Scientia cum Industria

eISSN 2318-5279

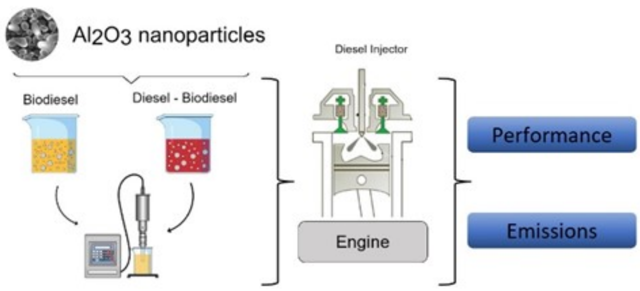
Original Research

Study of the influence of adding Al_2O_3 nanoparticles to biodiesel on the performance and emissions characteristics of a diesel engine

Marcos Moresco Smaniotto[1]
Josimar Souza Rosa[2]
Giovani Dambros Telli[1]*

[1] University of Caxias do Sul, Caxias do Sul, RS, Brazil.
[2] Instituto Federal de Educação, Ciência e Tecnologia Sul-Rio-Grandense – IFSul, Caxias do Sul, RS, Brazil.
* Corresponding author: gdtelli@ucs.br

Received: December 18, 2023
Revised: February 19, 2024
Accepted: February 27, 2024
Published: March 4, 2024



Abstract: The use of biodiesel in compression ignition (CI) engines has great potential to reduce emissions and the dependence on fossil fuels. However, the complete adoption of biodiesel in CI engines is limited by several drawbacks. A promising solution to these problems is the addition of nanoparticles to biodiesel or diesel-biodiesel blends. Hence, this paper studies the impact of adding aluminum oxide (Al_2O_3) nanoparticles on the performance and emission characteristics of a diesel engine running on biodiesel and a mixture of diesel and biodiesel. Al_2O_3 nanoparticles were added at concentrations of 50, 100 and 150 ppm to biodiesel (B100) and a mixture of 50 % biodiesel and 50 % commercial diesel (B50). The results indicated an increase in fuel conversion efficiency and a reduction in specific fuel consumption. The highest fuel conversion efficiency was 26.5 % for B50 with 100 ppm of Al_2O_3, indicating an improvement of around 28.6 % compared to diesel fuel (B0). In general, CO emissions were reduced with the addition of nanoparticles, with a maximum reduction of 42.8 % for B100 with 50 ppm Al_2O_3 compared to B0. The highest reduction in NO_X emissions was 30.3% for B50 with 100 ppm Al_2O_3 compared to pure diesel B0.

Keywords: Nanoparticles, aluminum oxide, Al_2O_3, biodiesel, engine.

Introduction

Internal combustion engines (ICE) are one of the most common power sources in the transportation sector, especially the compression ignition engines (CI). The main energy source for these machines are fossil fuels-gasoline and diesel fuel. The use of fossil fuels is a major issue for the environment due to greenhouse gas emissions (GHG) and pollutant emissions, which contribute to global warming, climate change, and air pollution [1,2].

One way to solve the environmental concern about ICE is replacing fossil fuels with renewable fuels that have cleaner combustion compared to fossil fuels. Generally, renewable fuels have the potential to achieve near zero CO_2 emissions in Well-to-Wheel balance, decreasing greenhouse gas emissions levels [3]. In the literature, many renewable fuels have been investigated and have emerged as a promising candidate to replace conventional fuels, such as biodiesel [4,5], ethanol [6,7] and straight vegetable oils [8,9].

In compression ignition engines, biodiesel seems to be an attractive alternative to diesel fuel due to its biodegradability, non-toxicity, and lower emissions of certain pollutants such as sulfur and particulate matter (PM) [10]. Biodiesel is derived from various sources, such as vegetable oils and animal fats, through the transesterification process [11]. Biodiesel production consists of the use of vegetable oils mixed with some primary alcohols and catalysts to convert the raw material into fatty acid methyl esters (FAMEs), which have characteristics similar to conventional diesel fuel. The main raw material used for biodiesel production in Brazil is soybean, representing 81 % of the biodiesel produced [12].

However, the complete adoption of pure biodiesel in CI engines is limited by certain difficulties and drawbacks [13]. Biodiesel has a higher density and viscosity compared to diesel fuel. As a consequence, it leads to fuel injection problems, poor atomization, spray formation, and fuel-air mixing, affecting the combustion process [14]. Biodiesel also has a lower heating value than diesel fuel, which increases fuel consumption and reduces fuel conversion efficiency [15]. Another disadvantage is the increase in nitrogen oxide (NOx) emissions from biodiesel combustion in CI engines as a result of its higher oxygen content compared to conventional diesel fuel. These drawbacks have hindered the complete use of pure biodiesel and motivate research in new solutions to overcome these problems and improve its properties and performance in CI engines [16].

In the literature, a promising solution to minimize the drawbacks of using biodiesel in CI is the incorporation of nanoparticles into biodiesel blends or diesel-biodiesel blends [17]. The use of nanoparticles has the potential to enhance thermophysical properties, heat transfer rate, catalyst reactivity, and stabilization of the fuel mixture [18]. Nanoparticles have dimensions ranging from 1 to 100 nm, have a high surface area -to-volume ratio, and have enhanced reactivity, making them attractive for several applications.

Metal oxide nanoparticles added to biodiesel blends or diesel -biodiesel blends have the potential enhance the combustion process and engine performance. Some advantages of nano additives are the improvement in thermophysical properties, improving fuel injection, spray formation, atomization, and vaporization of biodiesel. As a result, it leads to better fuel-air mixing and a shorter ignition delay [16,18]. Since nanoparticles have a larger surface area, they facilitate the contact between fuel and air, helping fuel oxidation and reducing unburned hydrocarbons and particulate matter emissions [19]. Additionally, nanoparticles can increase the energy content of biodiesel blends, improving thermal efficiency in CI engines. Nanoparticles also exhibit catalytic properties due to their oxygen content and their higher surface-to-volume ratio, which improves the combustion process [20]. Finally, the use of nanoparticles as additives also increases thermal conductivity, improving combustion stability, and overall engine performance [21].

