Terbit *online* pada laman web jurnal : https://metal.ft.unand.ac.id

METAL: Jurnal Sistem Mekanik dan Termal

| ISSN (Print) 2598-1137 | ISSN (Online) 2597-4483 |

Research article

Investigating the Influence of Alumina Additive Concentrations on specific Fuel Consumption and Exhaust Opacity in Biodiesel Fuel

Muh. Abdillah, Nurhidayanti, Ariawan Bayu Wicaksono, Ishak

Mechanical Engineering, State Polytechnic of Ujung Pandang, Makassar, Indonesia

ARTICLE INFORMATION

Article History:
Received : 24 September 2025
Revised : 17 October 2025
Accepted : 30 October 2025

KEYWORDS

Biodiesel

Alumina Nanoparticles,

Combustion Efficiency

CORRESPONDENCE

E-mail: muh.abdillah@poliupg..ac.id

A B S T R A C T

This study investigates the effect of alumina (Al_2O_3) nanoparticle additives on the performance and emission characteristics of B30 biodiesel fuel under various engine loads. Fuel samples of pure B30 and B30 blended with Al_2O_3 at concentrations of 30, 50, 70, and 90 ppm were tested using a 3.5 kW diesel engine. The evaluation focused on specific fuel consumption (SFC), and exhaust opacity at loads of 1, 5, and 9 kg. The results show that SFC generally decreased with increasing load, with the lowest values achieved at 90 ppm, indicating improved combustion efficiency. In terms of emissions, the addition of Al_2O_3 at 30–50 ppm significantly reduced opacity, with 50 ppm showing the greatest effect, particularly at high loads. However, higher concentrations such as 90 ppm tended to increase opacity due to nanoparticle agglomeration, which hinders homogeneous mixing and combustion. Overall, the optimal performance improvement was observed at 50 ppm for emission reduction and at 90 ppm for fuel efficiency, demonstrating the potential of Al_2O_3 nanoparticles as effective additives in biodiesel applications.

1. INTRODUCTION

Global primary energy demand has continued to rise in recent years, driven by economic growth, electrification and expanding transport and industrial activity; major energy outlooks report persistent dependence on oil and other fossil fuels despite rapid growth in renewables. [1]

The transport sector remains a leading source of air pollutants that harm human health and the environment[2]. Outdoor air pollution has been linked to millions of premature deaths worldwide, and transportation—particularly diesel-powered road traffic—contributes substantially to fine particulate ($PM_{2.5}$), nitrogen oxides (NO_x) and other harmful emissions that cause cardiovascular and respiratory disease [3]. Recent analyses estimate that transportation-related $PM_{2.5}$ and ozone are responsible for hundreds of thousands of premature deaths and a meaningful share of air-pollution burden globally [4].

Biodiesel is promoted as a renewable, lower-carbon alternative to petroleum diesel that can reduce lifecycle CO_2 emissions and improve energy security if produced sustainably [5], [6]. However, biodiesel and biodiesel–diesel blends also present technical challenges—such as differences in fuel stability, calorific value, and certain emission species—so research continues on fuel formulation and post-processing to optimize combustion and lower regulated pollutants [7], [8].

One active research direction is the use of nano- and micro-scale fuel additives to improve combustion performance and emissions [9].

https://doi.org/ 10.25077/metal.9.2.117-121.2025

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License

Metal-oxide nanoparticles (including alumina, Al_2O_3) and other nanoadditives have been shown in several experimental studies and reviews to enhance fuel atomization, accelerate oxidation reactions, and act as catalysts or soot-oxidation promoters—yielding improvements in brake/thermal efficiency and, in some cases, reductions in particulate and hydrocarbon emissions. Results vary with additive type, particle size, dispersion method, and concentration, and some studies report trade-offs (e.g., changes in NO_x), highlighting the need for systematic concentration-dependent investigations [10].

Specifically, several recent experimental works have investigated Al_2O_3 nanoparticles added to biodiesel or biodiesel–diesel blends and reported improvements in thermal efficiency and reductions in some pollutants at particular nanoparticle loadings; nevertheless, reported results are not yet fully consistent across feedstocks, engine types, and operating conditions [11], [12], [13]. This inconsistency motivates a focused study that systematically varies Al_2O_3 concentration in biodiesel blends and evaluates effects on specific fuel consumption, and opacity under controlled engine loads thereby addressing both practical performance goals and air-quality concerns.

