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Optimizing Performance and Reducing NOx Emissions: Quaternary and Ternary Green Blends with Carbon Nanotubes in a CRDI Engine

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Abstract:-This research compares the efficacy of green-synthesized carbon nanotubes in a ternary fuel blend (20% Chlorella vulgaris microalgae biodiesel, 20% bioethanol, and 60% diesel) and an innovative quaternary blend (diesel 60–70%, cottonseed oil 5%, Mahua biodiesel 15–20%, and n-butanol 15–20%) in a CRDI diesel engine. The ternary blend, with 100ppm carbon nanotubes, demonstrates improved performance, yielding a 9% enhance in brake thermal efficiency, an 11.76% decrease in brake specific fuel consumption, and a 12.79% decrease in brake specific energy consumption contrast to diesel. However, it exhibits a 13.42% increase in nitrogen oxides (NOx) and a 23.84% rise in heat release rate (HRR). On the other hand, the quaternary blend, particularly QB3-QB4, showcases enhanced efficiency with an 8% rise in BTE, a 29% decrease in specific energy consumption, and controlled combustion, resulting in a 14% reduction in the rate of pressure rise. QB3-QB4 also demonstrates a 10% decrease in NOx emissions and a 2% declined in smoke, although with a marginal increase in hydrocarbon (HC) emissions. Overall, these findings offer valuable insights into alternative fuel formulations, considering both ternary and quaternary blends, for optimizing engine performance and reducing fossil fuel dependency.

Keywords: *Ternary blends, Quaternary blends, IC Engines, Microalgae Biodiesel, CNT.*

1. Introduction

Fossil fuel has been the primary form of energy used by humans over time. Due to the limited reserve storage of fossil fuels, the investigator is presently exploring the potential for alternative energy sources. Moreover, the mining and processing of fossil fuels need expensive machinery, sophisticated operations, and increased emissions of pollutants. Hazardous pollutants of different kinds are also caused by the combustion of products derived from fossil fuel. Following burning, fuel produces carbon dioxide, carbon monoxide, and other gases that cause climate change and the formation of greenhouse gases[1].CO is more poisonous than CO_2 and should not be formed during combustion. In addition, these emissions cause genetic issues and are linked to a number of ailments, including lung and skin tumors[2].Alternative fuel sources, such as biodiesel, have the potential to significantly impact the energy problem by reducing dependence on fossil fuels. Fuels with inherent oxygen, such as biodiesel, assist in full combustion and minimize the release of pollutants such CO_2, CO, HC, and SO_2[3], [4].

According to reports, pure bio-oil made from vegetables has higher viscosity; hence blending mixture preparation is not advised. However, it is utilized in the creation of the blending mixture by converting oil to biodiesel. Many benefits of biodiesel based on oil include its accessibility, sustainability, low emission levels, and compliance with many ecologically friendly standards[5].Owing to a number of drawbacks, including reduced heating value, increased viscosity, increased density, increased fuel consumption, increased NO_X emissions, etc., biofuels are only utilized in small amountsbetween 5 and 20%in combination with diesel[6].

2. Literature Review

S. Janakiraman et al. [7] reported a modern technique for ternary blend with varying concentrations (35ppm to 65 ppm) of metal-doped TiO_2nanoadditives to estimate the consumption of fossil fuels and emissions with diesel. In order to test the different test fuel combinations on a diesel engine, the concentration levels of TiO_2nanoadditives were mixed with ternary fuel blends consisting of 70% diesel, 20% biodiesel, and 10% bio-ethanol, with variations in concentration. According to the results, Blend 6 (20% Biodiesel+10% Bio-ethanol+70% Diesel fuel+ TiO_2(65 ppm)) had the best and greatest fuel blends when compared to the other fuel blends. This was because it had a (2.1%) greater BSEC range comparable to pure diesel fuel and a (1.23%) minimal BTE. When compared to diesel, Blend 6 test sample (0.26%) has a elevated cylinder pressure and an inferior HRR rate (4.01%). Additionally, Blend 6 showed a considerable drop in CO (106.8%), UBHC (34.02%), smoke (34.01%), and NOx (29.79%) due to diesel. For this compelling reason, Blend6 was suggested as a superior substitute fuel to improve diesel engine performance and reduce emissions while meeting future requirements for energy.

