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# Exploring the Impact of Titanium Dioxide Nanoparticles as Fuel Additives in Candlenut Biodiesel–diesel Blends in a CI Engine

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## ABSTRACT

Candlenut, a renewable biodiesel synthesized *via* transesterification, offers a sustainable alternative to fossil-based diesel. This study aims to produce candlenuts using a transesterification method with methanol as a catalyst. Candlenut was blended with conventional diesel in varying volumetric proportions of B20, B40, and B60 to assess its viability as an alternative fuel. Furthermore, ultrasonic dispersion was used to incorporate $TiO_2$ nanoparticles into the biodiesel blends to enhance fuel properties, and the physicochemical characteristics of the nanoadditive-enriched fuel blends were systematically analyzed. A comprehensive experimental evaluation of combustion, performance, and emission parameters was conducted on a single-cylinder diesel engine using these modified fuel blends, with baseline diesel operation as the reference. The findings indicate that the B20 biodiesel blend, which has been added with $TiO_2$ nanoparticles, shows superior combustion characteristics, improved performance, and emission characteristics in comparison to conventional diesel.

**Keywords:** Candlenut biodiesel; $TiO_2$; Brake Thermal Efficiency (BTE); $NO_x$; CO; HC.

## 1. INTRODUCTION

To overcome the global power crisis, alternatives to fossil fuels, whose reserves are dwindling at an alarming rate, must be explored. The huge variations in crude prices are determined internationally according to the market demands, and current consumption rates limit petroleum reserves to nearly 40 years (Wei *et al.* 2017). Next to the U.S.A. and China, India is anticipated to become the next highest consumer of fuel in 2025, with consumption increasing at a 7.5% annual rate. 85% of imported oil is used for transportation and energy production, and the country's economy is heavily dependent on fossil fuel imports. Presently, India imports nearly 65% of its petroleum from other countries, and the fluctuating price of crude oil has scattered the Indian economy. For the last 50 years, several countries have been evolving new crops to boost the biomass substitute base for bioenergy production (Ashwarya, 2020). Bio-oils have been considered as a replacement for diesel in engines, particularly when vegetable oil was explored as an alternative. However, the use of oil as a diesel fuel was limited due to its high viscosity, which is approximately 10 times that of fossil fuels. The properties of vegetable oils have to be transformed to become compliant with existing engines (Musthafa, 2023). Numerous vegetable oil-derived products have been projected as an additional fuel for diesel engines. ASTM has established specific standards for biodiesel under ASTM D6751, which specifies the requirements for biodiesel made from vegetable oils, animal fats, and other renewable feedstocks. This standard ensures that biodiesel meets the necessary performance and safety criteria for use in diesel engines. During the 1980s and 1990s, significant research and development efforts were dedicated to biodiesel and its potential as a renewable energy source and substitute for conventional diesel fuel. This period was critical for establishing the technical foundation for biodiesel production, performance, and commercialization. Non-edible oils acquired from plant groups such as *Jatropha* and *Pongamia pinnata* are the major commodity sources of biodiesel in India. Bio-diesel can be intermingled with petroleum diesel at any ratio to produce a bio-diesel blend or used in its pure form. Biodiesel shares many similarities with petroleum diesel and can operate in CI engines with minimal or no modification. This is one of the key advantages of biodiesel as an alternative fuel for diesel engines. The similarities in properties make biodiesel a viable substitute for petroleum diesel in various applications, such as transportation, agriculture, and industry. Biodiesel has the advantage of being compatible with the existing fuel storage infrastructure used for petroleum diesel; it does not require separate storage facilities or significant infrastructure changes. This ease of integration into current systems makes biodiesel a convenient and cost-effective alternative fuel for diesel engines. Nitrogen oxide emissions tend to be higher when using biodiesel, particularly in higher concentrations (Anil, 2024)

