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Effect of Aluminum Oxide Nanoparticles on Particulate Emissions and Carbon Deposition in Compression Ignition Engines

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ABSTRACT

Rapid urbanization worldwide is driving increased demand for petroleum products. Yet, crude oil reserves—finite, geographically concentrated resources—are insufficient to meet this rising need, especially in countries lacking substantial fossil fuel reserves. This situation underscores the urgency of shifting toward alternative energy sources before reserves are exhausted. This study conducted particulate matter emissions and endurance testing using diesel fuel mixed with aluminum oxide nanoparticles. The endurance test involved a single-cylinder, horizontal diesel engine, running for 60 hours without modifications. Two fuel samples were examined: D100 (pure diesel) as the baseline and D97Al_2O_3 (97% diesel with 3% aluminum oxide nanoparticles). Engine performance metrics and sound pressure levels were recorded at a constant 1400 RPM, with variable loads from 0.0 to 1.6 Kg-m, incremented by 0.1 Kg-m. The load was set at 1.0 Kg-m for endurance testing with a constant 1400 RPM. Visual inspection of fuel injector tips helped analyze the deposition of aromatic compounds on injector surfaces for each fuel sample. Electron microscopy provided detailed insights into deposit formation, showing that carbon deposition was reduced by 22.22% when aluminum oxide was used as an additive further analysis of the particulate matter emissions the results shows that PM reduced by 12.08% in aluminum oxide compared to the diesel fuel. Because they aid in the creation of cleaner fuel technologies that can lessen reliance on traditional petroleum products and minimize pollution, the study's findings have wider energy and environmental ramifications.

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1. Introduction

Incorporating aluminum oxide (AlO_3) additives into engine systems provide significant sustainability benefits, tackling important worldwide environmental and energy issues. Aluminum oxide reduces mechanical deterioration, increases combustion efficiency, and improves thermal stability (Hsu et al., 2016). These characteristics result in notable decreases in fuel usage and detrimental emissions, including CO_2 and NO_x, which are the main causes of climate change. Under controlled circumstances, improved fuel-air mixing and uniform heat distribution lead to increased combustion efficiency, which can reduce CO2 emissions by up to 15% (Paulescu et al., 2016; Vivian et al., 2015).

Aluminum oxide's wear-resistant qualities prolong engine life while reducing maintenance and replacement requirements by reducing friction and surface roughness. Additionally, consistent engine performance even under stress is ensured by enhanced thermal conductivity and resistance to high-temperature deformation (Hsu et al., 2016; Neu, 2011). Together, these improvements lessen waste and its negative effects on the environment by promoting resource efficiency and supporting the ideas of the circular economy.

These developments have wider ramifications for environmental management and energy policy than just specific engine systems. Aluminum oxide additives help the world move towards renewable energy sources and lessen reliance on fossil fuels by increasing energy efficiency (Tomar & Kumar, 2020).

These advantages have a direct impact on attempts to mitigate climate change. In line with the Sustainable Development Goals, reducing fuel use lowers greenhouse gas emissions, especially CO_2, while lowering NO_x emissions enhances air quality and public health outcomes (Arshad et al., 2024). Additionally, the increased component durability promotes a circular economy model by reducing the environmental impact of material manufacturing and disposal (Geissdoerfer et al., 2017).

Emission profiles (CO_2, NO_x, and particulate matter), fuel efficiency gains, engine durability metrics (wear rates and friction coefficient), and lifecycle study of aluminum oxide additions are important factors for confirming these advantages (Zin et al., 2016). When taken as a whole, these metrics show how aluminum oxide has the potential to transform energy-intensive sectors, supporting both long-term climate resilience plans and global energy efficiency targets.

The main way that petroleum products have contributed to environmental deterioration is by releasing greenhouse gases (GHG), which fuel global warming and the problems that come with it (IPCC, 2014). Recent developments in nanotechnology have made it easier to produce nanosized particles, which, because of their high surface-to-volume ratio, greatly improve fuels' thermal characteristics and combustion performance (Farvardin et al., 2022).

