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PERFORMANCE EVALUATION OF A VARIABLE COMPRESSION RATIO ENGINE OPERATING ON ALGAE AND CALOPHYLLUM INOPHYLLUM OIL BLENDS WITH TITANIUM DIOXIDE NANO-ADDITIVES

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Research into biodiesel-based fuels for diesel engines has accelerated due to the growing need for sustainable fossil fuel substitutes. The combustion and emission properties of a hybrid biodiesel made from algal oil and *Calophyllum inophyllum* oil that has been converted into methyl esters are examined in this study. In order to enhance combustion efficiency, titanium dioxide (TiO_2) nanoparticles have been employed as nano-additives. A single-cylinder, four-stroke, water-cooled, variable compression ratio (VCR) diesel engine had been employed for the experiments under different load conditions like $3\ Kg$ to $12\ Kg$ along with compression ratio 16 and 18. Hybrid biodiesel blends B10, B15, B20, B25, B30, and B35 were used to run the engine, and the outcomes were contrasted with traditional diesel fuel. Combustion analysis revealed that the B25 blend for $12\ Kg$ load and compression ratio 18 delivered an improvement in brake power of about 6% and an 8% decrease in brake-specific fuel usage when measured against diesel. Analyses of emissions revealed notable 5% decreases in carbon dioxide (CO_2), while nitrogen oxide (NO_x) emissions exhibited only a marginal reduction of 1%. These findings show that a suitable low-emission substitute fuel for VCR diesel engines is TiO_2 nano-additive-assisted hybrid biodiesel.

Key words: Algae oil, *Calophyllum Innophyllum* oil, TiO_2 nano-additives, Exhaust emission characteristics, VCR diesel engine.

1. Introduction

The increasing worldwide demand for energy, quick exhaustion of fossil fuel supplies, and stringent emission regulations have intensified research efforts toward sustainable and environmentally benign alternative fuels for diesel engines. Biodiesel produced from renewable and non-edible feedstock's has become a promising substitute for standard diesel because it disintegrates naturally, diminished toxicity, and potential to lower greenhouse gas emissions. However, the widespread application of biodiesel is constrained by inherent limitations such as higher viscosity, lower calorific value, poor volatility, and altered combustion characteristics, which often result in reduced engine performance and increased nitrogen oxide (NO_x) emissions when compared to mineral diesel [1-3].

Among various biodiesel sources, algae-based biodiesel has attracted considerable interest owing to its high lipid productivity, rapid growth rate, non-competition with food crops, and capability to utilize wastewater and carbon dioxide during cultivation [4-6]. Experimental studies have demonstrated that algae biodiesel blends can significantly reduce carbon monoxide (CO), unburnt hydrocarbons (HC), and smoke emissions in CI engines due to their inherent oxygen content, although a moderate increase in NO_x emissions is frequently reported [7]. Similarly, *Calophyllum inophyllum*, a non-edible oilseed crop abundantly available

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in tropical regions, has been identified as a viable biodiesel feedstock due to its favourable cetane number and good lubrication properties [8]. Nevertheless, the relatively high density and viscosity of *Calophyllum inophyllum* biodiesel adversely affect spray atomization and combustion efficiency, necessitating fuel modification strategies for improved engine performance [9-10].

Recent developments in nanotechnology have offered effective approaches to address the limitations associated with biodiesel fuels. The incorporation of metal oxide nano-additives such as titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), zinc oxide (ZnO), and iron oxide (Fe_3O_4) into biodiesel blends has been shown to enhance combustion efficiency by improving fuel atomization, promoting micro-explosion phenomena, accelerating oxidation reactions, and enhancing heat transfer within the combustion chamber [11-16]. Among these additives, TiO_2 nanoparticles have gained significant attention due to their high surface area, thermal stability, oxygen buffering capability, and catalytic activity, resulting in improved brake thermal efficiency (BTE) and reduced exhaust emissions [17]. Nachippan *et al.* [18] and Mylapalli *et al.* [19] demonstrated that data-driven models can accurately predict engine performance and emission characteristics, reducing experimental complexity. Comprehensive review studies have further emphasized the growing integration of nanotechnology, optimization methods, and advanced modeling approaches in biodiesel engine research [20-23].

A critical review of the existing literature reveals that although algae biodiesel and *Calophyllum inophyllum* biodiesel have been widely investigated as individual alternative fuels, and titanium dioxide (TiO_2) nano-additives have consistently shown improvements in engine performance and emission characteristics, studies integrating these three aspects remain scarce. In particular, there is a noticeable lack of systematic experimental investigations on hybrid blends of algae and *Calophyllum inophyllum* biodiesel enhanced with TiO_2 nano-additives in a variable compression ratio (VCR) diesel engine. This gap highlights the need for a comprehensive study that examines the combined effects of hybrid biodiesel blends and nano-additives under varying compression ratios. Therefore, the present work aims to address this research gap by evaluating the performance characteristics of a VCR diesel engine fueled with algae *Calophyllum inophyllum* biodiesel blends incorporated with TiO_2 nano additives.

2. Materials and methods

2.1. Facility for experiments

The field trial was carried out at Apex Innovations Pvt. Ltd., Sangli, Maharashtra, India, utilized a four-stroke, single-cylinder, cooled by water ignition compression diesel engine that operated steadily. The engine was suitably modified to operate with variable compression ratio (VCR) to evaluate the performance of different fuel blends. Standard diesel (B00) was used as the reference fuel for comparison. The test fuels included hybrid biodiesel blends made from *Calophyllum inophyllum* oil methyl ester and algal oil methyl ester mixed in different ratios with diesel.

2.2. Hybrid biodiesel preparation

The high viscosity and low volatility of raw plant-based oils prohibit their direct use in diesel engines, which may lead to injector fouling, carbon deposition, and lubricating oil dilution. Several viscosity reduction techniques such as pyrolysis, micro-emulsification, dilution, and transesterification have been reported in the literature. Transesterification is the most popular and fiscally feasible of these processes since it effectively produces fuel with characteristics similar to those of traditional diesel.

In the present work, hybrid biodiesel was produced via transesterification, wherein algal oil and *Calophyllum inophyllum* oil were separately converted into their respective methyl esters using alcoholysis in the presence of a suitable catalyst. An excess amount of alcohol was used to drive the equilibrium reaction toward ester formation, resulting in reduced viscosity and improved fuel properties suitable for CI engine operation. The produced methyl esters were subsequently blended in appropriate proportions to form a hybrid biodiesel.