GholamhassanNajafi et al. [8] had studied to investigate the influence of adding single and multi-carbon nanotubes at 25, 50, and 75 parts per million on performance characteristics and emissions from diesel engines during combustion. A mixture of pure diesel and biodiesel (B5, B10, B15, and B20) serves as the base fuel. After the creation of nanotubes and the analysis of TEM and XRD, diesel with biodiesel blends at 25, 50, and 75 ppm were combined ultrasonically. Maximum pressure and heat generation rates could raise substantially as much as 18.88 parentages and 19.65 parentages, accordingly, when MCNT and SCNT are incorporated into fuel blends. While reducing BSFC by 6.5 to 6.9%, greater nanotube proportion in gasoline B10 mixes improved braking power, torque, and BTE by 4.7–4.8%, 3.1–3.2%, and 0.2–5.2%, correspondingly. Moreover, there was an increase in HC, CO2, and NOx emissions of 0.26–5.2%, 0.57–8.7%, and 0.36–6.8%, respectively.

A Praveen et al.[9] Investigated the fabrication and evaluation of chlorella vulgaris microalgae was used to produce the biodiesel, and blends of biodiesel were made by combining the 20% microalgae biodiesel with the 80% diesel (CVBD20) and adding different amounts of Al_2O_3 nanoparticles. Compared to the CVBD20 fuel, the BTHE for the CVBD20ANP25, CVBD20ANP50, CVBD20ANP75, and CVBD20ANP100 fuels increased by 1.15 percent, 3.62% percent, 6.5% percent, and 4.34% percent. When comparing the CVBD20ANP50 fuel to the biodiesel blend, the greatest reduction in NOx emissions was noted4.21%. When comparing the CVBD20 fuel sample to the CVBD20ANP100 fuel, the HC emissions were reduced by 14.47% and the CO emissions by 19.5%, respectively.At maximum load conditions, the CVBD20ANP50 fuel showed a 4.7% reduction in smoke opacity compared to the biodiesel mix.

HamitSolmaz et al.[10]this study examined the impacts of adding multi-walled carbon nanotubes into waste frying oil biofuel (B20) on the engine's operation, combustion process, and exhaust emissions using a DI compression ignition system. At four distinct loads and peak torque at the constant engine speed, experiments were conducted. The findings reveal that, when contrast to pure diesel, engine performance has significantly declined while using B20 fuel without the MWCNT additive. Fuel characteristics were enhanced by adding MWCNT to B20. This happened because the engine performance was enhanced by the MWCNT additive. The burning time of B20 fuel with a 100 ppm addition is shorter than that of plain diesel, suggesting that thermal efficiency has increased as heat losses have decreased.When utilizing a 100 ppm addition to B20 test gasoline at 15 Nm engine load, the maximum suggested thermal efficiency was measured at 33.16%. In addition, relative to the baseline clean diesel fuel with a 100 ppm augmentation to B20 test fuel declined unburnthydrocarbon, CO, and soot by 41, 36.4, and 31.8%, correspondingly. The engine performance was enhanced by the MWCNT addition through an improvement in the in-cylinder combustion processes. The temperature of the in-cylinder gas rose as combustion enhanced. Consequently, when MWCNT additive fuels were used instead of neat diesel, greater NOx emissions were achieved.

The research investigates the impact of nanoadditive integration concentrations employing common gasoline on engine performance and exhaust emissions. By studying various fuel blends, including ternary blends with additives and quaternary blends, the aim is to promote sustainable energy reservoirs such as bio-ethanol and biodiesel while reducing reliance on fossil fuels and exhaust. The study delves into combustion, emissions, and performance attributes of different fuel blends, including D100, B100, and TF blends with varying levels of CNT additives. Additionally, the research explores the potential of alcohol-based fuel, biofuel, and crude vegetable oil as substitutes for fossil fuels, particularly diesel, emphasizing the need for higher replacement percentages and novel injection strategies like split injection with quaternary blends. The aim is to achieve a trade-off among emission reduction, controlled combustion, and performance characteristics, ultimately aiming to replace fossil fuel dependency with ternary and quaternary biofuel blends. The study focuses on single-cylinder CRDI engines and evaluates the potential of local biofuel resources. Key performance parameters such as brake thermal efficiency, specific energy consumption, emissions, and combustion characteristics are analyzed, providing insights into the feasibility of utilizing biofuel quaternary blends up to 40% to achieve lower NOx-smoke emissions. The outcomes of ternary and quaternary blends are compared and explained in the subsequent sections.

3. Research Methodology

This research explores the utilization of both ternary and quaternary blends in CRDI engine to reduce the diesel fuel dependency up-to 30-40% and emissions as well. Ternary blends, composed of bioethanol, carbon nanotube, diesel, and microalgae Chlorella vulgaris, feature a higher biofuel content (30-40%) replacing diesel, with diesel comprising 70-60% of the blend. Additionally, binary fuels with an 80-20% ratio of diesel to biodiesel were investigated, along with the effects of pure diesel and biodiesel.

In the quaternary blend methodology, diesel is paired with biofuels, including Mahua biodiesel, raw cottonseed oil, and n-butanol alcohol, with a similar emphasis on a higher biofuel content (30-40%) and variations in binary fuel ratios (50-50%). The study delves into the performance and emissions implications of these blends, offering insights into their feasibility and effectiveness as alternative fuels.

