Optimization of Hybrid Nano Additives in Diesel-Ethanol Fueled CI Engines

Getachew Abera Bayisa

A Thesis Submitted to the Department of Mechanical Engineering

College of Mechanical, Chemical, and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Automotive Engineering

Office of Graduate Studies
Adama Science and Technology University

January 2025
Adama, Ethiopia

Optimization of Hybrid Nano Additives in Diesel- Ethanol fueled CI engines

Getachew Abera Bayisa

Advisor: Getachew Alemayehu (PhD)

A Thesis Submitted to the Department of Mechanical Engineering

College of Mechanical, Chemical, and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

January 2025

Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled "Optimization of Hybrid Nano Additives in Diesel- Ethanol fueled CI engines" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

______________________________ ___________________________ __________________

Name of student Signature Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "Optimization of Hybrid Nano Additives in Diesel- Ethanol fueled CI Engines" prepared under my guidance by **Mr. Getachew Abera** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Automotive Engineering. Therefore, I recommend submitting the revised version of the thesis to the department following the applicable procedures.

______________________	______________________	______________
Major Advisor	Signature	Date
______________________	______________________	______________
Co-advisor	Signature	Date

APPROVAL

I the advisor of the thesis entitled "Optimization of Hybrid Nano Additives in Diesel-Ethanol Fueled CI engines" and developed by Getachew Abera, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

______________________	______________________	______________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Reviewers of the proposal open defense by **Getachew Abera Bayisa**, have read and evaluated the thesis proposal entitled "Optimization of Hybrid Nano Additives in Diesel—Ethanol Fueled CI engines" and assessed the candidate's understanding of the proposed research. This is, therefore, to certify that the thesis proposal is accepted and that we recommend its implementation.

______________________	______________________	______________
Chairperson	Signature	Date
______________________	______________________	______________
Reviewer 1	Signature	Date
______________________	______________________	______________
Reviewer 2	Signature	Date

Final approval and acceptance of the thesis proposal is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

______________________	______________________	______________
Department Head	Signature	Date
______________________	______________________	______________
School Dean	Signature	Date
______________________	______________________	______________
Office of Postgraduate Studies, Dean	Signature	Date

ACKNOWLEDGMENTS

First and foremost, I give all glory and honor to **Almighty God**, the source of all wisdom and knowledge, for granting me the strength, perseverance, and divine guidance to undertake and complete this research project.

I want to express my sincere gratitude to my Advisor, **Dr. Getachew Alemayehu**, for his invaluable guidance, unwavering support, and insightful feedback throughout my research. His expertise, patience, and encouragement have been instrumental in completing this thesis.

I am deeply indebted to the faculty and staff of the Mechanical System and Vehicle Engineering department at Adama Science and Technology University and Addis Ababa Science and Technology University for their continuous support and for providing me with the resources and facilities necessary to undertake this research project.

I would also like to extend my heartfelt appreciation to the m thesis committee members, for their valuable time, constructive criticism, and insightful suggestions, which have greatly contributed to improving this work.

Special thanks go to my colleagues for their intellectual discussions, technical assistance, and for creating a stimulating and collaborative research environment.

Finally, I would like to express my deepest gratitude to my family and friends for their unwavering love, encouragement, and emotional support throughout this journey. Without their understanding and patience, this thesis completion would not have been possible.

Thank you all for your invaluable contributions to this endeavor.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ANOVA	Analysis of Variance
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CNT	Carbon Nanotube
DOE	Design of Experiment
EGT	Exhaust Gas Temperature
HC	Hydrocarbon
OA	Orthogonal Array
PPM	Parts Per Million
RPM	Revolution Per minute
RSM	Response Surface Methodology

ABSTRACT

This study investigated the performance and emission characteristics of diesel-ethanol blends enhanced with aluminum oxide (Al_2O_3) and cerium oxide (CeO_2) nanoparticles in a single-cylinder CI engine. Utilizing Taguchi's L_9 orthogonal array, the study systematically varied ethanol-diesel ratios (E10D90, E20D80, E30D70), nanoparticle concentrations (15, 30, and 45 ppm), and engine load (25%, 50%, and 80%). Quantitatively, the study revealed that the highest brake power (84.8 kW) and torque (324 Nm) were achieved with the E10D90 blend at 45 ppm of both nanoparticles under 80% load. The E30D70 blend demonstrated the highest brake thermal efficiency (32.5%) at 50% load. Increasing ethanol content from E10D90 to E30D70 improved fuel efficiency by 10.6%, reducing brake-specific fuel consumption (BSFC) from 260 g/kWh to 232 g/kWh, but increased exhaust gas temperature (EGT) by 10°C. NOx emissions decreased by 10% with ethanol blends, while CO and unburned hydrocarbons (UHC) increased by 12.5% and 19%, respectively. Adding 45 ppm Al_2O_3 and 15 ppm CeO_2 at 80% load further reduced BSFC by 2% and EGT by 5°C. Cerium oxide (CeO_2) was identified as the most crucial nanoparticle due to its superior catalytic properties, significantly enhancing combustion efficiency and reducing emissions. Its delta values of 2.66 in the "Larger is Better" S/N ratio (for performance metrics) and 0.47 in the "Smaller is Better" S/N ratio (for emissions) underscored its dominant influence compared to aluminum oxide and other parameters. However, concerns about engine wear arise with higher ethanol concentrations, such as E30D70, as ethanol's lower lubricity and higher corrosiveness can potentially accelerate engine component degradation over time. The decrease in NOx emissions with increasing ethanol concentration can be attributed to ethanol's higher oxygen content, which promotes more complete combustion and lowers peak combustion temperatures, thereby reducing thermal NOx formation. These findings demonstrated that increased ethanol content and cerium oxide concentrations generally enhanced performance, while increased load positively impacted key metrics.

Keywords: ethanol-diesel blends, nanoparticles, CI engine, Taguchi, emission, engine performance.

