calorific value (kJ/kg)	44,000	39,700	39,500

3. Experimental Setup

The experiment focused on a single-cylinder diesel engine to assess how adding (Al_2O_3) nanoparticles to Green Algae-Based biodiesel (GABME20) affected engine performance and emissions. A data acquisition system was used to capture data in real-time from sensors placed to record cylinder pressure, cylinder temperature and crank angle on the engine. A laser-based system was used to evaluate the in-cylinder airflow. The different fuel blends evaluated for the engine study included: pure diesel, GABME20 and GABME20 blended with 50 ppm of Al_2O_3 nanoparticles evenly dispersed in the fuel with ultrasonication.

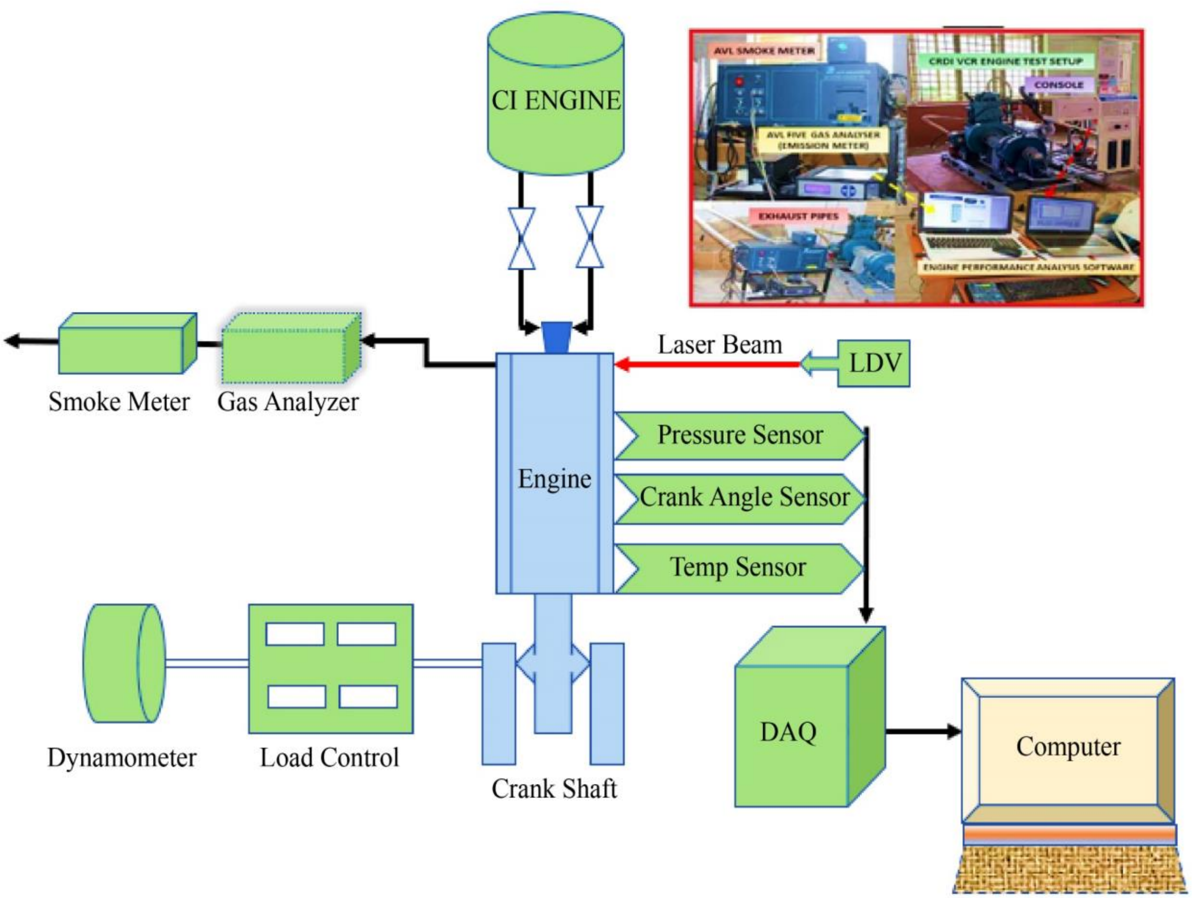

Fig. 2 Experimental setup

The engine was run continuously at a fixed speed of 1800 rpm, using varying loads. Emissions (CO, HC, NOx, smoke) were verified from the engine using gas analyzers and smoke analyzers, following the purpose of determining if the addition of nanoparticles might improve combustion and lower harmful emissions for a more sustainable and cleaner fuel.