Table 1 and **Table 2** illustrate the volume percentage distribution of fuels in ternary and quaternary blends. Meanwhile, **Table 3** and **Table 4** present the diverse properties, including cetane number, viscosity, heating value, latent heat of vaporization, density, etc., for Diesel, Biodiesel, alcohol, as well as binary, ternary, and quaternary blends.

Table: 1 Ternary Blend Fuel %Volume Share

Fuel /TF (vol. %)	Diesel	MCV	BE	CNT(ppm)
D100	100	0	0	0
B100	100	0	0	0
D80B20	80	20	0	0
TF	60	20	20	0
TF25	60	20	20	25
TF50	60	20	20	50
TF100	60	20	20	100

MCV: Microalgae Chlorella Vulgaris BE: Bio-ethanol CNT: Carbon Nanotube

Table: 2 Quaternary Blend Fuel %Volume Share

Fuel /QB (vol. %)	Diesel	CSO	MB	n-Butanol
D100	100	0	0	0
D50B50	50	0	50	0
B100	0	0	100	0
QB1	60	5	25	10

Fuel /QB (vol. %)	Diesel	CSO	MB	n-Butanol
QB2	60	5	20	15
QB3	60	5	15	20
QB4	60	5	10	25
QB5	70	5	15	10
QB6	70	5	5	20

CSO: Cotton Seed Oil MB: Mahua Biodiesel QB: Quaternary Blend

Table: 3 Characteristics of Ternary Blends

Sample	Units	D100	B100	D80B20	TF	TF+25CNT	TF+50CNT	TF+100CNT
Density	kg/m^3	830	860	823	814	814	822	821
LHV	kJ/kg	10034	9645	9667	9213	9434	9504	9597
HHV	kJ/kg	10619	10230	10253	9799	10020	10090	10183
Flash Point	^0C	53	83	76	43	42	43	45
Fire Point	^0C	56	89	82	49	48	48	51
KinematicViscosity @40^{0}C	cSt	2.09	5.57	3.72	3.0	3.07	3.14	3.22
Dynamic Viscosity@40^{0}C	cSt	1.73	4.79	3.06	2.44	2.50	2.58	2.64
Cetane Number	-	47	52.7	49.25	48.3	48.6	48.8	48.9

Table: 4 Characteristics of Quaternary Blends

Sample	Units	QB1	QB2	QB3	QB4	QB5	QB6	B100	D50B50	D100
Density	kg/m^3	844	834	829	826	829	823	891	841	830
LHV	kJ/kg	9761	9527	9294	9178	9816	9644	9135	9411	10269
HHV	kJ/kg	10347	10113	9880	9764	10402	10230	9721	9997	10855
Flash point	^0C	42	34	32	40	39	30	161	59	53
Fire Point	^0C	46	37	35	43	42	32	172	65	55
Kinematic Viscosity	cSt	2.38	2.24	2.09	2.14	2.29	2.19	4.58	2.57	2.09
Cetane No	-	49.33	49.3	49.21	49.09	48.99	48.89	52	48.72	48

Experimental Set-up

The engine setup used for the experimentation is depicted in **Figure.1**. Single cylinder CRDI engine with 18 CR and a rated power of 5HP running at 1500 RPM was used. The prepared fuel blends were tested at 0, 4, 8, and 12 kg loads for analyzing the engine performance and combustion characteristics “ICEngine software" was used. All measurements are communicated into digital signals and the data was obtained from the ICEngine software, which were used for analyzing the results. Separately, AVL five gas analyzer were used for assessing the emissions parameters.