2.3. Preparation of nano-enhanced fuel blends

Commercially available titanium dioxide (TiO_2) nanoparticles were procured from nano research lab, Gopalpur, Jharkhand, India. TiO_2 nanoparticles were added to the hybrid biodiesel blends at a concentration of $0.5\ wt.\%$, measured using an atom-scale digital balance. The nanoparticles were dispersed uniformly in the fuel blends to ensure stability and homogeneity prior to engine testing. TiO_2 nanoparticles were chosen because of their large surface area, robust thermal stability, efficient catalytic activity, and capacity to store oxygen, all of which enhance combustion efficiency and reduce exhaust emissions. The addition of TiO_2 is known to promote improved oxidation of carbonaceous particles and assist in NO_x reduction without adversely affecting fuel stability or engine components.

2.3.1. Nano-particle mixing process

The addition of nano-additives to biodiesel enhances fuel properties such as combustion efficiency, stability, and emission reduction. Suitable nano-additives (e.g., cerium oxide, aluminium oxide, or carbon nanotubes) are selected based on the desired outcome and added in small concentrations for $10\ ppm$. The nanoparticles are first dispersed in biodiesel or a solvent with a surfactant to prevent agglomeration, followed by ultra-sonication or mechanical stirring to achieve uniform dispersion. The prepared suspension is then blended with biodiesel (e.g., B10 to B35) and thoroughly mixed. The blend is allowed to stabilize for 24 hours to assess sedimentation; if instability occurs, further dispersion or improved surfactants may be required. Once a stable blend is obtained, it is evaluated for fuel properties (viscosity, density, cetane number), combustion characteristics, engine performance, and emission behaviour. Proper safety measures, including the use of personal protective equipment and adequate ventilation, must be followed throughout the process.

2.4. Fuel blend formulation

The prepared hybrid biodiesel was mixed with diesel fuel to obtain different blends, namely B10, B15, B20, B25, B30, and B35, where the numeral represents the volumetric percentage of hybrid biodiesel in diesel. Fig.1 shows The detailed blend compositions included B10 (10% hybrid biofuel and 90% diesel) in Fig.1(a), B15 (15% hybrid biofuel and 85% diesel) in Fig.1(b), B20 (20% hybrid biofuel and 80% diesel) in Fig.1(c), B25 (25% hybrid biofuel and 75% diesel) in Fig.1(d), B30 (30% hybrid biofuel and 70% diesel) in Fig.1(e), and B35 (35% hybrid biofuel and 65% diesel) in Fig.1(f).

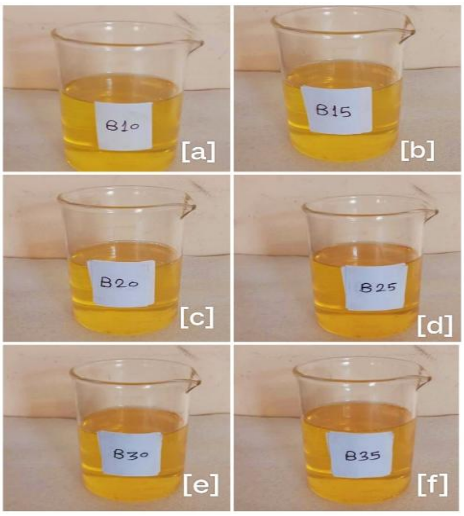


Fig.1. Different blends of hybrid methyl ester.

2.5. Fuel property analysis

The chemical and physical properties of each test fuel were determined using standard testing protocols. These characteristics included density, kinematic viscosity, dynamic viscosity, flash point, fire point, lower calorific value (LCV), and higher calorific value (HCV). The measured properties of diesel (B00) and nano-enhanced hybrid biodiesel mixtures are summarized in Table 1. Figure 2 presents the variation of fuel properties with improving hybrid biodiesel content. It was observed that the density increased by 4.36%, when LCV and HCV lowered by 9.86% and 9.33%, respectively, from B00 to B35. The flash point and fire point increased by 19.69% and 20%, respectively, indicating enhanced fuel safety. Additionally, kinematic and dynamic viscosities increased by 69.62% and 70.82%, respectively, with higher biodiesel concentration, attributed to the combined effect of biodiesel content and TiO_2 nanoparticle dispersion.

Table 1. Blends chemical and physical properties.

Blends sample	Density ρ $\left[\frac{kg}{m^3}\right]$	LCV $\left[\frac{cal}{g}\right]$	HCV $\left[\frac{cal}{g}\right]$	Flash point $[°C]$	Fire point $[°C]$	Kinematic viscosity ν $[cSt]$	Dynamic viscosity μ $[cP]$
B00	*825*	*10235*	*10821*	*53*	*56*	*2.09*	*1.73*
B10	*833*	*9826*	*10412*	*57*	*63*	*3.93*	*3.27*
B15	*840*	*9761*	*10347*	*58*	*63*	*4.59*	*3.86*
B20	*845*	*9502*	*10088*	*60*	*64*	*5.01*	*4.24*
B25	*851*	*9341*	*9927*	*61*	*68*	*5.74*	*4.88*
B30	*855*	*9203*	*9789*	*63*	*69*	*6.34*	*5.42*
B35	*861*	*9225*	*9811*	*66*	*70*	*6.88*	*5.93*

(a)

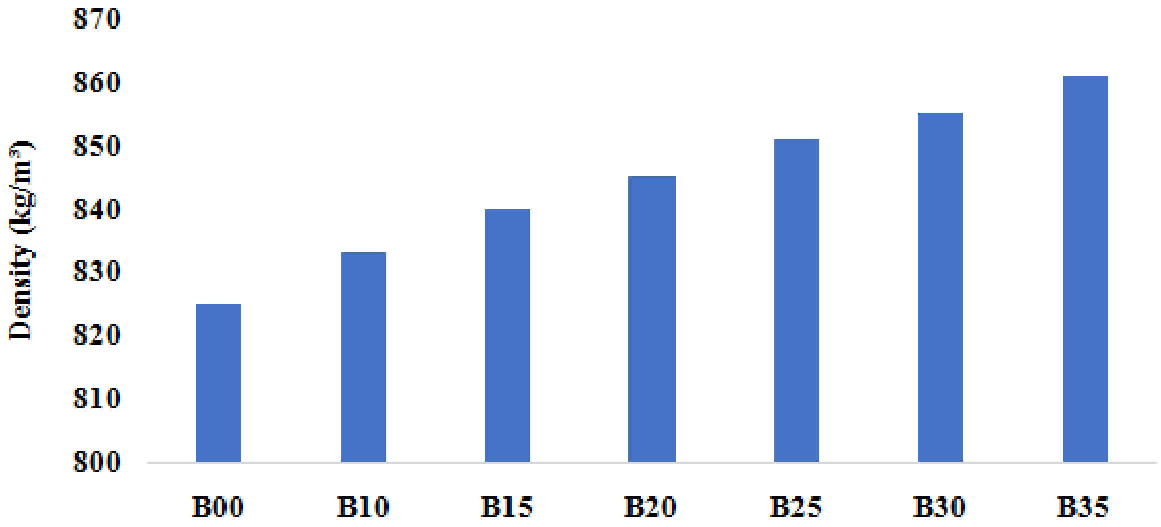


Fig.2. Properties with different blends of hybrid methyl ester: (a) density, (b) lower CV, (c) higher CV, (d) flash point, (e) fire point, (f) kinematic viscosity, (g) dynamic viscosity.