Using biodiesel instead of diesel fuel lowers carbon emissions, according to studies. It has been demonstrated that biodiesel can cut CO_2 emissions by up to 24% and by 20% in other situations (Corral Bobadilla et al., 2017). Additionally, engine power and torque are not significantly affected by biodiesel (Gaur et al., 2021). According to several studies, using biodiesel instead of diesel fuel reduces NO_x emissions while increasing particulate matter emissions (Nair et al., 2021; Temizer & Eskici, 2020). In four-stroke water-cooled diesel engines, for example, blend B10 of coconut oil is a feasible substitute fuel for diesel (Bhangwar et al., 2022). According to the literature, aluminum oxide has mostly been applied in short-term analyses to investigate performance and noise emissions; its use in diesel engines is quite limited. Aluminum oxide is utilized in this study to examine the consequences of deposition over an extended period of operation.

2. Research Methodology

The research approach utilized to accomplish the study's goals is described in this chapter. A compression ignition (CI) engine was used to evaluate three different fuel samples. Four main factors were the focus of the study: carbon deposits, kinematic viscosity or lubricating fluid, noise emissions, and engine performance (Saxena et al., 2017). The first assessment of fuel qualities followed ASTM (American Society of Mechanical Engineers) guidelines. Tests of engine performance and pressure level were conducted at a steady speed while varying loading circumstances were present. To evaluate engine wear and valve deposition, endurance tests were also performed. Figure 1 displays the final study diagram.

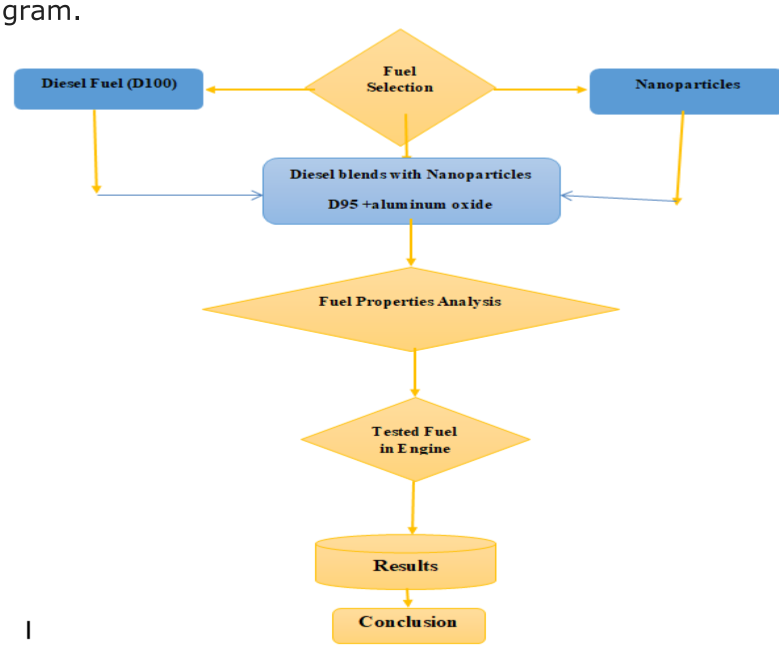

Figure 1: Flow Diagram of Research Methodology

2.1. Fuel Properties

Fuel characteristics are a significant parameter in compression ignition engines, as they directly impact fuel combustion. Biodiesel, an alternative fuel derived from natural feedstock, has properties that depend on its fatty acid composition. The structure of fatty acids influences key characteristics such as viscosity, density, cetane number, and heating value.

Table 1

Properties Of Prepared Biodiesel Samples

Properties	Diesel	(B30al2033%)	Standards
Kinematic Viscosity At 500 CST	1.95	2.52	ASTM D445
Density	887	912	ASTM D127
Calorific Value MJ/Mg	45.36	42.67	ASTM D240
Specific Gravity	0.840	0.846	ASTM D891

These fuel properties also affect spray characteristics, including droplet size distribution, spray angle, fuel evaporation, and flame distribution. Similarly, the properties of biodiesel influence engine performance, noise emissions, exhaust gas temperature, engine component deposits, and tribological parameters (Muralidharan & Vasudevan, 2011). The concentration of biodiesel in diesel fuel alters these properties, creating distinct combustion characteristics. In this work, biodiesel-diesel blends were prepared by volume percentage. The properties of the tested fuel samples are provided in Table 1.