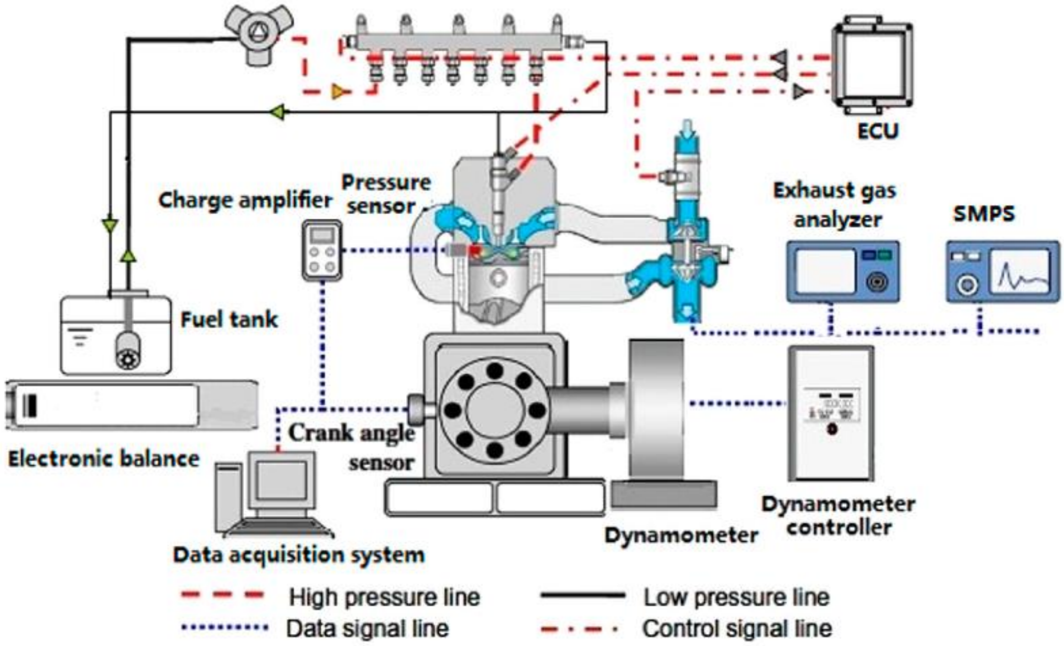


Figure: 1 CRDI diesel engine layout

4. Findings and Discussion

In the experimental analysis same CRDI engine was used for both the prepared blends such as ternary blends and quaternary blends. The engine was operated at varying loads (0, 4,8,12 kg) and at a rated power of 3.5kW @1500RPM.

Performance characteristics

From a performance perspective, the comparison between ternary and quaternary blends involved the consideration of Brake Thermal Efficiency, Brake Specific Fuel Consumption, and Exhaust Gas Temperature. The outcomes of this analysis are detailed in this section.

In the discourse on the ternary blend, BTE fluctuations were observed in **Figure: 2(a)**for D100, B100, and TF with 25ppm, 50ppm, and 100ppm CNT enhancers. Biodiesel had lower BTE than diesel at 100% load, improved marginally with bioethanol, and significantly with TF+100ppm CNT, surpassing diesel by 9%. CNTs' catalytic performance enhanced micro-explosion and evaporation, boosting BTE. **Figure: 3(a)**, BSFC at full load show higher values for D80B20, ternary fuel, and biodiesel than diesel, while TF+100ppm CNT exhibits the lowest BSFC at 0.3 Kg/kWhr[11], [12]. **Figure: 4(a)** illustrates EGT deviations, with D100 showing higher temperatures (292.4°C) due to oxygen presence, and TF+50ppm CNT & TF+100ppm CNT experiencing smaller temperatures (284°C), indicating improved combustion efficiency with CNT additives. Increased BTE with the inclusion of carbon nano tubes is in lined with the revealed discoveries [13].

In this section the use of quaternary fuels on the same CRDI engine and the observations recorded as drawn below. The BTE, specific energy utilization, and flue gas temperature parameters in a CRDI engine running at 3.5 kW with varying loads (0%, 33%, 66%, 100% of rated power at 1500 RPM). BTE exhibits a linear relationship with engine load, with QB3 and QB4 showing higher efficiencies at 34.3% and 33.6%, respectively. **Figure: 2(b)**indicates an 8.9% BTE improvement for QB3 and QB4 contrast to diesel and other blends, attributed to the lighter density of n-Butanol promoting better atomization and combustion[14]. QB3 and QB4 also report lower brake specific energy consumption can be seen from **Figure: 3(b)**, signifying efficient fuel utilization. Exhaust gas temperature (EGT) is lowest in QB3 and QB4 at 284°C**Figure: 4(b)**, attributed to increased latent heat of vaporization of alcohol fuel. All the emission parameters observed were found to be comparable to those in the investigation conducted by PrabhuAppavuet et al [15].

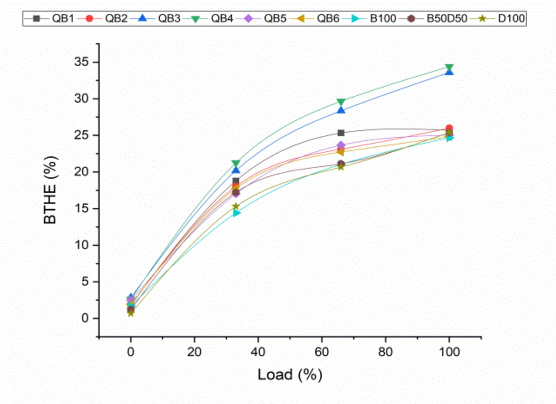


Figure: 2(a)