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

The increased need for alternative and renewable fuels has arisen due to the extensive reliance on fossil fuels, environmental issues, and the threat of global warming (Amiri & Shirneshan, 2020). Currently, there is a suggestion to enhance the performance, combustion, and emission characteristics of diesel engines by incorporating nanoparticle additives such as Al_2O_3, CeO_2, and NiO (Pullagura et al., 2021), ZrO_2 (Venu et al., 2019), and TiO_2 (Venu et al., 2019) into the diesel fuel.

Fuel blend utilization in diesel engines results in several outcomes, including heterogeneous combustion kinetics and accelerated ignition reactions thereby enhancing energy density (Elbanna et al., 2022). Heterogeneous combustion occurs when heat is transferred to the unburnt reactants, facilitating the completion of the formation of final products. Furthermore, the increased surface-to-volume ratio contributes to faster oxidation during combustion and higher combustion enthalpy (Mohanna, 2020). Nanoparticles also offer benefits, such as a high evaporation rate, effective atomization, sustainable flame characteristics, and improved air-fuel mixing (Küçükosman et al., 2022). Achieving effective atomization of fuel results in an earlier initiation of the combustion process. Metal nanoparticle additives incorporation leads to enhanced combustion and efficiency in conventional fuels. However, these additives come with certain drawbacks, the most significant being the potential presence of solid metal oxides in the engine's exhaust gases when using metal nanoparticle-fueled engines, posing a considerable health risk. Therefore, it becomes necessary to incorporate a particulate filter in engines that utilize nanoparticle additives. Other disadvantages include the risk of agglomeration, high costs associated with the supply of nanoparticles, and challenges related to achieving uniform dispersion (Kishore et al., 2023). Optimal engine performance and emissions can be achieved by minimizing the additional costs associated with nanoparticle supply, stabilization, and dispersion. Various approaches exist to prevent nanoparticle coagulation or settling. The utilization of surfactants, surface modification, steric repulsion, and electrostatic repulsion are fundamental mechanisms that prevent nanoparticle agglomeration and influence their stability (Wang et al., 2023).

Based on existing literature, nanoparticle additives have been shown to enhance engine performance by increasing power, torque, and combustion efficiency, simultaneously reducing brake-specific fuel consumption. Additionally, these additives can decrease emissions of hydrocarbons, carbon monoxide, and smoke (Vinayagam et al., 2021).

Experimental Design systematically analyzes control variables affecting responses through four phases: planning, screening, optimization, and verification. This study used DOE, experimental investigations, and a hybrid Grey-centered Taguchi technique to optimize multi-response functions, addressing complex interrelationships beyond the capabilities of the Taguchi method alone. Key control parameters included ethanol-diesel ratio, nanoparticle concentration, and engine loading, while responses focused on BT, BP, BSFC, BTE, EGT, NOx, HC, CO, and smoke emissions.

The study investigated the effect of hybrid nanoparticles, specifically Al_2O_3 and CeO_2, by varying their concentrations to analyze their impact on engine performance. The experiments utilized ethanol-diesel blends with three ratios: E10D90, E20D80, and E30D70. Additionally, the engine was tested under three loading conditions: 25%, 50%, and 80% of the maximum load. These parameters hybrid nanoparticle concentration, fuel blend ratio, and engine loading were systematically varied to evaluate their influence on the efficiency of the compression ignition engine.

1.2. Statement of Problems

Internal combustion engines running on a diesel-ethanol fuel blend offer the potential for greater efficiency and reduced emissions. To fully harness this potential, optimizing engine performance is crucial. One effective strategy is incorporating hybrid nano additives into the fuel mixture. These additives, consisting of a blend of nanoparticles, have been proven to enhance combustion, reduce emissions, and improve overall engine performance (Basha et al., 2022).

However, the optimal combination and concentration of these hybrid nano additives in diesel-ethanol hybrid nano additives optimal combination and concentration powered CI engines have not been thoroughly investigated. The challenge lies in determining the most effective combination of nanoparticles, their concentrations, and the appropriate fuel blend ratio to achieve the desired improvements in engine performance, combustion characteristics, and emission levels (Modi et al., 2024). The objectives of this study were to optimize hybrid nano additives for diesel-ethanol-powered CI engines with a focus on enhancing fuel efficiency, reducing emissions, improving combustion stability, and ensuring engine durability. By addressing this problem, valuable insights can be gained to develop more efficient and environmentally friendly engine technologies.

1.3. Objective of the Study

1.3.1. General Objective

The general objective of this study was to optimize hybrid nano additives in diesel-ethanol-fueled CI engines.

1.3.2. Specific Objectives

Specific objectives of the study were;

- ✓ To evaluate the impact of varying ethanol-diesel blend ratios (E10D90, E20D80, and E30D70) on the performance and emission characteristics of a compression ignition engine;
- ✓ To investigate the effect of hybrid nanoparticle concentrations (Al_2O_3 and CeO_2 at 15 ppm, 30 ppm, and 45 ppm) on combustion efficiency and emission reduction in a CI engine;
- ✓ To analyze the influence of engine loading conditions (25%, 50%, and 80%) on engine efficiency and emission characteristics;
- ✓ To optimize the engine performance and emission parameters using the Taguchi orthogonal array design and Grey-Taguchi method for multiple response optimization.

1.4. Significance of the Study

The optimization of hybrid nano additives in diesel-ethanol-powered CI engines is a significant research area due to the increasing demand for cleaner and more efficient engine technologies. The combination of diesel and ethanol as a fuel blend has gained attention as it offers the potential to reduce greenhouse gas emissions and dependence on fossil fuels. However, the full potential of this fuel blend can be realized by incorporating hybrid nano additives into the mixture. Hybrid nano additives, which consist of a combination of different nanoparticles, have shown promising results in improving combustion characteristics, reducing emissions, and enhancing overall engine performance. These additives can modify the fuel properties and combustion processes, leading to more efficient and cleaner combustion. By optimizing the combination and concentration of these additives, the performance of diesel-ethanol-powered CI engines can be significantly enhanced.

