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Experimental Investigation of Engine Characteristics Fuelled with Emulsified and Nano Emulsified Citrus Limon Seed Biodiesel

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Abstract

The exploration and advancement of alternative fuels serve as catalysts for innovation in energy technologies, fostering economic growth and offering sustainable solutions for transportation and industry. The process of emulsifying low-grade diesel fuel enhances the atomization and mixing of the fuel with air, resulting in improved combustion efficiency, decreased emissions, and enhanced fuel efficiency. The introduction of nanoparticles into the emulsion results in an increase in the surface area of the fuel droplets, leading to enhanced atomization and improved combustion efficiency. The enhanced dispersion of particles in the air facilitates improved interaction, leading to decreased emissions of nitrogen oxides and particulate matter, contributing to the promotion of environmental sustainability. This study examines the performance and emission characteristics of a single-cylinder diesel engine when biodiesel derived from citrus limon seeds is combined with emulsified citrus limon seed biodiesel and nano-emulsified biodiesel. The nECLB had 2.57–4.2% braking thermal efficiency above the ECLB. Specific fuel consumption was 7.8% to 13.4% lower for the nECLB than the ECLB. The nECLB emitted 8.5% less HC and 21% less CO than the ECLB. When utilising base diesel, nECLB reduced nitrogen oxide and smoke emissions by 50%–65% and 0.5%–1.5%, respectively.

Keywords: Aluminium oxide, citrus limon seed biodiesel, emissions, emulsification, nano-emulsified biodiesel.

Introduction

Research into clean alternative fuels for internal combustion engines has been driven by growing worries about the energy crisis and ambient air pollution. It has been found that biodiesel can serve as a partial substitute for fossilised fuels. Researchers have been pushed to investigate clean alternative fuels for use with internal combustion engines due to growing worries about the energy crisis and ambient air pollution. Biodiesel exhibits considerable potential as a viable substitute for compression ignition engines, owing to its manifold benefits including abundant availability, reduced operational expenses, minimal technical requirements, convenient storage capabilities, engine lubrication capabilities, biodegradability, absence of aromatic compounds, and environmental compatibility when compared to conventional diesel fuel (1, 2). Biodiesel has been scientifically demonstrated to possess a higher oxygen content compared to traditional diesel. The presence of an excessive amount of oxygen in biodiesel, along with the extended ignition delay associated with its use, results in an elevation of the peak temperature during combustion. Consequently, this leads to the generation of nitrogen oxides (NOx). NOx functions as an indirect greenhouse gas, primarily impacting air pollution by influencing tropospheric ozone levels and contributing to the development of smog and acid rain. Nevertheless, the surplus oxygen present in biodiesel leads to a rise in the maximum temperature reached during combustion, hence enhancing the production of NOx (3).

A rise in combustion temperature results in a higher rate of NOx formation, as per the well-known Zeldovich mechanism. This rate may be much higher if biodiesel, which contains a higher proportion of oxygen, is added. So far, efforts to lower the combustion temperature have focused on introducing water into the combustion chamber (4). Some of the more common methods include using the electronic fuel injection system to inject water directly into the cylinder or fumigation, which combines steam with intake air, to name a few. It must be said, nevertheless, that these methods are not without their limitations.

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As an example of a limitation, a hydro lock can happen if the piston contacts water at its minimum volume position. In addition, in colder climates, water can damage engine components. Engine system components are susceptible to physical deterioration and corrosion when used for an extended period of time (5). Utilising fuel that is emulsified with water is an effective way to decrease combustion temperature and harmful emissions while increasing thermal efficiency. This method requires no changes to the components of the existing diesel engine and has a lower corrosion susceptibility than other options. A biphasic mixture of polar water molecules dispersed in nonpolar fuels, like diesel, is called an emulsified fuel. One way to improve fuel efficiency is to add water droplets to the gasoline. These little explosions happen when the fuel is burned, which helps to distribute the fuel more evenly in the combustion chamber. Use of surfactants helps stabilize droplets in the dispersed phase by preventing them from merging and lowers the interfacial tension of mixable liquids like fuel and water (6, 7).

The formation of thermal NOx is hindered by high temperatures, which cause nitrogen to dissociate from atmospheric air and associate with oxygen. However, this is counteracted by a decrease in combustion chamber temperature caused by the heat sink effect of water vaporisation (8). This is because water has an elevated specific heat capacity and latent heat of vaporisation. Because of this impact, the ignition delay is prolonged, which permits more fuel combustion in premixed mode. Reduced smoke emissions are another benefit of a greater air/fuel ratio, which occurs when there is an excess of oxygen in the fuel. This is because the heterogeneous combustion occurring inside the cylinder has fewer fuel-rich zones (9).