3.1. Characterization of Aluminum Oxide Nanoparticles

In order to utilize the combustion and emissions performance of GABME20, (Al_2O_3) nanoparticles were introduced as fuel additives. Figure 3(a) displays the high-purity nanopowder that was utilized for this research.

These nanoparticles were chosen because of their high volume-to-surface ratio, ideal thermal stability, and catalytic activity, which has been shown to improve combustion kinetics in blends of biodiesel. SEM was used to perceive the surface structure and morphology of the Al2O3 nanoparticles.

SEM images of spherical agglomerated particles with nanoscale morphology are displayed in Figure 3(b), suggesting an average particle size of less than 100 nm. Fuel dispersion and fuel-air mixing are enhanced by the nanoscale form during combustion, leading to more effective combustion and reduced emissions. To minimise clustering effects and guarantee stable particle suspension, the nanoparticles remained added to the GABME20 fuel mixture at a absorption of 50 ppm using ultrasonication. The use of nanoparticles is critical for achieving optimal combustion performance without altering the engine, and it is an important step towards practical and scalable, greener biofuels for diesel engines.

(a) (b)

Fig. 3 Al_2O_3 nanoparticles: (a) As-received powder, and (b) SEM morphology showing nanoscale agglomerates.

4. Result and Discussion

4.1. Combustion

Figure 4 shows the changes in CP vs CA with four different considerations including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20 and GABME B20/Al_2O_3 nanoparticles induced 50ppm.

The crank angle moves towards TDC, the CP increases simultaneously, and at maximum load the pure diesel reaches aroud 72 bar. But induced of Al_2O_3 nanoparticles which have slightly decreased to around 70 bar at full load conditions.

So, the biodiesel GABME B20 without nanoparticle at full load achieved a peak pressure of nearly 68 bar, a reduction in pressure due to the lower calorific value of algae biodiesel mixes. The next blend GABME B20/Al_2O_3 nanoparticles, which improved the combustion performance to around 73 bar at full load condition, displays the lower calorific of algae biodiesel and Al_2O_3 nanoparticles induced better quality combustion consistency with thermal behavior through micro explosion and atomization of fuel combustion chamber.

Figure 5 shows the changes in HRR vs CA with four different considerations including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20 and GABME B20/Al_2O_3 nanoparticles induced 50ppm. The crank angle moves towards TDC, the HRR value at full load.

The pure diesel reaches around 68 J/°CA, so conventional diesel has good volatility and spray atomization behavior. But induced of Al_2O_3 nanoparticles with diesel shows a slightly increasing HRR around 70 J/°CA reason for nanoparticles improve atomization and thermal conductivity. The algae biodiesel GABME B20 without nanoparticle which reduce the combustion HRR performance around 65 J/°CA since of higher kinematic and poor volatility due to lower calorific value.

The next blend GABME B20/Al_2O_3 nanoparticles which increased the combustion performance around 75 J/°CA which promotes faster HRR, the nanoparticle which induced shows the spray, vaporization and catalytic oxidation reason for the highest HRR.