Optimization involves determining the most effective combination of nanoparticles, their concentrations, and the optimal fuel blend ratio. This requires a comprehensive understanding of the interactions between nanoparticles, fuel components, and the combustion process. Additionally, the effects of these additives on engine durability and long-term performance need to be considered. The optimization process will involve experimental investigations and computational modeling to evaluate the effects of different hybrid nano additives on engine performance, combustion characteristics, and emissions. Various parameters, such as BTE, BSFC, NOx emissions, particulate matter, CO, and UHC, will be analyzed to assess the impact of the additives. The results of this study will provide valuable insights into the optimal design and formulation of hybrid nano additives for diesel-ethanol-powered CI engines.

In conclusion, optimizing hybrid nano additives for diesel-ethanol-powered CI engines is a vital area of research aimed at maximizing the advantages of this fuel blend. By identifying the optimal concentration of nanoparticle combination, substantial enhancements in engine performance, combustion efficiency, and emission reduction can be realized. This research holds the potential to advance engine technology and support the transition toward a cleaner and more sustainable future.

1.5. Expected outcome of the study

The optimization of hybrid nano additives in diesel-ethanol-powered CI engines is anticipated to yield several significant outcomes that address performance, emissions, combustion characteristics, and long-term engine durability. A primary objective is to enhance engine performance by identifying the optimal combination and concentration of hybrid nano additives. This optimization is expected to improve key performance indicators such as brake thermal efficiency and brake-specific fuel consumption, reflecting enhanced fuel combustion efficiency. The integration of hybrid nano additives also aims to reduce emissions by minimizing harmful pollutants, including nitrogen oxides, particulate matter, carbon monoxide, and unburned hydrocarbons. Such reductions contribute to improved air quality and reduced environmental impact.

Moreover, hybrid nano additives are hypothesized to improve combustion characteristics by influencing ignition delay, combustion stability, and heat release rates. These improvements are anticipated to result in faster and more controlled combustion processes, promoting smoother engine operation and reducing issues related to incomplete combustion. Through experimental investigations and computational modeling, the study seeks to determine the most effective combination and concentration of hybrid nano additives. This approach is expected to identify specific nanoparticle formulations that achieve optimal performance and emission reduction for diesel-ethanol-powered CI engines.

Additionally, the study will evaluate the long-term effects of hybrid nano additives on engine durability, providing insights into their impact on critical engine components, lubrication systems, and overall lifespan. These findings are essential for understanding the practical implications of using these additives in real-world applications. Lastly, the research outcomes are expected to serve as a foundation for future engine design and regulatory standards. By offering evidence-based guidelines, this study can support the development of advanced engine technologies that incorporate hybrid nano additives and inform the creation of policies and standards for their implementation.

1.6. Scope of the Study

This study focuses on optimizing the performance and emission characteristics of a diesel-ethanol-powered compression ignition engine using hybrid nano additives (Al_2O_3 and CeO_2). The research involves preparing and testing fuel blends with varying ethanol-diesel ratios (E10D90, E20D80, and E30D70) and nanoparticle concentrations (15 ppm, 30 ppm, and 45 ppm) under controlled engine loading conditions (25%, 50%, and 80%) at a constant speed of 1500 rpm. Engine performance was evaluated through parameters such as brake thermal efficiency, brake-specific fuel consumption, power output, and torque. While, emission analysis measures pollutants including NOx, CO, HC, and particulate matter. Combustion characteristics, such as ignition delay, heat release rate, and stability, are also assessed. The study employs the Taguchi orthogonal array design and the Grey-Taguchi method for optimization, supported by computational modeling for deeper insights. Additionally, the long-term durability and reliability of the engine with hybrid nano additives are examined. The findings provide recommendations for optimal additive formulations and operational conditions to enhance engine performance and reduce emissions.

CHAPTER TWO

2. LITERATURE REVIE

2.1. Engine Emissions and Combustion Analysis of Alcohol-Blended Fuels

This section thoroughly reviews the performance, combustion, and emission characteristics of diesel blended with alcohols in a compression ignition engine. It validates the behavior of the blended fuels by analyzing their chemical and structural properties. Each subsection examines the impact of different alcohols blended with standard diesel and comprehensively summarizes the investigation on alcohol-diesel fuel combinations.

2.1.1. Ethanol

The use of ethanol in diesel engines is becoming more widespread due to its notable impact on reducing exhaust emissions. However, ethanol cannot be used directly as fuel, in diesel engines because of its lower viscosity, cetane number, and energy content. Instead, it is typically blended with diesel fuel for effective use. Ethanol is widely identified as a promising alcohol fuel for partial substitution in CI engines, with many countries implementing policies to use various ethanol-diesel blends in commercial vehicles (Loyte et al., 2022). Though better suited for spark-ignition engines due to its higher octane, ethanol's renewable nature, and improved miscibility with diesel compared to methanol make it attractive for CI applications. However, the substantial property differences between diesel and ethanol pose challenges for complete substitution, necessitating engine modifications to accommodate this alternative fuel (Taneja et al., 2021).

The brake-specific fuel consumption of ethanol-diesel blends is found to be higher than standard diesel fuel and tends to increase as the ethanol percentage in the blend is raised (Zhang et al., 2022). This is attributed to three key factors: the lower calorific value of ethanol, its reduced energy content compared to diesel, and the advanced start of combustion in blends with higher ethanol concentration. When ethanol is blended with biodiesels the overall heating value and viscosity of the resulting ethanol-biodiesel-diesel blend or emulsion become the major factors influencing the BSFC performance (Krishna et al., 2019). Regarding emissions, the carbon monoxide emissions of the ethanol-diesel blend increase as the fraction of ethanol in the blend is raised. This is because when the ethanol fraction is higher, the lower cetane number and higher heat of vaporization can lead to incomplete combustion, resulting in higher CO emissions (Nanthagopal et al., 2017). Shadidi et al. (2021) conducted experiments using ethanol-diesel blends as the test fuel and found that NOx and HC emissions were reduced compared to pure diesel fuel. Zhong et al. (2022) conducted experiments on diesel engines using diesel-ethanol-biodiesel blends and an increase in ignition delay and brake-specific fuel consumption, along with a decrease in brake thermal efficiency. Additionally, they observed reductions in carbon monoxide and nitrogen oxide emissions, while unburned hydrocarbons and carbon dioxide levels rose with higher ethanol concentrations in the blends. Several studies have found that increasing ethanol concentration in diesel fuel reduces smoke and nitrogen oxide emissions. This is due to the higher oxygen content in ethanol, which improves the combustion process (Ghareeb & Anjal, 2023). However, blending ethanol with diesel lowers the cetane number and calorific value, negatively impacting engine performance. To address this issue, researchers have explored various additives in diesel fuel. Recently, metal oxide nanoparticles have gained significant attention as a promising additive for diesel fuel.