Fuels made from water-in-diesel emulsions undergo secondary atomization, a process that includes micro-explosions. The base fuel's volatility, the emulsion type, the water concentration, the dispersed liquid's diameter, its position, and environmental factors like pressure and temperature largely influence this occurrence (9, 10). The impacts of micro-explosion inside the combustion chamber have been the subject of relatively few studies, despite the large number of experimental and numerical investigations into the phenomena. Conventional wisdom holds that the dispersed liquid behaviour of fuel is influenced by fuel injection and the flow of emulsified fuel through the small aperture of the injection nozzle. Consequently, research into micro-explosions within combustion chambers and how they impact processes like secondary atomization, evaporation, spray penetration, and mixture ignition is crucial (11, 12).

The performance and emission characteristics of a single-cylinder diesel engine are investigated in this research endeavour through the combination of emulsified citrus limon seed biodiesel (ECLB), nano-emulsified citrus limon seed biodiesel (nECLB), and biodiesel derived from citrus limon seeds. By facilitating the atomization and blending of low-grade diesel fuel with air, the emulsification process improves fuel efficiency, decreases emissions, and increases combustion efficiency. The incorporation of alumina nanoparticles into the emulsion causes an augmentation in the fuel molecules' surface area, which subsequently stimulates atomization and enhances the efficiency of combustion. Enhanced particle dispersion in the atmosphere promotes improved interaction, which in turn reduces nitrogen oxide and particulate matter emissions, thereby making a significant contribution to the advancement of environmental sustainability.

Material and Methods

Citrus Limon Seed Biodiesel

The extraction of citrus limon seed biodiesel is a complex procedure that commences with the collection and purification of the seeds to eliminate any contaminants. After undergoing the cleaning process, the seeds are subjected to oil extraction using techniques such as solvent extraction or mechanical pressing (Figure 1). Transesterification is a chemical process in which the extracted oil undergoes a reaction with an alcohol, such as methanol, and a catalyst, such as sodium hydroxide, resulting in the production of biodiesel and glycerin. Citrus limon seed-derived biodiesel demonstrates favourable characteristics,

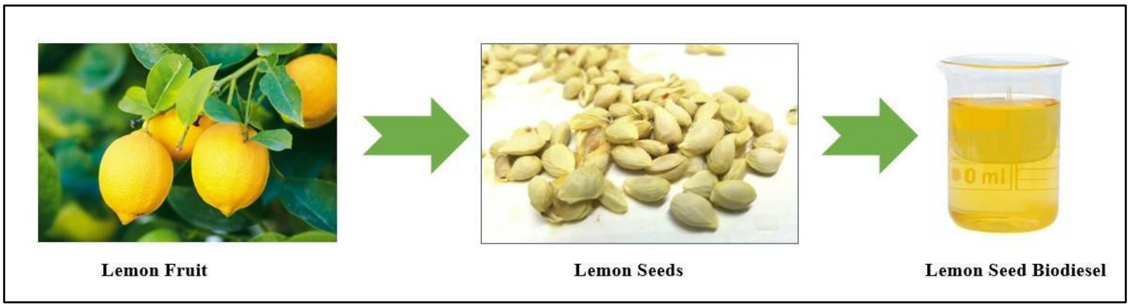

Figure 1: Formation of Citrus Limon Seed Biodiesel

such as a notable cetane number, little sulphur content, and commendable lubricating capabilities. The renewable characteristics of this energy source, coupled with its capacity to mitigate greenhouse gas emissions and decrease reliance on fossil fuels, render it a viable and ecologically sustainable substitute for traditional diesel fuel. Nevertheless, in order to expand the production of citrus limon seed biodiesel for commercial purposes, it is imperative to tackle obstacles such as the fluctuation in yield and the requirement for effective extraction methods.

When comparing the properties of diesel fuel to citrus limon seed biodiesel, notable differences emerge (Table 1). Diesel fuel typically boasts a higher calorific value at 44500 kJ/kg compared to citrus limon seed biodiesel's 38452 kJ/kg, suggesting that diesel provides more energy per unit mass. However, citrus limon seed biodiesel exhibits a higher density at 912 kg/m^3 compared to diesel's 824 kg/m^3, indicating that it occupies more volume per unit mass. In terms of viscosity, both fuels display similar characteristics, with diesel having a viscosity of 4.12 mm^2/s at 40°C, slightly lower than citrus limon seed biodiesel's viscosity of 4.78 mm^2/s at the same temperature. Additionally, citrus limon seed biodiesel showcases a higher cetane number of 55 compared to diesel's 52, indicating better ignition quality and potentially smoother combustion. These differences in properties highlight the distinct characteristics and potential advantages of citrus limon seed biodiesel as a renewable alternative to traditional diesel fuel.

Aluminium Oxide

Aluminium oxide, also known as alumina, possesses a diverse range of properties that helps with temperature management and prevents overheating because to its high thermal conductivity, which is usually around 30 to 40 W/(m·K). In addition to extending the lifespan of engines, aluminium oxide is a great additive for improving fuel stability and reducing corrosion because of its chemical inertness and resistance to corrosion. In addition, the fuel supply systems are made safer and electrical arcing is prevented by its electrical insulating qualities, which usually have resistivity values between 10^{14} and 10^{16}Ω·cm. The additive potential of aluminium oxide to enhance fuel performance, durability, and dependability in engines is highlighted by these features. When examined under a microscope, aluminium oxide usually shows a crystalline structure with oxygen and aluminium atoms packed closely together. Al_2O_3 looks like tiny, closely packed grains or particles with sharp corners and flat surfaces when viewed under a microscope. Crystal forms of aluminium oxide can range from cubic to rhombohedral, depending on the technique of creation and subsequent processing. Furthermore, crystal lattice impurities or flaws can manifest as minuscule dislocations or abnormalities. The microscopic appearance of aluminium oxide is depicted in Figure 2.