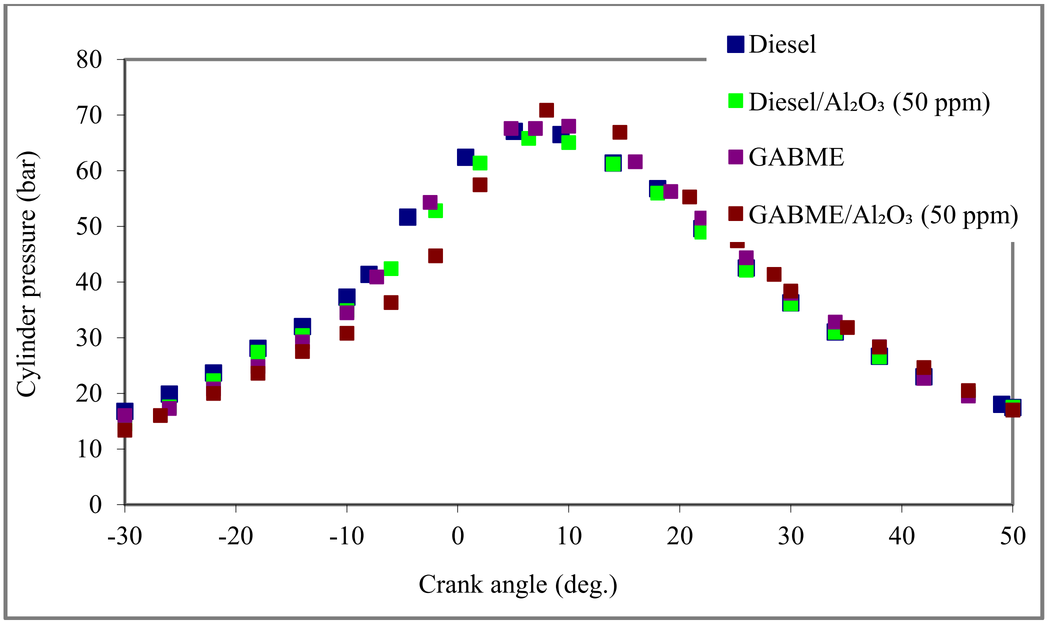

Fig. 4 CP Characteristics of Diesel/Algal/Nanoparticle fuel blends

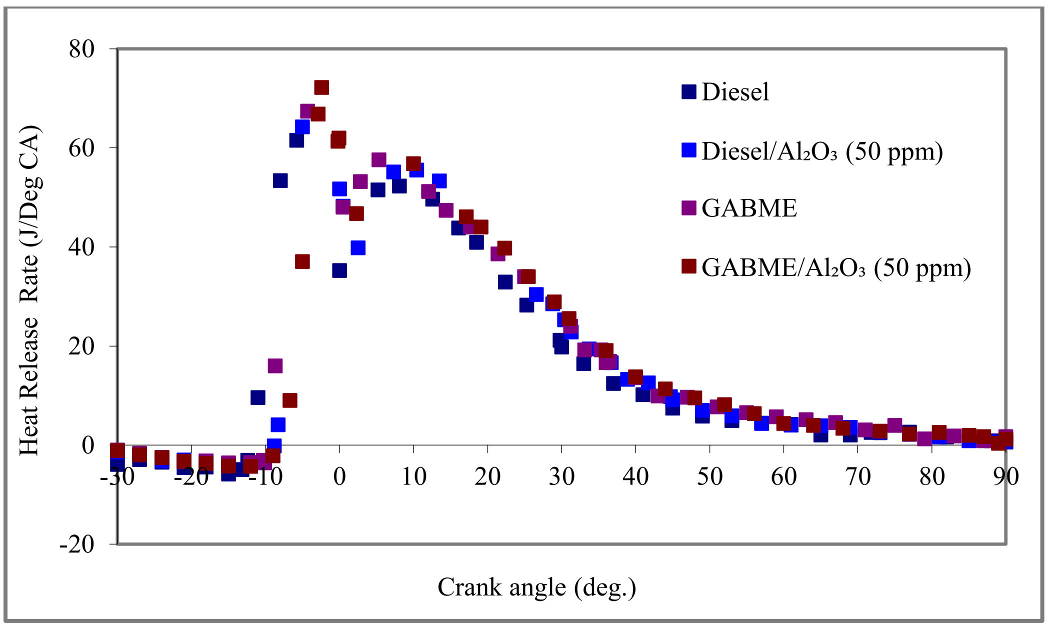

Fig. 5 HRR characteristics of diesel/algal/nanoparticle fuel blends

4.2. Performance

Figure 6 shows the changes in BTE vs BP with four different considerations, including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20 and GABME B20/Al_2O_3 nanoparticles induced 50ppm. The pure diesel performance of BTE shows 28.2% shows the conventional diesel has good volatility and spray atomization behavior. When compared to diesel induced Al_2O_3 nanoparticles produce 30% which approximately increase 6.38% because of improved combustion efficiency and heat transfer of induced nanoparticle. The algae biodiesel GABME B20 without nanoparticle which reduced its performance by around 27.5% because of higher kinematic and lower calorific val. of algae biodiesel blend approximately decreased 2.48%. The next blend GABME B20/Al_2O_3 nanoparticles which increased the combustion performance 29.1% partly compensating for algae biodiesel drawbacks which nearest to the baseline diesel value and increased by around 3.19% because of the high viscosity of nanoparticle mixes. The results for the biodiesel with the nanoparticle show clearly the performance of their base diesel for the full load condition. Even though GABME blends show slightly lower BTE than diesel, their performance becomes competitive when induced with nanoparticle mixes.