(b) (c) (d)

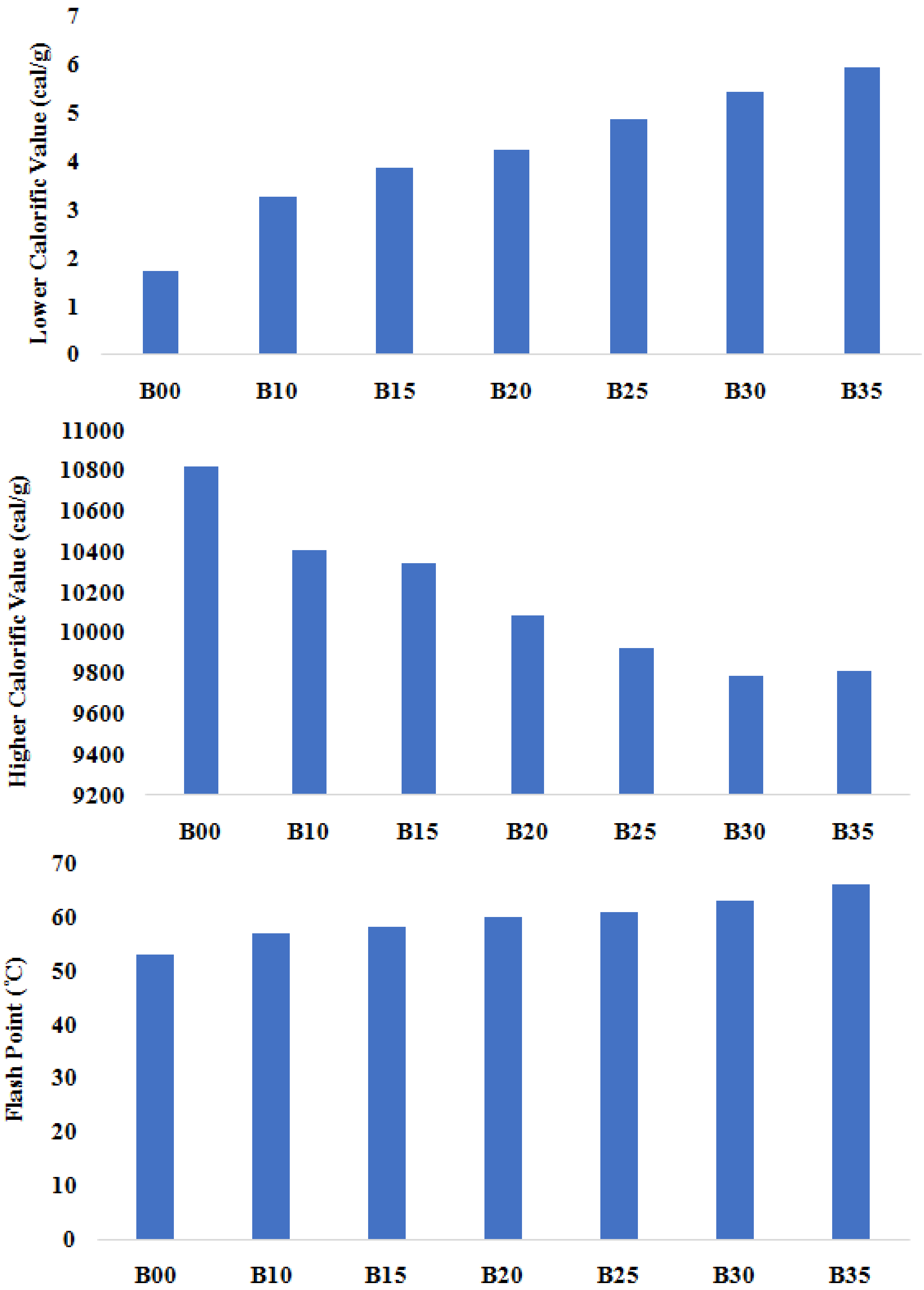


Fig.2 cont. Properties with different blends of hybrid methyl ester: (a) density, (b) lower CV, (c) higher CV, (d) flash point, (e) fire point, (f) kinematic viscosity, (g) dynamic viscosity.