Nanoparticles are high-energy-density additives known for their strong catalytic activity and high surface-to-volume ratio, which enhance fuel properties and combustion efficiency in diesel engines. Dinesha et al. (2021) utilized CeO_2 nanoparticles in biodiesel blends and observed an increase in fuel heating value, along with improved emission and performance characteristics of the diesel engine. Similarly, Sivathanu and Anantham (2020) conducted experiments on a diesel engine fueled with carbon nanotubes blended with waste fishing net oil. Their results demonstrated a 3.83% increase in brake thermal efficiency, a 3.87% reduction in brake-specific fuel consumption, and significant decreases in carbon monoxide, nitrogen oxide, hydrocarbon, and smoke emissions.

2.1.2. Methanol

Methanol has been added to diesel and biodiesel since it is highly volatile and oxygenated. Methanol’s increased oxygen content enhances combustion, offsetting its lower energy content. However, its lower cetane number results in poor ignition behavior and a prolonged ignition delay, hindering its complete substitution for diesel fuel (Saeed & Henein, 1989).

To use alcohol in compression ignition engines, researchers have looked into a variety of approaches. These include emulsification to produce stable alcohol-diesel or alcohol-biodiesel mixtures; advanced injection techniques to optimize the fuel delivery process;

direct blending of alcohols with diesel and biofuels to create homogenous fuel blends; and alcohol fumigation, which introduces alcohol as a supplemental fuel alongside the primary diesel or biodiesel. When employing alcohol-based fuels in compression ignition applications, these strategies seek to improve combustion characteristics and emissions by addressing the drawbacks of alcohols, such as their lower cetane number and energy density. When methanol-diesel fuel blends are used instead of regular diesel fuel, the engine power output is typically decreased. This power reduction becomes more pronounced as the percentage of methanol in the blend increases. The primary reasons for this power decrease are the lower density and lower calorific energy values of the methanol-diesel blends, which negatively impact the overall energy content and combustion characteristics of the fuel mixture in the engine (Ciniviz et al., 2011).

Methanol-diesel fuel mixtures have higher brake thermal efficiency when the engine load increases. However, when using methanol-diesel blends instead of pure diesel fuel, the BTE is lower due to the lower heating value of methanol, particularly while the speed is constant. In contrast, running diesel engines with methanol blends at higher speeds is less advantageous because the BTE of the methanol blends drops significantly when the engines are driven at middle-speed ranges. The main cause of the variances in BTE is the distinction between the energy content and combustion properties of normal diesel fuel and methanol-diesel blends (Yusaf et al., 2013). Experimental techniques, operating conditions, and fuel characteristics influence CI engine performance. Alcohol-blended diesel or biodiesel fuels can affect measured metrics like power, efficiency, and emissions, depending on factors like load, speed, injection timing, and test protocols. Consequently, it is essential to consider the operating settings and experimental methodologies used when assessing and contrasting the performance of CI engines with different fuel combinations.

Studies have shown that blending methanol in lower quantities with biodiesels can improve brake thermal efficiency at higher engine load conditions. However, using higher blend ratios of methanol tends to inhibit fuel atomization due to increased viscosity, resulting in lower BTE values. Additionally, the lower calorific value of methanol leads to higher brake-specific fuel consumption for methanol-diesel blends. This higher BSFC can be mitigated at higher engine speeds, as the higher oxygen content in the higher methanol blends helps offset the reduced energy density compared to diesel fuel (Sathish Kumar & Suresh Kumar, 2015).

Methanol's oxygenated nature and lower carbon-to-hydrogen ratio allow for more thorough burning, which reduces CO emissions in CI engines. Enhancing fuel atomization and air-fuel mixing increases injection pressure and improves injection timing to lower CO emissions further. However, methanol's low cetane rating and oxygenated nature can raise NOx emissions; nevertheless, at lower loads, the cooling effect reduces this, particularly when combined with biodiesels. Due to the polar nature of methanol-reducing oil absorption and improved combustion brought about by higher heat release rates and temperatures, methanol-diesel blends exhibit lower HC emissions. Compared to diesel, methanol blending also lowers smoke and particulate matter emissions. Overall, the emission impacts of methanol blending depend on the engine operating conditions and the specific fuel blend composition (Abd Alla et al., 2002).

2.1.3. Propanol

Methanol and ethanol tend to have a strong affinity for water, and their miscibility issues with diesel (Carneiro et al., 2017) have led researchers to explore propanol as a potential additive. However, research conducted so far focused on using propanol as a solvent in ternary blends, rather than directly blending it with diesel, despite propanol having better properties for this purpose (Haigh et al., 2012). Blending alcohols like methanol, ethanol, and propanol with diesel or biodiesel-diesel blends decreases the cetane number and density of the resulting fuel mixture. This increases the ignition delay period and improves the spray characteristics, leading to higher brake thermal efficiency (Balamurugan & Nalini, 2016). The lower overall cetane number of the blends also results in higher premixed combustion, further increasing the BTE (Murayama et al., 1982). When blended with biodiesel-diesel, the inherent oxygen content of the biodiesel and the higher laminar flame speed contribute to the higher BTE observed (Vijayakumar & Mukesh Kumar, 2017).