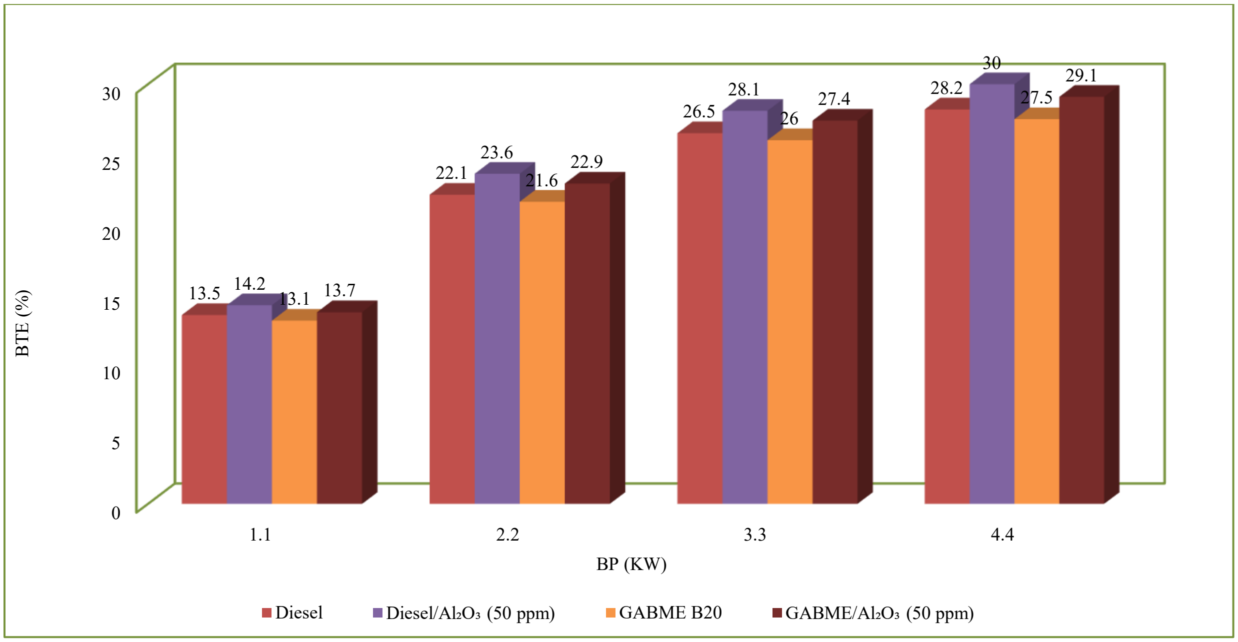

Fig. 6 BTE characteristics of diesel/algal/nanoparticle fuel blends

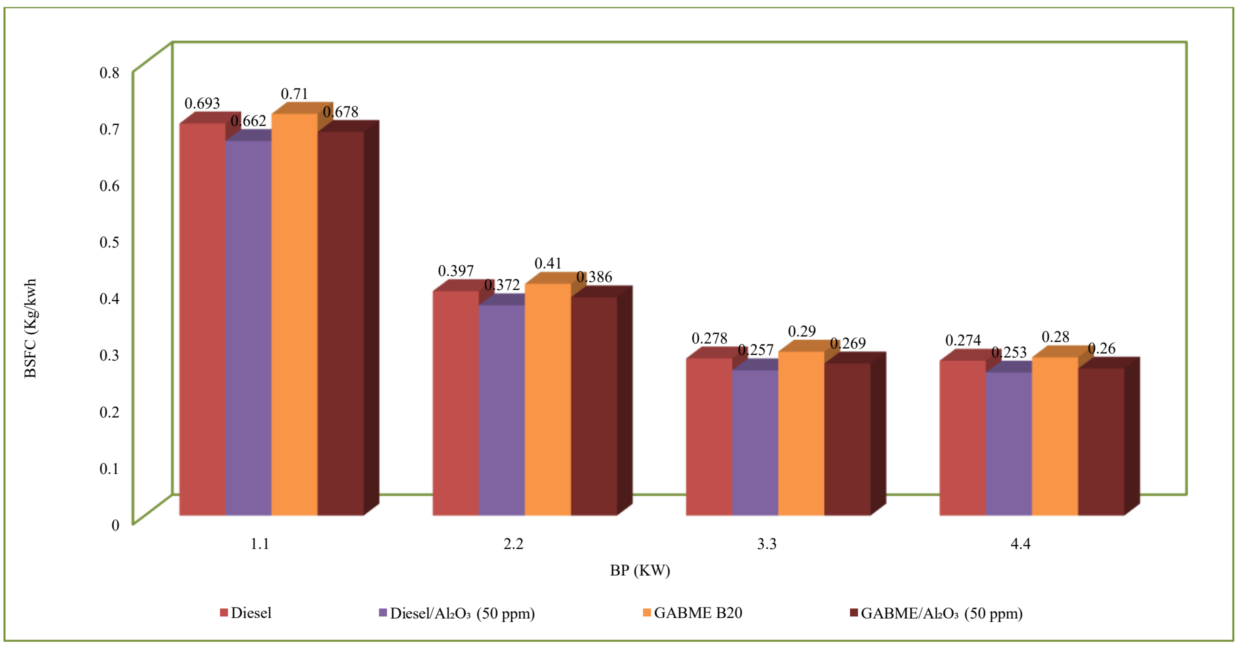

Fig. 7 BSFC characteristics of diesel/algal/nanoparticle fuel blends

Figure 7 shows the changes in BSFC vs BP with four different consideration includes diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20 and GABME B20/Al_2O_3 nanoparticles induced 50ppm. The pure diesel performance of BSFC shows 0.693 kg/kWh shows the conventional diesel has good volatility and spray atomization behavior. When compared to diesel induced Al_2O_3 nanoparticles producing 0.662 kg/kWh which approximately decrease 4.47% because of improve combustion and atomization reduce fuel consumption, lowering BSFC induced nanoparticle. The algae biodiesel GABME B20 without nanoparticle, which improves the specific fuel consumption around 0.71 kg/kWh, because of the higher kinematic and lower calorific value of algae biodiesel blend approximately decreases 2.45% requiring more fuel for the same power, which increases BSFC. The next blend GABME B20/Al_2O_3 nanoparticles which decreased the fuel combustion 0.678 kg/kWh partly compensating for algae biodiesel drawbacks which nearest to the baseline diesel value and decreased around 2.16% because of while biodiesel alone increases BSFC due to inferior diesel properties and reduced due to induced nanoparticle mixes.