Candlenut trees thrive in tough and desert areas owing to their low watering requirements. Consequently, candlenut may be planted in underutilized areas, particularly in underdeveloped nations, along coastlines, riverbanks, deserts, and other unproductive regions unsuitable for culinary crops. Moreover, candlenut seed possesses a substantial oil content ranging from 30 to 60%. Consequently, candlenut oil is a viable resource for commercial biodiesel production (Shaah *et al.* 2021). The Candlenut, or *Aleurites moluccana*, sometimes referred to as Candleberry, is mostly located in Asian nations. The candlenut seed contains twenty percent oil, which comprises oleic acid, linoleic acid, and linolenic acid. It has elevated levels of unsaturated fatty acids. The performance and emission characteristics of an engine powered by mixed biodiesel are assessed. A reduced concentration of hydrocarbons and carbon monoxide was recorded in the engine utilizing blended biodiesel (Antony *et al.* 2021). Biodiesel has virtually no sulfur content, unlike petroleum diesel, which can contribute to the formation of sulfur dioxide ($SO_2$) and acid rain. This makes biodiesel cleaner in terms of sulfur emissions. Biodiesel contains no aromatics, which are compounds typically found in petroleum diesel that can contribute to the formation of soot and particulate matter during combustion (Huang *et al.* 2023).

Rezania *et al.* (2022) found that the trans-esterification process was affected by several parameters, including the ratio of (molar) oil and alcohol (1:4), the quantity of reagent (catalyst – 0.1 g), response time for accomplishment (1 hour), and the process temperature (80 °C). Under the best conditions, the maximum rate of biodiesel production was more than 92% at 80 °C for 1 1-hour reaction time. The presence of lanthanum titanate (III) nanoparticles ($LaTiO_3$ NPs) was recorded. Sayyed *et al.* (2022) conducted experiments with six sets of dual biodiesel blends with four different biodiesels. The author concluded that at full load condition, the B10 blend reduces the carbon monoxide by around 47%, and BTE increased by about 37%. The findings indicated that under low engine loads, emissions of $NO_x$, $CO_2$, and opacity rose; however, at high engine load circumstances of 3000 W, $NO_x$ emissions reduced by 34.21%, $CO_2$ emissions declined by 20.24%, and opacity reduced by 17.14% in comparison to the use of pure diesel. This study emphasizes the viability of candlenut seed biodiesel as a sustainable alternative fuel (Abed *et al.* 2019). Saravanan *et al.* (2020) conducted experiments with dual biodiesel blends (rapeseed and mahua) and concluded that for the blended fuel BL20, emission properties are reduced in comparison to pure diesel. A slight increase in $NO_x$ level was witnessed. An increase in brake thermal efficiency (BTE) and reduction in specific fuel consumption (SFC) was observed with lower value of biodiesel; the emission levels were found lower than clear diesel. Dubey and Gupta, 2018; Baskar *et al.* 2019 have carried out various experiments with dual biodiesel with diesel mixture in CI engine of different ratios, and improved in performance and emission characteristics were found.