For propanol-diesel blends, the brake-specific fuel consumption is lower than standard diesel and decreases further as the propanol fraction increases. This is due to the higher volatility and, lower viscosity of propanol, which improves vaporization and spray characteristics, leading to more efficient combustion and lower BSFC (Savariraj et al., 2012). In contrast, the BSFC values for propanol-biodiesel blends are higher than standard diesel. This is attributed to the lower heating values, lower calorific values, and lower density of the blends, requiring the engine to consume more fuel to deliver the same power output (Zhang & Balasubramanian, 2016).

The oxygen presence in propanol aids the combustion process and significantly reduces carbon monoxide emissions at higher engine loads in propanol-diesel blends. However, at lower and medium loads, the higher latent heat of vaporization of propanol lowers the operating temperature, which can increase CO emissions (Balamurugan & Nalini, 2014a). For propanol-biodiesel-diesel blends, the density and viscosity of the biodiesel, as well as the engine load, play a major role in determining CO emissions (Chen et al., 2007). Nitrogen oxide emissions for propanol-diesel blends are lower than standard diesel, and they decrease further as the propanol fraction in the blend increases. This is due to the cooling effect caused by the higher latent heat of vaporization of propanol, which lowers the combustion temperature and reduces NOx emissions (Chen et al., 2007). Similar results are observed when propanol is blended with biodiesel-diesel. In addition to the cooling effect of propanol, the oxygen content of the biodiesel also contributes to the reduction in NOx emissions (Atmanli, 2016).

Hydrocarbon emissions are higher for propanol-diesel blends, and they increase with a rise in the propanol fraction in the blend. The difference in HC emissions between diesel and propanol-diesel blends is comparatively higher at lower and medium engine loads, but this gap reduces at higher loads. This is explained by the development of a quenching layer, which reduces the in-cylinder temperature, slows down the vaporization process, and results in poor air-fuel mixture formation (Shih, 1998). Other reasons for the higher HC emissions include the lower viscosity, increased delay period, and lower cetane number of the propanol-diesel blends (Balamurugan & Nalini, 2014b). However, the combustion of propanol-diesel blends could enhance the premixing process due to the longer ignition delay, resulting in lower soot emissions (Muthaiyan & Gomathinayagam, 2016). Additionally, the oxygen enrichment of propanol promotes lean burn operation, which leads to lower soot formation. This reason is also proposed for the lower smoke emissions in propanol-biodiesel-diesel blends, along with the presence of fewer carbon atoms in biodiesel (Deep et al., 2014). Soot formation in these blends is lower than in diesel, and it decreases further as the propanol percentage in the blend increases. This is attributed to the presence of the hydroxyl group in the chemical structure of propanol, which actively oxidizes the particulate matter and reduces soot formation (Pinzi et al., 2017).

2.1.4. Butanol

Among the higher alcohols, researchers have paid significant attention to the utilization of butanol in compression ignition engines. This is primarily due to butanol superior properties and its ease of transportation compared to lower alcohols like ethanol. Butanol has a higher cetane number, higher heating value, higher miscibility factor in diesel, and higher energy content compared to lower alcohols. The hydrophobic nature of butanol enables its transportation and distribution through the existing fuel infrastructure, unlike ethanol which has a stronger affinity for moisture and is more corrosive in the fuel pipeline (Kim, 2010). Furthermore, butanol easily blends with diesel without facing the phase separation problems commonly observed with lower alcohols. This eliminates the need for emulsifiers or co-solvents to maintain a homogeneous fuel blend (Rakopoulos et al., 2011).

The higher oxygen content and latent heat of evaporation of butanol-diesel blends lower the air-fuel mixture temperature inside the combustion chamber. This contributes to lower brake power and torque output compared to pure biodiesel and diesel fuels (Qi et al., 2013). However, higher brake thermal efficiency is observed for butanol-diesel blends compared to standard diesel. The BTE further increases with a rise in the butanol fraction in the blend. The oxygen content of butanol helps in achieving more complete combustion during the diffusion combustion phase. Additionally, the lower cetane number of the blends prolongs the ignition delay, allowing a larger fraction of the fuel to burn during the premixed combustion mode, which enhances efficiency (Laza & Bereczky, 2011). The higher laminar burning velocity of butanol compared to diesel fuel is also stated as a contributing factor to the higher BTE (Farrell et al., 2004). On the other hand, lower BTE is observed for ternary blends containing biodiesel. The overall higher viscosity and lower heating value of these blends are proposed to be the contributing factors to the lower combustion efficiency (Atmanlı et al., 2013). The lower heating value and calorific value of butanol necessitate higher fuel consumption to achieve the same torque output as standard diesel, resulting in higher brake-specific fuel consumption for butanol-diesel blends (Cheng et al., 2016). The lower cetane number of the ternary blends also elongates the ignition delay, which retards the start of combustion and leads to a higher amount of fuel being present for the chemical reaction (Atmanlı et al., 2014). Similar observations and reasons are stated when butanol is blended with biodiesel-diesel (Atmanlı et al., 2015).

2.2. Nano-additives

Many researchers widely accept the use of nano-additives as a fuel enrichment technique. These nano-additives are employed to achieve desired fuel properties, enhance performance characteristics, and effectively control emissions in compression ignition engines, all without requiring any modifications. In their study, Ribeiro et al. outlined the essential requirements for fuel additives when added to commercially available diesel fuels in varying quantities to fulfill specific functions (Ribeiro et al., 2007). These requirements include: (i) reducing exhaust emissions, (ii) increasing oxygen concentration in the engine and particulate filter, (iii) improving fluid stability across a wide range of conditions, (iv) enhancing the viscosity index, (v) decreasing ignition delay time and flash point, and (vi) improving chemical-to-chemical contact instead of metal-to-metal contact under high-load conditions to minimize the wear agents that adhere to metal surfaces.