Among nanoparticles, metal oxides of ZnO, CuO, Al_2O_3, TiO_2, and $FeCl_3$ are commonly used as fuel additives [22–25]. Alumina (Al_2O_3) is generally widely used in industrial applications and is available in large quantities. Anchupogu et al. [26] investigated the effects of aluminum oxide nanoparticles as additives to a mixture of 20 % biodiesel (extracted from *Calophyllum inophyllum*) and 80 % diesel. The concentration of alumina used was 40 ppm. The test was carried out on a diesel engine, with 20 % exhaust gas recirculation (EGR). The results showed an increase of 5.0 % and 7.7 % in thermal efficiency and a reduction of 11.5 % and 17.8 % in specific fuel consumption with the use of Al_2O_3 and Al_2O_3 + EGR, respectively, compared to baseline fuel. The addition of Al_2O_3 also reduced CO, HC, NO_X emissions, and smoke opacity. Sharma et al. [27] studied the application of aluminum oxide nanoparticles as an additive to biodiesel. The nanoparticles have sizes of 20 nm, and 30 nm and concentrations were 25 ppm, 50 ppm and 75 ppm. The authors reported an increase in engine performance and NO_X emissions, as well as reductions in brake-specific fuel consumption, HC, CO, and smoke opacity.

Kaushik et al. [28] studied the addition of 25 ppm and 50 ppm concentrations of alumina nanoparticles in diesel and biodiesel blends (B0 to B100) to evaluate the performance and emissions of a single-cylinder diesel engine. The results indicated that the engine performance was improved with a reduction in CO emissions of 37 % and 31 % in HC emissions. Akkoli et al. [29] explored the addition of alumina (in concentrations of 5 mg/l, 10 mg/l, 15 mg/l and 20 mg/l) to a mixture of fish oil methyl ester and biodiesel. The authors found some advantages compared to conventional diesel fuel. The results showed reductions of 48.3 % in CO, 17.5 % in HC and 16.5 % in NO_X emissions levels. Soudagar et al. [30] also explored the use of Al_2O_3 nanoparticles in 20 % biodiesel and 80 % diesel blends. The authors quote that aluminum oxide nanoparticles in B20 fuel demonstrated an overall improvement in engine characteristics.

The addition of aluminum oxide nanoparticles as additives in biodiesel has the potential to overcome the inherent limitations of biodiesel and improve engine performance. In this regard, this paper studies the influence of adding Al_2O_3 nanoparticles to biodiesel and diesel-biodiesel mixtures on the performance and emissions characteristics of a diesel engine. The Al_2O_3 nanoparticles were incorporated into biodiesel and a biodiesel-diesel mixture at concentrations of 50, 100 and 150 ppm. In the literature, most studies explored a maximum Al_2O_3 nanoparticle concentration of 75 or 100 ppm in the base fuel. In this work, a maximum concentration of 150 ppm was evaluated. Furthermore, the experiments were carried out using Brazilian biodiesel, which in this case is exclusively produced from soybeans. This work will help improve knowledge about the use of Al_2O_3 nanoparticles in biodiesel blends. In addition, it will also help reduce the dependence of fossil fuels and reduce the GHG and pollutant emissions by replacing a fossil fuel with a renewable fuel.

Experimental Section

Fuel preparation

In this study, eight different fuel samples were investigated. The two baseline fuels are pure diesel fuel (B0) and pure biodiesel (B100). The diesel fuel is the S500, which is commonly found in fuel stations in Brazil (containing 500 ppm sulfur). Biodiesel was obtained from Bocchi Agrobios and is 100 % produced from soybean oil. The main properties of the baseline fuels are shown in Table 1.

The oxide of aluminum nanoparticles (Al_2O_3) nanoparticles was manufactured by Sigma-Aldrich Brazil. According to the manufacturer of the nanoparticles, it has a molecular weight of 101.96 g/mol and a particle size smaller than 50 nm, measured by the transmission electron microscopy (TEM) technique.

One of the most important steps in fuel preparation is to achieve a homogeneous and stable blend. If the nanoparticle is not prepared correctly, it is possible to have some clusters, agglomeration, sedimentation, and also some possible problems

Sci. cum Ind. **2024**, 13(1), e241301. DOI: 10.18226/23185279.e241301

in the engine fuel system. In the literature, the most common method of preparing homogeneous and stable test fuels with nanoparticles is the ultrasonication technique [19]. In this way, the materials are exposed to ultrasonic waves for a certain duration and a more homogeneous mixture can be achieved. This technique consists of generating high-frequency acoustic waves in the mixture, generally above 20 kHz. This process is capable of agitating the fluid and nanoparticles on a microscopic scale, causing acoustic cavitation in the mixture, increasing the miscibility of the solution, and enabling it to be homogenized. In this regard, we used the Hielscher ultrasonicator, model UP400S, for 5 minutes at 24 kHz to prepare homogeneous and stable fuel samples. All this process was also done with the help of a Shimadzu digital scale.

Table 1. Fuel properties [31,32].