In this paper we therefore examine the influence of alumina additive concentrations on the thermal performance and pollutant emissions of biodiesel fuel, aiming to identify concentration ranges that maximize combustion.

2. METHOD

This research involves testing several fuel samples, including B30 biodiesel, B30 blended with Al_2O_3 at concentrations of 30 ppm, 50 ppm, 70 ppm, and 90 ppm. The samples were evaluated using a diesel engine.

2.1 Experimental Setup

In this study, a diesel engine with a rated power of 3.5 kW was utilized. Various sensors integrated into the engine were employed to automatically gather data through a computer system using the IC-Engine application, enabling the collection of engine performance. The engine was tested under loads of 1, 5, and 9 kg, with a compression ratio set at 18:1.

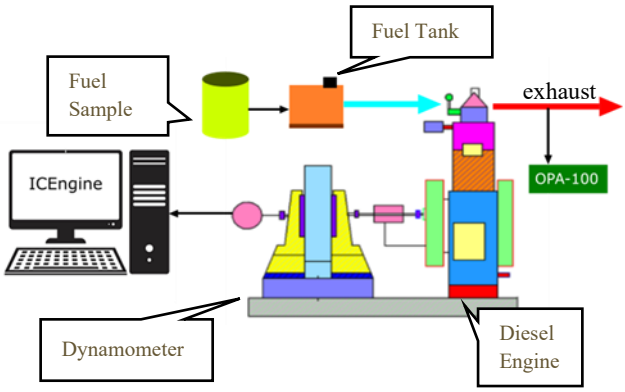


Figure 1. Experiment Setup

2.2 Preparation of Biodiesel with Nanoparticle Al_2O_3

This study examines the addition of Al_2O_3 nanoparticles to B30 biodiesel fuel in concentrations of 30, 50, 70, and 90 ppm. The B30 fuel used originates from products of state-owned enterprises in Indonesia and is commercially available at gas stations. It consists of 30% vegetable-based components derived from palm oil blended with pure diesel. As depicted in Figure 2, the fuel and Al_2O_3 nanoparticles were blended using a magnetic stirrer for 30 minutes at a temperature range of 80–90°C. To prevent sedimentation after mixing, an ultrasonic cleaner operating at 40 kHz was applied for 30 minutes. The fuel samples were then allowed to return to room temperature before being directly used in the engine.