Table 1: Properties of Citrus Limon Seed Biodiesel and Diesel

S.No	Fuel Property	Diesel	Citrus Limon Seed Biodiesel
1	Calorific Value (kJ/kg)	44500	38452
2	Density (kg/m^3)	824	912
3	Viscosity (mm^2/s at 40^{o}C)	4.12	4.78
4	Cetane Number	52	55

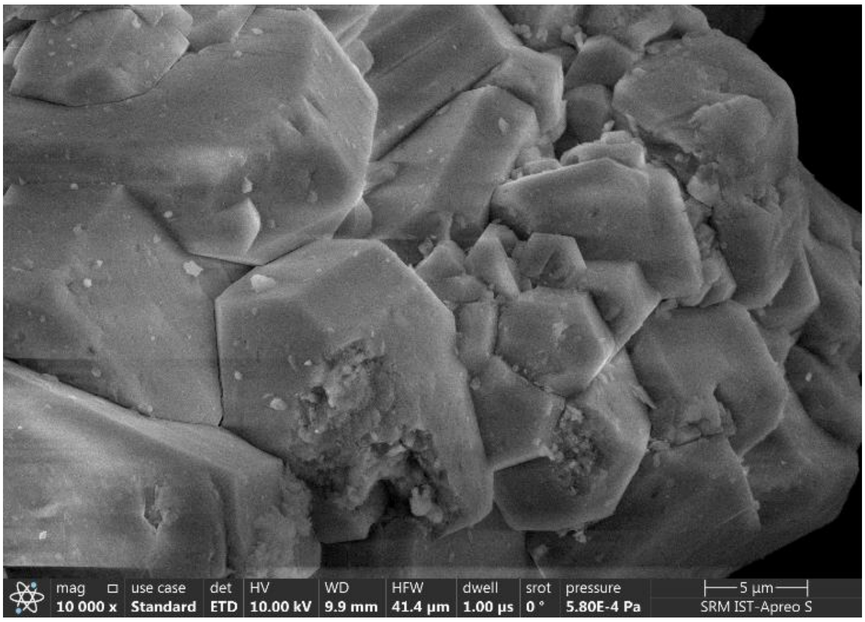

Figure 2: Microscopic image of aluminium oxide

Emulsified Biodiesel

To achieve the formation of a stable emulsion, it is important to thoroughly combine its constituent components. Ultrasonic mixers and other forms of mechanical mixers are the most often employed techniques for combining the constituents of emulsions, with the aim of enhancing emulsion stability through the employment of an emulsifier. The duration of the mixing process and the magnitude of the applied power are crucial factors in determining the outcome. The gradient of the reduction of discrete phase droplets exhibits an upward trend as the mixing power is augmented. Irrespective of the level of mixing strength, the percentage of droplets reaches a specific minimum. However, it has been observed that as the mixing power increases, the rate at which discrete phase droplets reach their minimum size also increases (3). The immiscibility of water and fuel can be attributed to the polar nature of water as a liquid and the non-polar nature of hydrocarbon liquids. The process of mechanically mixing polar and non-polar liquids results in the disruption of surface tension, leading to the fragmentation of the dispersed phase into smaller droplets. Irrespective of the energy input during the mixing procedure, the scattered phase droplets will exhibit a tendency to amalgamate and disengage from the continuous phase. Emulsifiers are employed to enhance the stability of the amalgamation of polar and non-polar liquids. Emulsifiers facilitate the mitigation of thermodynamic instability in emulsions, thereby reducing the surface tension between liquid phases and constraining the expansion of interfacial free energy. The utilisation of a surfactant results in an augmentation of the duration required for the liquid to separate. In addition, the incorporation of an emulsifier leads to a decrease in surface tension, hence facilitating the completion of the emulsification process with a reduced amount of external force. An emulsion is formed when a surfactant is added to a combination (13). An emulsion is a heterogeneous blend of two liquids that are insoluble from each other, often water and oil. The incorporation of an emulsifier, commonly referred to as a surfactant, is necessary to achieve a homogeneous mixture. Selecting a surfactant with a hydrophilic-lipophilic balance (HLB) ratio below 7 is of utmost importance. The surfactant employed in the formulation of a water-diesel emulsion was SPAN 80, possessing an HLB value of 4.2. Span 80, also known as sorbitan monooleate, is a non-ionic surfactant that finds application in several industries including food, pharmaceuticals, and cosmetics. Its primary function is to achieve homogeneity between immiscible fluids, such as oil and water. The substance's ability to reduce surface tension makes it well-suited for applications involving coating, spreading, and wetting. The virtue of excellent solubilisation of Span 80 renders it ideal for a diverse range of formulations.