The results for the biodiesel with the nanoparticle shows the clearly the performance of their base diesel for the full loads condition. Even though GABME blends show slightly lower BSFC than diesel, their performance becomes competitive when induced with nanoparticle mixes.

4.3. Emission

Figure 8 shows the changes in CO emissions vs BP with four different considerations, including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20, and GABME B20/Al_2O_3 nanoparticles induced 50ppm.

The pure diesel CO emission shows 0.162% vol, which shows the conventional diesel has good volatility and spray atomization behavior. When compared to diesel-induced Al_2O_3 nanoparticles shows a 0.1296% vol the high surface zone and catalytic motion of Al_2O_3 nanoparticles encourages oxidation of intermediate CO to CO_2 enhancing the post-flame oxidation efficiency decreases around 20%.

The algae biodiesel GABME B20 without nanoparticle shows 0.14% vol because the inherent oxygen content in biodiesel molecules surrounds more complete oxidation during the initial phase, which helps to reduce CO emission by around 13.58% compensating for algae biodiesel promotion, which is nearest to the baseline diesel value. The next blend GABME B20/Al_2O_3 nanoparticles which decreased the CO emission 0.112% vol because the combined effect of individual oxygen in biodiesel and the catalytic motion of Al_2O_3 leads to the lowest CO emission around 30.86%. The results for the biodiesel with the nanoparticle show a clear decrease when induced with nanoparticle mixes.

