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Innovative Solutions for Clean Transportation: Variable Compression Ratio Engine Performance using Algae Biodiesel

R. Arunraj[1]*, M. Amala Justus Selvam[1], Asit Mohanty[2,3]* and Anteneh Mohammed Tahir[4]

[1]Department of Automobile Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India
[2]Institute of Power Engineering, Universiti Tenaga Nasional (National Energy University), Jalan IKRAM-UNITEN, Kajang, Selangor, Malaysia
[3]Division of Research and Development, Lovely Professional University, Phagwara, Punjab, 144411, India
[4]Department of Mechanical Engineering, WOLLO University, Kombolcha Institute of Technology, Kombolcha, Post Box No: 208, Ethiopia
*Corresponding author (e-mail: cherryarun28@gmail.com; amohanty@miet.edu.in)

Boosting energy independence, improving air quality and the environment, and enhancing safety are all advantages of using biodiesel as fuel. This study focuses on evaluating the performance and emission properties of an algal biodiesel in a VCR engine.Third generation biofuel is used in a potential way to meet our future energy needs. Spirulina algae biodiesel, designated as B10, B20, B30, B40, and B100, is to be tested on a diesel engine by blending it with diesel on a volume basis. The spirulina algae blend athigher load levels lower fuel consumption from 2.8% to 13% compared to diesel. At greater loads, B100's brake thermal efficiency (BTE) drops to 4.8% and B20's BTE rises to 8.6% compared to the standard diesel. At about 9% lower, the biodiesel blend's EGT was lower than diesels. In full load conditions, algae blend considerably reduce harmfulemissions like CO, HC, NOx, and smoke when compared to diesel.

Keywords: Algae biodiesel; emission; VCR engine; cylinder; performance parameter

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The world is currently grappling with severe issues such as sudden climate changes, the disturbance of delicate ecological habitats, and the exacerbation of global warming [1]. These challenges stem from the excessive use of petroleum-based fuels in industries and automobiles [2]. Consequently, there is a growing global awareness aimed at preventing a fuel crisis by developing alternative sources of fuel for engine applications. Numerous research programs are underway to replace diesel fuel with a viable alternative such as biodiesel [3-4]. While biodiesel also has its environmental costs, substituting petroleum-based fuels with biofuels has the potential to diminish a nation's reliance on imported oil and, in turn, mitigate overall environmental harm [4-6]. Jenoris et al. reported that the technological viability of microalgal biodiesel is established. The various chemical and physical qualities underwent testing, and the results were compared to ASTM standards. Diesel and petroleum byproducts, including nitrogen oxides (NOx), Hydrocarbon (HC), carbon monoxide (CO), and carbon-dioxide (CO_2), emit large amounts of emissions [7]. Products made from biodiesel can be made from a variety of sources, including used cooking oil, animal fat, vegetable oils, and algal oil. Incomplete fuel combustion and petroleum products decreased waste the most. According to Ramadhas, researchers tested a compression ignition engine using biodiesel, diesel, and pure rubber seed oil [8]. A variable compression ratio engine used to test output braking thermal efficiency and emissions must be employed in the transesterification process of microalgae spirulina algae to produce biodiesel [9]. The study conducted by Alwayzy et al. examined the effects of B10 and B20 on emissions and thermal efficiency. It also found that a study was conducted on the use of Chlorella protothecoides microalgae biodiesel as a diesel engine substitute [10]. Biodiesel blends were tested for thermal efficiency and emission level. To assess the performance, combustion, and emission properties of the fuel, the experimental tests were conducted before biodiesel and pure diesel.

In light of the literature papers mentioned above, various efficiencies and emission characteristics of the blends used to produce biodiesel are analyzed. Most combined materials are exceedingly uncommon and challenging to collect [11-12]. Chen et al. reported that findings showed that when the oxygen level fluctuated between 20 and 80 vol., algae biodiesel was proposed in this research,and its mechanical, thermal, and emission properties were examined. In addition, algae fuels can be used in place of well-known biofuel sources like corn and sugarcane. The majority of studies have been done on microalgae-derived biodiesel from this potential feedstock. The first generation

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of oleaginous crops and the second generation of raw materials [13]. Algae oil-based biodiesel is produced from oil-rich algae, which are photosynthetic microorganisms that can be cultivated in various environments. Algae are a diverse group of aquatic microorganisms that naturally produce oils and can be formulated to increase their oil content. Algae biodiesel is carbon-neutral or carbon-negative because the CO_2 released when burning it roughly balances the CO_2 absorbed during algae growth [14]. Cultivating algae for biodiesel production can help reduce a nation's dependence on foreign oil sources and enhance energy security. Algae-based biodiesel can be used with little or no modification in diesel engines andis compatible with the current fuel distribution infrastructure. Algae biodiesel produces fewer sulphur and nitrogen oxide emissions than conventional diesel, improving air quality [15].

