Optimizing Biodiesel Blend Performance with Nano Additives in Diesel Engines for Sustainable Environmental Impact

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Abstract: Biodiesel, a sustainable alternative to traditional petroleum-based diesel, can be derived from various sources such as vegetable oils, animal fats, and recycled cooking oils. Its production and use have gained momentum due to its potential to reduce greenhouse gas emissions and diminish our reliance on fossil fuels. The combustion of fossil fuels contributes significantly to climate change and various forms of pollution. In India's agricultural sector, the production of biodiesel from non-edible plant oils has witnessed a surge in popularity. However, the current supply of these biodiesels falls short of meeting the growing demand for fossil fuels. To address this challenge, a novel biodiesel formulation using non-edible oils has been developed. This study aims to create an innovative biodiesel blend comprising 50% cottonseed biodiesel, 50% rapeseed biodiesel, and diesel with the addition of cerium oxide. The results obtained with CR20N50 indicate a substantial 15–18% reduction in fuel consumption, a notable 12–22% decrease in carbon monoxide emissions, and a significant 13–20% reduction in hydrocarbon emissions compared to conventional diesel fuel.
Keywords: Biodiesel, vegetable oil, greenhouse gas emissions, non-edible plant oils, cerium oxide, CR20N50.

1. Introduction

The escalating demand for fossil fuels is a direct consequence of the modern world's burgeoning population and rapid urbanization. This unrestrained consumption is inexorably depleting conventional fuel reserves, portending a future energy crisis. Fossil fuel combustion releases a plethora of detrimental emissions and greenhouse gases (GHGs), culminating in global warming and various forms of environmental pollution. In light of these challenges, there is an urgent imperative to seek alternative energy sources that are sustainable and environmentally friendly.

One prominent contender among alternative fuels is biodiesel-diesel blends, which has garnered significant attention from the academic community in the quest for sustainable energy solutions for diesel engines. Biodiesel, derived from diverse feedstocks, boasts qualities remarkably akin to commercial diesel fuel, positioning it as a promising alternative for diesel engines. The adoption of biodiesel has the potential to ameliorate environmental conditions in urban, suburban, and rural areas by curbing harmful emissions from the automotive sector, while simultaneously diminishing our reliance on conventional, non-renewable fossil fuels.

Addressing the challenges of vegetable oil viscosity enhancement, various methods such as mixing, pyrolysis, and emulsification have been explored, although their efficacy may not always be assured. In contrast, extensive research has demonstrated the effectiveness of transesterification in enhancing the fuel characteristics of oils and fats. Through transesterification, vegetable oil can be seamlessly converted into biodiesel, a diesel substitute that can be directly utilized in standard diesel vehicles without any modifications. Numerous attempts have been made to employ vegetable oil esters as substitutes for diesel fuel, and numerous studies have corroborated its viability. Implementing vegetable oil esters as a fuel for diesel engines has consistently exhibited reduced hazardous exhaust emissions, while maintaining comparable engine performance to traditional diesel fuel. Furthermore, biodiesel has been found to produce fewer harmful emissions in comparison to regular diesel, contributing to mitigating climate change by decreasing carbon dioxide (CO_2) emissions and diminishing the concentrations of greenhouse gases (GHGs), such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x).

Numerous research endeavors have been dedicated to identifying the most suitable non-edible oils for the production of biodiesel. The process of selecting oil seeds from suitable trees proved to be a time-intensive endeavor, particularly when contrasted with the selection of cultivable oil seeds. Biodiesel production has been thoroughly explored across multiple facets, encompassing investigations into feedstock choices, catalysts, free fatty acid content, biodiesel additives, and transesterification methods . Additionally, studies have scrutinized the advantages of biodiesel in comparison to conventional diesel, the efficacy of biodiesel substitutes, and crucial fuel characteristics such as viscosity, density, calorific value, and cetane value.