Makepa *et al.* 2024 conducted several experiments using Jatropha biodiesel with methanol as an additive. His results indicated a good BTE for jatropha biodiesel, diesel, and dual fuel with an ration of 29%, 30.2%, and 28.7% respectively. Venkataramana and Ramanaiah (2023) selected oils from palm kernel and added methyl ester of palm kernel in the ratio of 15%, 10%, and 5% by volume and piloted a test in a VCR diesel engine with mixed diesel fuel. They concluded that the properties of biodiesel are like those of diesel (Venkataramana and Ramanaiah, 2023). Rozina *et al.* (2022) demonstrated the preparation of *Citrus medica* biodiesel by using green and eco-friendly nanoparticles (NPs) of synthesized CuO. With using aqueous *Portulaca oleracea* extract. Sateesh *et al*., (2021) used $Al_2O_3$-based Nano Fluids and Nano Partcles utilized in biodiesel blends, which resulted in higher levels of nitric oxide by 32.6%, lower smoke emissions by 23.2%, lower hydrocarbon and carbon monoxide emission levels by 18.2-21.4%, and greater brake thermal efficiency by 11.5%. Their study was aimed at enhancing the performance and emulsion properties of biodiesel derived from mahua oil by utilizing $TiO_2$ nanoparticles as an addition. Blended biodiesel and nanoparticle-based biodiesel reduce CO emissions by 37.42% and 46.54%, respectively, compared to diesel mode. Blended biodiesel reduces HC emissions by 22.54% and nanoparticle-based biodiesel by 28.4% compared to diesel mode. Blended and nanoparticle-based biodiesels reduce $NO_x$ emissions by 4% and 2.3%, respectively, compared to diesel mode (Jit *et al.* 2023). $NO_x$ is a pollutant that contributes to the formation of ground-level ozone, acid rain, and smog. The reason for the increase in $NO_x$ is that biodiesel generally has a higher cetane number (which improves ignition quality), leading to higher combustion temperatures. These higher temperatures can promote the formation of $NO_x$ (Dhairiyasamy and Murugesan, 2024). The increased concentration of $TiO_2$ nanoparticles (40 ppm) in the C20D resulted in soot nanoparticles measuring 19 nm, which were smaller than the 23 nm soot nanoparticles generated from the lower concentration of $TiO_2$ nanoparticles (25 ppm) incorporated into the C20D (Fayad *et al.* 2023). Some researchers examined $TiO_2$ nano-additive in micro-algae biodiesel. They observed that $TiO_2$ nano-additive reduces CO, HC, and $NO_x$ emissions. They also discovered that $TiO_2$ doses of 25, 50, 75, and 100 ppm decreased brake thermal efficiency (Verma, *et al*. 2023). One potential way to mitigate this issue is the integration of an Exhaust Gas Recirculation (EGR) system. EGR reduces $NO_x$ emissions by recirculating a portion of the exhaust gases back into the engine's combustion chamber, which helps lower the peak combustion temperature and, in turn, reduces $NO_x$ formation (Esakki *et al.* 2022).

In this work, raw candlenut oil is transformed into biodiesel through the transesterification process. After that, biodiesel is blended with diesel in the ratio of B20, B40, and B60, with $TiO_2$ as nanoparticles, at 100 ppm. Furthermore, the performance and emission characteristics of CI engines are evaluated with blended fuel and neat diesel.


**Fig. 1: Experimental engine setup**

## 2. MATERIALS AND METHODS

The present study uses candlenut biodiesel, synthesized using a dual-phase transesterification procedure, combined with diesel fuel and supplemented with $TiO_2$ nanoparticles. These fuel blends were employed in a water-cooled, four-stroke, single-cylinder variable compression ratio engine as shown in Fig. 1. Biodiesel can be produced by the transesterification process of vegetable oils. Sodium hydroxide and potassium hydroxide are examples of homogeneous bases that act as catalysts, which allows the possible reaction of triglycerides derived from oils with alcohols like methanol or ethanol. In this study, the B100 biodiesel is blended with diesel fuel at varying volume proportions (20, 40, and 60), and the physicochemical properties are presented in Table 1. Furthermore, the test blends of DCN (diesel + CN biodiesel+ Nanoparticles) as B20, B40, and B60 were evaluated to find the performances and emissions characteristics of the engine without any modification made on it and keeping the compression ratio as 17.5, running at constant speed 1500 rpm. Five Gas Analyzer (AVL DI GAS 444N) measured the CO, HC, and $NO_x$. Smoke meter (AVL 437C) is measured the smoke opacity. The test engine's configuration is included in Table 2.

**Table 1. Properties of biodiesel and diesel**

| Description | B0 | B100 |
|---|---|---|
| Viscosity @40°C, cSt | 3.2 | 4.8 |
| Flash point, °C | 70 | 156 |
| Cetane Number | 45.8 | 33 |
| heating value, kJ/kg | 43,260 | 38730 |
| Density, kg/m$^3$ | 837 | 912 |

**Table 2. Research engine specifications**

| | |
|---|---|
| Manufacture | Kirloskar, AV-1, Water-cooled, 4 Stroke |
| Type | Direct Diesel Injection |
| Fuel | Diesel |
| Bore x Stroke | 87.5 mm x 110 mm |
| Compression Ratio | 17.5 |
| Speed | 1500 rpm |
| Nozzle Opening Pressure | 200 bar |
| Rated Power | 5.2 kW @ 1500 rpm |
| Cycle | Four Stroke |
| Cooling | Water-cooled |