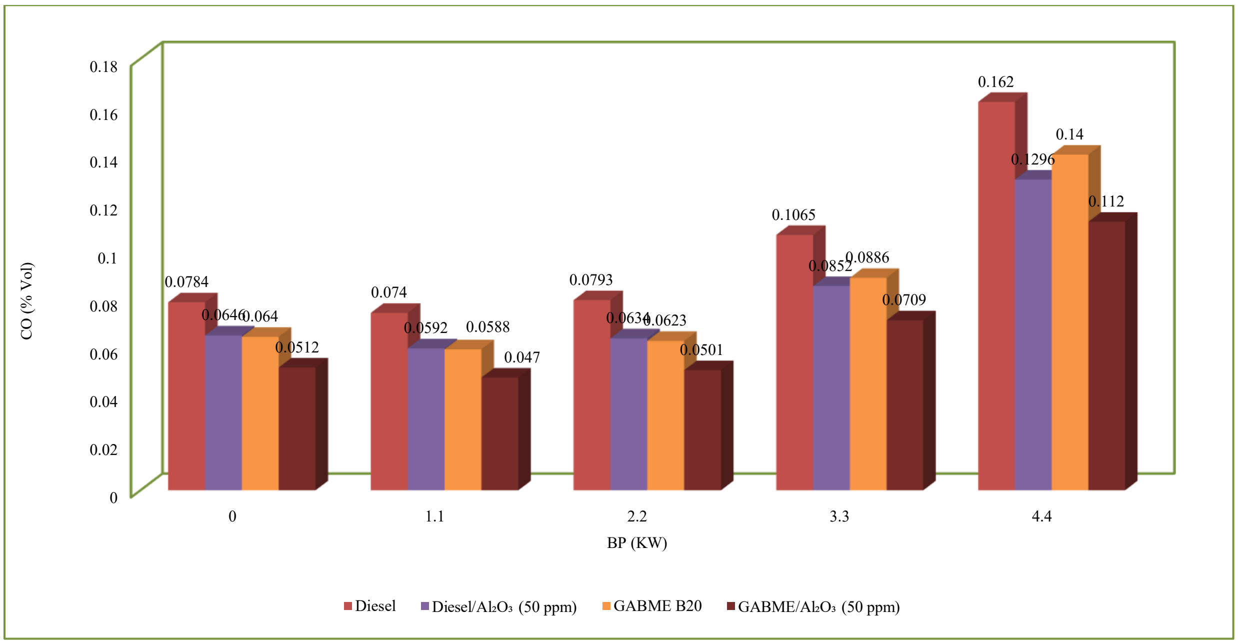

Fig. 8 CO emission characteristics of diesel/algal/nanoparticle fuel blends

Figure 9 shows the changes in HC emission vs BP with four different considerations includes diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20 and GABME B20/Al_2O_3 nanoparticles induced 50ppm. The pure diesel HC emission shows 52 ppm shows the conventional diesel has good volatility and spray atomization behavior.

When comparing to diesel-induced Al_2O_3 nanoparticles shows the 45.8 ppm, enhance in-cylinder oxidation by increasing local temperature and supplying catalytic motion, leading to lower unburnt HC around 11.92 reducing when compare to base diesel. The algae biodiesel GABME B20 without nanoparticle which shows 56 ppm because higher viscosity and proper atomization of biodiesel result in incomplete combustion and fuel-rich zones, increasing HC emission around 7.69% compensating for algae biodiesel promotion.

The next blend GABME B20/Al_2O_3 nanoparticles, which decreased the HC emission of 47.6 ppm because nanoparticles improve fuel–air mixing, vaporization and oxidation kinetics, reducing HC significantly compared to plain biodiesel around 8.46%. Figure 10 shows the changes in NOx emission vs BP with four different considerations, including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20 and GABME B20/Al_2O_3 nanoparticles induced 50ppm. The pure diesel NOx emission shows 324 ppm, indicating that the conventional diesel has good volatility and spray atomization behavior. When compared to diesel-induced Al_2O_3 nanoparticles, the 355 ppm, higher combustion temperature, and improved oxidation outcome of Al_2O_3 nanoparticles increase NOx formation via the thermal induced mechanism around 9.57 increasing when compare to base diesel. The algae biodiesel GABME B20 without nanoparticle, which shows 420 ppm, because combined oxygen enrichment and nanoparticle induced thermal transfer peak flame temperature and resident O_2 availability outcome the highest NOx levels around 29.63% compensating for algae biodiesel promotion. The next blend GABME B20/Al_2O_3 nanoparticles which increased the NOx emission 455 ppm because nanoparticles O_2 availability, resulting in the highest NOx levels, increasing NOx significantly compared to plain biodiesel around 40.43%. The results for the biodiesel with the nanoparticle shows the clearly increasing when induced with nanoparticle mixes and all biodiesel blends.