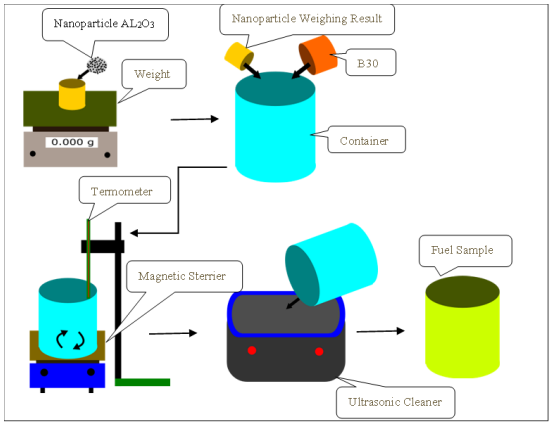


Figure 2. Preparation of Biodiesel with Nanoparticle Al_2O_3

https://doi.org/ 10.25077/metal.9.2.117-121.2025

3. RESULT AND DISCUSSIONS

3.1. Fuel Consumption

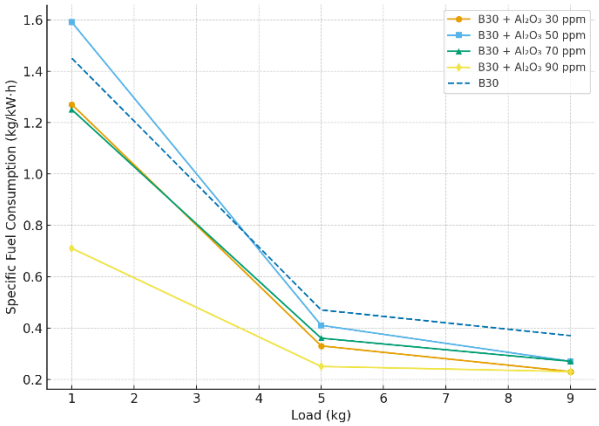


Figure 3. Specific Fuel Consumption vs Opacity

Figure 3 illustrates the variation of specific fuel consumption (SFC) with engine load using B30 and a mixture of B30 + Al_2O_3 at different concentrations. At a low load of 1 kg, the highest SFC was observed in B30 + Al_2O_3 50 ppm (1.59 kg/kW·h), followed by pure B30 (1.45 kg/kW·h), B30 + Al_2O_3 30 ppm (1.27 kg/kW·h), B30 + Al_2O_3 70 ppm (1.25 kg/kW·h), and the lowest value was obtained with B30 + Al_2O_3 90 ppm (0.71 kg/kW·h). At a medium load of 5 kg, the highest SFC was again recorded with B30 + Al_2O_3 50 ppm (0.41 kg/kW·h), while the lowest was observed at 90 ppm (0.25 kg/kW·h). Pure B30 had a slightly higher value (0.47 kg/kW·h) compared to mixtures with 30–70 ppm additives. At a high load of 9 kg, the SFC values became closer, with pure B30 (0.37 kg/kW·h) showing the highest, while the lowest was obtained with B30 + Al_2O_3 90 ppm (0.23 kg/kW·h). The addition of Al_2O_3 nanoparticles significantly reduced SFC, particularly at higher loads, indicating improved combustion efficiency due to enhanced atomization and catalytic effects [14], [15]. However, at lower loads, some variations such as 50 ppm produced higher SFC than pure B30, which may be attributed to incomplete utilization of nanoparticles at light engine conditions. In general, SFC decreased with increasing engine load, which is consistent with diesel engine characteristics where higher loads improve fuel utilization efficiency [16]. The mixture of B30 + Al_2O_3, especially at 90 ppm, demonstrates the strongest potential to reduce SFC and enhance thermal efficiency compared to pure B30 fuel.

3.2. Opacity

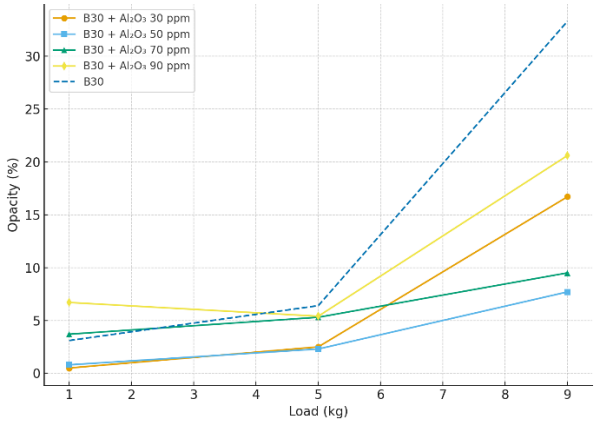


Figure 4. Load vs Opacity

Figure 4. llustrates the change in exhaust opacity with respect to engine load using B30 and a mixture of B30 + Al_2O_3 at different concentrations. At a low load of 1 kg, the lowest opacity was produced by B30 + Al_2O_3 30 ppm (0.5%), followed by B30 + Al_2O_3 50 ppm (0.8%), while pure B30 showed a higher value of 3.1%. The highest opacity at this load was observed in B30 + Al_2O_3 90 ppm (6.7%), indicating that excessive nanoparticle concentration may negatively influence combustion. At a medium load of 5 kg, the opacity of pure B30 reached 6.4%, while B30 + Al_2O_3 30 ppm and 50 ppm resulted in much lower values of 2.5% and 2.3%, respectively. The addition of 70 ppm and 90 ppm produced higher opacity values of 5.3% and 5.4%, showing a decline in the effectiveness of alumina additives at higher concentrations. At a high load of 9 kg, pure B30 generated the highest opacity (33.3%), while the lowest was recorded with B30 + Al_2O_3 50 ppm (7.7%), followed by B30 + Al_2O_3 70 ppm (9.5%) and 30 ppm (16.7%). The highest opacity at this load was again observed with B30 + Al_2O_3 90 ppm (20.6%). The results suggest that alumina additives significantly reduce smoke opacity, especially at 30–50 ppm concentrations, due to improved atomization and catalytic oxidation effects [17], [18], [19]. However, at higher concentrations (90 ppm), opacity tends to increase, likely due to nanoparticle agglomeration that inhibits uniform distribution in the fuel and reduces combustion

efficiency [20], [21]. In general, opacity increases with engine load, which is consistent with diesel engine behavior where higher loads demand more fuel supply, leading to incomplete combustion and higher particulate emissions [13], [22]. The addition of Al_2O_3 nanoparticles, particularly at 50 ppm, shows strong potential in reducing particulate emissions and improving combustion efficiency compared to pure B30 fuel.