Furthermore, research has demonstrated that biodiesel derived from jatropha oil (JB), possessing the appropriate chemical and physical properties, can be effectively utilized in diesel engines. The evaluation involved the use of both conventional fuel and blends of jatropha biodiesel (JB) with tire-derived fuel throughout the testing phases. The performance parameters revealed that the adoption of these blends led to an increase in brake specific fuel consumption (BSFC) and a decrease in brake thermal efficiency (BTE) across the entire range of engine operations. In contrast to pure biodiesel, which exhibited a maximum efficiency of 28%, pure diesel achieved a maximum efficiency of 29% in experimental settings .

To further optimize engine performance, additional tests were conducted, involving variations in injection pressure, timing, and compression ratio, alongside a 100-hour durability test . Comparative analyses between diesel and blends of JB at different percentages with waste tire-derived fuel showcased a notable reduction in nitric oxide (NOx) emissions and an increase in soot emissions, albeit with an increase in brake specific fuel consumption (BSFC) efficiency .

Given the ready availability and wide usage of non-edible oils, a plethora of studies have been conducted in this domain. Biodiesel is recognized for its advantageous properties, including low exhaust gas emissions, biodegradability, and the ability to maintain a consistent level of atmospheric carbon dioxide (CO2). An additional study highlighted that augmenting the percentage of methyl ester in fuel blends led to heightened fuel density and viscosity. Moreover, higher methyl ester percentages in the blends resulted in enhanced oxidation stability when compared to single fuel sources .

Numerous research studies have consistently shown that the emissions of carbon monoxide (CO), carbon dioxide (CO2), smoke, and hydrocarbons (HC) are lower when using biodiesel compared to baseline levels. This reduction in emissions can be attributed to the oxygen content in biodiesel. However, it's worth noting that biodiesel tends to produce higher levels of nitrogen oxides (NOx) compared to conventional diesel fuel. Biodiesel derived from non-edible oils has also demonstrated the potential to aid in land remediation, which is an encouraging environmental benefit.

Another noteworthy finding is that the performance of diesel fuel is nearly indistinguishable from a combination of vegetable oil and biodiesel. The use of biodiesel from sources like Castor oil, Algae, and sunflowers in compression ignition (CI) engines has been linked to lower overall emissions, although NOx emissions tend to be higher in these cases.

Researchers have observed that a diesel engine running on a blend of 20% biodiesel and 80% diesel fuel performs well. While biodiesel blends have been shown to reduce emissions, they can also lead to increased fuel consumption, decreased power output, and higher nitrogen oxide emissions compared to pure diesel fuel. Particularly, jatropha biodiesel and its mixtures exhibit lower Brake Thermal Efficiency (BTE) and higher Brake Specific Fuel Consumption (BSFC) levels compared to diesel.

In conclusion, the literature review strongly supports the successful use of biodiesel as an alternative fuel for diesel engines. However, the availability of biodiesel is a critical factor to consider. Common biodiesel sources such as neem seed, cottonseed, and rapeseed, and their derivatives, can be readily used in diesel engines with minimal adjustments. Biodiesel, produced through the transesterification of raw vegetable oil, has consistently proven to be a viable replacement for diesel fuel.

It's important to note that pure biodiesel may not be suitable for CI engines, as various scientific studies have concurred. Instead, the most practical and sensible approach is to use a blend of biodiesel and diesel fuel in CI engines. Studies have shown that a 50% blend of cottonseed biodiesel and rapeseed biodiesel with diesel fuel can exhibit performance attributes comparable to traditional diesel. The exploration of novel biodiesel compositions containing nanoadditives for diesel engines is an avenue worth pursuing for further research to enhance performance and emissions characteristics.

2. Materials and Methods

Biodiesel, a renewable alternative to fossil fuels, can be produced from recycled cooking oils, animal fats, or vegetable oils. It holds the promise of reducing greenhouse gas emissions and enhancing energy independence compared to traditional petroleum-based diesel. However, several key factors must be considered to ensure the sustainability of biodiesel production and consumption. Firstly, the raw materials used for biodiesel production must come from sustainable sources, avoiding practices that lead to deforestation, habitat destruction, or environmental harm. Ideally, these materials should be grown using sustainable agricultural methods such as crop rotation, reduced tillage, and integrated pest management. Secondly, the production process itself should be environmentally friendly, minimizing waste, emissions, conserving water and energy, and avoiding the use of toxic chemicals. It should not compete with food production or cause social and economic issues like land grabbing or displacement of local communities. Thirdly, the use of biodiesel should result in a net environmental benefit, including reduced greenhouse gas emissions, improved air and water quality, and decreased reliance on fossil fuels.