The algae biodiesel industry can create jobs and stimulate local economies through algae cultivation, harvesting, and processing. Algae can be grown in wastewater, helping clean water while producing biodiesel, showcasing a sustainable approach to resource recycling. The development of algae-based biodiesel has sparked research and innovation in biotechnology, genetics, and engineering, leading to advances in various fields [16]. Algae biodiesel is part of a broader effort to diversify energy sources and reduce reliance on finite and environmentally harmful fossil fuels. While algae oil-based biodiesel holds significant promise, there are challenges related to scaling up production, cost-effectiveness, and commercial viability. However, ongoing research and development efforts continually improve the technology and its potential applications. As a renewable and sustainable energy source, algae biodiesel is poised to play an increasingly important role in promoting a more sustainable energy future. Algae biodiesel has recently gained significant attention among researchers due to its potential to address environmental, economic, and energy security concerns [17]. Kesharvani and Dwivedi [18] reports that algae biodiesel has demonstrated thatthe engine performance, namely the BSFC and BTE, can be enhanced by adding the right quantity of additives to the biodiesel blend. Additionally, this can lead to a reduction in tailpipe emissions, particularly NOx. Rajpoot et al. [19] performed Neochloris oleoabundans algae-based biodiesel for transportation applications. In addition to this algae biodiesel cerium oxide and copper oxide nano particles were added to enhance the thermal efficiency reduction in emission performance. The findings suggest that incorporating nanoparticles into Neochloris oleo abundance biodiesel enhances various aspects of engine performance. Specifically, there is an increase of 0.79–3.7% for BTE, 0.75–1.67% of cylinder pressure, and heat release rate (HRR) by 2.35–5.0%. Additionally, there are reductions in brake specific fuelconsumption (BSFC) by 5.19–9.5% and CO_2 emissions by 5.18–9.5%. However, these improvements come at the expense of increased NOx emissions, which rise by 22.67–70.69%. Boopathi et al. [20] investigated the engine performance of algae biodiesel with ethanol as an additive with various concentration. It was found that B20 biodiesel exhibits reduced HC and CO emissions compared to B10 and B30 across all levels of load. For all loads, B20 biodiesel exhibits lower NOx than B10 and B30 biodiesel.

The effectiveness of biodiesel depends on its chemical properties, which are mainly determined by its fatty acid composition. Understanding viscosity is crucial for optimizing flow, combustion, and engine performance, while considering cold flow properties is essential for determining its usability in low temperatures. Having a strong oxidative stability is crucial for maintaining the quality and longevity of products, as well as ensuring optimal performance of engines by preventing degradation. Understanding the cetane number is crucial for maximizing combustion efficiency and ensuring optimal ignition quality. With its low sulfur content, emissions are reduced, resulting in improved air quality. Having expertise in managing glycerin content is crucial to avoid filter plugging and fuel instability. Blending biodiesel with diesel modifies certain properties such as viscosity and emissions, providing a level of versatility. By focusing on these chemical characteristics, biodiesel can be optimized to function as a sustainable alternative to traditional diesel fuels.

Novelty of this Study

This research focuses on microalgae-based biodiesel, highlighting its unique advantages and potential as a sustainable fuel source. Previous studies have explored different biodiesel sources, but this study specifically examines microalgae and its potential as a clean energy alternative. The study thoroughly examines combustion characteristics, exhaust gas composition, and engine performance metrics such as Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC), providing a complete understanding of the fuel's behavior in engines. It highlights substantial decreases in smoke, carbon monoxide (CO), and hydrocarbon (HC) emissions when compared to pure diesel. This suggests that microalgae-based biodiesel has the potential to improve air quality and reduce environmental pollution. The study also emphasizes the significant reduction in carbon dioxide (CO_2) emissions linked to the use of biodiesel blends, underscoring the positive impact of incorporating microalgae-based fuels into transportation systems. Despite a small rise in nitrogen oxides (NOx) emissions caused by higher oxygen levels in biodiesel blends, this discovery offers valuable insights into the compromises associated with using alternative fuels and emphasizes the significance of refining fuel compositions to minimize environmental harm.

Figure 1. Shows the Image of Spirulina and its Powder Form.

Practical Implications: This study provides valuable insights into the consequences and benefits of incorporating microalgae-based biodiesel into sustainable transportation. It offers actionable information for policymakers, industry stakeholders, and researchers interested in promoting environmentally friendly fuel alternatives.

This research significantly contributes to the advancement of knowledge in the field of alternative fuels. It highlights the performance and environmental characteristics of microalgae-based biodiesel, which can play a crucial role in the pursuit of sustainable transportation solutions.

EXPERIMENTAL

Materials and Methods

Botanical Biography of Spirulina Algae Fuel

Derived from the microalgae species Spirulina, spirulina algae fuel shows great potential as a sustainable alternative to traditional fossil fuels. With its rapid growth rates and high lipid content, Spirulina is a nutrient-rich cyanobacterium that is highly sought after as a feedstock for biofuel production. Figure 1 shows the image of spirulina algae and its powder.