2.2. Engine Performance Procedure & Experimental Setup

Engine tests have been carried out in the thermodynamics lab; and mechanical engineering laboratory of Quaid-e-Awam University of Engineering, Science & Technology Nawabshah. In this regard, the performance parameters are calculated using a single horizontal cylinder water-cooled 4-stoke diesel engine. The name of the test bed is DWE-6/10-js-Dv, fully equipped with different instruments such as a tachometer, dynamometer system, etc. They are two fuel tanks for a diesel engine attached to a test bed. A common pipeline has been used to transfer fuel to the engine. However, both fuel tanks are linked to the common line; flow can be controlled with two separate valves. One tank is filled with diesel fuel (D100) and another one is filled by selecting the alternative fuel. In this work, 2 fuel samples have been tested namely diesel 100% (D100), diesel 97%, and nanoparticles Aluminum oxide 3%, ($B30Al_20^33$) details are given in Table 1. These parameters are determined at constant speed and load varying. The load varies from 0 to 1.6 Kg-m at 1400 rpm. However, first data is collected from the engine at a speed of 1400 rpm while the engine is on off-load. While 1400 RPM offers clear advantages, exploring a range of RPMs (e.g., low-load 800 RPM or high-load 2000 RPM conditions) could provide a more comprehensive understanding of the additive's effects across varied operational scenarios. This would help identify potential limitations or specific advantages of aluminum oxide nanoparticles under dynamic engine conditions. Engine performance data is collected when engine stabilization occurs after approx. 10 minutes. For each outcome, three readings were taken to average the results. Would you like assistance in proposing broader RPM testing or interpreting the findings under different operating conditions? By focusing on a single blend, the study does not explore the cost-benefit implications of adopting $B30Al_2O_3$ compared to other blends or additive technologies:

Table 2
Biodiesel Composition by Volume

Sr No.	Composition Name	Composition By Volume
1	D100	Diesel 100%
3	B30Al2033%	Diesel 97% + Al2033% (Aluminum oxide 3%)

2.3. Analysis of Particulate Matter Emission

For this purpose, data on PM (particulate matter) emissions from diesel engines operating on pure diesel fuel and biodiesel blend fuels will be gathered. The speed, load, and fuel quality of an engine all affect how much pollution it emits. Using four particle sizes (pm 1.0, pm2.5) at the same speed and under various load situations, diesel fuel and biodiesel combined fuels. The exhaust particulate matter emissions will be measured every 10 hours during a long-term run engine. The characterize PM in diameter in Micron four particle sizes of PM (pm 1.0, pm2.5.).

2.4. Endurance Test

In this research study, three fuel samples were tested, including D100 and $B30Al_2O_3$ (3% concentration). These tests were conducted with the fourth objective: measuring durability through a 60-hour endurance test. The engine was operated at a constant load of 9.8 N·m and a constant speed of 1400 RPM for endurance testing. During the first phase, the engine ran for 60 hours on diesel fuel (D100). After completing the 60-hour duration, the fuel injectors were replaced for deposition analysis. Before switching to the alternative fuel, the engine ran on diesel for 10 minutes to warm up. Following the warm-up phase, the engine operated under the same constant load and speed as the alternative fuel. This objective aims to determine the elemental deposition on the engine head fuel injectors. In total, two fuel injectors were tested, each running for 60 hours on a specific fuel. After 60 hours of operation on the compression ignition (CI) engine at constant load and throttle speed, elemental deposition formed on the surface of the engine head fuel injectors. Microscopic and visual inspection tests were conducted at various locations on the fuel injector to examine the elemental deposition. After the engine had been running for 60 hours, aromatic compound elements began to deposit on the injector surface. These elemental deposits, formed by aromatic compounds on the surface of the engine head, inlet, and exhaust valves during the endurance test, were examined using a microscopic test with energy-dispersive X-ray (EDX) analysis.

2.5. Potential Limitations of Using Aluminum Oxide

2.5.1. Economic Feasibility

The 3% concentration of aluminum oxide might be cost-prohibitive for some industries. Testing lower concentrations could highlight cost-effective alternatives.