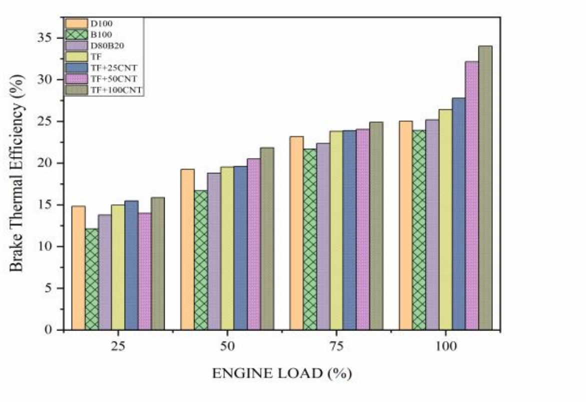


Figure: 2(b)

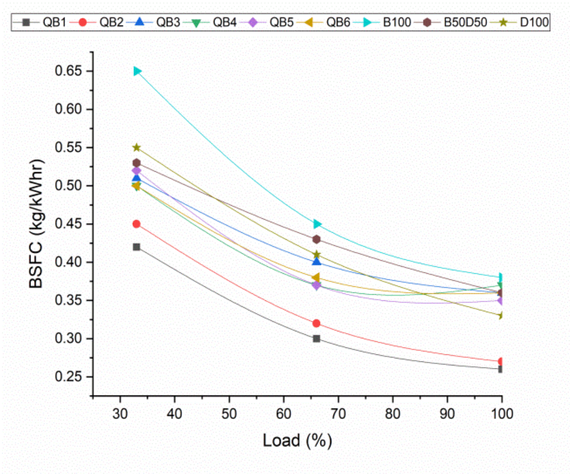


Figure: 3(a)

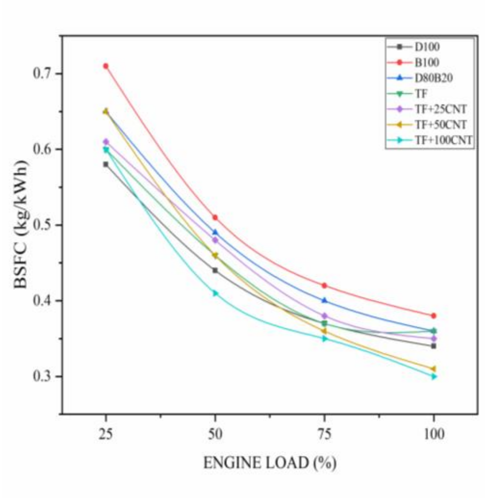


Figure: 3(b)

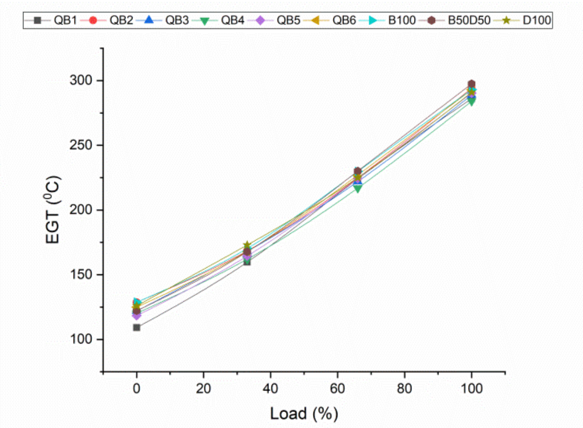


Figure: 4(a)

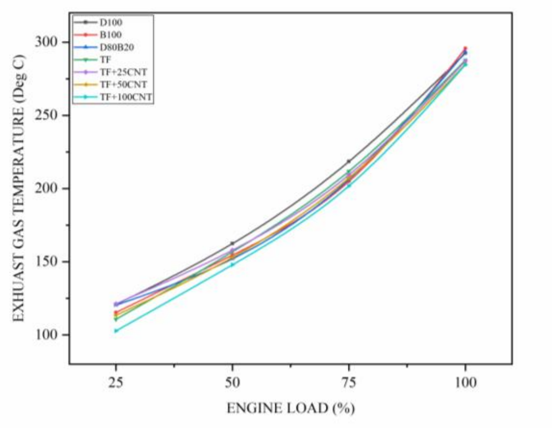


Figure: 4(b)

Emissions Characteristics

The **ternary blends**study reveals that, higher cetane number and oxygen content in the base fuel contribute to lower hydrocarbon (HC) emissions. B100, as raw fuel, reduces HC emissions at various engine loads compared to diesel. The addition of bioethanol in ternary fuel (TF) further decreases HC emissions, with TF+100ppm of carbon nanotubes (CNT) showing the most significant reduction[16]. Carbon nanotubes aid in better fuel atomization, combustion, and reduced HC pollutants Figure: 5(a). CO emissions decrease with load for all test blends, with TF emitting less CO than B100, and TF+100ppm of CNT exhibiting a 14% drop compared to diesel at full load Figure: 6(a)[17]. Additionally, TF reports higher NOx emissions due to elevated in-cylinder temperature and enhanced combustion, with TF+100ppm of CNT showing a 13.42% increase contrast to diesel. Employing nanoparticles contributes to increase in-cylinder temperature and higher cetane value but results in lower brake thermal efficiency and less NOx emissions; contrasting with the traditional belief that biodiesel enhances NOx emissions due to increased combustion temperature Figure: 7(a)[18].