Finally, the end-of-life management of biodiesel and its by-products should follow sustainable practices, such as recycling, reuse, or environmentally responsible disposal. Rapeseed oil is a commonly used raw material for biodiesel production due to its high oil content and favorable fatty acid composition. Biodiesel made from rapeseed oil offers lower greenhouse gas emissions compared to traditional diesel, reducing the carbon footprint. It is biodegradable, promoting natural breakdown and reducing pollution risks. Additionally, biodiesel from rapeseed oil can enhance engine performance due to its high cetane number, resulting in smoother operation and improved fuel economy. Rapeseed is a widely cultivated crop, ensuring a readily available raw material, although the production cost can be relatively high due to cultivation, harvesting, and oil extraction expenses.

Cerium oxide (CeO2) serves as a catalyst in biodiesel production, enhancing fuel quality and reducing emissions. Its addition to the transesterification process accelerates reactions, increases biodiesel yield, and minimizes unwanted by-products. Cerium oxide can also function as an oxidation catalyst, enhancing fuel stability by reducing free radical formation and oxidation, which can lead to deposits and increased emissions. Furthermore, cerium oxide contributes to reduced soot and particulate matter during combustion, improving combustion efficiency and reducing harmful pollutant emissions. Its application has shown promise in enhancing biodiesel quality and emissions reduction, but responsible usage is crucial to minimize potential environmental and health risks. Transesterification is the chemical process used to convert materials like vegetable oils and animal fats into biodiesel. It involves three primary steps: pretreatment of feedstock materials to remove impurities, mixing the pre-treated feedstock with alcohol and a catalyst in a reactor, and heating and agitating the mixture to facilitate the transesterification reaction. This reaction converts triglycerides into biodiesel and glycerol, which are then separated. The glycerol can be further processed, while the biodiesel is washed and dried to remove impurities. Transesterification is a critical and scalable process in biodiesel production, suitable for both small-scale and large-scale operations. Its simplicity and affordability make it a key component of biodiesel manufacturing.

In summary, biodiesel holds significant promise as a sustainable alternative to traditional diesel. Ensuring sustainability in biodiesel production involves responsible sourcing of raw materials, environmentally friendly production processes, achieving a net environmental benefit from its use, and sustainable end-of-life management. Additionally, the choice of raw materials, such as rapeseed oil, and the use of catalysts like cerium oxide play vital roles in enhancing biodiesel's environmental and performance attributes.

3. Experimental Details

The research was conducted with the assistance of a single vertical cylinder diesel engine employing the standard four-stroke cycle. This engine was water-cooled and maintained at a constant speed throughout the experiments. A specialized test engine, connected to an eddy current dynamometer, was employed to apply a controlled braking load during the tests. The experimental setup began with the use of conventional diesel fuel to start and warm up the engine for approximately ten minutes. Subsequently, this was replaced with biodiesel for the main experiments. Exhaust gases were then passed through an analyzer to quantify CO, HC, and NOx emissions, while a smoke meter was used to measure smoke density. Additionally, AVL software in conjunction with relevant sensors and equipment was utilized to calculate engine pressure and crank angle, as detailed in the engine pressure and crank section. The technical specifications of the test engine are provided in Table 1.

To comprehensively assess the engine's performance, multiple trials were conducted at a constant speed of 1500 revolutions per minute, with varying loads ranging from no load to full load. These load levels were incrementally increased by 25% between each of the four levels. Alongside conventional diesel fuel, several biodiesel blends were employed as test fuels, including CR20N50, CRA40N50, and CR100N50. To ensure data reliability, the engine tests were repeated three times, and the results were averaged after each iteration. Furthermore, an uncertainty analysis was carried out to validate the accuracy of the experiments.