Experimental Setup

In this investigation, a single-cylinder variety of kirloskar engines is renowned for its exceptional durability and high performance, making it highly suitable for a wide range of applications. These engines have been carefully designed to achieve ideal power delivery and efficiency, including a bore size of 80mm and a stroke length of 110mm. With a rotational speed of 1500 rpm and produces a peak power output of 3.7 kW. The engine possesses a swept volume of 780 cm^3, which guarantees sufficient displacement. Additionally, a compression ratio of 17:1 further enhances combustion efficiency and fuel economy. The experimental injection pressure was 200 bar. When it comes to managing and dissipating combustion heat, a water-cooled engine typically uses a liquid coolant, which typically consists of water and antifreeze. Through a network of tubes and channels, the engine block and cylinder head dissipate heat generated by engine components. A radiator is used for air cooling, and the coolant is pumped there. The radiator lowers the temperature of the coolant by transferring heat to the air. A thermostat regulates the temperature of the engine and makes sure it gets to its ideal operating temperature fast. Engines that are cooled by water are superior in several ways: they dissipate heat more effectively, use less fuel, regulate emissions, last longer, and run more quietly. Figure 3 shows the experimental set up of a single cylinder diesel engine and Table 2 shows the instrument's details utilized for this investigation.

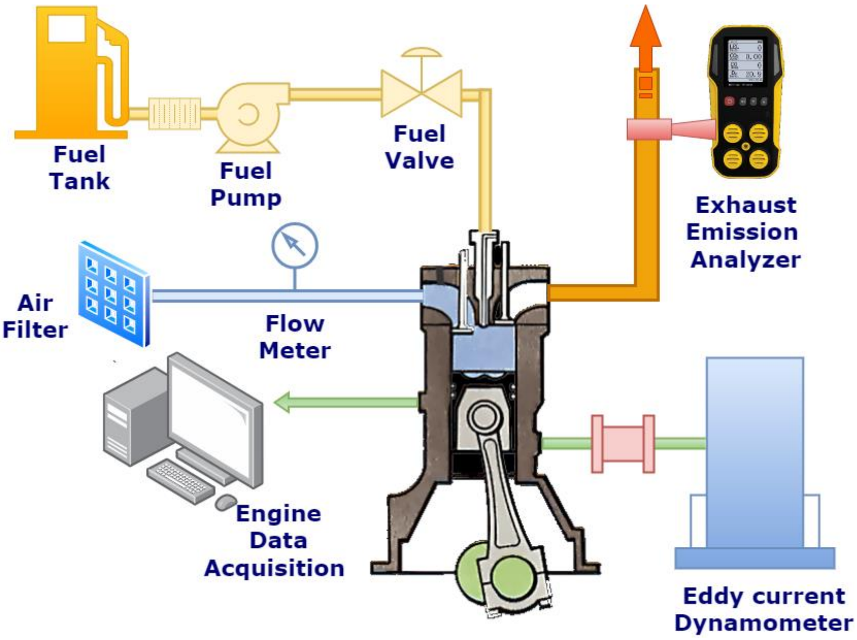

Figure 3: Schematic diagram of experimental setup

Table 2: Experimental instruments details

Measurement	Instrument	Range	Resolution	Accuracy
Load	Load cell	-	0.1 kg	± 0.1 kg
Fuel Quantity	Burette	0-50 cm^3	0.1 cm^3	± 0.1 cm^3
Hydrocarbon	AVL DI GAS Analyser	0 to 20000 ppm	1 ppm	± 10 ppm
Carbon Monoxide		0 to 15%	0.1% vol	± 0.03%
Nitrogen Oxides		0 to 5000 ppm	1 ppm	± 10 ppm
Smoke	AVL Smoke Meter	0 to 15%	0.1% vol	± 0.03%

Result and Discussions

Brake Thermal Efficiency

It is highly possible to increase brake thermal efficiency (BTE) by incorporating nano-emulsified biodiesel into engine fuel systems. The nECLB had more brake thermal efficiency than the ECLB, around 2.57 to 4.2% as shown in Figure 4. But the emulsified biodiesel recorded less efficiency than the diesel. Biodiesel can be more thoroughly mixed with air during combustion through nano-emulsification, which entails breaking it down into ultra fine droplets distributed throughout the fuel. The combustion process is improved, and energy losses are decreased as a result of this finer dispersion. Optimal engine performance and increased BTE are outcomes of using nano-emulsified biodiesel, which promotes more complete combustion and so decreases pollutants and unburned hydrocarbons (14).

The enhanced combustion efficiency can be attributed to the metal nanoparticles, which provide improved air-fuel mixing and result in a greater specific surface area to volume ratio. The inclusion of alumina nanoparticles is also noteworthy. The increased combustion efficiency can be attributed to the relatively high oxygen content of alumina nanoparticles, leading to a greater number of oxygen atoms participating in the combustion reaction.