## 3. RESULTS AND DISCUSSION

### 3.1 Specific Fuel Consumption (SFC)

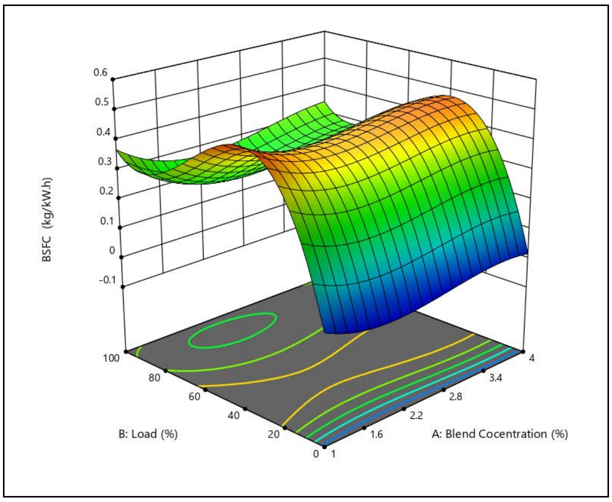


**Fig. 2: Variations in SFC *vs.* Load**

Specific fuel consumption of candlenut bio-diesel under various loads in the engine for different mixes were illustrated in Fig. 2. Specific fuel consumption was found to be less with an increase in percentage of load for all ratios of blended biodiesel. This is mainly because of the kinematic viscosity and the good calorific values of the biodiesel. The chart shows that as the load increases, SFC decreases. SFC is continuously lower for DCN blends (B20) than for diesel with biodiesel blends over a range of volume proportions at every loading rate.

### 3.2 Brake Thermal Efficiency (BTE)

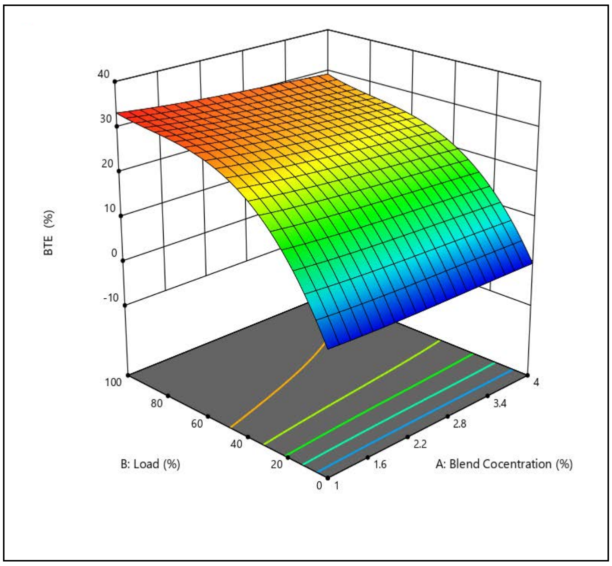


**Fig. 3: Variations of BTE *vs.* Load**

Fig. 3 depicts that BTE rises during increase in break power for diesel and candlenut biodiesel mixes. The brake thermal efficiency of diesel is higher compared to candlenut biodiesel blends; in addition, it is well known that the BTE of lower-ratio blends is closer to that of pure diesel compared to candlenut biodiesel blends. This disparity in BTE for various biodiesel mixes is owing to higher viscidness and reduced instability, which leads to deprived blend formation. This results in a reduction of BTE for candlenut biodiesel mixes. Additionally, enhanced fuel film formation and higher evaporation rates in the combustion chamber are the result of the combined impact of increased specific surface area, as illustrated in Fig. 3, for diesel with biodiesel blend (B20) containing $TiO_2$ nanoparticles. Subsequently, this leads to an increase in the BTE of DCN blends at all loading rates.

### 3.3 Cylinder Pressure

Figure 4 represents the variations of Cylinder pressure with respect to the different test fuel blends at various load conditions. It was witnessed from the experiment that the maximum pressure of cylinder of candlenut biodiesel mixes is lesser than that of pure diesel. It is primarily due to the higher viscosity and smaller volatility of candlenut biodiesel. From Fig. 4, we can observe that the maximum engine cylinder pressure of diesel is 66 kg/cm$^2$ and B20 is 59 kg/cm$^2$.