Fuel properties	Diesel	Biodiesel
Density (g/cm^3) at 20 °C	0.843	0.881
Lower heating value (MJ/kg)	42.8	37.3
Carbon (%, mass)	86.08	79.3
Hydrogen (%, mass)	12.44	13.2
Nitrogen (%, mass)	0.04	-
Oxygen + halogens + ashes (%, mass)	1.4	7.5
Sulfur (%)	0.04	-

The Al_2O_3 nanoparticles were mixed with pure biodiesel at concentrations of 50, 100 and 150 ppm. The Al_2O_3 nanoparticles were also mixed with a blend of 50 % biodiesel and 50 % diesel fuel at the same concentrations of Al_2O_3 (50, 100 and 150 ppm). Figure 1 presents the blends of biodiesel and diesel-biodiesel (50 % - 50 %) mixed with Al_2O_3 nanoparticles.

Fuel samples are defined as: 100 % diesel fuel (B0), 100 % biodiesel (B100), 50 % biodiesel and 50 % diesel fuel (B50). These alumina nanoparticles were added to the B100 and B50 sample at concentrations of 50, 100 and 150 ppm.

Figure 1. Biodiesel and diesel sample mixed with Al_2O_3 nanoparticles.

Experimental test

The goal of this paper is to evaluate the impact of the use of aluminum nanoparticles in diesel/biodiesel fuel on the performance and emissions characteristics of the CI engine. The experiments were carried out on a single-cylinder, compression ignition engine with direct injection. No modifications have been made to the original engine. Figure 2 illustrates the experimental scheme. The main characteristics of the engine are shown in Table 2. The engine was coupled to an electric generator running at a constant speed of 1800 rpm and producing 3.2 kW of electric power at 60 Hz, which represents around 320 kPa of brake mean effective pressure of the engine.

Table 2. Engine characteristics.

Parameter	Specification
Type	Single cylinder, compression ignition, air forced cooling
Bore x Stroke (mm)	90 x 105
Displacement (cc)	668
Compression ratio	20:01
Maximum power (kW/rpm)	8.8/2400
Injection type	Direct injection
Injection pressure (bar)	180
Injection timing	21° BTDC

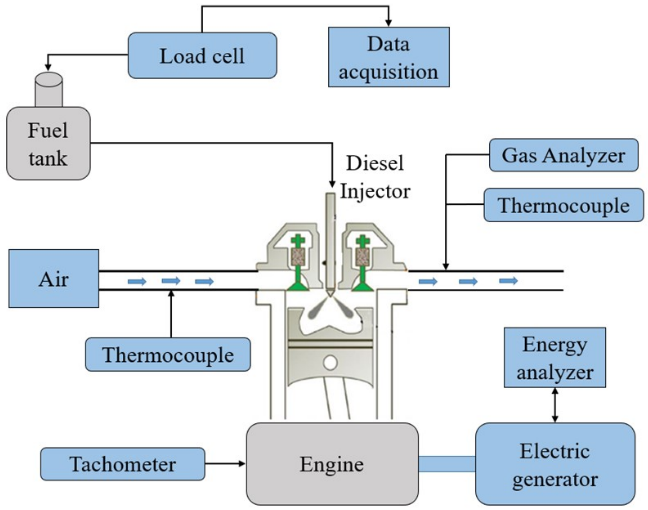


Figure 2. Experimental scheme.

The electric energy produced was dissipated on the electric resistances immersed in running water. The frequency, voltage, current, and power of the electric generator were monitored by an energy analyzer (Embrasul RE6000). The engine speed was verified by means of a tachometer and the engine exhaust temperature was verified by means of a K-type thermocouple. The thermocouple was installed in contact with the combustion gases in the engine exhaust manifold at a point closest to the outlet of the combustion chamber. Exhaust emissions were investigated using a MRU Instruments Optima7 gas analyzer. This device allows the acquisition of the emissions levels of gases such as O_2, CO_2, CO, NO, NO_2, NO_X, and SO_2, as well as the relative air-fuel ratio.

Sci. cum Ind. **2024**, 13(1), e241301. DOI: 10.18226/23185279.e241301

Fuel consumption was measured using a load cell. The data was recorded using an HBM QuantumX MX440B data acquisition board with Catman software. The change in mass over a certain period of time and the fuel mass flow rate. Information about the instruments and uncertainties are shown in Table 3.

Table 3. Instrument range and uncertainties.

Instrument	Range	Uncertainty
Energy analyzer - Voltage	50 - 500 V	0.2 % of full scale
Energy analyzer - Current	0.2 - 1000 A	0.2 % of full scale
Engine speed	2 – 99999 rpm	1 % reading
K-type thermocouples	−50 to 1300 °C	0.4% or 1.1 °C
Load cell	0 – 2 kg	± 2 %
Gas analyzer – O_2	0 – 25 %	± 0.2 Vol-% abs.
Gas analyzer – CO_2	0 – 100 %	± 0.3 % or 3 % reading
Gas analyzer – CO	0 – 500 ppm	± 2.0 ppm
Gas analyzer – NO	0 – 300 ppm	± 2.0 ppm
Gas analyzer – NO_2	0 – 100 ppm	± 2.0 ppm

The specific fuel consumption (*sfc*) is given by Equation (1). $\dot{m}_f$ represent the fuel mass flow rate and *P* represents the brake power.

$$sfc = \frac{\dot{m}_f}{P} \quad (1)$$

The brake fuel conversion efficiency (η_f) was calculated by Equation (2). *LHV* represents the fuel lower heating value

$$\eta_f = \frac{P}{\dot{m}_f\, LHV} = \frac{1}{sfc\, LHV} \quad (2)$$

Specific emissions were calculated by Equation (3). ISZZ represents the specific emissions of a ZZ species, C_{ZZ} is the concentration of the ZZ species (ppm·10^{-6}), ρ_{ZZ} is the specific mass of the ZZ species under exhaust gas conditions, ρ_{GE} is the specific mass of the exhaust gases. To determine the specific mass of the exhaust gases, the ideal gas equation was adopted. Finally, $\dot{m}_a$ represents the air mass flow rate.

$$ISZZ = \frac{C_{ZZ}\left[\dot{m}_a + \dot{m}_f\right]\frac{\rho_{ZZ}}{\rho_{GE}}}{P} \quad (3)$$

Results and Discussion

This section presents in detail the results of a diesel engine fueled with pure biodiesel (B0), pure diesel fuel (B100) and a mixture with 50 % biodiesel and 50 % diesel fuel. Al_2O_3 nanoparticles were added to the baseline fuels (B100 and B50) at 50, 100 and 150 ppm. The effects of Al_2O_3 nanoparticles on efficiency and emissions are demonstrated in this section.