The progress in nanotechnology, nanoscience, and material technology has resulted in the emergence of nano-scale particulate matter, which exhibits diverse physicochemical properties compared to micron-scale elements from the same source material. These properties include a larger contact surface area, improved stability, rapid oxidation, lower melting point, high heat of combustion, reduced fusion rate, and enhanced heat and mass transfer rates (Demirbas, 2009b; Saxena et al., 2017). Many researchers are familiar with fuel modification and revision techniques aimed at achieving specific fuel properties.

Numerous studies have investigated the effects of adding nanoparticles to fluids. For instance, nanoparticles have been used as additives to enhance the combustion rate of fuels by improving physical properties such as thermal conductivity, evaporation rate, and shortened delay period, as well as promoting secondary atomization (Keskin et al., 2007). The catalytic performance is enhanced by the substantial surface area-to-volume ratio and high energy level associated with nanoparticles (Khond & Kriplani, 2016). Nano-Al particles, for example, facilitate the occurrence of micro-explosions during combustion, leading to better air-fuel mixing and complete combustion. Cobalt nano-additives reduce the production of nitrogen oxides, while magnalium particles act as heat sinks inside the combustion chamber, lowering the overall temperature and preventing hotspots, thereby reducing NOx production (Debbarma & Misra, 2018; Demirbas, 2009b; El-Seesy, Hassan, et al., 2018). Mn-based nanoparticle additives are effective in reducing emissions of polycyclic aromatic hydrocarbons (Fazliakmetov & Shpiro, 1997). Ichikawa et al. reported that TiO_2 nano-additives generate hydrogen from water through their photoelectric catalytic effect and their ability to activate the molecular bonds in water-diesel emulsions (Ichikawa, 1997).

The literature is based on research conducted on fuels containing nano-additives, which were obtained from various sources such as ferro materials, polymeric materials, ceramics, non-organic materials, metal oxides (such as aluminum, carbon, titanium, iron), and CNTs. Due to advancements in blending techniques and the ease of preparation, this method has opened up numerous opportunities for manufacturing various nano-fuels using different types of nanoparticles. These fuel additives serve to improve the quality of the fuel, while also acting as catalysts to accelerate chemical reactions and provide additional oxygen for complete fuel combustion, thereby enhancing the characteristics of the engine. In a similar vein, the impact of nano-additives can be understood as having catalytic effects. Numerous studies have indicated that the use of biodiesel can result in higher emissions of greenhouse gases, hydrocarbons, and particulate matter. However, advancements in technology, specifically the utilization of nano-additives in biodiesel, have been found to effectively reduce these emissions. This demonstrates the potential of nano-additives as fuel additives capable of mitigating environmental impacts. Research studies have been undertaken to investigate the impact of nanoparticles on various aspects, such as heat generation, extended storage life, stability, reduction of adverse health effects, and emission reduction. In some experiments, nanofluids were directly employed in the engine, while attempts were made to combine different nanoparticles, including $TiO_2/PrSO_3H$, MWCNT, Graphistrenght C100, and Zn/CaO. However, there are several gaps in the existing research. These include the cost feasibility, solubility in liquid fuels, high energy density, heterogeneous combustion kinetics, formation of unstable nanoparticles, fuel suspension, the introduction of water in nanoparticles, and fuel blends to improve engine characteristics (Paramashivaiah & Rajashekhar, 2016; Shaafi & Velraj, 2015). Scholars have attempted to assess the feasibility of these modified fuels with real diesel engines. Some notable findings documented in the literature include a significant improvement in the combustion behavior of spray flame with reduced CO emissions by incorporating Al_2O_3 nanoparticles into diesel fuel (Solero, 2012). Additionally, Keskin et al. reported the effects of metallic nanoparticles on the performance characteristics of a CI engine with biodiesel. The inclusion of metal fuel additives enhanced the physicochemical properties of biodiesel fuels, such as viscosity values and pour points (Keskin et al., 2007).

The incorporation of organic-based manganese additives into diesel fuel resulted in a significant decrease in the freezing point. Similarly, multiple researchers have concluded that these additives lower the flash point and viscosity (Gürü et al., 2010). The combustion process in an engine is complex, and various parameters have the potential to influence the amount of engine emissions (Khalife et al., 2017). The presence of oxygenated additives leads to a reduction in particulate matter emissions due to the more complete and cleaner combustion of fuels. Alcohols such as ethanol and methanol, when blended with diesel, are commonly used as oxygenated additives. However, in some studies, blends with methanol showed higher BSFC values compared to ethanol blends. Additionally, the dilution of oxygenated additives in diesel blends results in a decrease in the calorific value of the base fluid (Farkade & Pathre, 2012).

Nanoparticles can be broadly categorized based on their material, shape, size, origin, and occurrence. Metal oxide additives, including aluminum (Al), manganese (Mn), titanium (Ti), zirconium (Zr), cerium (Ce), copper (Cu), and zinc (Zn), typically function as catalysts for the complete combustion of fuel. They not only minimize fuel consumption but also reduce emissions. Metallic additives have been used as diesel fuel additives since the year 2000, but their progress has declined over the years. However, there has been a recent resurgence of interest in metallic-based nanoparticles (Yetter et al., 2009). These nanoparticles contribute to the reduction of flue gas emissions in compression ignition engines through two mechanisms.

2.2.1. Aluminum oxide (Al_2O_3)

Aluminum oxide nanoparticles have acted as an effective combustion catalyst. The addition of Al_2O_3 nanoparticles has been found to reduce pollutant emissions while also improving the overall combustion behavior in diesel engines. Larger quantities of alumina nanoparticles are typically added to diesel-biodiesel blended fuels, as these blended fuels tend to provide lower emissions than standard diesel in most cases when the Al_2O_3 nanoparticles are incorporated. In summary, the inclusion of aluminum oxide nanoparticles has demonstrated the ability to enhance combustion and reduce harmful emissions, especially when used in combination with diesel-biodiesel fuel blends.