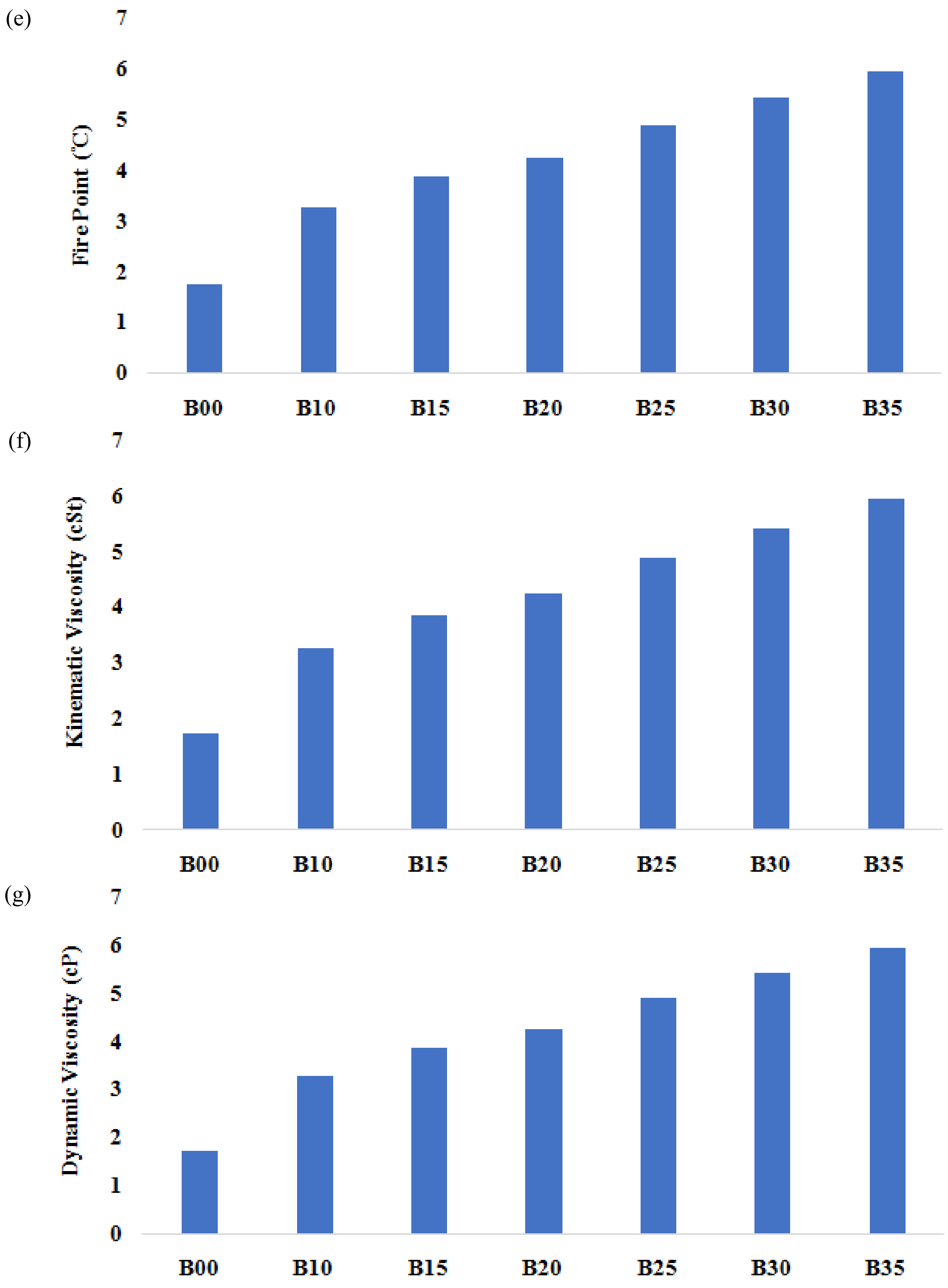


Fig.2 cont. Properties with different blends of hybrid methyl ester: (a) density, (b) lower CV, (c) higher CV, (d) flash point, (e) fire point, (f) kinematic viscosity, (g) dynamic viscosity.

3. Experimentation

The experimental test rig used for the experimental trails is shown in Figs 3(a) and 3(b). The detail engine specifications are mention in Table 2. A 4-stroke, single-cylinder, cooled by water VCR CI engine with a $3.5\ kW$ power rating powers the experimental test setup. Figure 3(c) illustrates the compression ratio setting and Fig.3(d) presents tilting block arrangement of engine. Experimental conditions include a compression ratio between 16 and 18, a constant speed of $1500\,rpm$ and a load ranging from 3 to $12\ Kg$. Various engine performance parameters, including BSFC, BTE, BP, and mechanical efficiency (ME), were evaluated during experimentation, and emission characteristics, include CO_2, NO_x, and EGT, are analyzed. Figure 3(d) shows an image of the tilting cylinder block on the engine cylinder. This arrangement enables the engine to function as a variable compression ratio (VCR) engine, allowing the CR to be adjusted to a desired value within a specific range without changing the combustion chamber geometry and without stopping the engine.

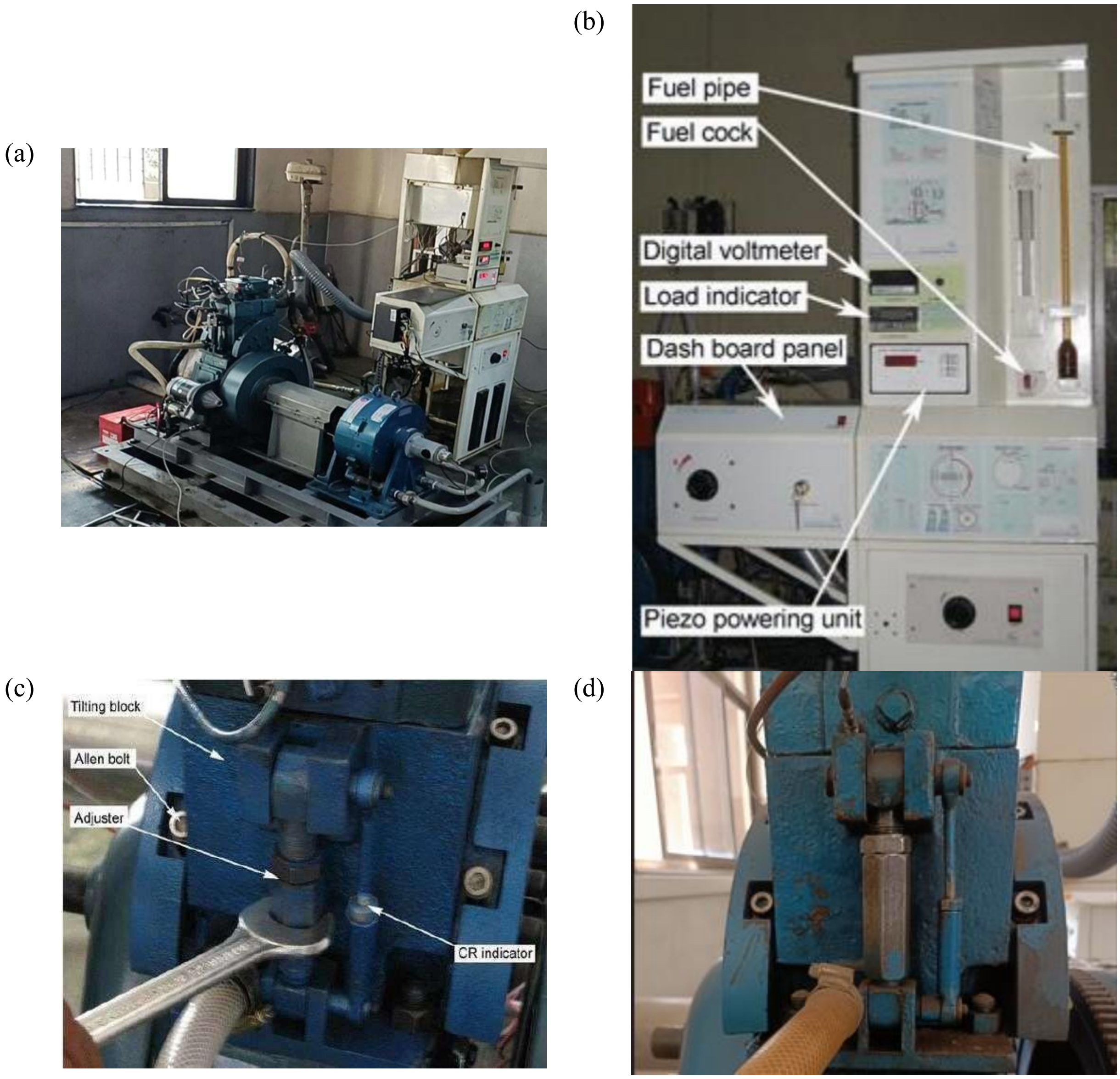


Fig.3. Details of test rig: (a) VCR diesel engine, (b) front panel of VCR diesel engine, (c) compression ratio setting, (d) tilting block arrangement.

Table 2. Engine specifications.