This green fuel has numerous benefits: Spirulina can be cultivated in large quantities using minimal land and water resources, resulting in a high yield of biomass per unit area. Spirulina has the unique ability to absorb carbon dioxide during photosynthesis. This means that when it is used as fuel and burned, the carbon emissions released are balanced out by the CO_2 it had previously sequestered. As a result, Spirulina can be considered a carbon-neutral energy source.

Spirulina algae fuel is known for its reduced emissions, which means it produces lower levels of harmful pollutants like sulfur oxides and particulate matter. This not only helps improve air quality but also reduces the overall environmental impact. Spirulina biomass can be transformed into different biofuel forms, such as biodiesel, bioethanol, and biogas, providing adaptability to fulfill a wide range of energy requirements. The use of Spirulina algae fuel has the potential to revolutionize various sectors, including transportation, electricity generation, and heating. This renewable and sustainable energy solution holds promise for a greener future.

Although there are advantages to consider, ongoing research and development are focused on addressing challenges related to cost-effectiveness, scalability of production, and technological advancements in cultivation and processing techniques. In general, Spirulina algae fuel shows great potential in addressing energy security, environmental sustainability, and climate change mitigation.

Transesterification

Figure 2 illustrates the process of esterification using algae oil. Given the abundance of molecules with fatty acids, biodiesel tends to exhibit a higher viscosity and density. To produce ester from the lipids, one must carry out a reaction using methanol and an acid catalyst. This process results in the formation of monoalkyl esters. The conversion efficiency, which impacts biodiesel production and yield, is directly related to the molar ratio of alcohol to oil [22]. After the conversion was finished, the extract was left in a separating funnel overnight to separate on its own. The extract had three distinct layers. At the base of the separation funnel, a distinct layer of glycerin and impurities is visible. The presence of a viscous layer between the upper and lower layers necessitates their separation [23].

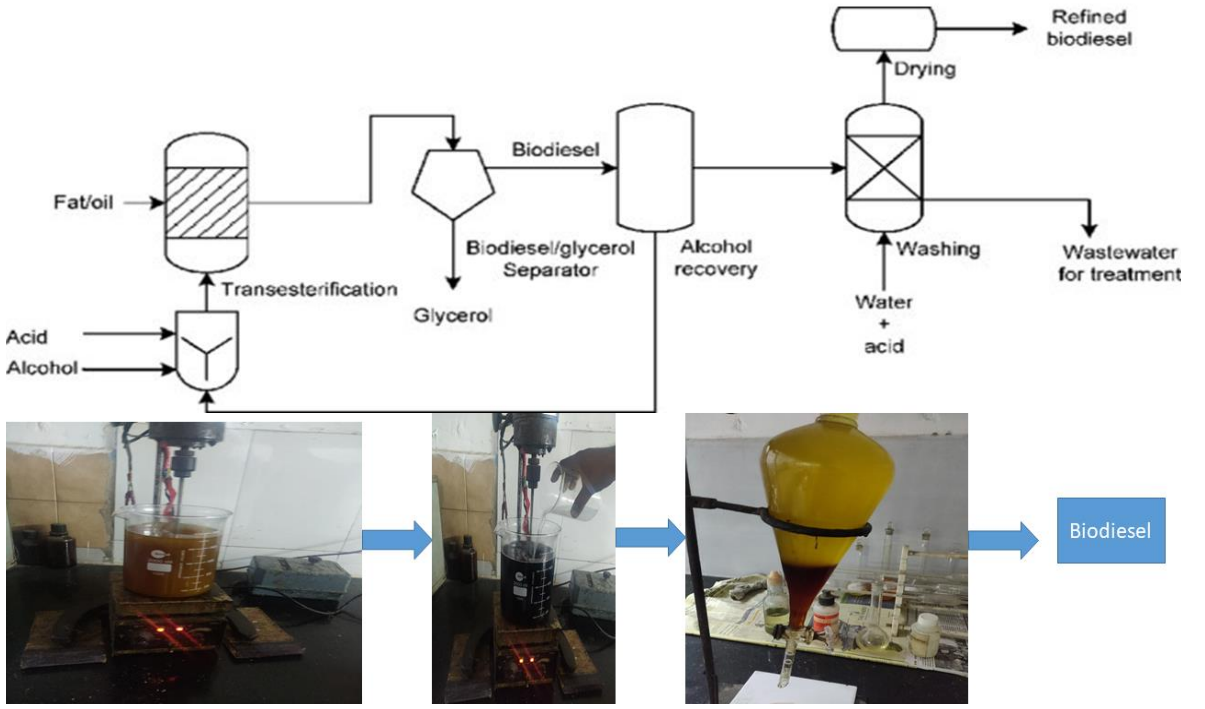

Figure 2. Transesterification Process.

Properties of Algae Biodiesel and Diesel

Table 1 lists the diesel and algal biodiesel combined with their respective attributes. You may find a list of the precise instruments used to measure diesel and algal biodiesel properties at B10, B20, B30, B40, and B100 in Table 1. A variety of properties were noted, including as density, acidity, fire point, iodine value, flash point, calorific value, specific gravity, cetane number, and kinematic viscosity. B10, B20, B30, B40, B100, and D100 test parameters were examined. In terms of density and kinematic viscosity, there was no discernible improvement. Blends of petrol outperformed B20 in terms of flash point.