4. Result and discussion

The BSFC ratio serves as an indicator of the rate at which fuel is burned relative to the engine's power output . Figure 1 illustrates how changes in BSFC impact braking power for a range of fuel mixtures and diesel concentrations. Experimental investigations encompassing various mixtures and loads have revealed that as BSFC increases, braking power decreases significantly. Notably, diesel blends, particularly CR20, exhibit notably lower BSFC levels when compared to other blends.

Biodiesel, owing to variations in density, viscosity, and heating value, exhibits a higher BSFC compared to conventional diesel fuel. This is because, due to the volumetric characteristics of biodiesel injection during each engine cycle, a greater volume of diesel is required to achieve the same level of output. Additionally, the higher cetane number of biodiesel in comparison to standard diesel may necessitate adjustments in injection and combustion timing, resulting in an elevation in BSFC for certain mixtures.

4.1 Exhaust gas temperature

To assess the fuel efficiency of the engine, it is imperative to measure the exhaust gas temperature (EGT), which quantifies the heat generated during fuel combustion and is typically expressed in degrees Celsius.

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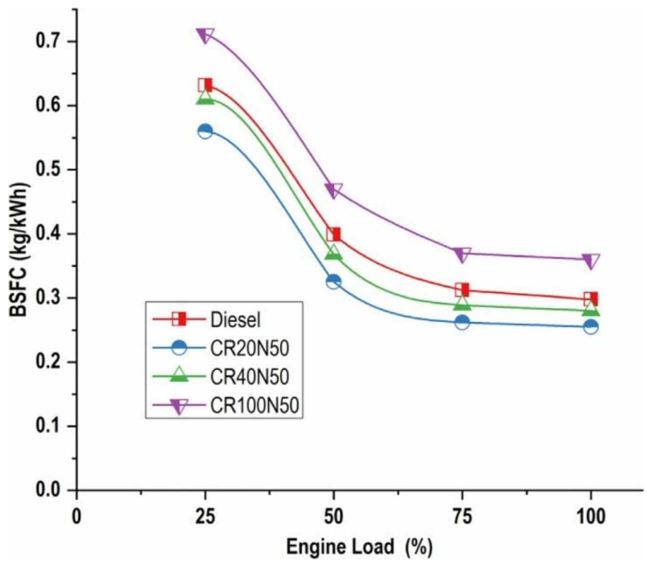

Fig 1: Study of specific fuel consumption with biodiesel**.**

The combustion process can be broken down into four distinct stages: ignition lag, uncontrolled combustion, controlled combustion, and afterburning. Notably, if there are issues like misfire, faulty injection timing, or if the engine is in the afterburning phase, EGT levels may be lower.

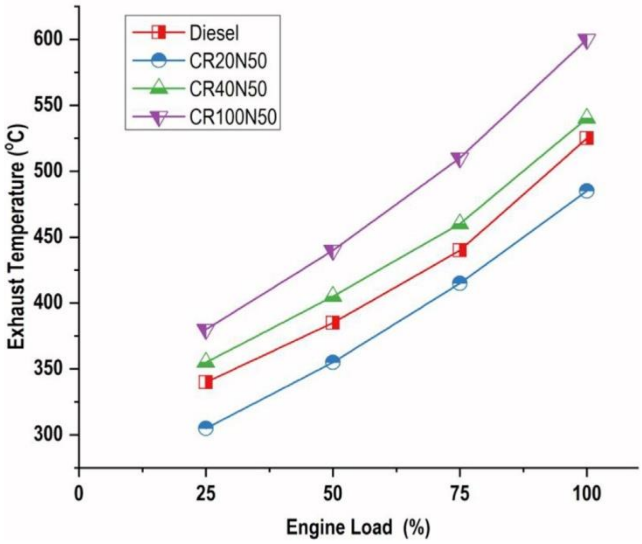

Fig 2: Study of exhaust gas temperature with biodiesel.