4. CONCLUSION

The experimental results demonstrate that the addition of Al_2O_3 nanoparticles to B30 biodiesel significantly influences engine performance and emissions. In terms of fuel consumption, specific fuel consumption (SFC) consistently decreased with increasing engine load, reflecting the inherent characteristics of diesel engines. The incorporation of Al_2O_3, particularly at 90 ppm, resulted in the lowest SFC values, indicating enhanced combustion efficiency due to better fuel atomization and catalytic effects. However, at lighter loads, certain concentrations such as 50 ppm produced higher SFC than pure B30, suggesting incomplete utilization of nanoparticles under low combustion intensity.

Regarding exhaust opacity, the results reveal that B30 fuel alone generated the highest smoke levels across all loads. The addition of Al_2O_3 at 30–50 ppm concentrations significantly reduced opacity, with 50 ppm showing the strongest effect, particularly at high load conditions. Conversely, higher concentrations such as 90 ppm tended to increase opacity, which may be linked to nanoparticle agglomeration that hinders fuel homogeneity and combustion.

Overall, the optimal performance improvement was observed at 50 ppm for emission reduction and 90 ppm for fuel efficiency, highlighting the potential of Al_2O_3 as an effective additive in biodiesel applications.

REFERENCES

[1] International Energy Agency, "Executive summary – World Energy Outlook 2021 – Analysis - IEA," *World Energy Outlook*, 2021.

[2] R. N. Colvile, E. J. Hutchinson, J. S. Mindell, and R. A. Warren, "Millennium Review for submission to Atmospheric Environment," pp. 1–28, 1997.

[3] J. Lelieveld, J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer, "The contribution of outdoor air pollution sources to premature mortality on a global scale," *Nature*, vol. 525, no. 7569, pp. 367–371, 2015, doi: 10.1038/nature15371.

[4] S. C. Anenberg, J. Miller, D. K. Henze, R. Minjares, and P. Achakulwisut, "The global burden of transportation tailpipe emissions on air pollution-related mortality in 2010 and 2015," *Environ. Res. Lett.*, vol. 14, no. 9, 2019, doi: 10.1088/1748-9326/ab35fc.

[5] Y. Zhu and H. Fan, "Use of biodiesel in non-road mobile machineries for low-carbon construction: Policy review and lifecycle analysis," *J. Clean. Prod.*, vol. 421, p. 138543, 2023, doi: https://doi.org/10.1016/j.jclepro.2023.138543.

[6] O. E. Ajala, F. Aberuagba, T. E. Odetoye, and A. M. Ajala, "Biodiesel: Sustainable Energy Replacement to Petroleum-Based Diesel Fuel – A Review," *ChemBioEng Rev.*, vol. 2, no. 3, pp. 145–156, 2015, doi: 10.1002/cben.201400024.

[7] L. Pidol, B. Lecointe, L. Starck, and N. Jeuland, "Ethanol–biodiesel–Diesel fuel blends: Performances and emissions in conventional Diesel and advanced Low Temperature Combustions," *Fuel*, vol. 93, pp. 329–338, 2012, doi: https://doi.org/10.1016/j.fuel.2011.09.008.

[8] R. Senthil and G. A. Vijay, "Review of physicochemical properties and spray characteristics of biodiesel," *Environ. Sci. Pollut. Res.*, vol. 30, no. 25, pp. 66494–66513, 2023, doi: 10.1007/s11356-023-27250-4.

[9] R. R. Sahoo and A. Jain, "Experimental analysis of nanofuel additives with magnetic fuel conditioning for diesel engine performance and emissions," *Fuel*, vol. 236, pp. 365–372, 2019, doi: https://doi.org/10.1016/j.fuel.2018.09.027.