The **Quaternary blends**study reveals that, increased n-butanol concentration in QB3 to QB6 led to higher unburnt hydrocarbon emissions, possibly due to an extended delay period and lower cetane number. QB1 and QB2 exhibited emissions more closely aligned with diesel fuel, attributed to their n-butanol ratio. QB2 at part load showed the least HC, likely due to a balanced blend of mahua biodiesel and n-butanol, providing sufficient oxygen for combustionFigure: 5(b).CO emissions decrease with load for all test blends as seen fromFigure: 6(b). QB2 and QB4 disclosed higher NOx emissions, indicating that a higher mahua blend concentration reduced NOx emissions, possibly due to lower combustion chamber temperature and pressureFigure: 7(b). Smoke emissions were minimal in QB fuels, with QB2-QB6 showing almost zero smoke opacity owing to the elevated proportion of n-butanol. Overall, the study's findings align with similar investigations in the literature[14], [15].

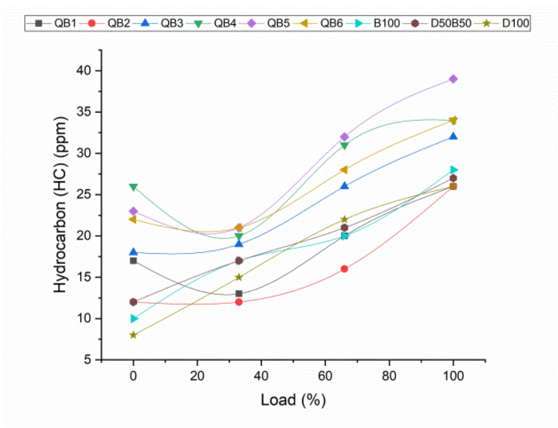


Figure: 5(a)

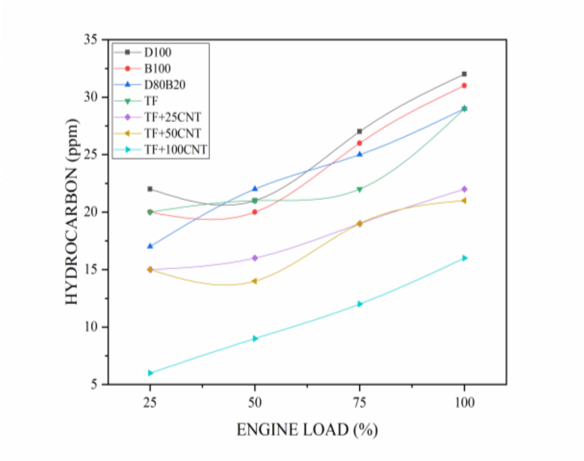


Figure: 5(b)

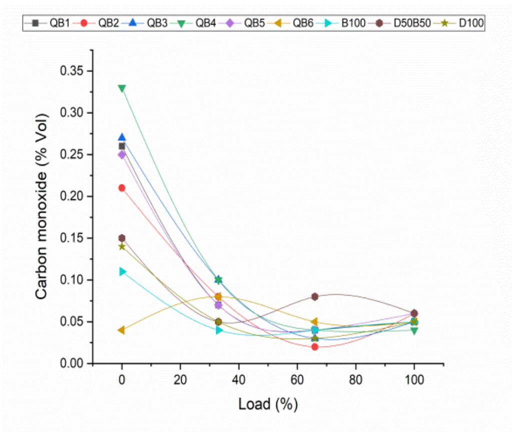


Figure: 6(a)