Figure 2 illustrates the relationship between EGT and braking power, showcasing how EGT varies based on the ratio of diesel to biodiesel used. The results reveal that EGT increases with rising power levels across different conditions and loads. Interestingly, the analysis highlights that CR20 exhibits the lowest EGT among all the evaluated blends. When substituting biodiesel for diesel, there is only a marginal uptick in exhaust gas temperature because the oxygen content in biodiesel enhances the combustion process. The slower combustion rate of CR20, owing to its higher viscosity and lower volatility, contributes to the higher exhaust gas temperatures observed. In internal combustion engines, an increase in biodiesel content results in elevated exhaust gas temperatures, as it introduces more oxygen into the mixture, leading to improved combustion and higher internal temperatures.

4.2 Hydrocarbon emissions

The primary culprits behind hydrogen emissions are inadequate combustion or the presence of unburned fuel in the combustion chamber. These issues affect both the cylinder lining, where wall wetting and flame quenching can occur, and the crack region, where fuel particles are released . Across all tested blends and loads, it has been consistently observed that hydrocarbon (HC) emissions increase with higher levels of braking power. Interestingly, among the mixtures examined, CR20 stands out for its significantly lower HC emissions. This can be attributed to a combination of factors, including reduced oxygen supply and incomplete combustion, which lead to slightly higher HC emissions from conventional diesel fuel when compared to biodiesel.

Biodiesel, owing to its higher oxygen content that facilitates more efficient combustion, results in lower HC emissions in the CR20 blend when compared to diesel. Furthermore, HC emissions tend to rise with increasing biodiesel mix ratios due to biodiesel's lower calorific value and higher viscosity, a trend that holds even when other biodiesel blends have a high oxygen content.

4.3 Carbon monoxide emission

Carbon monoxide (CO) emissions in the environment are primarily influenced by two key factors: the composition of the fuel-air mixture being burned and the carbon content present in the fuel. When carbon in the fuel reacts with oxygen from the air, it initiates combustion, resulting in the release of both carbon dioxide (CO2) and carbon monoxide (CO) into the atmosphere. Initially, the carbon in the fuel is converted into CO2, and over time, CO2 is expelled as part of the exhaust emissions. Figure 4 provides insights into how CO concentration varies with brake power for different diesel and biodiesel blends . The results consistently reveal that as brake power increases for each fuel/load combination studied, CO emissions decrease. This reduction can be attributed to the higher oxygen concentration present in biodiesel blends, which promotes more complete combustion and subsequently leads to a decrease in CO emissions. Notably, CR20 stands out for its significant reduction in CO emissions compared to other blends. In contrast, diesel fuel exhibits higher CO emissions due to its relative oxygen deficiency when compared to biodiesel blends.

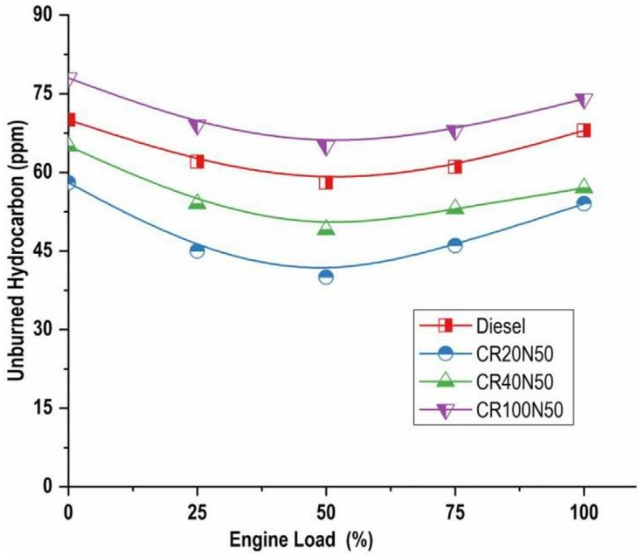

Fig 3: Study of hydrocarbon emission with biodiesel.