[10] M. Ali Ijaz Malik, M. A. Kalam, M. Mujtaba Abbas, A. Susan Silitonga, and A. Ikram, "Recent advancements, applications, and technical challenges in fuel additives-assisted engine operations," *Energy Convers. Manag.*, vol. 313, no. March, p. 118643, 2024, doi: 10.1016/j.enconman.2024.118643.

[11] H. Venu and V. Madhavan, "Effect of Al2O3 nanoparticles in biodiesel-diesel-ethanol blends at various injection strategies: Performance, combustion and emission characteristics," *Fuel*, vol. 186, pp. 176–189, 2016, doi: https://doi.org/10.1016/j.fuel.2016.08.046.

[12] S. H. Pourhoseini and M. Ghodrat, "Experimental investigation of the effect of Al2O3 nanoparticles as additives to B20 blended biodiesel fuel: Flame characteristics, thermal performance and pollutant emissions," *Case Stud. Therm. Eng.*, vol. 27, p. 101292, 2021, doi: https://doi.org/10.1016/j.csite.2021.101292.

[13] S. H. Pourhoseini and M. Ghodrat, "Experimental investigation of the effect of Al2O3 nanoparticles as additives to B20 blended biodiesel fuel: Flame characteristics, thermal performance and pollutant emissions," *Case Stud. Therm. Eng.*, vol. 27, p. 101292, Oct. 2021, doi: 10.1016/J.CSITE.2021.101292.

[14] A. T. Hoang, "Combustion behavior, performance and emission characteristics of diesel engine fuelled with biodiesel containing cerium oxide nanoparticles: A review," *Fuel Process. Technol.*, vol. 218, no. January, p. 106840, 2021, doi: 10.1016/j.fuproc.2021.106840.

[15] S. K. Nayak and B. P. Pattanaik, "Experimental Investigation on Performance and Emission Characteristics of a Diesel Engine Fuelled with Mahua Biodiesel Using Additive," *Energy Procedia*, vol. 54, pp. 569–579, Jan. 2014, doi: 10.1016/J.EGYPRO.2014.07.298.

[16] A. Hegab, A. La Rocca, and P. Shayler, "Towards keeping diesel fuel supply and demand in balance: Dual-fuelling of diesel engines with natural gas," *Renew. Sustain. Energy Rev.*, vol. 70, pp. 666–697, Apr. 2017, doi: 10.1016/J.RSER.2016.11.249.

[17] M. Channappagoudra, "Influence of the aluminium oxide (Al2O3) nanoparticle additive with biodiesel on the modified diesel engine performance," *Int. J. Ambient Energy*, vol. 42, no. 15, pp. 1776–1784, 2021, doi: 10.1080/01430750.2019.1614992.

[18] S. N. Kumar Reddy and M. M. Wani, "Engine performance and emission studies by application of nanoparticles and antioxidants as additives in biodiesel blends," *Rev. des Compos. des Mater. Av.*, vol. 30, no. 3–4, pp. 175–180, 2020, doi: 10.18280/rcma.303-408.

[19] M. Abdillah, N. Amaliyah, A. E. E. Putra, and Surahman, "Biodiesel Performance Improvement with the Addition of Al2O3 Nanoparticles on Diesel Engine," *Int. J. Heat Technol.*, vol. 41, no. 2, pp. 423–430, 2023, doi: 10.18280/ijht.410217.

[20] Ü. Ağbulut, M. Karagöz, S. Sarıdemir, and A. Öztürk, "Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine," *Fuel*, vol. 270, p. 117521, Jun. 2020, doi: 10.1016/J.FUEL.2020.117521.

[21] W. A. Majewski and H. Jääskeläinen, "Smoke Opacity," dieselnet.com. Accessed: Sep. 27, 2022. [Online]. Available: https://dieselnet.com/tech/measure_opacity.php#pmmass

[22] A. Tuan Hoang and V. Viet Pham, "2-Methylfuran (MF) as a potential biofuel: A thorough review on the production pathway from biomass, combustion progress, and application in engines," *Renew. Sustain. Energy Rev.*, vol. 148, p. 111265, Sep. 2021, doi: 10.1016/J.RSER.2021.111265.