Figure 3 presents the excess air for all samples tested. The excess of air was measured by the gas analyzer in the engine exhaust manifold. According to the figure, excess air was reduced when Al_2O_3 nanoparticles were added to samples compared to the B0, B50 and B100 without alumina. The B0 and B100 samples obtained a very close excess of air values. The excess of air for the B50 sample was approximately 374 % and was almost constant when Al_2O_3 nanoparticles were added, ranging from 350 to 370 %. The same trend can be observed for the pure biodiesel sample that was 340 % for the B100 with 50 ppm Al_2O_3 and slightly increased to 360 % for the B100 with 150 ppm Al_2O_3 nanoparticles.

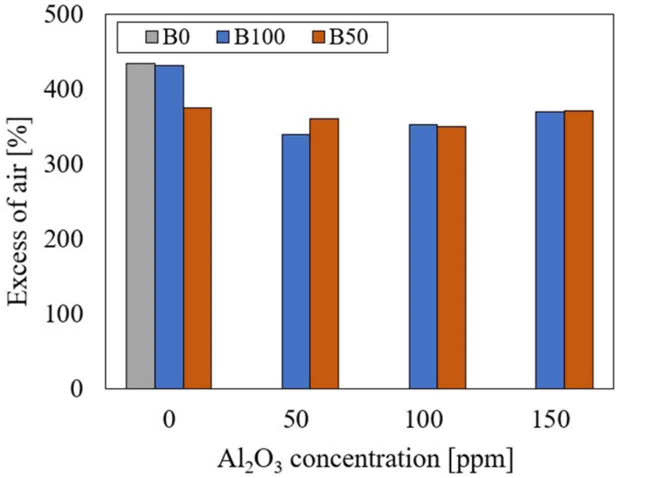


Figure 3. Excess of air.

It is possible to note that even with more oxygen available in the combustion process with the Al_2O_3 nanoparticles, it did not have a significant effect in the excess of air. A possible explanation might be the small amount of oxygen coming from the alumina, since the concentrations are too small in relation to the oxygen available in the diesel or biodiesel fuel.

Brake fuel conversion efficiency and specific fuel consumption are shown in Figure 4. The dashed lines in Figure 4 represent the trendlines according to a second-order polynomial function. It is possible to see that pure biodiesel demonstrated a fuel conversion efficiency of around 17 %, which is 17.3 % lower than the pure B0 sample. This result is expected because pure biodiesel has a lower heating value than diesel fuel, increasing fuel consumption and decreasing the fuel conversion efficiency. In addition, as previously commented, pure biodiesel also leads to poor atomization and spray formation because of its higher density and viscosity. Then, it could also be a possible explanation for the reduction in efficiency of pure biodiesel compared to the pure diesel fuel.

What is interesting to note in Figure 4 (a) is the increase in fuel conversion efficiency when Al_2O_3 nanoparticles were added to the fuel samples (B100 and B50). The efficiency increased to 19.4% for B100 with 50 ppm of Al_2O_3, representing an increase of 13.4% compared to pure biodiesel. However, for 100 and 150 ppm of Al_2O_3 nanoparticles, the efficiency decreased to 18.7% and 17.7% for B100, respectively. Nevertheless, the fuel conversion efficiency was

higher when Al_2O_3 nanoparticles were added to biodiesel compared to pure biodiesel. Even with this increase in fuel conversion efficiency for B100 with the addition of Al_2O_3 nanoparticles, they were still below the fuel conversion efficiency of pure diesel (B0).

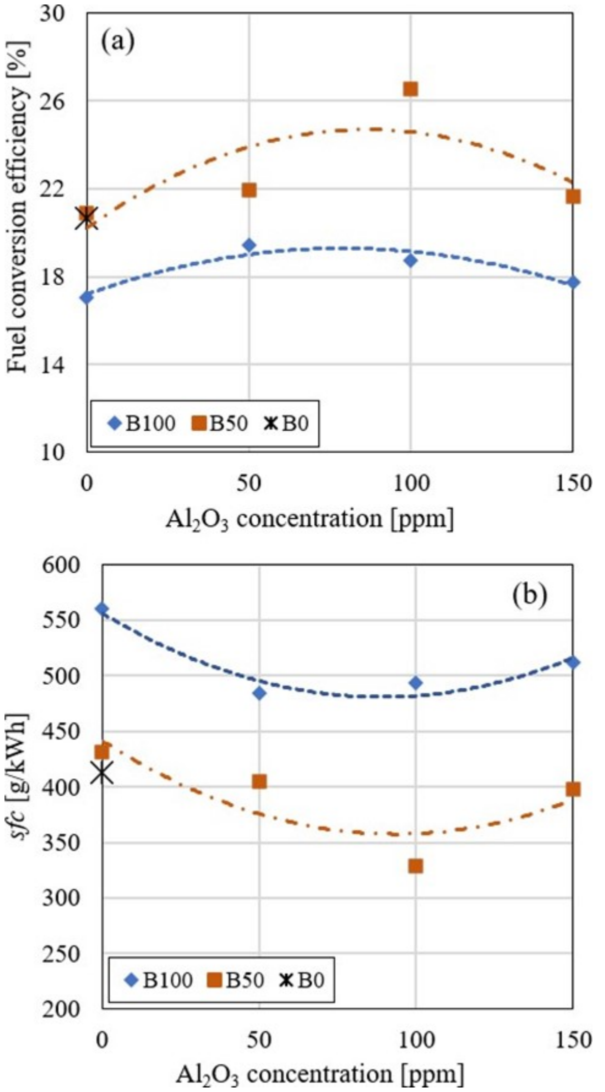


Figure 4. Brake fuel conversion efficiency (a) and specific fuel consumption (b).