2.5.2. Practical Implementation

Higher biodiesel blends (e.g., B50, B100) might offer greater environmental benefits but could require engine modifications. The study does not address whether the additive's advantages outweigh these practical challenges. The 60-hour test duration is highly relevant for providing valuable insights into the short-term and mid-term effects of fuel blends and additives like aluminum oxide (Fonseca & Schlueter, 2013). It mimics real-world operating conditions for a variety of industrial and commercial engines, enabling the study to assess carbon buildup, engine wear, emissions, and overall performance. However, while this duration provides useful data on immediate impacts, future research could benefit from longer testing periods to fully assess the long-term durability and effects of the additive on engine components and fuel efficiency.

3. Results and Discussion

The results of this research are primarily based on engine performance, noise emissions, and durability testing. In this study, two fuel samples—D100 and B30Al_2O_3 (3%)—were tested and compared. The endurance test was conducted over 60 hours, with each fuel being tested for 60 hours under constant load and constant RPM conditions.

Before conducting these tests, the fuel properties—such as kinematic viscosity, density, calorific value, cetane number, fire point, and specific gravity—were initially measured according to ASTM standards. The analyzed characteristics of diesel fuel were then compared with the prepared fuel samples, as discussed.

3.1. Analysis of carbon depositions of fuel injector

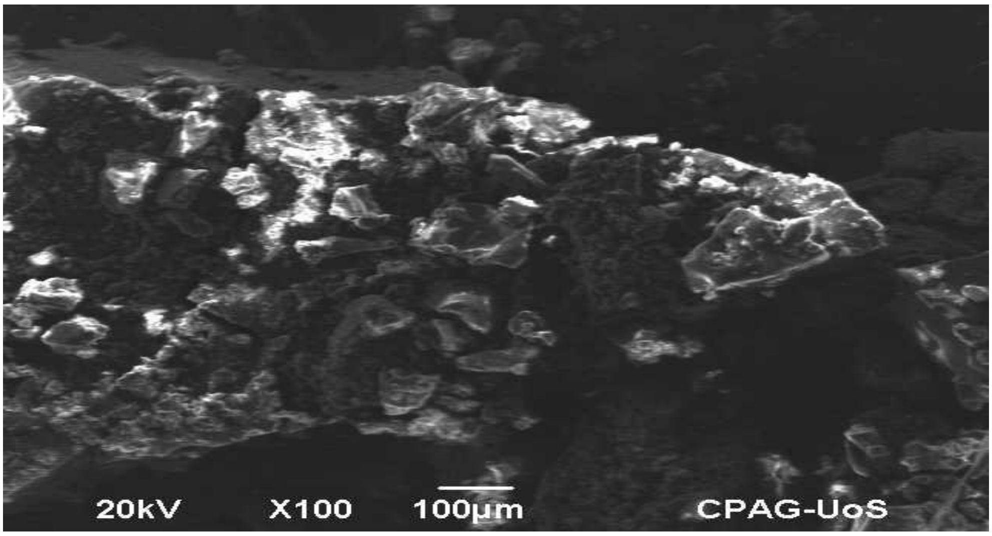

Figure 2 SEM Analysis of Fuel Injector At Pure Diesel (D100)