Manufacturer	M/s Kirloskar Oil Engines Ltd.
Model	TV 1
Cycle	4 Strokes
Rated power	$3.5\,kW$ @ $1500\,rpm$
Type of combustion system	Direct injection
No. of cylinders	1 Cylinder
Bore/Stroke	$87.5\,/\,110\ mm$
Compression ratio	$17.5:1$ modified to VCR 12 to $18:1$
Swept volume	$0.661cc$
Type of cooling	Water cooled
Fuel injection	Inline

Fig.4. Exhaust gas analyse.

The emission monitoring system, which includes an exhaust gas analyzer (AVL India Pvt Ltd, Gurgaon, India), is used to measure the components of exhaust gas. The CO_2, NO_x, and EGT components of exhaust gases are measured by the exhaust gas analyzer. Figure 4 displays a picture of the exhaust gas analyzer that was used in the demonstration.

3.1. Uncertainty analysis

Measurement uncertainty was evaluated to ensure the reliability of experimental results. The overall uncertainty was calculated using the root sum square (RSS) method by combining the uncertainties of individual measured parameters. RSS equation expressed as:

$$U = \sqrt{\left(u_1^2\right) + (u_2^2) + (u_3^2) + \ldots + (u_n^2)}\,, \tag{3.1}$$

where $u_1, u_2, \ldots, u_n$ represent the individual uncertainties associated with each measured parameter. The uncertainties of key instruments were: load $(\pm 0.5\%)$, speed $(\pm 1\ rpm)$, fuel consumption $(\pm 1\%)$, temperature $(\pm 1°C)$, CO_2 $(\pm 0.02\%)$, and NO_x $(\pm 10\ ppm)$. Based on these, the estimated uncertainties for derived parameters were: brake thermal efficiency $(\pm 2.1\%)$, brake specific fuel consumption $(\pm 2.5\%)$, brake power $(\pm 1.5\%)$, and mechanical efficiency $(\pm 2.0\%)$. These low uncertainty values indicate that the experimental results are reliable and within acceptable limits.

4. Result and Discussion

Using hybrid biodiesel blends, the variable compression ratio (VCR) diesel engine's performance and emission characteristics were assessed experimentally and contrasted with baseline diesel (B00). An AVL exhaust gas analyzer was used to measure exhaust emissions, and a computerized data gathering system was used to get engine performance parameters. With a focus on full load operation, the analysis was conducted across the whole load range at compression ratios (CR) of 16 and 18.

4.1. Performance characteristics

This section discusses the engine analytical characteristics, such as BTE, BSFC, BP, and mechanical efficiency (ME) at compression ratios 16 and 18.

4.1.1. Brake thermal efficiency

The change in brake thermal efficiency (BTE) when the engine is operating at compression ratios of 16 and 18, respectively, is depicted in Figs 5-6. Improved combustion efficiency and decreased heat losses at greater loads caused BTE to rise for all fuels. At CR 16, all biodiesel blends except B35 exhibited higher BTE than diesel at full load. Among the tested fuels, B25 achieved the highest BTE of 30.48%, compared to 26.62% for diesel. This improvement is attributed to the enhanced oxygen availability of biodiesel combined with the catalytic activity of TiO_2 nanoparticles, which promoted faster and more complete combustion. At CR 18, diesel recorded the maximum BTE of 35.00% owing to higher in-cylinder pressure and temperature. Among the biodiesel blends, B20 showed the highest BTE of 29.35%, followed by B25 (29.15%). Fuel atomization was negatively impacted by higher blend ratios (B30 and B35), which led to decreased BTE because of increased viscosity and a lower calorific value. Comparative observation shows that, moderate biodiesel blends $(20-25\%)$ exhibited optimum thermal efficiency, while higher compression ratio favoured diesel fuel.

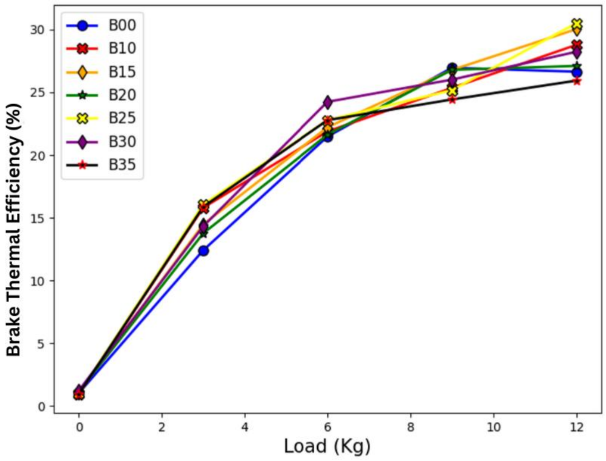


Fig.5. Variation of brake thermal efficiency with load for CR 16.

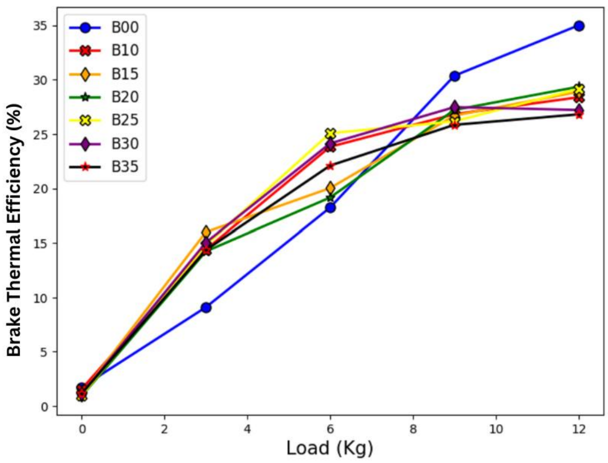


Fig.6. Variation of brake thermal efficiency with load for CR 18.

4.1.2. Brake specific fuel consumption (BSFC)

Brake specific fuel consumption (BSFC) at CR 16 and CR 18 varies with load, as seen in Figs 7-8, respectively. For all test fuels, BSFC dropped as load increased, which is in line with higher loads resulting in better combustion efficiency. At CR 16, blends B10, B15, and B25 exhibited lower BSFC than diesel, with B15 recording the minimum BSFC of $0.29\,\frac{kg}{kWh}$. This behaviour is explained by biodiesel's greater oxygen concentration and TiO_2 nanoparticles' ability to promote burning, which offset the lower heating value of biodiesel. At CR 18, BSFC values for blends B10-B25 were comparable to diesel, with a minimum value of $0.31\,\frac{kg}{kWh}$, while B35 exhibited the highest BSFC of $0.34\,\frac{kg}{kWh}$. Increased compression ratio enhanced fuel evaporation and reduced ignition delay, thereby minimizing differences between diesel and biodiesel blends. From Comparative observation it revils that, blends containing up to *25%* biodiesel demonstrated competitive fuel economy, while higher biodiesel content resulted in increased BSFC.