What is interesting to note in Figure 4 (a) is the increase in fuel conversion efficiency when Al_2O_3 nanoparticles were added to the fuel samples (B100 and B50). The efficiency increased to 19.4 % for B100 with 50 ppm of Al_2O_3, representing an increase of 13.4 % compared to pure biodiesel. However, for 100 and 150 ppm of Al_2O_3 nanoparticles, the efficiency decreased to 18.7 % and 17.7 % for B100, respectively. Nevertheless, the fuel conversion efficiency was higher when Al_2O_3 nanoparticles were added to biodiesel compared to pure biodiesel. Even with this increase in fuel conversion efficiency for B100 with the addition of Al_2O_3 nanoparticles, they were still below the fuel conversion efficiency of pure diesel (B0).

The B50 samples demonstrated a similar trend to the B100 when Al_2O_3 nanoparticles were added – higher fuel conversion efficiencies were found for samples with Al_2O_3 nanoparticles than pure B50. The fuel conversion efficiency increased with the use of alumina nanoparticles, reaching a maximum value of 26.6 % for 100 ppm of Al_2O_3. The increase in fuel conversion efficiency with the addition of Al_2O_3 nanoparticles to the B100 and B50 samples may be related to an improvement in the combustion process. It occurs because Al_2O_3 helps in the rapid vaporization of the fuel, resulting in a better fuel-air mixing, which provides additional surface area for the fuel to react with oxygen molecules, improving the combustion process.

These results are consistent with the literature [28,30], where it was reported that there was an increase in efficiency of 4.5 % and 10.6 % with the addition of the nanoparticles, respectively. According to [30], the higher thermal efficiency for nano fuels blends is due to the higher heat release rate and better homogenization of the air fuel mixture, which improved the combustion characteristics, decreased the ignition delay and combustion duration and intensified thermal efficiency.

It can be seen that the fuel conversion efficiency decreased after a certain level of Al_2O_3 concentration (100 and 150 ppm Al_2O_3 for B100 and 150 ppm for B50). This is possibly due to an increase in fuel viscosity, which worsens fuel atomization and increasing the rate of fuel consumption at these points. Consequently, the brake fuel conversion efficiency decreased.

The specific fuel consumption is shown in Figura 4 (b). Specific fuel consumption has the inverse behavior of fuel conversion efficiency. What can be clearly seen in this figure is that the fuel consumption for pure biodiesel was 560.2 g/kWh, which is higher than that of pure diesel fuel (412.6 g/kWh) and pure B50 (432.0 g/kWh). This occurred because of the lower heating value of pure biodiesel compared to diesel fuel or the mixture of 50 % biodiesel and 50 % diesel. Therefore, a greater amount of biodiesel is required to supply the same amount of energy and produce the same amount of electric power, resulting in higher fuel consumption when the engine runs on B100.

However, when Al_2O_3 nanoparticles were added to B100 and B50 the fuel consumption decreased for all cases. The fuel consumption for the B100 with 50 ppm of Al_2O_3 decreased to 483.9 g/kWh, representing a reduction of 13.6% compared to the pure B100. Although, it was higher than the pure diesel fuel. For the B50 sample with 100 ppm of Al_2O_3, the fuel consumption decreased to 329.0 g/kWh, being 23.8 % lower than pure B50 and 20.2 % lower than the pure diesel fuel.

A possible explanation for the reduction of fuel consumption with the addition of Al_2O_3 nanoparticles to the fuels is the better air-fuel mixing and vaporization of the fuel, improving the combustion process. According to the literature, another reason is that aluminum oxide acts as a fuel catalyst and an oxygen promoter for biodiesels to generate high pressure and temperature during the combustion. Consequently, the fuel consumption is reduced and it helps in achieving a similar diesel fuel power output [24,25,30]. Fuel conversion efficiency and fuel consumption results are in accordance with the results demonstrated in [23,30].

Figure 5 presents the specific emissions of CO (a) and NO_X (b). CO emissions for pure diesel fuel, pure biodiesel and B50 mixture were almost the same, varying from 7.0 to 7.4 g/kWh. It can be seen that there was a reduction in CO emissions with the addition of Al_2O_3 nanoparticles for all B50 samples tested. The lowest CO emissions achieved was 4.7 g/kWh for B50 with Al_2O_3 concentration of 100 ppm, representing a reduction of 36.5 % compared to the pure B50 mixture. The lowest CO emissions value was 4.0 g/kWh obtained by the B100 sample with 50 ppm of Al_2O_3, indicating a reduction about 42.8 % compared to the pure diesel and biodiesel fuel. However, CO emissions increased for higher concentrations of alumina in the B100 samples, exceeding the pure B100 sample.

A possible explanation for the drop in CO emissions with the addition of Al_2O_3 nanoparticles could be the higher oxygen availability and the catalytic effect of the nanoparticles, which helps the CO oxidation and improved the combustion process. According to [29], nanoparticles have the potential to accelerate chemical reactions due to their catalytic action and decrease the activation energy. As a result, chemical reactions occur at lower temperatures and there is the possibility of reoxidation of unburned fuels, reducing the CO emissions. Ampah et al. [17] mentioned that at high temperatures, Al_2O_3 dissociates to Al_2O and O, but the Al_2O is very unstable at those very high temperatures, and this further decomposes it into 2Al and $0.5O_2$. Then, CO_2 is produced from the reaction of this oxygen molecule with CO, reducing the CO formation.