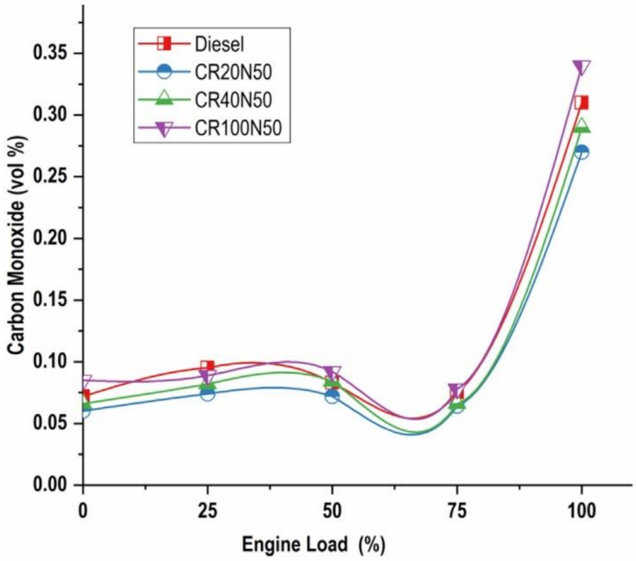

Fig 4: Study of carbon monoxide emission with biodiesel**.**

As the percentage of biodiesel in the fuel mix increases, there is a corresponding rise in carbon monoxide emissions. This is primarily due to the high viscosity of biodiesel, which hinders its atomization, leads to an uneven fuel mixture, and provides only a fraction of the fuel required for each combustion event.

4.4 Oxides of nitrogen emission

The in-cylinder air temperature plays a pivotal role in shaping the levels of nitrogen oxides (NOx) generated by an engine. NOx emissions result from the interaction of diesel fuel and ester-based biodiesel with the nitrogen present in the ambient air, constituting about 78% of the atmospheric nitrogen. Fig. 5 illustrates the NOx emissions and efficiency observed at different proportions of biodiesel blends and diesel fuel.

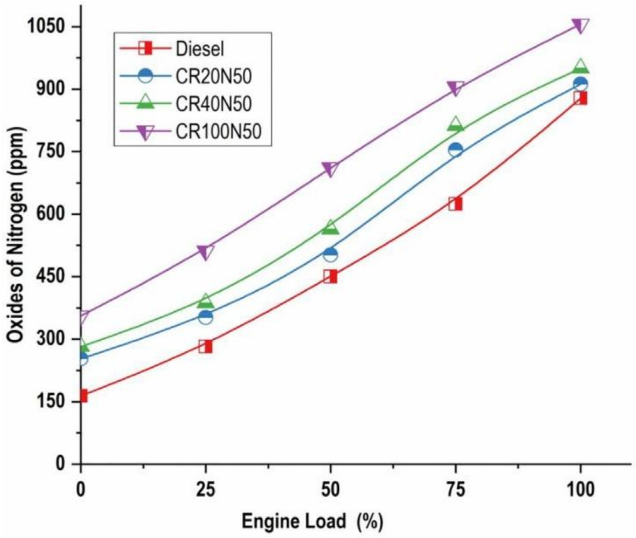

Fig 5: Study of oxide of nitrogen emission with biodiesel

The findings consistently reveal that as braking power increases across all loads, NOx emissions rise for all biodiesel blends. Notably, CR20 stands out by exhibiting a substantial reduction in NOx emissions compared to the other blend ratios. This disparity in emissions can largely be attributed to the lower oxygen content in diesel fuel, which results in relatively lower NOx emissions [24]. In contrast, when biodiesel is burned, the combustion chamber reaches higher temperatures due to the increased oxygen content, expediting the combustion process and consequently leading to higher nitrogen oxide (NOx) emissions. Fig. 5 serves as a visual representation of the NOx emission characteristics in relation to load variations with varying biodiesel blend proportions and diesel fuel.

4.5 Smoke emission

The primary culprit behind the production of smoke in compression ignition (CI) engines is the incomplete combustion of hydrocarbons, presenting an ongoing challenge in combustion technology. The quantity of smoke emitted is highly sensitive to both the fuel type employed and the specific combustion conditions. Fig. 6 provides a visual representation of smoke emissions in relation to braking power for various proportions of biodiesel and diesel.Across all blend ratios and under varying loads, the results consistently show a substantial reduction in smoke production as braking power increases. This phenomenon can be attributed to biodiesel's enhanced oxygen content, which significantly improves combustion and leads to a marked decrease in smoke production. Notably, the increased smoke intensity observed in some of the other biodiesel blends used in the experiments can primarily be attributed to their lower calorific value, which results in incomplete combustion. As the mixture ratio increases, the oxygen content rises, contributing to better combustion and ultimately reducing smoke emissions.