Table 1. Algae Blends and Diesel Properties.

Sl.No	Parameters	Unit	B10	B20	B30	B40	B100	D100
1	Density at 30 $^{\circ}$C	gm/ml	0.8203	0.8232	0.8292	0.8203	0.856	0.842
2	Cetane number	-	52.93	53.61	49.27	52.93	47.01	57.08
3	Acid value	mg KOH/g	0.22	0.45	0.52	0.22	1.09	0.08
4	Calorific value	kcals/kg	10191	10363	10402	10191	41807	41807
5	Specific gravity	kg/m^3	0.8198	0.8228	0.8289	0.8198	0.8712	0.8813
6	Kinematic viscosity at 40 $^{\circ}$C	cSt	2.75	2.98	3.34	2.75	1.65	2.73
7	Iodine value	gms	19.09	26.06	45.15	19.09	102.93	100
8	Flash point	$^{\circ}$C	60	68	67	60	118	55
9	Fire point	$^{\circ}$C	70	73	79	88	126	70

Experimental Details

In this work, investigations were conducted in a VCR engine, four-stroke, that was water cooled and aspirated. The engine generates a power output of 4.4 kW at 1500 rpm, while maintaining a compression ratio of 18 to 1. An eddy current dynamometer was used to activate the engine. Diverse sensors and devices were employed to quantify the essential data needed for these investigations. The AVL Di Gas Analyzer was employed for the purpose of monitoring hydrocarbons and carbon monoxide. The AVL smoke metre quantifies the level of smoke emissions. Furthermore, it includes a process indication and an engine indicator.

Rotameters are strategically incorporated into the setup to measure the rates of cooling and calorimeter water flow. Figure 3(a) and Figure 3(b) display the comprehensive block diagram and experimental test rig of the design. The main objective of this configuration is to carry out experiments that enable researchers to investigate different facets of engine performance, suchas input and output powers, power losses due to friction, brake and indicated mean effective pressures, BTE, SFC, air-fuel ratio, and heat balance. A software package for engines is utilized to improve the precision and effectiveness of these trials, enabling real-time evaluation and data analysis through LabVIEW. Within the realm of sustainable mobility research, this configuration assumes a pivotal position. By conducting a careful analysis of engine performance characteristics, researchers can devise engine designs that are both more environmentally friendly and more efficient. Accurate quantification of combustion pressure, for example, assists in maximizing combustion efficiency, resulting in decreased emissions and enhanced fuel efficiency. Moreover, the utilization of electronic injection pressure for estimating pressure aids in the advancement of diesel engines that are both cleaner and more efficient. Table 2 presents comprehensive specs for the test engine. Subsequently, the water supply was inspected to ensure the engine was effectively dissipating heat. The dynamometer was calibrated, and the quantity of lubricating oil was verified to pre-vent any inaccuracies in loading. Various combinations of biodiesel were tested in the diesel engine, including blends with 10%, 20%, 30%, 40%, and 10% biodiesel content. Following that, the results of various mixes were contrasted with those of pure diesel (D100), the standard fuel for all types of engines. Using regular diesel fuel, the engine was started, and the key parameters were recorded. Once the engine stabilized, we tested the biodiesel's performance and emission characteristics.

Ambiguity Examination

Instrument errors can often be attributed to factors such as the condition of the instrument, the surrounding environment, the method of observation, and the testing procedure. There may be some experimental uncertainty due to differences in instrument manufacturers, calibration procedures, and data acquisition procedures. By incorporating uncertainty analysis, one can effectively minimize variations in desired experimental results.

$$\text{Total uncertainty (TU)} = \sqrt{(Total\ performance\ deeds)^2 + (Total\ performance\ deeds)^2} \quad (1)$$

$$TU=\sqrt{(UC_{BTE})^2 + (UC_{BSEE})^2 + (UC_{HC})^2 + (UC_{CO})^2 + (UC_{NOx})^2 + (UC_{Smoke})^2} \quad (2)$$

TU=$\pm$1.378%.