The specific emission of NO_X is shown in Figure 5 (b). From the figure, it is evident that there is no clear trend in the results. It can be seen that the NO_X emissions from B100 with the addition of alumina nanoparticles decreased to 5.6 g/kWh for a concentration of 50 ppm and increased to 6.0 and 6.1 g/kWh for 100 and 150 ppm, respectively. It indicated a slight increase of 5% for the B100 with 150 ppm and slight decrease of 3.4 % for the B100 with 50 ppm of Al_2O_3. The NO_X emissions increased to 5.6 g/kWh for the B50 with 50 ppm of Al_2O_3. The formation of NO_X is closely related to the temperature and oxygen available during the combustion process. The increase trend for the B100 sample with alumina can be possible explained by the higher oxygen availability in biodiesel and the Al_2O_3, resulting in a minor increase in NO_X formation. On the other hand, some reductions in the NO_X emissions were observed for some points. The highest reduction was about 25 % for B50 with 100 ppm of Al_2O_3 compared to pure B50 while the B50 with 150 ppm decreased to 5.0 g/kWh, being close to the pure B50 sample. According to [17], it could be related to the increased surface area of Al_2O_3, which reduces the ignition delay and help the reaction of hydrocarbon with oxygen, and reduce the reaction of nitrogen with oxygen. As a result, the NO_X emissions could be reduced.

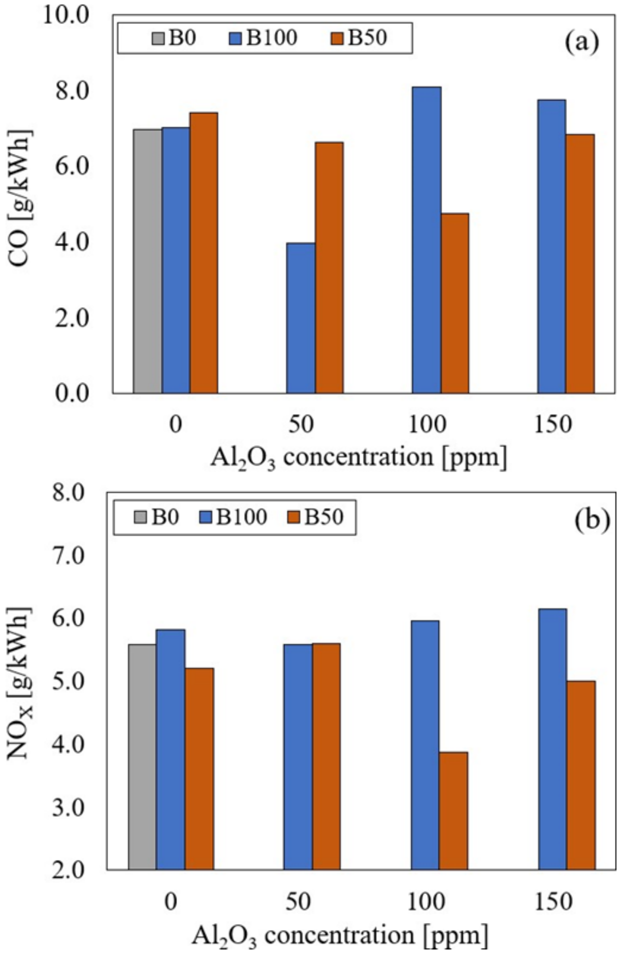


Figure 5. Specific emissions of CO (a) and NOX (b).

Conclusion

The objective of this work was to evaluate the effects of adding Al_2O_3 to diesel and biodiesel blends on the performance and emissions characteristics of a diesel engine. The alumina nanoparticles were added at concentrations of 50, 100 and 150 ppm in pure diesel and biodiesel and also a mixture with 50% biodiesel and 50% diesel fuel. The samples were carefully prepared to ensure that the samples were stable and homogeneous.

The results indicated an increase trend in the fuel conversion efficiency with the addition of the nanoparticles to the baseline fuels. The highest fuel conversion efficiency was 26.5 % for the B50 with 100 ppm of Al_2O_3, indicating a efficiency improvement of around 28.6 % compared to the pure diesel fuel. However, the fuel conversion efficiency for all biodiesel samples were lower than the diesel fuel for all tested conditions.

The specific fuel consumption decreases significantly with the addition of Al_2O_3 nanoparticles. The best condition for the B100 samples was for a concentration of Al_2O_3 of 50 ppm, which decreased the fuel consumption to 13.6 % compared to the pure B100. In addition, the fuel consumption for the B50

Sci. cum Ind. **2024**, 13(1), e241301. DOI: 10.18226/23185279.e241301

with 100 ppm of Al_2O_3 decreased 23.8% compared to the pure B50, and it was 20.2 % lower than the pure diesel fuel.

Regarding CO and NO_X emissions, in general, the results indicated a reduction in CO emissions compared to the pure diesel fuel for all B50 cases with alumina and for B100 with 50 ppm of alumina, which was the lowest value achieved (4.0 g/kWh). On the other hand, the NO_X emissions results indicated a slight increase trend for the B100 samples. The lowest value obtained was 3.9 g/kWh for B50 with a concentration of Al_2O_3 of 100 ppm, 30 % lower than pure diesel fuel (B0).

Acknowledgments

J.S. Rosa would like to thank FAPERGS for the financial support.

Authors Contribution

M.M. Smaniotto: Investigation, Methodology, Writing Original Draft; J.S. Rosa: Conceptualization, Methodology, Writing - review and editing; G.D. Telli: Conceptualization, Investigation, Writing; review and editing, Supervision. All authors have approved the final version of the manuscript.