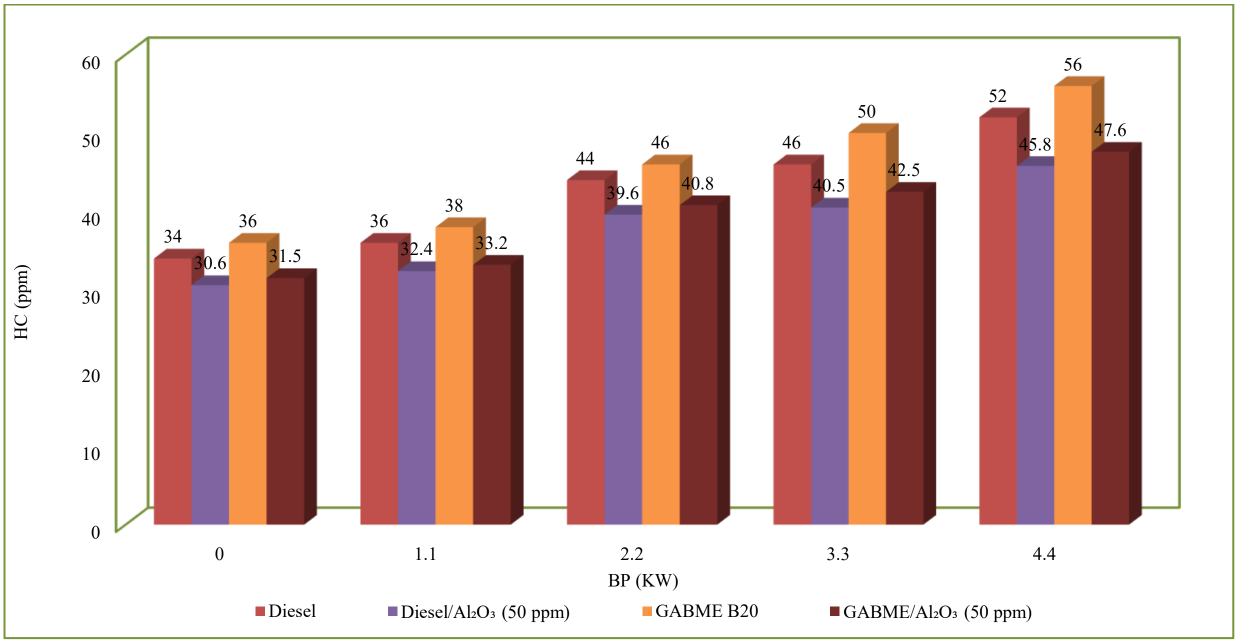

Fig. 9 HC emission characteristics of diesel/algal/nanoparticle fuel blends

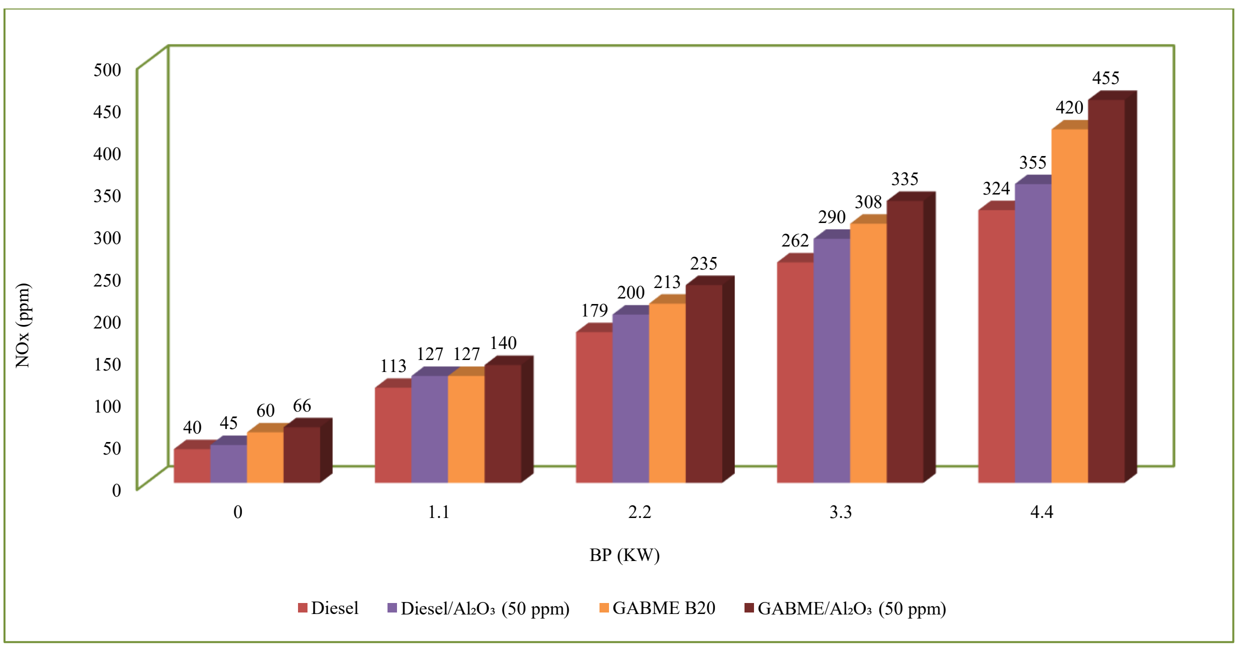

Fig. 10 NOx emission characteristics of diesel/algal/nanoparticle fuel blends

Figure 11 shows the changes in smoke emission vs BP with four different considerations, including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20, and GABME B20/Al_2O_3 nanoparticles induced 50ppm. The pure diesel smoke emission shows 30% shows the conventional diesel has good volatility and spray atomization behavior.

When comparing to diesel-induced Al_2O_3 nanoparticles shows the 25.5%, because the enhance oxidation of soot emission by increasing combustion temperature and providing catalytic reaction, reducing smoke intensity around 20.31% decreasing when compare to base diesel. The algae biodiesel GABME B20 without nanoparticle, which shows 24 ppm because the inherent oxygen in biodiesel promotes lesser combustion and reduces formation of hydrocarbons emission lowering soot emission around 25% compensating for algae biodiesel promotion.

The next blend GABME B20/Al_2O_3 nanoparticles which decreased the soot emission 20.5% because the combined oxygen enrichment and catalytic reaction quicken soot emission and overpower particle resulting the outcome of yielding the lowest smoke emission around 35.94%. The results for the biodiesel with the nanoparticle shows the clearly decreasing when induced with nanoparticle mixes and all biodiesel blends.