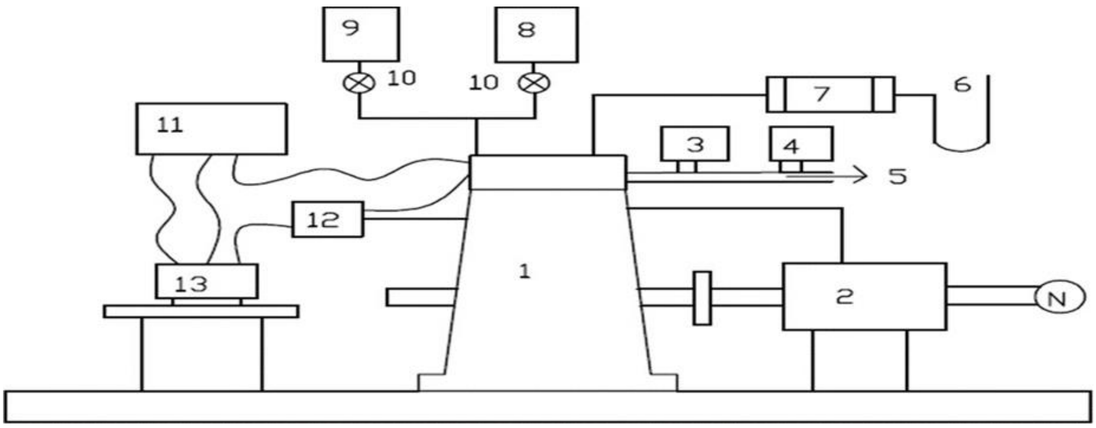

Figure 3(a). Schematic Diagram of the Experimental Setup.

Parts name: 1. Engine, 2. Eddy-Current Dynamometer, 3. Smoke Meter, 4. Gas Analyzer, 5. Exhaust Gas, 6. U-Tube Mano Meter, 7. Air-box, 8. Diesel Tank, 9. Bio Diesel Tank, 10. Controll Valve, 11. Control panel, 12. Amplifier, 13. Monitor

Figure 3(b). Experimental Test Engine.

Table 2. Engine Specifications.

Manufacturer Type	Kirloskar TV-I
Specification	Single-cylinder, water cooled, direct injection engine,constant speed, 4-stroke diesel engine.
Compression Ratio	17.5 : 1
Power	5.2 kW
Injection Starts	23° before TDC
Stroke	110 mm
Bore	87.5 mm
Loading Device	Eddy current dynamometer
Speed	1500 rpm
Injection Pressure	220 kgf/cm^2

RESULTS AND DISCUSSION

Brake Thermal Efficiency

The amount of power that is transferred from the engine to the fuel is represented by the brakethermal efficiency. The data produced by brake thermal efficiency is less than that of pure diesel. BTE increases compared for different types of loads, as shown in Figure 4. For both diesel andalgae, biodiesel mixes with the BTE as the applied load rises. It happens be-cause a cylinder temperature is raised and results from increased fuel injection as the applied load goes from low to high. This component shortens the ignition delay and enhances air-fuel mixing, which results in fuel combustion also being completed. B100 has a lower BTE of 4.8% at higher load conditions, and B20 has a higher BTE of 8.6% than the base diesel. Pure algal oil has a higher viscosity than other oils, and because of its density, it atomizes poorly, reducing BTE. This viscosity is higher; adding to that situation is poor volatility and air-fuel mixing in biodiesel. Spray quality is poor because this attribute will increase, and researchers reported that fuel burns after that expansion stroke as a result of the ignition delay [24-25].

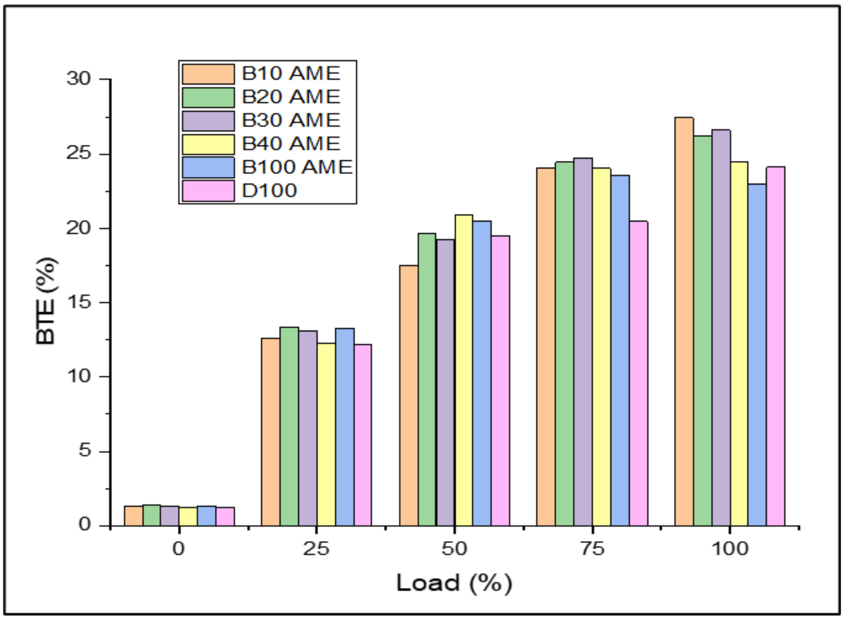

Figure 4. Variation of loads and BTE.

Brake Specific Fuel Consumption

The BSFC decreases compared with various forms of loads, as shown in Figure 5. BSFC alludes to the quantity of fuel used for brake power. The load is improving, increasing the rate of fuel combustion. It displays the effectiveness of the provided fuel. According to the pattern,BSFC for diesel and algae blends diminishes as the applied load improves. Diesel fuel uses theleast amount of fuel to produce energy when compared to algal blends. The primary part is that the calorific value is compared between algae biodiesel and pure diesel. Algae and blends use up more fuel when under lower load situations compared to diesel.