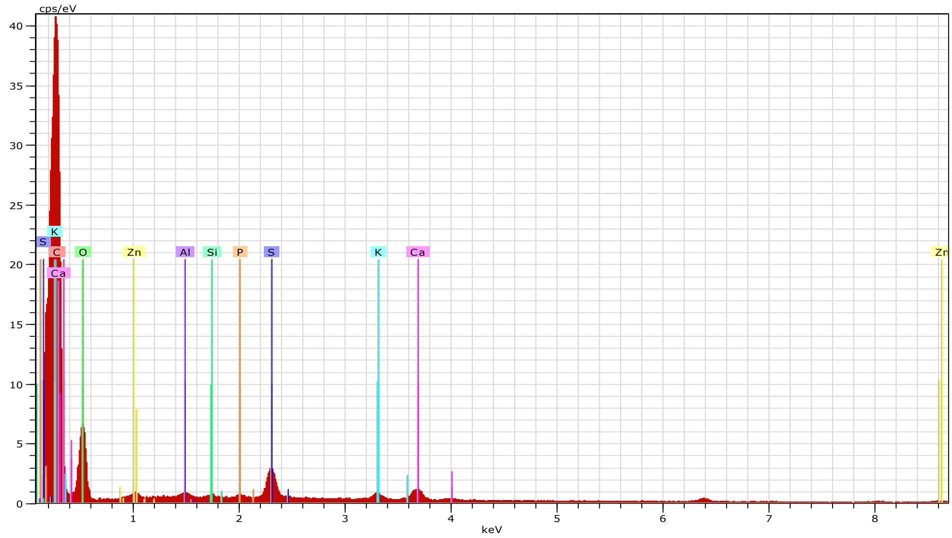

Figure 3 EDX Analysis of Fuel Injector at Pure Diesel(D100)

Table 3
Quantities Analysis of Fuel Injector at D100

Element	unn. C [wt.%]	C Atom [at. %]	Error [%]
Carbon	56.52	64.45	17.3
Oxygen	40.04	34.34	12.5
Sulfur	1.44	0.62	0.1
Calcium	0.97	0.33	0.1
Iron	0.58	0.14	0.0
Zinc	0.54	0.11	0.0