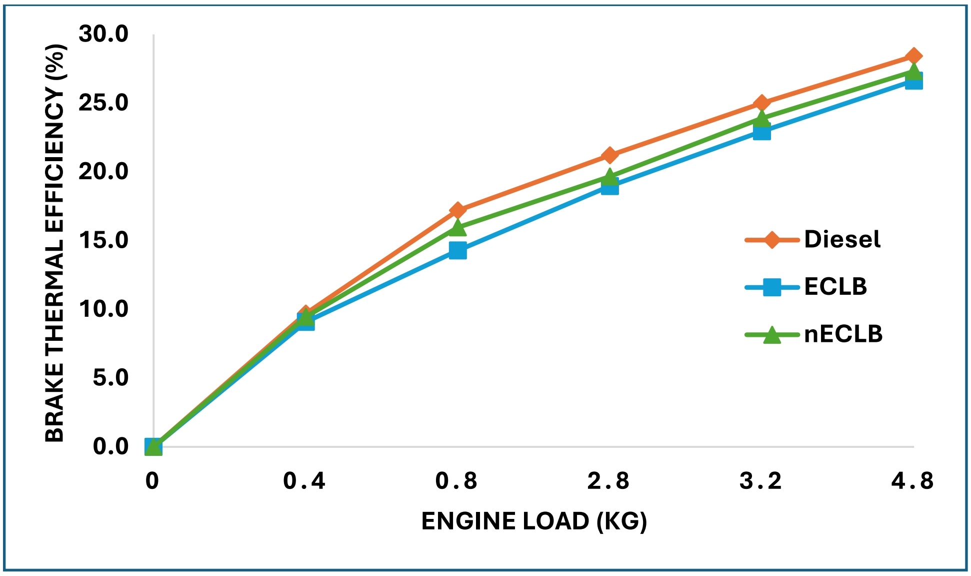

Figure 4: Study on brake thermal efficiency

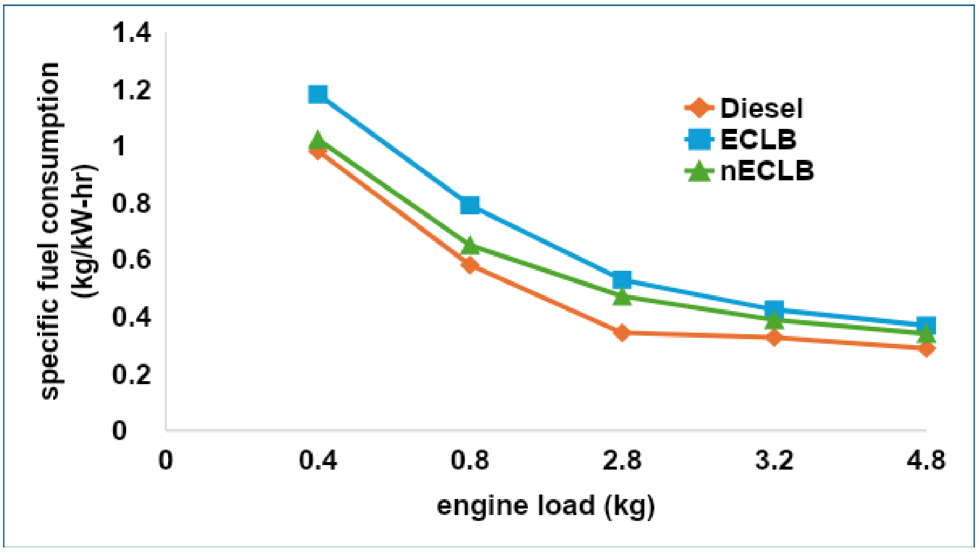

Figure 5: Study on specific fuel consumption

Specific Fuel Consumption

Fuel consumption and utilisation per unit of power and time is referred to as SFC. In general, diesel-biodiesel exhibits a higher brake specific fuel consumption (SFC) compared to diesel fuel. This is mostly attributed to the lower calorific value of diesel-biodiesel fuel relative to diesel while the engine output remains constant. Consequently, a greater amount of fuel is required to sustain the same power output. The nECLB exhibited a lesser specific fuel consumption compared to the ECLB, ranging from around 7.8% to 13.4% as shown in Figure 5. The dispersion of nanoparticles in the diesel-biodiesel combination effectively resolved obstruction and atomization, resulting in an enhanced air-fuel mixture. Furthermore, the utilisation of these nanoparticles results in an augmentation of the surface area to volume ratio, hence enhancing combustion efficiency and reducing fuel consumption (15). Oxygen in biodiesels enhances combustion in places abundant in fuel, hence enhancing combustion efficiency. Nevertheless, it is important to note that in the majority of instances, the enhancement of combustion efficiency was unable to compensate for the insufficient energy content present in the biodiesel fuel, leading to an elevated SFC. Ultimately, it is plausible that the evaporation and expansion of water droplets within the emulsion fuel during the combustion process resulted in an augmented overall rate of heat release in comparison to ordinary diesel.