It is primarily ignition delay time and lesser air/diesel or biodiesel mixture, which is accessible during the combustion and ignition. Hence, it has added burning in the diffusion-burning stage than in the pre-mixed burning point. Because of the above reasons the maximum engine cylinder pressure is smaller for candlenut biodiesel/diesel mixes.

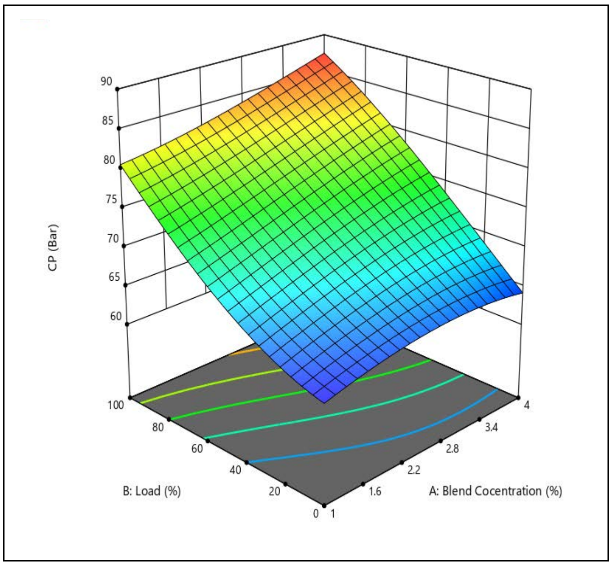


**Fig. 4: Variations of BTE *vs.* Load**

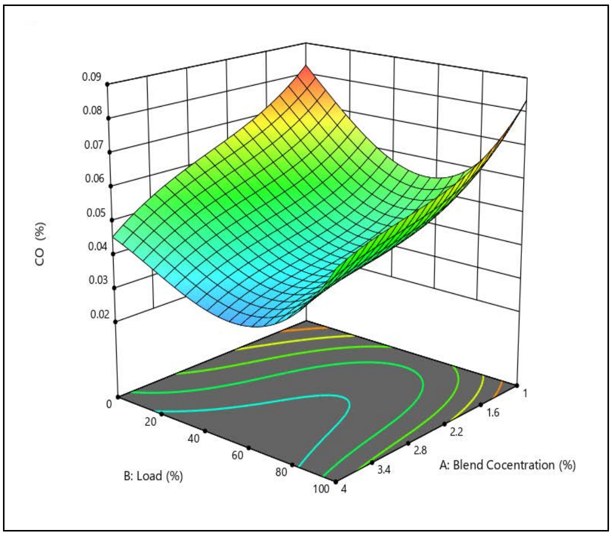


**Fig. 5: Variations of CO emission *vs.* Load**

### 3.4 Carbon Monoxide (CO)

Emission of carbon monoxide with different proportional of load for candlenut biodiesel mix of 20, 40, and 60% with diesel and pure diesel are depicted in Fig. 5. Lesser emission of CO was observed with increase in engine load during part load and an increase during full load. It might be due to the maximum fuel consumption due to a rich air-fuel mixture. It can be concluded that throughout the engine load, there is a substantial drop in CO emission of the candlenut biodiesel blend B20 in comparison to neat diesel. It is primarily because of the higher oxygen level in biodiesel than in neat diesel. The effects of the combustion process on temperature and the role of additional oxygen from biodiesel and nanoparticle-specific surface areas on CO emissions are highlighted. Similar results show that CO emissions decrease with nanoparticle blended diesel + biodiesel blends for volume proportions of 20 to 100%, compared to $TiO_2$ blends. This emphasizes the role of combustion characteristics in reducing CO emissions.