The reason for this tendency is that algae have a higher viscosity. The algae blends have comparable BSFC under higher load conditions with 2.8% to 13% lower than diesel. At zero load and part load situations, a maximum variance in BSFC and the viscosity of algae mixes reduce as load in the cylinder increases, which improves combustion and output in lower SFC [9].

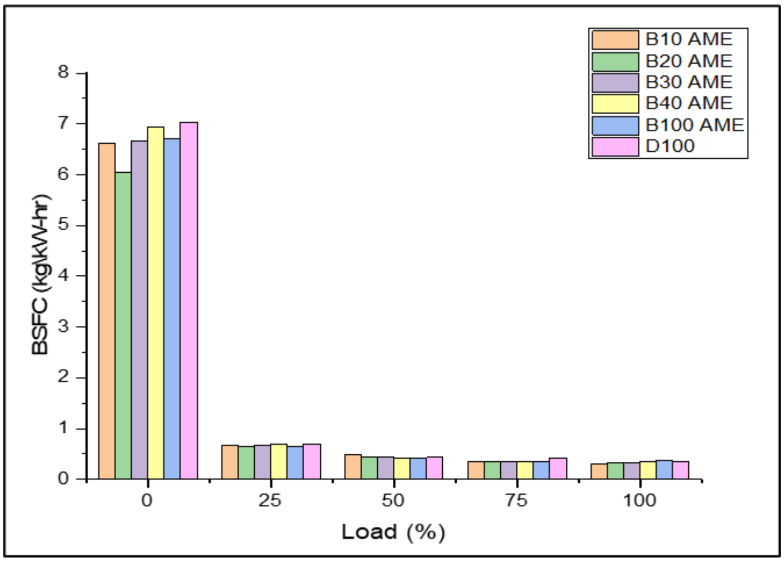

Figure 5. Variation of Loads and BSFC.

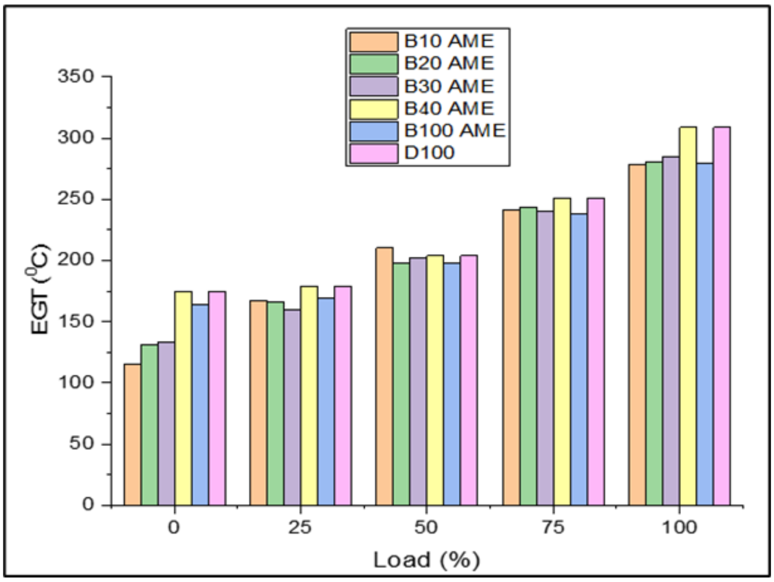

Figure 6. Variation of loads and EGT.

Exhaust Gas Temperature

Exhaust gas temperature (EGT) fluctuations for diesel/ algal biodiesel mixtures are shown in Figure 6. It seems from the trends that the temperature is not very variable, but there are noticeable variances between diesel and algae mixes. The combination of diesel and algae exhibits the highest temperature differential. This level of coherence indicates the occurrence of heat loss. Biodiesel blend recorded lower EGT than diesel around 9%. The energy usage is similar for the different fuels used. The fuel-to-air ratio has a direct impact on the exhaust gas temperature. Diesel engine exhaust fumes contain several dangerous contaminants that are produced due to elevated gas temperatures [26].

Hydrocarbon

Figure 7 shows the variation in hydrocarbon emissions for different types of fuel. According to the data, HC emissions are high at low loads in the experiments, and they drop dramaticallyas the loads increase. B30 blend results in about 15% reduced HC emissions. The main reasonfor the HC release is the creation of a rich air-fuel mixture at low in-cylinder temperatures. When algae is mixed with biodiesel, the mixture becomes thick and dense, which increases HC emissions even at low loads. The atomization process is extremely inefficient and results in a lean mixture.