Hydrocarbon Emissions

When the air-to-fuel ratio is too high, the fuel does not burn completely, which results in HC emissions. All circumstances showed a considerable rise in HC emissions, which is in line with the majority of the literature. The nECLB exhibited lesser hydrocarbon emissions compared to the ECLB, ranging from approximately 4.9% to 8.5% as shown in Figure 6. Because the surfactants' surplus carbon and hydrogen atoms were not completely burned, they ended up in the exhaust manifold, which is why this happened. One possible explanation for these elevated emissions is the greater spray penetration caused by micro explosions or by decreased combustion chamber temperatures, which can lead to spray wall impingement (16). This could be because the emulsified fuel is thicker than diesel and has different spray properties following the injector, both of which contribute to the observed increases.

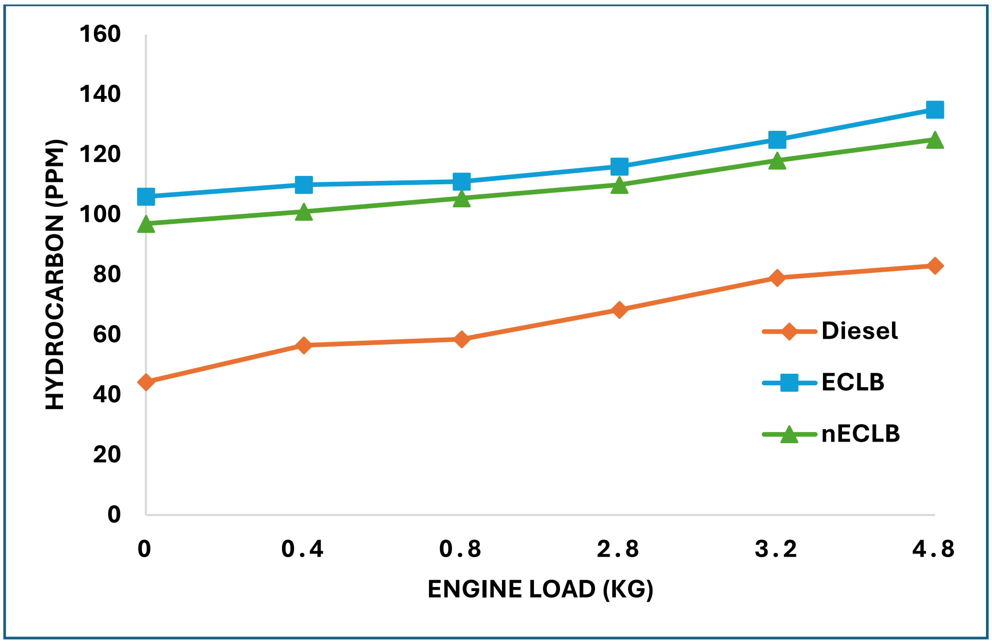

Figure 6: Study on hydrocarbon emissions

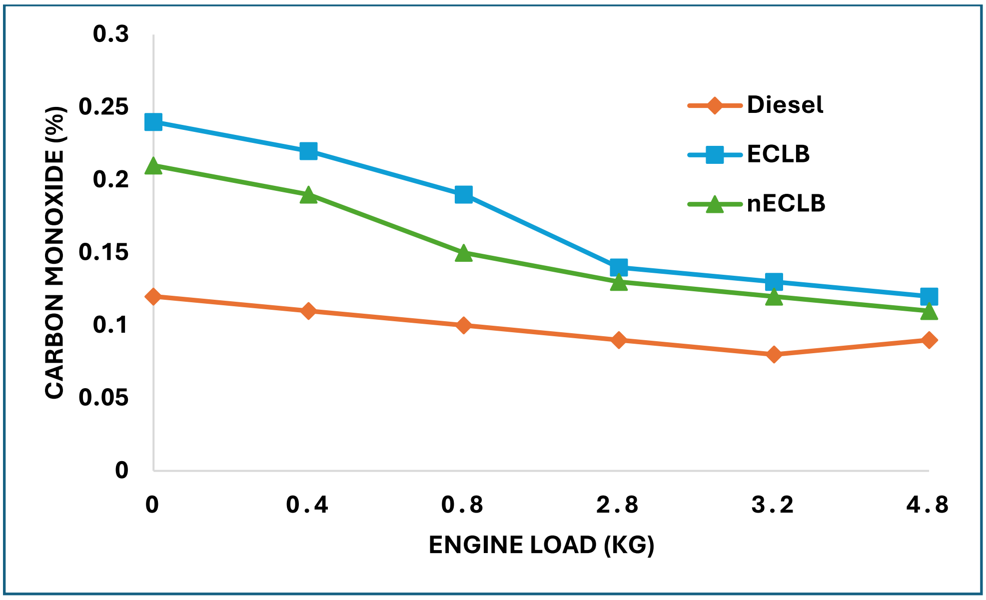

Figure 7: Study on carbon monoxide emissions

Carbon Monoxide Emissions:

Carbon monoxide (CO) emissions arise from the imperfect combustion process. Consistent with the prevailing body of research, a notable escalation in carbon monoxide (CO) emissions was reported for the emulsion under all experimental settings. The nECLB recorded carbon monoxide emissions that were approximately 7–21% lower than those recorded by the ECLB as shown in Figure 7. Both fuels have a positive correlation between engine load and CO emissions. The presence of surplus carbon atoms in the exhaust manifold can be ascribed to the incomplete combustion of surfactants, potentially resulting from lower combustion temperatures. The observed increases may possibly be attributed to the higher viscosity of the emulsified fuel in comparison to diesel, as well as the distinct spray characteristics following the injector. The reduced CO emissions and more thorough combustion of diesel fuel may be attributed to its higher cetane number, which is a result of a shorter ignition delay. There may be a way to lessen the amount of carbon monoxide emitted when engines burn nano-emulsified biodiesel (14).

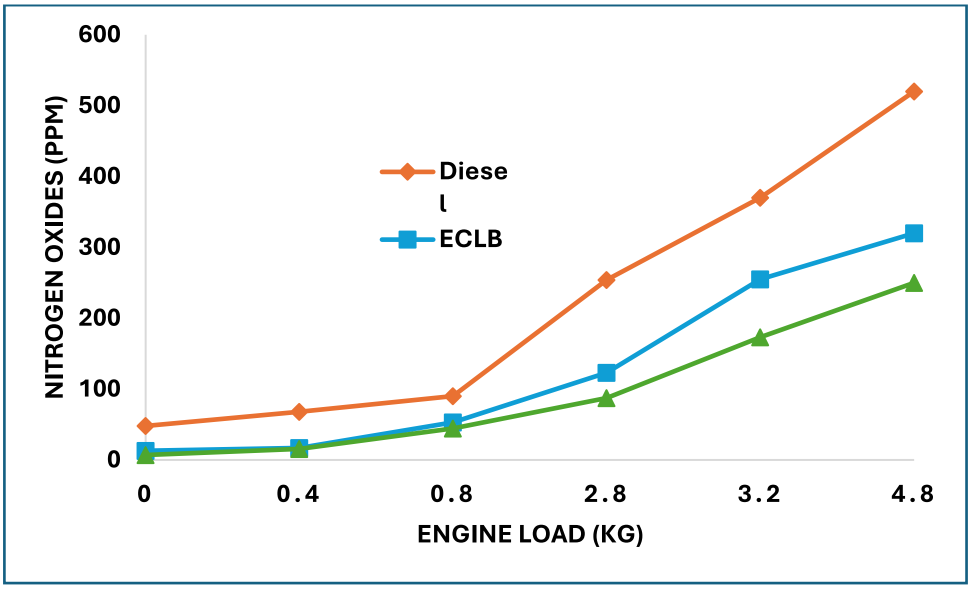

Figure 8: Study on nitrogen oxides emissions

To improve combustion efficiency, nano-emulsification is used to break down biodiesel into incredibly fine droplets distributed throughout the fuel. There are less unburned hydrocarbons, which are precursors to CO generation, because this finer dispersion allows for more thorough combustion. Further contributing to lower CO emissions is the better combustion properties exhibited by nano-emulsified biodiesel, which frequently include a reduced ignition latency and more efficient burning. Additionally, nanoparticles in the emulsion may increase combustion efficiency by lowering CO generation through improved oxygen utilisation.

Nitric Oxide Emissions

The above results align with prior studies, demonstrating that emulsion fuel effectively decreased NO levels across all engine loads in comparison to diesel fuel. The nitrogen oxide emissions of the nECLB were lower than those of the ECLB, ranging from approximately 16% to 46%. In addition, when using base diesel, nECLB exhibited reduced nitrogen oxide emissions ranging from 50% to 65% as shown in Figure 8. Thermal NO, the primary source of NO emissions, is generated through the combination of nitrogen and oxygen in the atmosphere. However, this process is hindered by the evaporation of water droplets, which reduces the temperature of the combustion chamber. The primary reason for this outcome is the heat sink effect of water, which hinders the dissipation of heat through the cylinder walls due to the physical change that occurs when water molecules absorb heat from burning. More effective combustion is achieved through nano-emulsification, which breaks down biodiesel into extremely fine droplets scattered inside the fuel. Reduced peak combustion temperatures in the engine's combustion chamber are possible results of this finer dispersion's improved fuel-air mixing. Therefore, it is possible to reduce the production of nitrogen oxides (NOx), which are by products of combustion at high temperatures. Further contributing to lower NOx emissions is the better combustion characteristics exhibited by nano-emulsified biodiesel, which includes a shortened ignition latency and more complete combustion (5, 14).