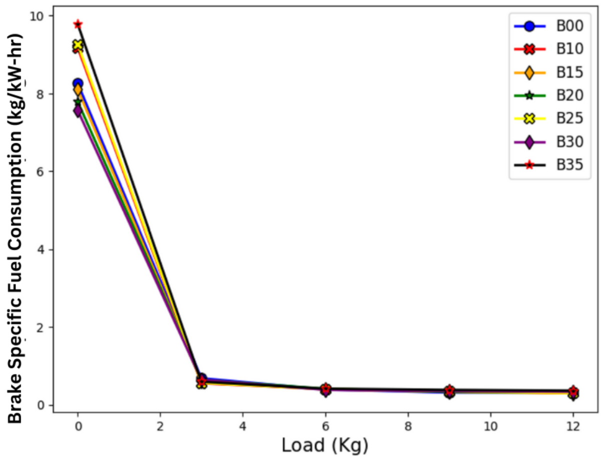


Fig.7. Variation of BSFC with load for CR 16.

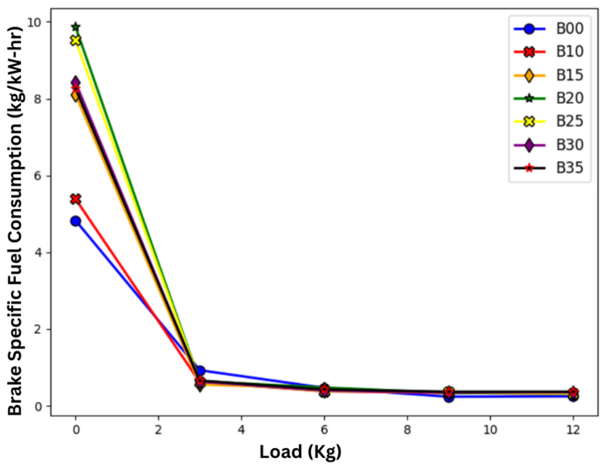


Fig.8. Variation of BSFC with load for CR 18.

4.1.3. Braking power (BP)

Figures 9-10 illustrate how the brake power varies with load at CR 16 and CR 18, respectively.

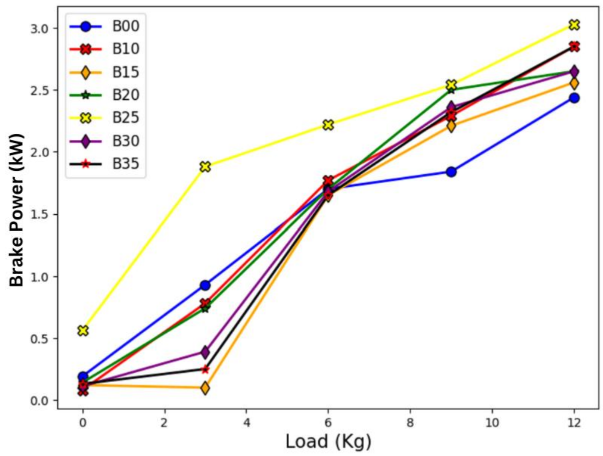


Fig.9. Variation of brake power with load for CR 16.

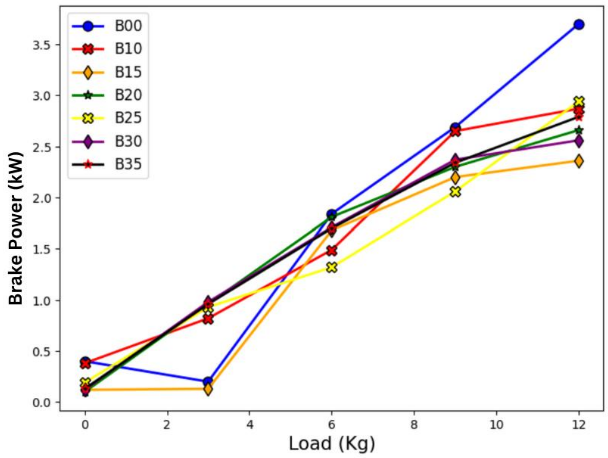


Fig.10. Variation of brake power with load for CR 18.

For every test fuel, brake power climbed linearly with load. At CR 16, B25 produced the highest brake power of $3.03\ kW$, exceeding diesel $(2.44\ kW)$. This improvement is ascribed to increased combustion efficiency brought about by the complementary action of TiO_2 nano-additives and hybrid biodiesel. At CR 18, diesel produced the maximum brake power of $3.70\ kW$. Among biodiesel blends, B25 $(2.94\ kW)$ and B10 $(2.87\ kW)$ delivered brake power values closest to diesel. Higher blend ratios exhibited reduced brake power due to increased viscosity and reduced heating value. From the results it is found that, B25 emerged as the most suitable blend for maximizing brake power at both compression ratios.

4.1.4. Mechanical efficiency (ME)

The change in mechanical efficiency with load at CR 16 and CR 18 is illustrated in Figs 11-12, respectively. The greatest mechanical efficiency, 60.35%, was attained by B25 at CR 16, which was just slightly greater than that of diesel (60.24%). Improved combustion smoothness and reduced frictional losses contributed to this behavior. At CR 18, diesel exhibited significantly higher mechanical efficiency (71.15%) due to enhanced combustion pressure. Among biodiesel blends, B10 showed the highest mechanical efficiency of 60.04%, whereas B30 recorded the lowest value due to increased viscous losses. Experimental results show that, Lower biodiesel blends performed better in terms of mechanical efficiency, particularly at higher compression ratio.

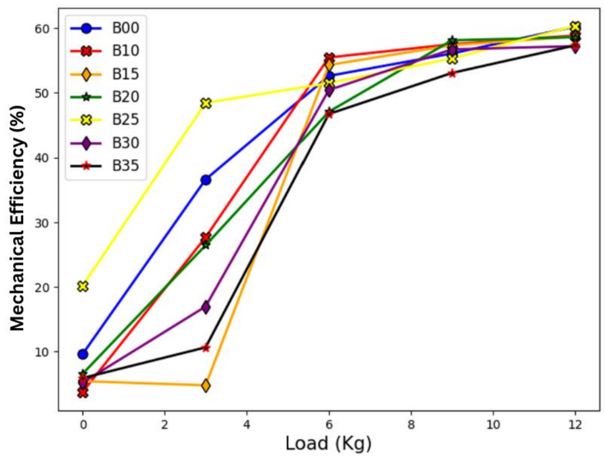


Fig.11. Variation of mechanical efficiency with load for CR 16.