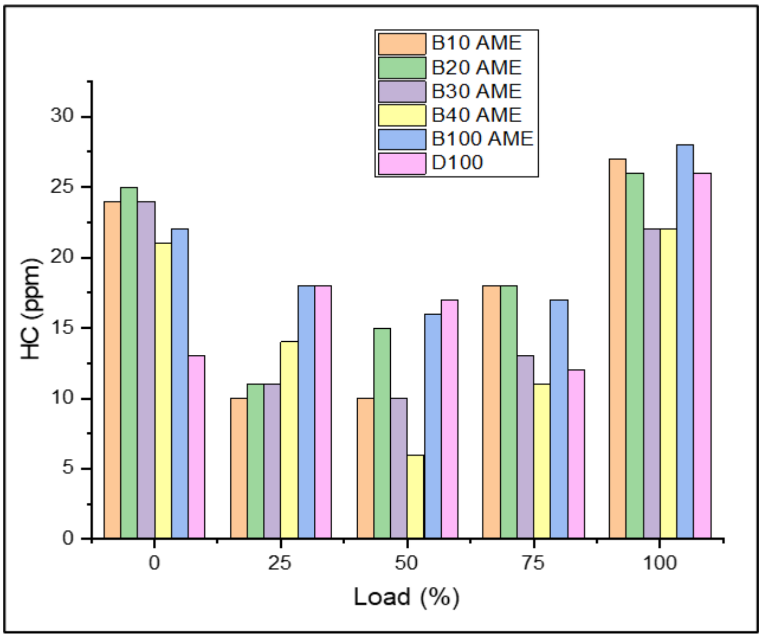

Figure 7. Variation of Loads and HC Emission.

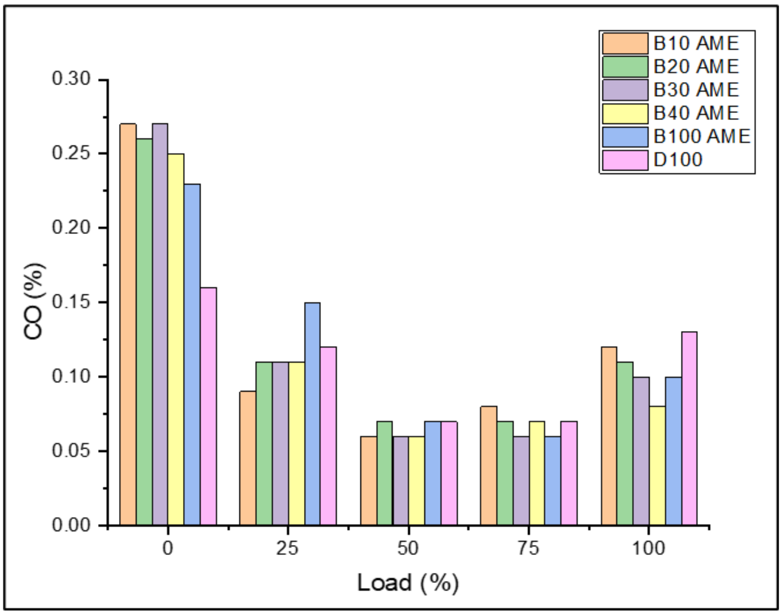

Figure 8. Variation of Loads and CO Emission.

Lower HC emissions for both diesel and algae mixtures are a consequence of an increase in molecular oxygen content and a rise in cylinder temperature under higher load conditions, which promote oxidation and decrease viscosity [27].

Carbon Monoxide

The variance in carbon monoxide emissions for various fuel types is depicted in Figure 8. The collected trend demonstrated that CO emissions at low experimental loads are high and decrease very slowly with increasing experimental loads. Nearly 50% more CO emissions are produced at low loads for biodiesel than at high loads.

The primary cause of the CO release is a rich air-fuel mixture that is generated at a low in-cylinder temperature within the cylinder. Algae blends reported 7% to 38% less CO than diesel at higher loads. The algae blend a viscosity and density result in increased carbon monoxide emissions at very low loads; biodiesel atomization is also poor; and lean mixtures. When there is more load, the cylinder temperature goes up and the molecular oxygen content goes up. This makes oxidation happen faster and lowers viscosity, which means that less CO is released for both diesel and algal mixes [8, 10].

Nitrogen Oxide

As demonstrated in Figure 9, this graph illustrates the rise in NOx emissions as a function of both the applied load and the change. NOx emissions are reduced due to the short combustion duration and the limited time available for the conversion of nitrogen to NOx. With a decrease in the average petrol temperature, NOx emissions are decreased.

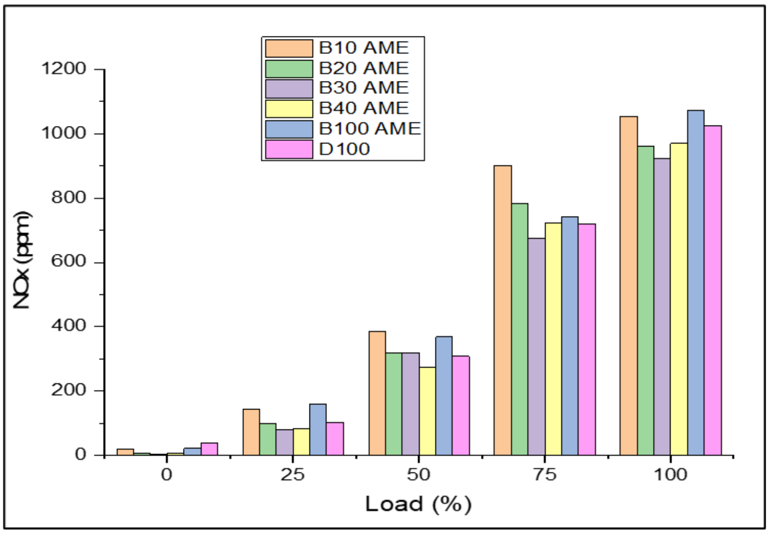

Figure 9. Variation of Loads and NOx Emission.