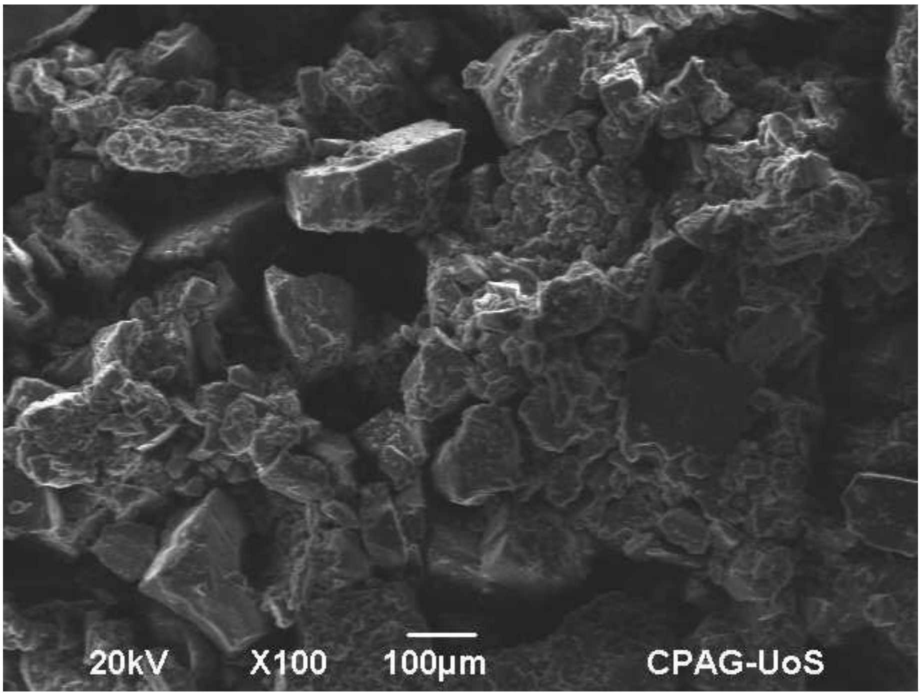

Figure 4: SEM Analysis of Fuel Injector at Aluminum Oxide

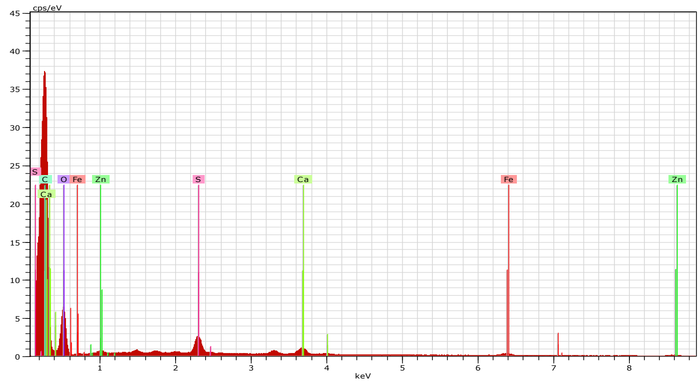

Figure 5 EDX Analysis of Fuel Injector at Aluminum Oxide

Table 4
Quantities Analysis of Fuel Injector at Aluminum Oxide

Element	norm. C [wt.%]	Atom. C [at. %]	Error [%]
Carbon	34.30	41.93	19.5
Oxygen	61.55	56.48	19.4
Sulfur	1.42	0.65	0.1
Potassium	0.54	0.20	0.0
Calcium	1.04	0.38	0.1
Phosphorus	0.08	0.04	0.0
Silicon	0.05	0.03	0.0
Aluminum	0.20	0.11	0.0
Zinc	0.82	0.18	0.1

Energy Dispersive X-ray Spectroscopy (EDX) was performed following the Scanning Electron Microscopy (SEM) analysis. Several locations were identified on the surface of the fuel injector for examination. EDX results were obtained at deposit locations with a magnification of 100X. Due to high temperatures, elemental carbon (C) and oxygen (O) were detected. The carbon was produced through two mechanisms: the decomposition of hydrocarbons into their primary components—hydrogen and carbon—and the polymerization of hydrocarbon components into large polynuclear aromatic hydrocarbons (PAHs), resulting in carbonaceous deposits on the surfaces of the fuel injector.

In the figure depicting the fuel injector used with diesel fuel (D100), the results show that 56.52% of the fuel injector surface consists of carbon deposits. In contrast, the figure for the diesel blend with additives (B30Al_2O_3) shows 34.30% carbon deposition on the injector surface. In addition to carbon, oxygen, silicon, and sulfur, other elements such as aluminum, phosphorus, calcium, iron, and zinc also appeared on the valve surfaces in the D100 sample. The higher temperature and increased viscosity contribute to the enhanced formation of deposits on the valve surfaces.