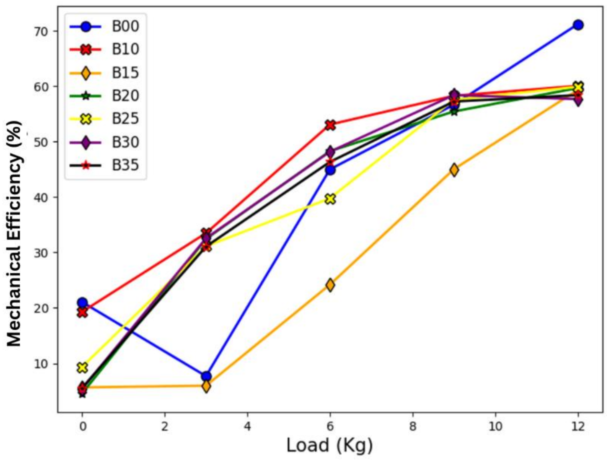


Fig.12. Variation of mechanical efficiency with load for CR 18.

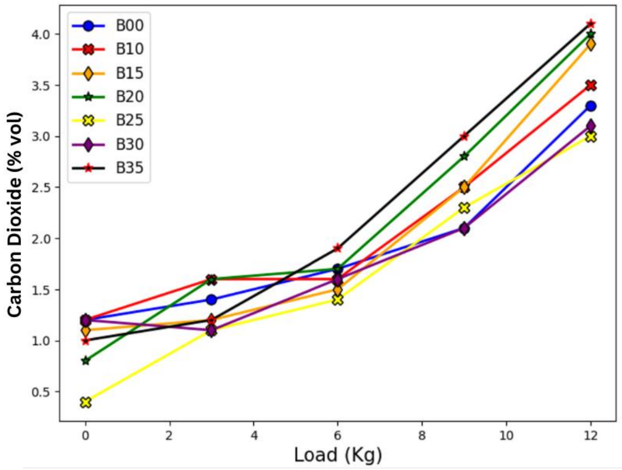
4.2. Emission characteristics

The emission characteristics of exhaust system of engine like CO_2, NO_x, EGT at compression ratio 16 and 18 are measured by exhaust gas analyzer and results are discussed below.

4.2.1. Carbon dioxide emissions

Figures 13-14 shows the variation of carbon dioxide (CO_2) emissions at CR 16 and CR 18 under full-load conditions. CO_2 emissions serve as an indicator of combustion completeness. At CR 16, B25 exhibited the lowest CO_2 emission of 3.0%, while B35 recorded the highest value of 4.1%. At CR 18, B30 demonstrated the lowest CO_2 emission of 2.8%, whereas B20 showed the highest emission of 4.4%.

Comparative observation shows that, moderate biodiesel blends achieved improved combustion efficiency with lower CO_2 emissions compared to higher blend ratios.



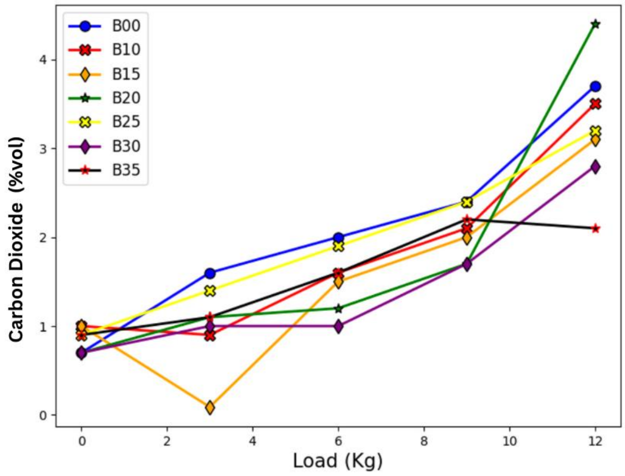
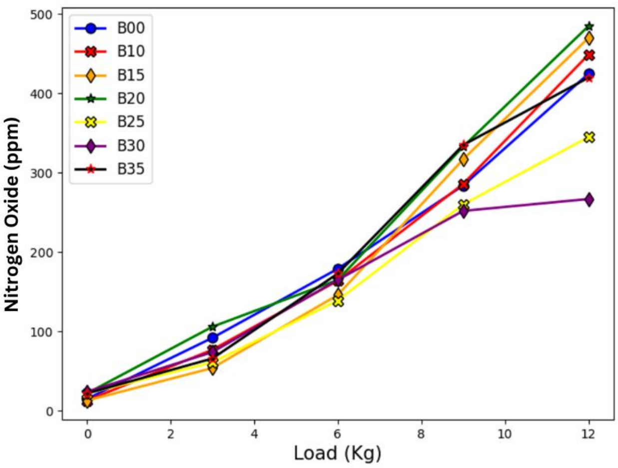


Fig.13. Load with carbon dioxide (CO_2) for CR 16. Fig.14. Load with carbon dioxide (CO_2) for CR 18.

4.2.2. Nitrogen oxides emissions

Nitrogen oxide (NO_x) emissions at CR 16 and CR 18 are shown in Figs 15-16.



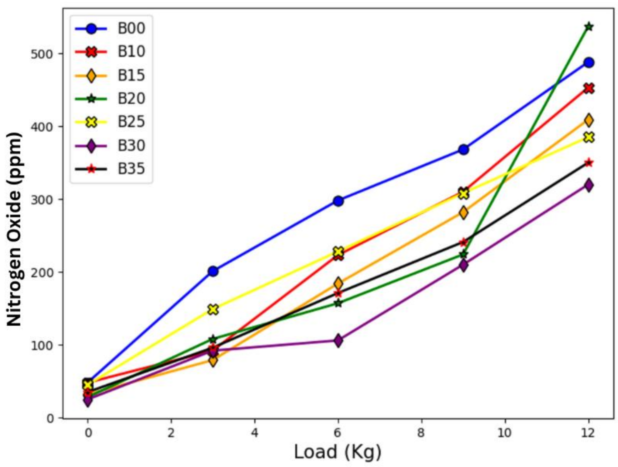


Fig.15. Load with nitrogen oxides (NO_x) for CR 16. Fig.16. Load with nitrogen oxides (NO_x) for CR 18.

Peak in-cylinder temperature and oxygen availability have a significant impact on NO_x productionB20 reported the highest NO_x emission at CR 16, at $485\ ppm$, while B30 produced the least amount of pollutants, at $267\ ppm$. At CR 18, overall NO_x levels increased due to elevated combustion temperature; however, B35 exhibited the lowest NO_x emission of $311\ ppm$, while B20 again showed the maximum value of $537\ ppm$. The cooling impact of biodiesel and the NO_x-mitigating properties of TiO_2 nanoparticles are responsible for the decrease in NO_x emissions for higher biodiesel blends. Comparative observation shows that, higher biodiesel content combined with nano-additives was effective in suppressing NO_x formation, particularly at higher compression ratio.