Smoke Emissions

Engine fuel systems that use nano-emulsified biodiesel significantly reduce combustion-related smoke emissions. The nECLB exhibited lower levels of smoke emissions compared to the ECLB, ranging from around 1.5% to 4.6%. In addition, when using base diesel, nECLB exhibited reduced smoke emissions ranging from 0.5% to 1.5% as shown in Figure 9. Biodiesel can be more uniformly burned by nano-emulsification, which entails breaking it down into extremely small droplets distributed throughout the fuel. Reduced smoke emissions are the result of improved fuel-air mixing and more complete combustion made possible by this finer dispersion. In addition to reducing smoke formation, nano-emulsified

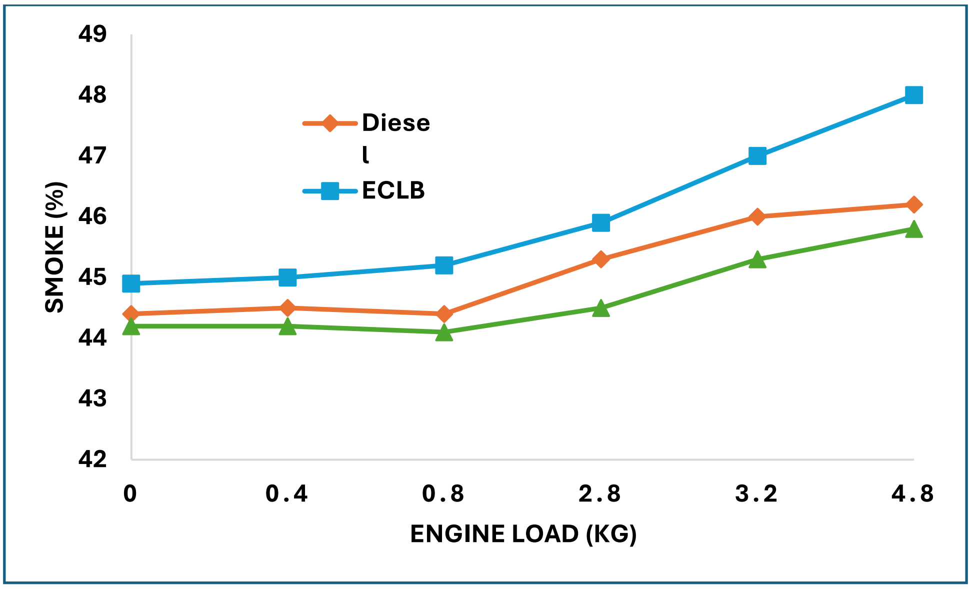

Figure 9: Study on smoke emissions

biodiesel typically has better combustion characteristics, such as a shorter ignition delay and more efficient burning. Nanoparticles in the emulsion may help combustion by increasing oxygen utilisation and decreasing smoke and soot production. Therefore, a potential strategy to reduce engine smoke emissions and promote environmental sustainability is to use nano-emulsified biodiesel (12).

Conclusion

The investigation and progression of alternative fuels act as drivers for innovation in energy technologies, nurturing economic expansion and providing sustainable answers for transportation and industry. Emulsifying biodiesel diesel fuel enhances its atomization and blending with air, consequently boosting combustion efficiency, reducing emissions, and improving fuel economy. Incorporating nanoparticles into the emulsion further amplifies the fuel droplets' surface area, thereby augmenting atomization and refining combustion efficiency. This study examines the performance and emission characteristics of a single-cylinder diesel engine when biodiesel derived from citrus limon seeds is combined with emulsified citrus limon seed biodiesel and nano-emulsified biodiesel. ECLB brake thermal efficiency was 2.57 to 4.2% lower than nECLB. Compared to the ECLB, the nECLB consumed 7.8% to 13.4% less fuel. The nECLB emitted 4.9% to 8.5% less hydrocarbons than the ECLB. The nECLB had 7–21% fewer carbon monoxide emissions than the ECLB. The nECLB emitted 16% to 46% less nitrogen oxide than the ECLB. Using base diesel, nECLB reduced nitrogen oxide emissions by 50%–65%. Compared to the ECLB, the nECLB emitted 1.5% to 4.6% less smoke. Using base diesel, nECLB reduce smoke emissions by 0.5% to 1.5%. Reduced emissions from biodiesel with nanoparticles added can improve air quality and safety for the general population. Consumers and the planet alike stand to gain from reduced fuel consumption made possible by its improved fuel efficiency. The renewable energy industry might see an uptick in activity and the addition of new jobs if nano-biodiesel technology continues to progress.

Abbreviation

Al_2O_3	-	Aluminum Oxide
BTE	-	Brake thermal efficiency
BTE	-	Brake Thermal Efficiency
CLB	-	citrus limon seed biodiesel
CO	-	Carbon monoxide
CO_2	-	Carbon Dioxide
ECLB	-	emulsified citrus limon seed biodiesel
H/C ratio	-	Hydrogen to Carbon
HC	-	Hydrocarbon
HLB balance	-	hydrophilic-lipophilic
nECLB	-	nano-emulsified citrus limon seed biodiesel
NOx	-	Nitrogen Oxides
SFC	-	specific fuel consumption

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Author Contributions

All authors contributed equally to bringing out this research article.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Ethics Approval

This research article is the authors' own original research work, which has not been previously published elsewhere. This research article is not currently being considered for publication elsewhere. The results are appropriately placed in the context of prior and existing research. All data and sources used are properly disclosed. No animal or human studies were involved.

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