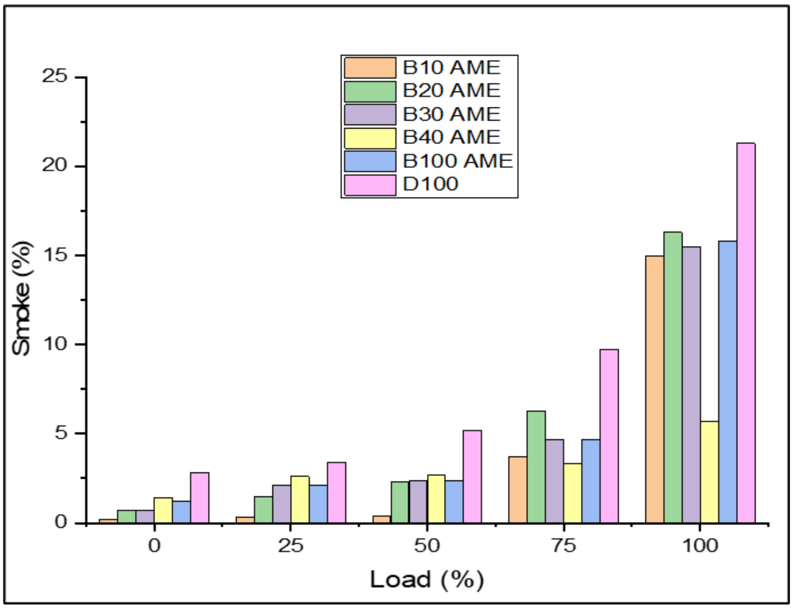

Figure 10. Variation of Loads and Smoke Emission.

NOx emissions are reduced from idle to full load when algal biodiesel mixtures are used. At that time, the combustion product and temperature are both affected by oxygen, according to Subramaniam et al. The addition ofoxygen concentration in algal biodiesel blends reduces NOx emissions by approximately 10% [7].

Smoke

Smoke emissions are developed by the creation of a rich mixture during combustion, and they are mixed through the combustion chamber in a diesel engine. Smoke emission for various loadgraphs is shown in Figure 10. The data observed demonstrates that for algae and blends, smoke emissions gradually decreased. When compared to diesel, a 30% reduction in algae biodiesel blends demonstrates a significant reduction. Algae biodiesel is oxygenated for the reactions that were also previously mentioned. The algae biodiesel has a low combustion pressure and calorific value. Smoke emissions are also minimal, and temperatures are also very low [9], [26].

CONCLUSION

A biodiesel testing procedure that involves spirulina algae is currently being researched by the VCR engine. An investigation was carried out on the diesel engine under different operating conditions, including both no-load and full-load scenarios. The algal biodiesel at B10, B20, B30, B40, and B100 was evaluated by comparing it to D100, which served as a benchmark. Based on the investigation, it was found that spirulina algae yielded more favorable results when used on the diesel engine. When using spirulina algae biodiesel blends at higher load levels, fuel consumption can be reduced by 2.8% to 13% compared to diesel. Under increased loads, the BTE of B100 decreases to 4.8% while the BTE of B20 increases to 8.6% when compared to regular diesel. The EGT of the biodiesel blend was approximately 9% lower compared to diesel. Under full-load conditions, algae blends have been found to significantly decrease the release of harmful emissions such as CO, HC, NOx, and smoke in comparison to diesel fuel.

1. Exploring the potential advantages of utilizing spirulina algae biodiesel blends in diesel engines, such as decreased fuel consumption and decreased emissions of harmful pollutants.

2. Investigating the effects of various blend ratios (B10, B20, B30, B40, B100) on the performance and efficiency of diesel engines when utilizing biodiesel derived from spirulina algae.

3. Examining the performance characteristics of spirulina algae biodiesel blends at different load levels in comparison to traditional diesel fuel.

4. Assessing the practicality and economic viability of incorporating spirulina algae biodiesel blends into commercial vehicles or industrial machinery to promote sustainable energy production.

5. Exploring future research directions to enhance the production process and improve the performance outcomes of algal biodiesel, which can serve as a sustainable energy source for transportation.

DECLARATION OF COMPETING INTEREST

The authors herein affirm that they have no known competing financial interests or personal relationships that may have seemed to affect the results of this work.

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