4.2.4. Exhaust gas temperature (EGT)

Exhaust gas temperature (EGT) variation with load at CR 16 and CR 18 is depicted in Figs 17-18. For all fuels, EGT increased with increasing load because of higher fuel input. At CR 16, B30 exhibited the lowest EGT, while B10 showed the highest value. At CR 18, EGT values of biodiesel blends were comparable to diesel, with B10 exhibiting slightly lower EGT, indicating improved heat utilization during combustion. Comparative observation shows that, Blends with $20-30\%$ biodiesel exhibited favorable exhaust temperature characteristics.

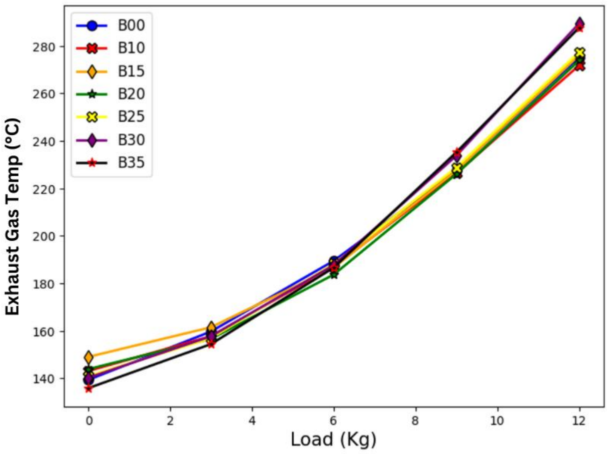


Fig.17. Load with exhaust gas temperature for CR 16.

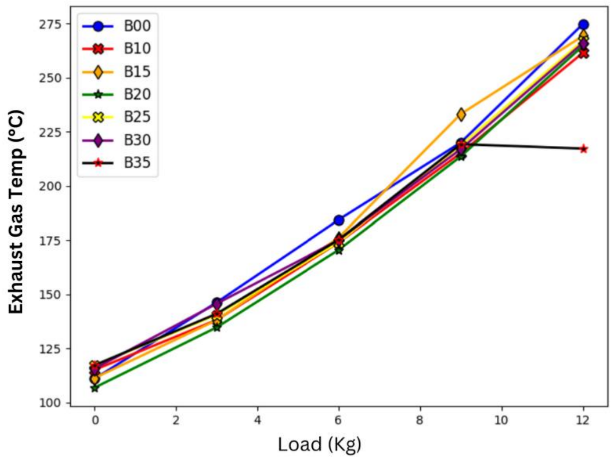


Fig.18. Load with exhaust gas temperature for CR 18.

4.3. Overall comparative assessment

Based on the combined performance and emission analysis, B25 emerged as the optimum blend at CR 16, offering superior brake thermal efficiency, brake power, and mechanical efficiency with acceptable emissions. At CR 18, B20 and B10 demonstrated balanced performance, while higher biodiesel blends (B30 and B35) were effective in reducing NO_x emissions.

4.4. Discussion and comparison with previous research work

The comparison indicates that the present study achieves a balanced improvement in engine performance and emissions through the combined use of hybrid biodiesel and TiO_2 nano-additives.

Table 3. Comparison of present study with previous research work.

Study / Reference	Fuel type & Additives	Key findings	Comparison with present study
Present work	Hybrid biodiesel (Algae + *Calophyllum inophyllum*) + TiO_2	Brake power increased by approximately 6%, while brake specific fuel consumption decreased by about 8%. Additionally, carbon dioxide emissions were reduced by nearly 5%, and nitrogen oxides showed a slight decrease of around 1%.	Shows balanced improvement in performance and emissions with hybrid + nano approach

Table 3 cont. Comparison of present study with previous research work.

Study / Reference	Fuel type & Additives	Key findings	Comparison with present study
4	Algae biodiesel blends	Reduced CO, HC, PM; slight NO_x increase; comparable performance	Present study achieves NO_x reduction due to nano-additives and hybridization
5	Algae biodiesel + Al_2O_3 / CeO_2 nanoparticles	Improved BTE, reduced HC, CO, better combustion	Similar improvement trends; TiO_2 shows comparable catalytic effect
17	Biodiesel + TiO_2 nanoparticles	Brake thermal efficiency increased by up to approximately 6.5%, while brake specific fuel consumption decreased. Emissions were generally reduced, except for a slight variation observed in nitrogen oxides.	Strong agreement with performance improvement and BSFC reduction
1	Conventional diesel variants	Overall performance improved by up to approximately 20%, accompanied by a reduction in emissions.	Higher performance but lacks sustainability; present study offers eco-friendly alternative

While earlier studies on algae biodiesel reported reductions in CO and HC emissions with a tendency for increased NO_x, the current work shows a slight reduction in NO_x due to improved combustion control. Similar to previous nano-additive studies, enhancements in brake power and reduction in fuel consumption are observed, confirming the catalytic role of nanoparticles. Although conventional diesel studies report higher performance gains, they lack sustainability benefits. Therefore, the present approach offers a favourable compromise between efficiency and environmental impact, highlighting the advantage of hybrid biodiesel with nano-additives.

5. Conclusions

The emission and performance characteristics of a variable compression ratio (VCR) diesel engine running on nano-enhanced hybrid biodiesel blends made from *Calophyllum inophyllum* and algal oil were experimentally examined in this work. Titanium dioxide (TiO_2) nanoparticles were added to enhance combustion performance, and engine experiments were performed at compression ratios of 16 and 18 across different load conditions. The findings demonstrated that for all fuels, brake thermal efficiency increased with loading. The B25 blend outperformed diesel at CR 16 with the maximum brake thermal efficiency (30.48%), thanks to improved combustion made possible by the oxygen content of the biodiesel and the catalytic activity of TiO_2. At CR 18, diesel exhibited the highest efficiency, while B25 performed best among biodiesel blends. Brake specific fuel consumption decreased with increasing load; B15 showed the lowest BSFC at CR 16, and blends up to B25 demonstrated BSFC values comparable to diesel at CR 18. The B25 blend produced the highest brake power at CR 16, whereas at CR 18, B25 and B10 delivered brake power close to diesel. Higher biodiesel blends (B30 and B35) significantly reduced NO_x emissions at both compression ratios, while B25 and B30 exhibited lower CO_2 emissions. Overall, the study demonstrates that

TiO_2 nano-enhanced hybrid biodiesel blends, especially B25 at CR 18 and $12\ Kg$ load, may be utilized in VCR diesel engines without modification, providing better performance and lower emissions.

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Nomenclature

BP – brake power $[kW]$

$BSFC$ – brake specific fuel consumption $\left[\frac{kg}{kWh}\right]$

CO_2 – carbon dioxide

EGT – exhaust gas temperature

ME – mechanical efficiency $[\%]$

NO_x – nitrogen oxide

TiO_2 – titanium dioxide

μ – dynamic viscosity $[cP]$

ν – kinematic viscosity $[cSt]$

ρ – density $\left[\frac{kg}{m^3}\right]$

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