Conflicts of Interest

The authors have declare no conflicts of interest.

References

[1] P. Punov, T. Evtimov, R. Chiriac, A. Clenci, Q. Danel, G. Descombes, Progress in high performance, low emissions, and exergy recovery in internal combustion engines. *International Journal of Energy Research,* vol. 41, pp. 1229–1241, 2017. DOI: 10.1002/er.3666.

[2] G. D. Telli, C. R. Altafini, C. A. Costa, J. S. Rosa, L. A. O. Rocha, G. Lorenzini, Experimental Study of a Dual-Fuel Generator Set Operating on Diesel Fuel Direct Injected and Hydrous Ethanol Fumigation at Different Loads. *International Journal of Design & Nature and Ecodynamics*, vol 15, pp. 777–784, 2020. DOI: 10.18280/ijdne.150602.

[3] N. Duarte Souza Alvarenga Santos, V. Rückert Roso, A. C. Teixeira Malaquias, J. G. Coelho Baêta, Internal combustion engines and biofuels: Examining why this robust combination should not be ignored for future sustainable transportation. *Renewable and Sustainable Energy Reviews*, vol 148, pp. 111292, 2021. DOI: 10.1016/j.rser.2021.111292.

[4] A. T. Doppalapudi, A. K. Azad, M. M. K. Khan, Advanced strategies to reduce harmful nitrogen-oxide emissions from biodiesel fueled engine. *Renewable and Sustainable Energy Reviews*, vol. 174, pp. 113123, 2023. DOI: 10.1016/j.rser.2022.113123.

[5] T. W. B. Riyadi, M. Spraggon, S. G. Herawan, M. Idris, P. A. Paristiawan, N. R. Putra, M. F. R, R. Silambarasan, I. Veza, Biodiesel for HCCI engine: Prospects and challenges of sustainability biodiesel for energy transition. *Results in Engineering*, vol. 17, pp. 100916, 2023. DOI:10.1016/j.rineng.2023.100916.

[6] M.A. Vailatt, C.R. Altafini, G.D. Telli, J.S. Rosa, Experimental Analysis of a Small Generator set Operating on Dual Fuel Diesel-Ethanol. *Scientia cum Industria*, vol 5, pp. 1–9, 2017. DOI: 10.18226/23185279.v5iss1p1.

[7] J. S. Rosa, G. Lorenzini, C. R. Altafini, P. R. Wander, G. D. Telli, L. A. O. Rocha, Performance effects and economic viability of high-hydrated ethanol fumigation and diesel direct injection in a small compression ignition engine. *Mathematical Modelling of Engineering Problems*, vol 6, pp. 1–9, 2019. DOI: 10.18280/mmep.060101.

[8] D. Mishra, N. Kumar, R. Chaudhary, Effect of orange peel oil on the performance and emission characteristics of diesel engine fueled with quaternary blends. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol 45, pp; 650–60, 2023. DOI: 10.1080/15567036.2023.2171510.

[9] G. D. Telli, C. R. Altafini, J. S. Rosa, C. A. Costa, Experimental analysis of a small engine operating on diesel –natural gas and soybean vegetable oil–natural gas. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol 40, pp. 547, 2018. DOI: 10.1007/s40430-018-1469-x.

[10] Y. S. M. Altarazi, A. R. Abu Talib, J. Yu, E. Gires, M. F. Abdul Ghafir, J. Lucas, T. Yusaf, Effects of biofuel on engines performance and emission characteristics: A review. *Energy,* vol 238, pp. 121910, 2022. DOI: 10.1016/j.energy.2021.121910.

[11] A. S. Mohammed, S. M. Atnaw, A. V. Ramaya, G. Alemayehu, A comprehensive review on the effect of ethers, antioxidants, and cetane improver additives on biodiesel-diesel blend in CI engine performance and emission characteristics. J*ournal of the Energy Institute*, vol 108, pp. 101227, 2023. https://doi.org/10.1016/j.joei.2023.101227.

[12] P. André Cremonez, M. Feroldi, W. Cézar Nadaleti, E. de Rossi, A. Feiden, M. P. de Camargo, F. E. Cremonez, F. F. Klajn, Biodiesel production in Brazil: Current scenario and perspectives. *Renewable and Sustainable Energy Reviews*, vol 42, pp. 415–428, 2015. DOI: 10.1016/j.rser.2014.10.004.

[13] C. W. Mohd Noor, M. M. Noor, R. Mamat, Biodiesel as alternative fuel for marine diesel engine applications: A review. *Renewable and Sustainable Energy Reviews*, vol 94, pp. 127–142, 2018. DOI: 10.1016/j.rser.2018.05.031.

[14] M. Gülüm, A. Bilgin, Optimization of Transesterification of Waste Cooking Oil with Methanol by Cubic Spline Interpolation. *Journal of Fuels and Lubricants*, vol 13, pp; 04-13-02–0009, 2020. DOI: 10.4271/04-13-02-0009.

[15] A. E. Atabani, A. S. Silitonga, I. A. Badruddin, T. M. I. Mahlia, H. H. Masjuki, S. Mekhilef, A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews*, vol 16, pp. 2070–2093, 2012. DOI: 10.1016/j.rser.2012.01.003.

[16] M. G. Bidir, N. K. Millerjothi, M. S. Adaramola, F. Y. Hagos, The role of nanoparticles on biofuel production and as an additive in ternary blend fuelled diesel engine: A review. *Energy Reports*, vol 7, pp. 3614–3627, 2021. DOI: 10.1016/j.egyr.2021.05.084.