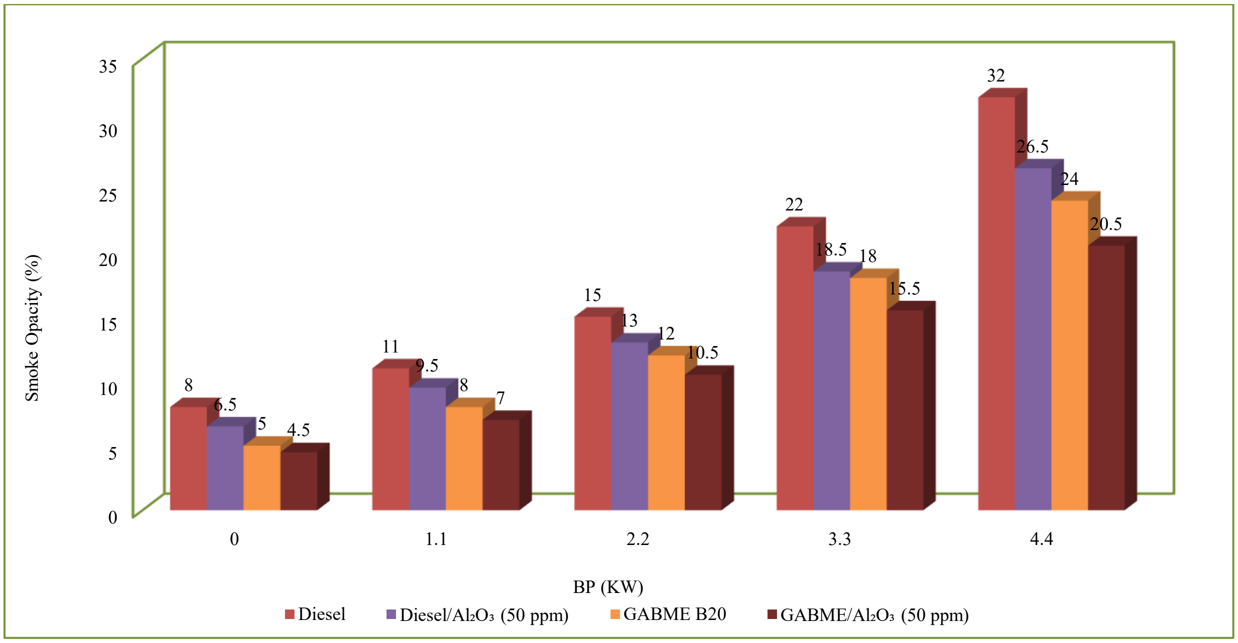

Fig. 11 Smoke opacity characteristics of diesel/algal/nanoparticle fuel blends

5. Conclusion

The experimental results concluded with four different considerations, including diesel, diesel/Al_2O_3 nanoparticles induced 50ppm, biodiesel GABME B20, and GABME B20/Al_2O_3 nanoparticles induced 50ppm.

- The peak cylinder pressure for base diesel was 68 bar when the addition of Al_2O_3 nanoparticles was made, which increased to around 70 bar due to enhanced combustion rate and improved atomization.
- The HRR for diesel is 70 J/°CA when algae biodiesel is blended with a maximum HRR of 75 J/°CA for induced GABME + Al_2O_3, indicating quicker and more complete combustion due to improved atomization and thermal conductivity.
- BTE increased from 28.2% to 30% around 6.38% diesel-to-induced nanoparticles, when algae biodiesel blend, the BTE improved from 27.5% to 29.1% around 3.19%.
- The BSFC decreased from 0.693 to 0.662 kg/kWh, around 4.47% diesel-induced nanoparticles; when an algae biodiesel blend was used, the BSFC was reduced from 0.71 to 0.678 kg/kWh, around 2.16%.
- CO emissions were reduced by 20% for Diesel + Al_2O_3 and 30.86% for GABME + Al_2O_3 comparative to Diesel. HC emissions decreased by 11.92% and 8.46% respectively, while NOx increased by 9.57% and 40.43% due to higher in-cylinder temperature and oxygen availability. Smoke opacity showed a marked reduction: 20.31% for Diesel + Al_2O_3, 25% for GABME (B20) and 35.94% for GABME + Al_2O_3 compared to Diesel.

The effect of diesel and biodiesel-induced Al_2O_3 nanoparticle catalysis on the reaction improved combustion efficiency and reduced incomplete combustion emissions, but resulted in a moderate increase in NOx emissions. In the future, it will focus on reducing the use of technical EGR setups or additive concepts.

5.1. Future Research

NOx emissions increased due to higher combustion temperatures. Future research can focus on NOx reduction techniques, such as Exhaust Gas Recirculation (EGR) or optimized injection timing.

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