The addition of aluminum oxide (alumina) nanoparticles to standard diesel fuel acts as an oxygen buffer, promoting more complete combustion. This results in higher brake thermal efficiency for the alumina-added diesel compared to standard diesel. The BTE for alumina-added diesel is found to increase with higher dosing levels of the nanoparticles. A similar trend is observed for biodiesel-diesel blends with alumina addition, where the BTE is higher than standard diesel. Apart from the oxygen buffering effect, the nanoparticles also help in the micro-explosion of the primary fuel droplets, leading to a higher evaporation rate. Furthermore, the fuel consumption is found to be lower for diesel with alumina nanoparticles. This is because the alumina addition improves the physical characteristics of the fuel, such as atomization and combustion, leading to more efficient utilization. Similarly, in biodiesel-diesel blends with alumina, the brake-specific fuel consumption is lower than standard diesel. It is suggested that the addition of nanoparticles enhances the catalytic effect by increasing the surface area-to-volume ratio of the fuel blend, resulting in reduced fuel consumption.

The addition of nanoparticles has helped improve fuel droplet evaporation and achieve better air-fuel mixing. Specifically, the addition of aluminum oxide (alumina) nanoparticles has been found to decrease the ignition delay in both diesel and biodiesel-diesel blends. This is due to the higher thermal conductivity and increased surface area-to-volume ratio of the alumina nanoparticles, which enhances the fuel evaporation rate and reduces the physical delay during the ignition process (El-Seesy, Attia, et al., 2018). Furthermore, the heat release rate is observed to be higher when alumina nanoparticles are added to the fuels. This is attributed to the improved ignition and heat conduction properties of the alumina nanoparticles (Sadhik Basha & Anand, 2013). Additionally, the exhaust gas temperature is lower when the fuel is blended with alumina particles. This is because the nanoparticles help reduce the formation of rich mixture zones during the diffusion combustion mechanism (Kao et al., 2008b). In summary, the incorporation of alumina nanoparticles into diesel and biodiesel-diesel fuels enhances the physical and chemical properties of the fuel, leading to improved combustion characteristics, higher heat release, and lower exhaust temperatures.

Carbon monoxide emissions are found to decrease when diesel fuel is blended with aluminum oxide nanoparticles. The CO emissions continue to decrease as the dosage of the nanoparticles is increased. This is because the alumina nanoparticles are uniformly dispersed due to their catalytic activity, which improves the air-fuel mixing and leads to more complete combustion. The oxygen buffering effect of the nanoparticles also ensures better oxidation of carbon monoxide into carbon dioxide. Similar results are observed when alumina is blended with biodiesel-diesel blends, further aided by the higher oxygen content in biodiesel.

Nitrogen oxide emissions are lower than standard diesel for fuel blends containing alumina nanoparticles, and decrease further as the nanoparticle dosage increases. This is because the alumina nanoparticles support more complete combustion due to greater oxygen availability, higher surface area, and catalytic properties, which reduce the in-cylinder temperature and hence lower NOx formation. However, in some cases of blending with biodiesel-diesel, higher NOx emissions have been observed. This is due to the shorter ignition delay and peak pressure associated with biodiesel combustion during the diffusion phase, which can sometimes outweigh the positive effects of the nanoparticles. Smoke emissions are also lowered when alumina nanoparticles are added to fuel blends. This is explained by the improved ignition characteristics, shorter ignition delay, and enhanced evaporation rate provided by the alumina nanoparticles. The presence of alumina aids the secondary atomization process during transesterification, forming a more homogeneous air-fuel mixture inside the engine cylinder.

Nassir and Shahad (2018) conducted a study to investigate how the addition of Al_2O_3 and TiO_2 nanoparticles affects the combustion timing of diesel fuel (Nassir & Shahad, 2018). The inclusion of nanoparticles resulted in improvements in fuel properties. For example, the cetane number increased from 51.6 to 54.3 with the addition of 150 ppm Al_2O_3 nanoparticles. The presence of nanoparticles had a noticeable impact on the delay time and the distribution of heat release during combustion. The results showed that a higher concentration of nanoparticles led to a decrease in the delay period before combustion was initiated. The influence of Al_2O_3 nanoparticles on viscosity, temperatures, and the cetane number was more significant compared to the effect of TiO_2 nanoparticles. However, TiO_2 nanoparticles had the most pronounced effect in reducing the delay period, which can be attributed to the higher viscosity of Al_2O_3.

Fayad and Dhahad (2021) conducted a study where they added 50 nm Al_2O_3 nanoparticles to diesel fuel and assessed the combustion performance and emission characteristics of the resulting diesel blend. The experiments were performed using a four-stroke, single-cylinder diesel engine under various load conditions and fuel blends. They blended 0.5 g and 1 g of 50 nm Al_2O_3 nanoparticles into 1 L of diesel fuel. The findings of this study were similar to those of a previous study conducted by Venkatesan and Kadiresh, even though they used smaller nanoparticles (40 nm) and a different fuel rate (1 and 1.5 g/L) (Venkatesan & Kadiresh, 2015). These results suggest that the size of the nanoparticles has a significant influence on ignition and combustion, with smaller particles exhibiting a more intense reaction. Moreover, the addition of nanoparticles was found to improve combustion characteristics and enhance the surface-to-volume ratio. This led to enhanced burning efficiency as more diesel fuel reacted with the oxidizer. The results also showed a significant increase in BTE and a notable reduction in NOx and unburned hydrocarbon content across all engine loads compared to pure diesel fuel. These improvements can be attributed to the enhanced combustion characteristics of the nanoparticles and the improved air-fuel mixing ratio.

Dhahad and Chaichan (2020) conducted a study examining the combustion performance of a diesel fuel blend containing Al_2O_3 nanoparticles. The analysis revealed that the diesel fuel blend exhibited a notable increase in BTE and a slight reduction in harmful pollutants such as NOx, CO, and smoke compared to pure diesel fuel. The addition of Al_2O_3 nanoparticles to diesel fuel enhanced the combustion efficiency of the diesel engine. However, ongoing research is being conducted to address the potential release of nanoparticles from the exhaust to prevent environmental pollution. In a separate experimental investigation by Kao et al., a single-cylinder horizontal diesel engine was used to study the effects of Al_2O_3 additive diesel fuel with varying percentages of water (3-6%). The results showed a significant decrease in BSFC and harmful pollutants. The addition of Al_2O_3 nanoparticles to the diesel fuel provided a larger surface area for interaction between water molecules and fuel particles. The high surface activity of the water molecules led to the decomposition of hydrogen atoms from the water during combustion, thereby promoting complete combustion (Kao et al., 2008a).