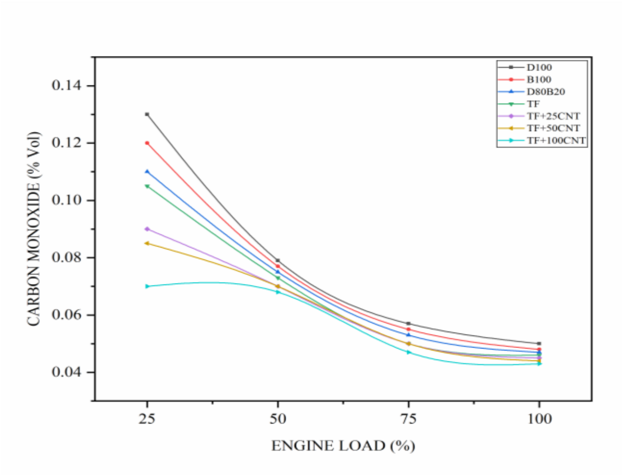
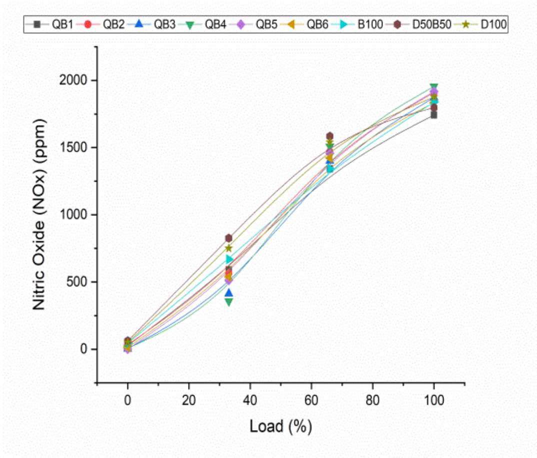


Figure: 6(b)



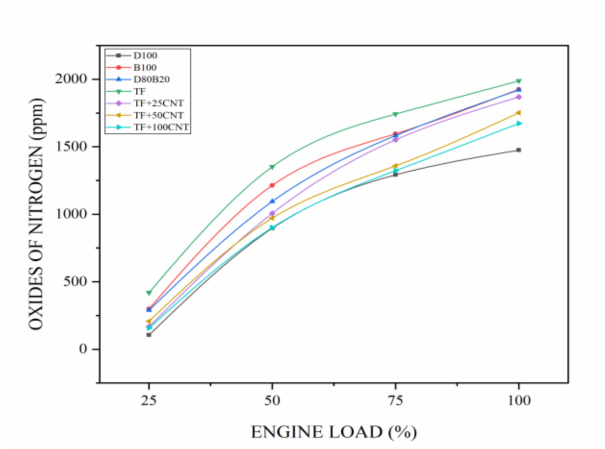


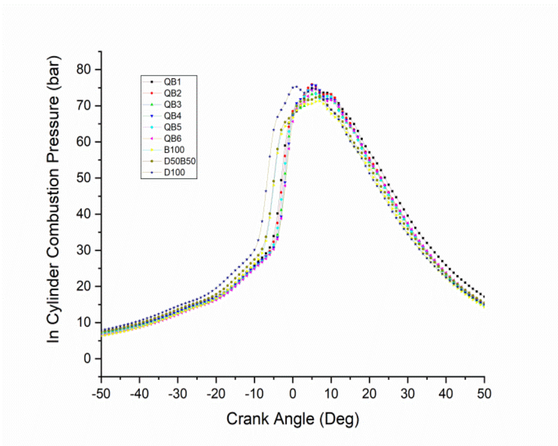
Figure: 7(a)

Figure: 7(b)

Combustion Characteristics

Combustion behavior of **ternary blend** fuel had the highest pressure (77.1bar) at full load, CNT additives increased pressures (TF+50ppm: 76.7bar, TF+100ppm: 76.63bar) due to improved thermal conductivity. Figure 8(a).TF100CNT had the highest peak pressure (76.63bar), D100 the lowest (75.71bar), TF had the highest, and diesel had the lowest pressure. Higher nanoparticle concentrations led to increased peak HRR; TF100CNT, TF, and TF50CNT outperformed with peak HRR of 53.34, 53.31, and 53.03 J°/CA, respectivelyFigure 9(a). Diesel blends had lower HRR. TF100CNT achieved the highest HRR due to enhanced heat transfer and ignition performance [11], [19].

In the context of **quaternary blends** the combustion study explores in-cylinder pressure, net heat release Figure 8(b) and Figure 9(b). QB2 and D100 exhibit the highest combustion pressure at 76 bar . Atomization and spontaneous combustion influence chamber pressure and flame temperature. QB1, QB2, and D100 reach maximum mean gas temperatures of 1469 to 1540^{0}C. QB3 shows lower pressure and temperature (68 bar, 1276^{0}C) possibly due to higher alcohol concentration. QB3 reports the least combustion noise, attributed to more n-butanol and biodiesel, acting as a cooling fluid in combustion[20], [21].