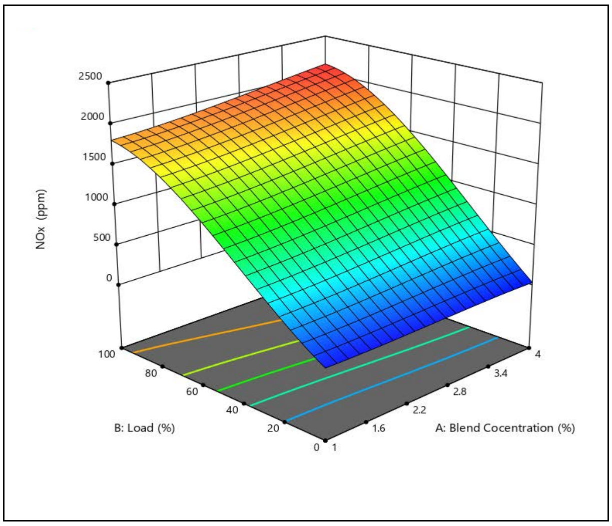


**Fig. 6: Variations of $NO_x$ emission *vs.* Load**

## 3.6 Hydrocarbon

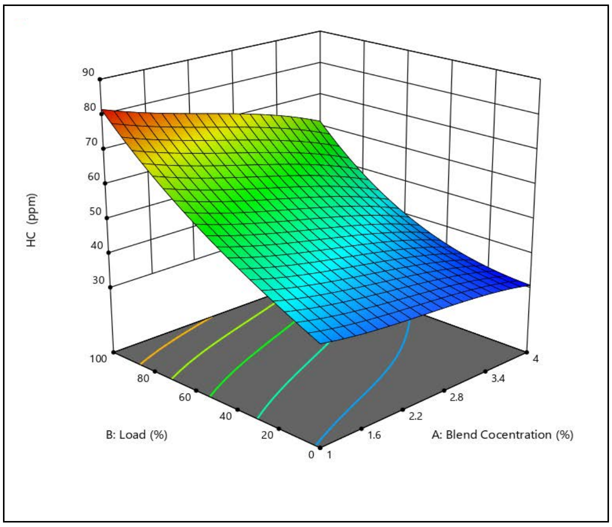


**Fig. 7: Variations of HC emission *vs.* Load**

## 3.5 $NO_x$

From the $NO_x$ emission of diesel fuel and candlenut biodiesel blend (Fig. 6), it was discovered that release of $NO_x$ was higher than pure diesel fuel for all candlenut bio-diesel. The increase in combustion temperature and the increase in flame temperature could be key reasons for the higher $NO_x$ emissions observed when using biodiesel or vegetable oil blends in diesel engines. $NO_x$ formation was mostly due to a surge in cylinder combustion temperature and percentage of oxygen level. From the test results, it was found that higher $NO_x$ release observed from test blends compared to pure diesel. Moreover, the inclusion of $TiO_2$ nanoparticles and increased oxygen content in the fuel led to reduced $NO_x$ formation in DCN blend B20, compared to diesel.

Variations of HC emission with engine load while using various mixes of candlenut biodiesel and pure diesel is shown in Fig. 7. For all the loads tested, HC emissions were lesser at engine load, although it has increased during higher engine load. This is mainly because of larger fuel particle size and timing of injection; chocking of the nozzle also changed the combustion timing. It is mainly because of lesser oxygen being present during more fuel injection at higher loads. The key cause of unburnt hydrocarbon is owing to lower ignition delay linked with fuels having higher cetane number. The above results were in line with the references. Fig. 7 demonstrates that blends containing $TiO_2$ nanoparticles contribute to better fuel film formation, evaporation rates, and reduced UBHC emissions in the combustion chamber (Chivu *et al.* 2023).

## 3.7 $CO_2$ Emission

Fig. 8 represents the $CO_2$ emission of candlenut biodiesel at 20, 40, and 60% with pure diesel at different engine loads. During the increase in engine load, an increase in $CO_2$ release was observed which might be due to greater fuel consumption linked with the increase in load. Lower $CO_2$ release was observed for various mixes of biodiesel candlenut and compared with clean diesel fuel. The drop in $CO_2$ release can be attributed to the greater oxygen content in biodiesel mixes of candlenut biodiesel B20 with $TiO_2$ as compared to pure diesel fuel.