3.2. Analysis of Particulate Matter Emissions

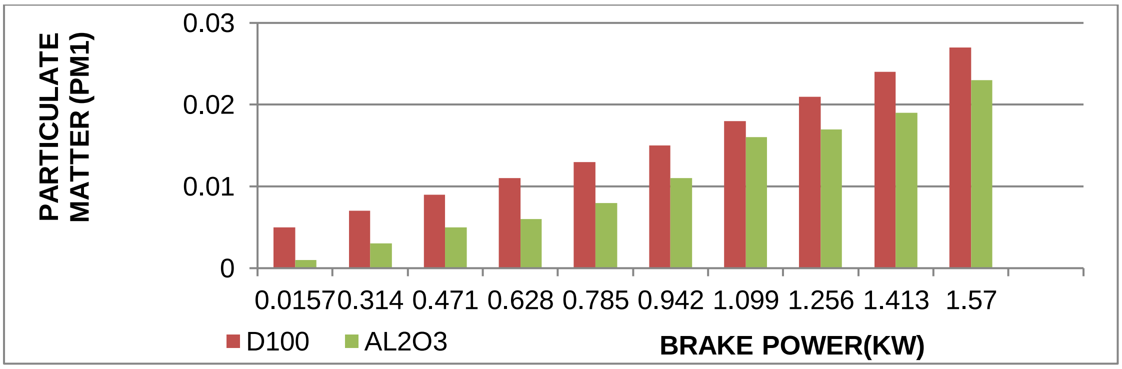

Figure 6: Particulate Matter Emissions (PM1) Vs Brake Power

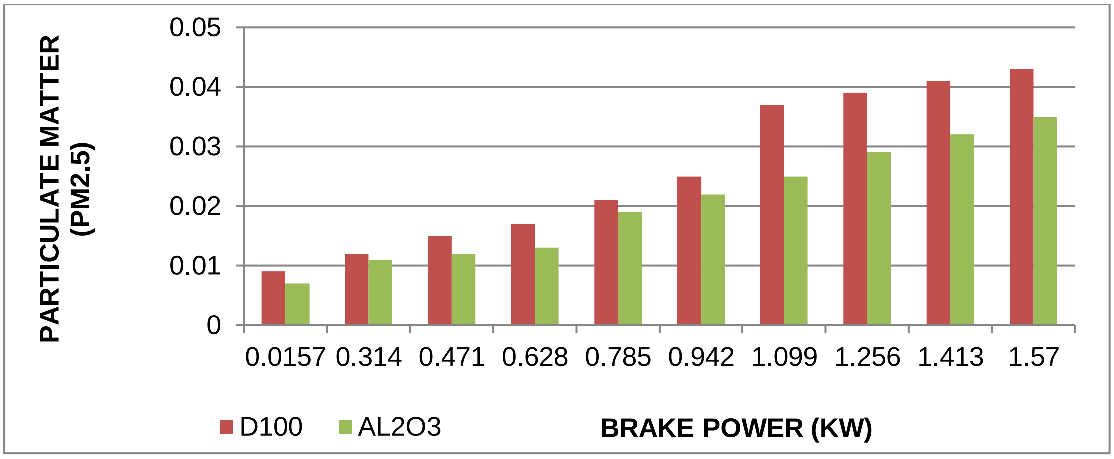

Figure 7: Particulate Matter Emissions (PM2.5) Vs Brake Power

The purpose of this research was to examine how different fueling alternatives affect particulate matter (PM) emissions, specifically comparing diesel alone with diesel mixed with nanoparticles. When compared to diesel as a fuel, nanoparticles significantly reduce PM emissions in standard diesel engines with little or no modification.

4. Conclusion

In this study, an endurance test was conducted by running an engine for 60 hours under constant load and constant RPM conditions. After 60 hours of operation, significant carbon and other aromatic compound deposits were found in the engine using D100 (pure diesel). The carbon deposition was particularly high compared to other aromatic compounds.

In contrast, for the $B30Al_2O_3$ (3%) fuel blend, free-form carbon was detected on the fuel injector, but this form of carbon did not negatively affect engine performance. The presence of the aluminum oxide additive in the B30 blends likely helped reduce harmful carbon build-up and other deposits, allowing the engine to maintain performance even with some deposition.

Overall, while D100 led to higher deposits that could impair engine performance, the $B30Al_2O_3$ blend showed less problematic carbon deposits, suggesting its potential advantage in long-term engine durability. This study highlights the dual benefits of using $B30Al_2O_3$ (3%) fuel blends: improved engine durability through reduced deposits and broader environmental advantages through lower emissions. The findings not only address gaps in prior research on the long-term effects of nanoparticle additives but also establish a strong case for integrating such blends into energy policies aimed at sustainability and climate resilience.

4.1. Suggestions for Future Work

In this study, engine performance parameters, engine sound pressure level emission, and endurance tests for 60 hours have also been analyzed. Over all three fuel samples have been tested. In this regard future suggestions are given below:

This work can be enhanced by increasing the percentage of blends as well as additives. In this work, alcohol family additives are used. To enhance the work of this research, another additive may be used. The engine performance results are performed at variable loads and constant rpm, whereas; at constant load and variable rpm, the engine performance results can be determined.

Authors Contribution
Sher Muhmmad Ghoto: Initiated the core idea of performed data analysis and drafting.
Ramez Raja: conclusion of the paper
Sajjad Bhnagwar: Concept topic idea and supervisor over all
Faisal Rehman: help in the writeup of the paper
Abdullah Qazi: Assist in writeup and complete the paper
Habib Ahmed: Reviewed and revised overall quality
Tooba Waseem: Grammar and proofread the paper

Conflict of Interests/Disclosures
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References

Arshad, K., Hussain, N., Ashraf, M. H., & Saleem, M. Z. (2024). Air pollution and climate change as grand challenges to sustainability. *Science of The Total Environment*, 172370. https://doi.org/10.1016/j.scitotenv.2024.172370

Bhangwar, S., Ghoto, S. M., Abbasi, A., Abbasi, M. K., Rind, A. A., Luhur, M. R., & Mastoi, S. (2022). Analysis of particulate matter emissions and performance of the compression ignition engine using biodiesel blended fuel. *Engineering, Technology & Applied Science Research*, *12*(5), 9400-9403. https://doi.org/10.48084/etasr.4704