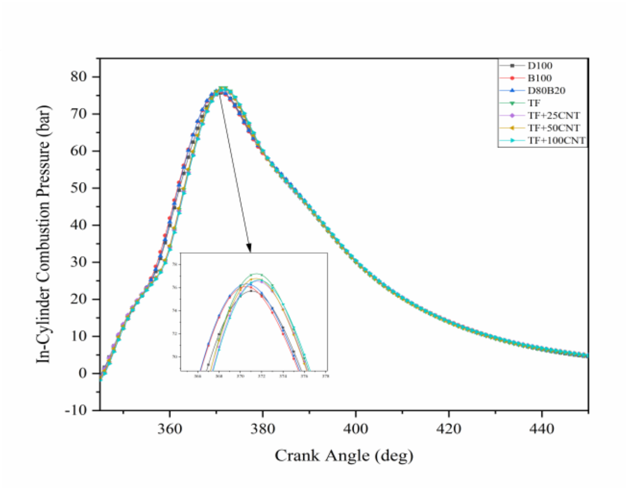


Figure: 8(a)

Figure: 8(b)

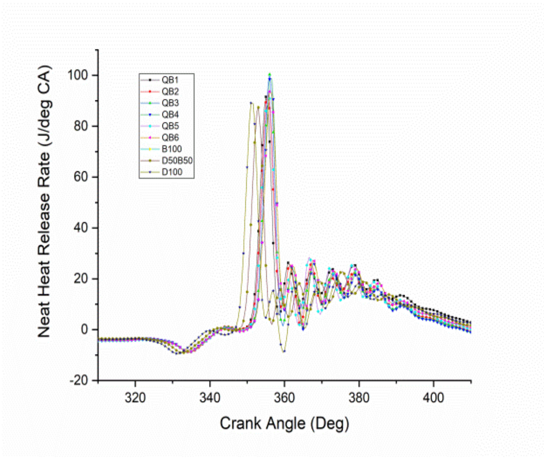


Figure: 9(a)

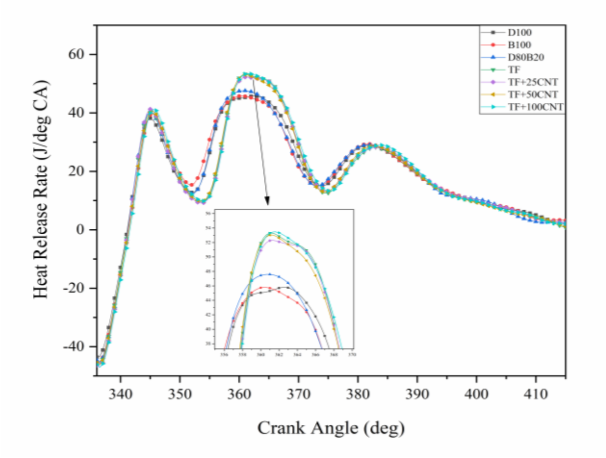


Figure: 9(b)

5. Conclusion

The experimental investigation on **Ternary blends**, combining diesel, microalgae biodiesel, and bioethanol with carbon nanotubes (CNT), revealed improved engine performance. The addition of CNT enhanced calorific value and cetane number, resulting in increased Brake Thermal Efficiency (BTE) and reduced emissions. Specifically, TF+100ppm of CNT blend exhibited the highest BTE increment (9%) and substantial decreases in smoke opacity, HC, and CO emissions. Controlled combustion, shorter in-cylinder pressure, and improved combustion efficiency were observed with CNT addition. Overall, the CRDI engine fuelled with ternary fuel and 100ppm CNT blend demonstrated superior efficiency and emissions reduction compared to traditional diesel.

In the case of **Quaternary blends**, incorporating Mahua biodiesel and n-butanol, up to 15% and 20% respectively, resulted in outstanding performance, with QB3 (D60C5MB15Bu20) showcasing the highest relative Brake Thermal Efficiency (BTHE) increase. These blends achieved lower emissions, especially QB3, which demonstrated controlled combustion and reduced NOx-soot emissions. Notably, the quaternary blends, QB2, QB3, and QB4, outperformed other blends and D100 in terms of efficiency, combustion, and emissions characteristics. In summary, both ternary and quaternary blends, with tailored additives or biofuel combinations, exhibit significant promise for improving engine efficiency and reducing emissions compared to traditional diesel fuels.

In summary, both ternary and quaternary blends, with the incorporation of specific additives or biofuel combinations, showcase potential for enhanced engine performance, improved efficiency, and reduced emissions, offering promising alternatives to traditional diesel fuels.

Further Research

Ternary Blends

1. Investigate other emissions (CO_2, particulate matter, Toluene, Acetaldehyde, Acetone, and Formaldehyde) for a comprehensive analysis.
2. Explore further emission reduction by modifying engine components (nozzle, piston geometry) and adjusting injection timing, pressure, and exhaust gas recirculation.
3. Conduct tribology analysis on the same fuel blends for enhanced understanding.

Quaternary Blends

1. Study the impact of Exhaust Gas Recirculation for additional NOx reduction.
2. Explore split fuel injection strategies to optimize performance further.

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