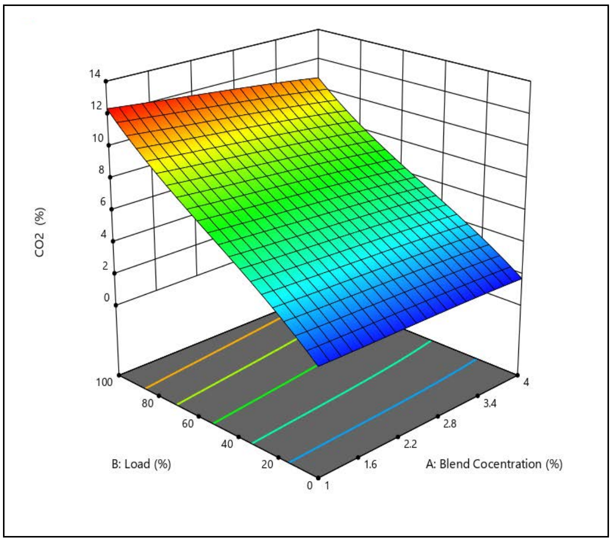


**Fig. 8: Variations in $CO_2$ emission *vs.* Load**

### 3.8 Smoke Opacity

The smoke opacity of all candlenut biodiesel mixtures with various engine loads and pure diesel is shown in Fig. 9. For comparison purposes, clean diesel smoke opacity is also added to the graph. It is primarily owing to change in fuel usage in the higher side which causes rich air-fuel mixture. As the higher percentage of oxygen molecules is more and carbon content is small in the candlenut biodiesel in comparison to pure diesel, it caused great burning, and hence, reduction in smoke emission was observed. Soot formation, a key contributor to smoke, is influenced by Unburned Hydrocarbons (UBHC) emissions and carbon residuals combined with ash and metallic particles during the exhaust stroke. Furthermore, it reduces smoke emissions in $TiO_2$ nanoparticle-blended diesel–biodiesel blends, indicating improvements in combustion characteristics. Fig. 9 reveals that biodiesel blend B20 containing nanoparticles contributes to enhanced fuel evaporation, reduced ignition delay, and decreased smoke emissions in the combustion chamber.

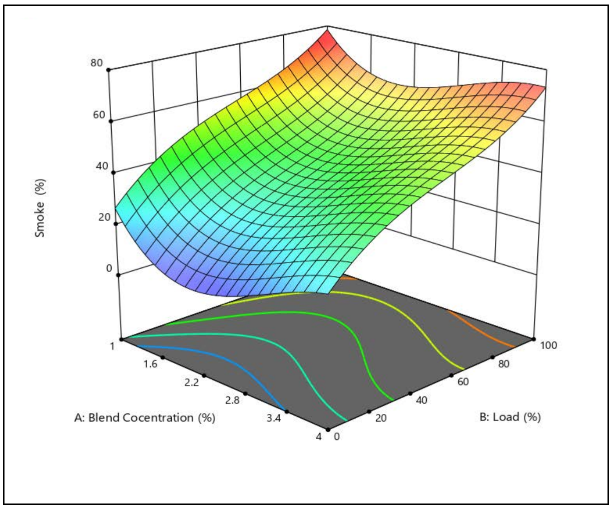


**Fig. 9: Variations in Smoke opacity *vs.* Load**

## 4. CONCLUSION

A direct injection diesel cylinder with a single cylinder was used to run with different blends of candlenut biodiesel in the ratio of 20%, 40%, and 60% with clean diesel. Performance studies of engine and exhaust emission characteristics were calculated during several engine loads of 0, 25, 50, 75, and 100% at a speed of 1500 rpm. Emissions such as CO, HC, smoke opacity, $CO_2$, and $NO_x$ were examined. Brake thermal efficiency, cylinder pressure and specific fuel consumption were also studied and related with pure diesel.

The investigation of $TiO_2$-incorporated candlenut biodiesel mixtures demonstrates substantial improvements in combustion, performance, and emission attributes. Among these mixes, B20 with 100 ppm $TiO_2$ fuel additive is the superior option, exhibiting the least difference from pure diesel fuel regarding in-cylinder peak pressure, brake thermal efficiency, and brake-specific fuel consumption. This blend demonstrates improved emission reductions for CO, HC, and smoke, although $NO_x$ emissions decrease inversely with increasing quantities of candlenut biodiesel. The potential for improved combustion efficiency and decreased emissions using nanoparticle-enhanced fuels highlights the necessity for further study in this promising domain. The car industry's pursuit of cleaner and more sustainable propulsion systems suggests that the findings of this study may contribute to a more environment-friendly and energy-efficient future.

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## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.



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