Corral Bobadilla, M., Lostado Lorza, R., Escribano García, R., Somovilla Gómez, F., & Vergara González, E. P. (2017). An improvement in biodiesel production from waste cooking oil by applying multi-response surface methodology using desirability functions. *Energies*, *10*(1), 130. https://doi.org/10.3390/en10010130

Farvardin, M., Hosseinzadeh Samani, B., Rostami, S., Abbaszadeh-Mayvan, A., Najafi, G., & Fayyazi, E. (2022). Enhancement of biodiesel production from waste cooking oil: Ultrasonic-hydrodynamic combined cavitation system. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *44*(2), 5065-5079. https://doi.org/10.1080/15567036.2021.1907752

Fonseca, J. A., & Schlueter, A. (2013). Novel approach for decentralized energy supply and energy storage of tall buildings in Latin America based on renewable energy sources: Case study–Informal vertical community Torre David, Caracas–Venezuela. *Energy*, *53*, 93-105. https://doi.org/10.1016/j.energy.2013.02.019

Gaur, A., Mishra, S., Chowdhury, S., Baredar, P., & Verma, P. (2021). A review on factors affecting biodiesel production from waste cooking oil: An Indian perspective. *Materials Today: Proceedings*, *46*, 5594-5600. https://doi.org/10.1016/j.matpr.2020.12.697

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Hsu, P.-C., Huang, B.-J., Lin, W.-C., Chang, Y.-J., Chang, C.-J., Li, K., & Lee, K.-Y. (2016). Effect of switching scheme on the performance of a hybrid solar PV system. *Renewable Energy*, *96*, 520-530. DOI: 10.1016/j.renene.2016.05.004

IPCC. (2014). Climate change 2014 synthesis report. *IPCC: Geneva, Szwitzerland*, 1059-1072.

Muralidharan, K., & Vasudevan, D. (2011). Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. *Applied Energy*, *88*(11), 3959-3968. https://doi.org/10.1016/j.apenergy.2011.04.014

Nair, J. N., Singh, T. S., & Raju, V. D. (2021). Effect of addition of bio-additive clove oil to ternary fuel blends (diesel-biodiesel-ethanol) on compression ignition engine. 10.1088/1742-6596/2070/1/012212

Neu, R. (2011). Progress in standardization of fretting fatigue terminology and testing. *Tribology International*, *44*(11), 1371-1377. doi:10.1016/j.triboint.2010.12.00

Paulescu, M., Stefu, N., Calinoiu, D., Paulescu, E., Pop, N., Boata, R., & Mares, O. (2016). Ångström–Prescott equation: Physical basis, empirical models and sensitivity analysis. *Renewable and Sustainable Energy Reviews*, *62*, 495-506. https://doi.org/10.1016/j.rser.2016.04.012

Saxena, V., Kumar, N., & Saxena, V. K. (2017). A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled CI engine. *Renewable and Sustainable Energy Reviews*, *70*, 563-588. DOI: 10.1016/j.rser.2016.11.067

Temizer, İ., & Eskici, B. (2020). Investigation on the combustion characteristics and lubrication of biodiesel and diesel fuel used in a diesel engine. *Fuel*, *278*, 118363. https://doi.org/10.1016/j.fuel.2020.118363

Tomar, M., & Kumar, N. (2020). Influence of nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel, and blends–a review. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *42*(23), 2944-2961. https://doi.org/10.1080/15567036.2019.1623347

Vivian, J., Manente, G., & Lazzaretto, A. (2015). A general framework to select working fluid and configuration of ORCs for low-to-medium temperature heat sources. *Applied Energy*, *156*, 727-746. https://doi.org/10.1016/j.apenergy.2015.07.005

Zin, V., Barison, S., Agresti, F., Colla, L., Pagura, C., & Fabrizio, M. (2016). Improved tribological and thermal properties of lubricants by graphene based nano-additives. *RSC advances*, *6*(64), 59477-59486. https://doi.org/10.1039/C6RA12029F