[17] J. D. Ampah, A. A. Yusuf, E. B. Agyekum, S. Afrane, C. Jin, H. Liu, I. M. R. Fattah, P. L. Show, M. Shouran, M. Habil, S. Kamel, Progress and Recent Trends in the Application of Nanoparticles as Low Carbon Fuel Additives—A State of the Art Review. *Nanomaterials*, vol 12, 2022 DOI: 10.3390/nano12091515.

[18] M. S. Gad, Ü. Ağbulut, A. Afzal, H. Panchal, S. Jayaraj, N. A. A. Qasem, A. S. El-Shafay, A comprehensive review on the usage of the nano-sized particles along with diesel/biofuel blends and their impacts on engine behaviors. *Fuel*, vol 339, 2023. DOI: 10.1016/j.fuel.2022.127364.

[19] X. Wang, J. Zhang, Y. MA, G. Wang, J. P. Han, M. Dai, Z. Y. Sun, A comprehensive review on the properties of nanofluid fuel and its additive effects to compression ignition engines. *Applied Surface Science*, vol 504, 2020. DOI: 10.1016/j.apsusc.2019.144581.

[20] V. Saxena, N. Kumar, V. K. Saxena, A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled C.I. engine. *Renewable and Sustainable Energy Reviews*, vol 70, pp. 563–588, 2017. DOI: 10.1016/j.rser.2016.11.067.

[21] Ü. Ağbulut, Understanding the role of nanoparticle size on energy, exergy, thermoeconomic, exergoeconomic, and sustainability analyses of an IC engine: A thermodynamic approach. *Fuel Processing Technology*, vol 225, 2022. DOI: 10.1016/j.fuproc.2021.107060.

[22] M. E. M. Soudagar, N. N. Nik-Ghazali, M. Abul Kalam, I. A. Badruddin, N. R. Banapurmath, N. Akram, The effect of nano-additives in diesel-biodiesel fuel blends: A comprehensive review on stability, engine performance and emission characteristics. *Energy Conversion and Management,* vol 178, pp. 146–177, 2018. DOI: 10.1016/j.enconman.2018.10.019.

[23] S. Karami, A. Gharehghani, Effect of nano-particles concentrations on the energy and exergy efficiency improvement of indirect-injection diesel engine. *Energy Reports*, vol 7, pp; 3273–3285, 2021. DOI: 10.1016/j.egyr.2021.05.050.

[24] N. K. Gurusala, V. A. M. Selvan, Effects of alumina nanoparticles in waste chicken fat biodiesel on the operating characteristics of a compression ignition engine. *Clean Technologies and Environmental Policy*, vol, 17, pp. 681–692, 2015. DOI: 10.1007/s10098-014-0825-5.

[25] M. Srinivasa Rao, R. B. Anand, Performance and emission characteristics improvement studies on a biodiesel fuelled DICI engine using water and AlO(OH) nanoparticles. *Applied Thermal Engineering*, vol 98, pp. 636–645, 2016. DOI: 10.1016/j.applthermaleng.2015.12.090.

[26] P. Anchupogu, L. N. Rao, B. Banavathu, Effect of alumina nano additives into biodiesel-diesel blends on the combustion performance and emission characteristics of a diesel engine with exhaust gas recirculation. *Environmental Science and Pollution Research*, vol 25, pp; 23294–23306, 2018. DOI: 10.1007/s11356-018-2366-7.

[27] A. Sharma, H. S. Pali, M. Kumar, N. K. Singh, E. A. Rahim, Y. Singh, N. K. Gupta, Effect of α-aluminium oxide nano additives with Sal biodiesel blend as a potential alternative fuel for existing DI diesel engine. *Energy and Environment*, 2022. DOI: 10.1177/0958305X221133257.

[28] Y. Kaushik, V. Verma, K. K. Saxena, C. Prakash, L. R. Gupta, S. Dixit, Effect of Al2O3 Nanoparticles on Performance and Emission Characteristics of Diesel Engine Fuelled with Diesel–Neem Biodiesel Blends. *Sustainability (Switzerland)*, vol 14, 2022. DOI: 10.3390/su14137913.

[29] K. M. Akkoli, S. C. Kamate, S. N. Topannavar, A. R. Bhavimani, N. R. Banapurmath, I. Veza, M. E. M. Soudagar, T. M. Y. Khan, A. S. El-Shafay, M. A. Kalam, M. M. Shivashimpi, A. M. Gulli, Influence of Injection Pressure and Aluminium Oxide Nano Particle-Added Fish Oil Methyl Ester on the Performance and Emission of Compression Ignition Engine. *Energies*, vol 15, pp. 9491, 2022. DOI: 10.3390/en15249491.

[30] M. E. M. Soudagar, N. N. Nik-Ghazali, M. A. Kalam, I. A. Badruddin, N. R. Banapurmath, M. A. Bin Ali, S. Kamangar, H. M. Cho, N. Akram, An investigation on the influence of aluminium oxide nano-additive and honge oil methyl ester on engine performance, combustion and emission characteristics. *Renewable Energy*, vol 146, pp. 2291–2307, 2020. DOI: 10.1016/j.renene.2019.08.025.

[31] A. A. da S. Mamede, A. A. S. Lopes, R. B. Marques, J. Q. Malveira, M. A. de S. Rios, Soybean and babassu biodiesel production: a laboratory scale study and an exergy analysis approach. *Matéria (Rio de Janeiro)*, vol 25, pp. 1–8, 2020. DOI: 10.1590/s1517-707620200004.1150.

[32] G. D. Telli, C. R. Altafini, J. S. Rosa, C. A. Costa, Experimental investigation of a compression ignition engine operating on B7 direct injected and hydrous ethanol fumigation. *Energy*, vol 165, pp. 106–117, 2018. DOI:10.1016/j.energy.2018.09.171.