4.6 Biodiesel towards eco-sustainability

Biodiesel production holds significant promise for advancing environmental sustainability on multiple fronts. This sustainable fuel can be derived from diverse sources such as vegetable oils, animal fats, and even algae. When burned, biodiesel emits substantially lower levels of carbon dioxide compared to conventional diesel fuel, thus contributing to a reduction in greenhouse gas emissions and mitigating the impacts of climate change. Importantly, biodiesel can be manufactured locally, using locally sourced feedstocks, thereby reducing reliance on foreign oil and enhancing energy security.

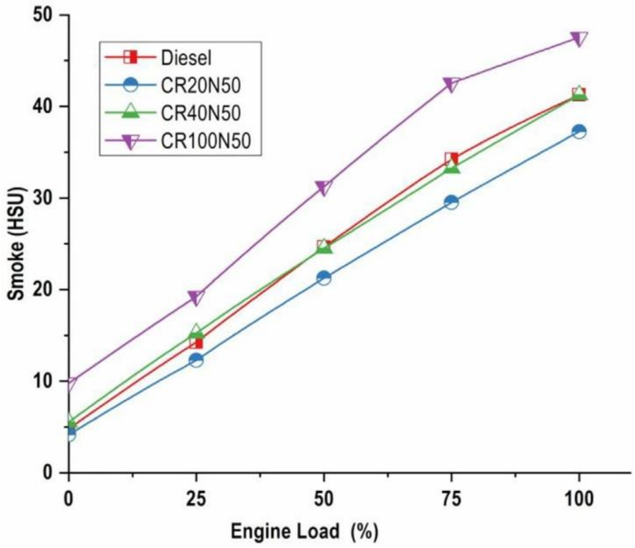

Fig 6: Study of smoke emission with biodiesel.

The production of biodiesel feedstocks can align with sustainable practices, minimizing environmental impact. For instance, certain feedstocks, like algae, can be cultivated on non-arable land without competing with food crops for resources. Furthermore, biodiesel can be produced from waste materials, such as used cooking oil, diverting these substances from landfills and fostering a circular economy. Biodiesel combustion is cleaner than that of conventional diesel fuel, resulting in fewer emissions of harmful pollutants like particulate matter and nitrogen oxides, which ultimately enhances air quality and reduces the health hazards associated with air pollution. In summary, biodiesel's potential contributions to environmental sustainability encompass carbon emissions reduction, sustainable feedstock production, waste reduction, air quality improvement, and decreased dependence on fossil fuels. However, it is crucial to ensure that biodiesel production adheres to responsible and environmentally friendly practices, taking into consideration the environmental and social implications associated with feedstock production, transportation, and processing.

5. Conclusion

Biodiesel stands as a renewable fuel sourced from plant-based feedstocks, and its domestic production using locally available resources holds a dual advantage. Firstly, it reduces dependence on imported oil, enhancing energy independence. Secondly, as the global demand for fossil fuels continues to rise, the development of innovative biodiesel blends becomes increasingly important. This research aims to create a novel biodiesel blend by combining cottonseed biodiesel, rapeseed biodiesel, diesel, and cerium oxide. Among various potential mixtures, CR20 demonstrated the most promising performance, significantly reducing exhaust pollutants. Conversely, CR100 exhibited the least favorable outcomes, emitting higher pollutant levels when compared to other blends. Although most biodiesel blends were found to increase NOx emissions, CR20 exhibited the lowest levels of this pollutant.

CR20 not only outperforms other blend ratios in terms of emissions and performance but also offers the aforementioned advantages. These results substantiate that CR20 is the most suitable choice for diesel vehicle usage due to its optimal performance, combustion characteristics, and emission profiles. Commitment to sustainability translates into tangible benefits for society, reducing carbon footprints and curbing the release of harmful toxins into the environment, thus promoting a safer and cleaner ecosystem.