Elkelawy et al. (2023) conducted a study to explore the impact of Al_2O_3 and CuO nanoparticles in diesel fuel. They prepared nanoparticle fuel blends with a concentration level of 50 ppm and compared the performance, combustion, and emission characteristics of these blends with standard diesel fuel. The testing was carried out within a range of 1,200 to 3,600 rpm, with intervals of 250 rpm. According to their findings, the Brake Specific Fuel Consumption (BSFC) of the nanoparticle fuel blend was lower compared to that of pure diesel fuel. The addition of CuO and Al_2O_3 additives resulted in a decrease in BSFC by up to 0.5% and 1.2%, respectively. When Al_2O_3 was added to pure diesel, there were reductions in CO, HC, and NOx emissions by up to 11%, 13%, and 6% respectively. On the other hand, the addition of CuO led to reductions in CO, HC, and NOx emissions by up to 5%, 8%, and 2% respectively. The presence of excess oxygen and nanoparticles in diesel fuels improved the fuel properties and combustion efficiency, which contributed to lower BSFC and reduced emissions of harmful pollutants (Kao et al., 2008a; Reddy et al., 2019).

Balasubramanian et al. (2019) conducted a study to examine the impact of Al_2O_3 nanoparticles in lemongrass oil biodiesel using a single-cylinder diesel engine. They prepared different concentrations of nanoparticle additives (10, 20, and 30 ppm) and blended them with lemongrass oil biodiesel using an ultrasonicator. The researchers found that the best engine combustion performance and exhaust emissions were achieved with a dosing level of 20 ppm. At this concentration level, the addition of Al_2O_3 nanoparticles resulted in a significant improvement in BTE, which increased by 11.5% compared to the neat biodiesel. Moreover, all emissions such as HC, CO, NOx, and smoke emissions decreased by 40%, 6%, 31%, and 39% respectively, in comparison to the neat biodiesel. It is noteworthy that the incorporation of Al_2O_3 nanoparticles in lemongrass oil biodiesel led to enhanced engine combustion performance and reduced harmful emissions. These improvements were attributed to lower NOx emissions and better combustion characteristics resulting from the addition of Al_2O_3 nanoparticles.

A recent study conducted by Soudagar et al. explored the potential of using Al_2O_3 nanoparticles as a fuel additive in Honge oil methyl ester biodiesel. The researchers investigated different dosing levels of 20, 40, and 60 ppm of nanoparticles. Through their experiments, they found that the biodiesel fuel blend with a nanoparticle concentration of 40 ppm exhibited superior engine combustion performance compared to blends with 20 and 60 ppm (Soudagar et al., 2020). At the dosing level of 40 ppm, the addition of nanoparticles resulted in a 10.57% increase in BTE and an 11.65% reduction in BSFC. Additionally, there were significant reductions in HC, CO, and smoke emissions, which decreased by 26.72%, 48.43%, and 22.84% respectively. However, it's important to note that the addition of nanoparticles led to an 11.27% increase in NOx emissions.

2.2.2. Cerium oxide (CeO_2)

Cerium oxide is the most abundant element in the rare earth family, with the unique ability to switch between trivalent (Ce^{3+}) and tetravalent (Ce^{4+}) oxidation states, enabling effective redox cycling. This material exhibits good thermal stability and high catalytic activity, largely due to its large surface area-to-volume ratio. These favorable properties make cerium oxide a valuable material for a variety of applications, particularly in catalysis and energy conversion/storage systems where its redox capabilities and high surface area can be leveraged to enhance performance.

The addition of cerium oxide nanoparticles to diesel fuel has been found to increase the thermal efficiency of the engine while simultaneously decreasing fuel consumption. This is because the cerium oxide nanoparticles reduce the physical delay and fuel evaporation time. The enhanced thermal conductivity property of the cerium oxide nanoparticles accelerates the chain reactions during the combustion stage. Furthermore, the inherent oxygen content in cerium oxide promotes it as an effective catalyst, enabling more complete and rapid combustion, which in turn leads to higher BTE (Mei et al., 2016). The BSFC is also observed to decrease further as the dosage of cerium oxide nanoparticles is increased. This is because the cerium oxide nanoparticles effectively disperse the fuel in the combustion chamber, leading to higher fuel spray penetration length and thereby reducing overall fuel consumption (Saraee et al., 2017).

While higher dosages of cerium oxide nanoparticles can increase the agglomeration probability, which could reduce the effectiveness of the catalytic behavior, an optimum level of dosing should be determined. Adding cerium oxide beyond the optimum level can increase the viscosity of the fuel, leading to larger fuel droplet sizes during spray atomization. This in turn can result in higher fuel consumption, offsetting some of the benefits observed at lower dosage levels (Saraee et al., 2017). In the case of certain biodiesel blends, the higher density and lower calorific value of the biodiesel itself can have a degrading effect on the positive performance improvements offered by the cerium oxide nanoparticles. As a result, the BTE and BSFC may not surpass that of standard diesel, despite the addition of the nanoparticles (Bafghi et al., 2015).

Cerium oxide has the unique ability to act as both a reductant and an oxidant by extracting or adding oxygen between its valence states (Ce^{3}+ and Ce^{4}+). The addition of cerium oxide nanoparticles to diesel fuel has been found to decrease CO emissions, and the reduction in CO emissions increases with higher engine speeds. Furthermore, the CO emissions decrease further as the dosage of cerium oxide nanoparticles is increased. The reduction in CO emissions is attributed to the fact that cerium oxide nanoparticles act as an "oxygen buffer", storing and releasing oxygen during the combustion process to facilitate the oxidation of carbon monoxide into carbon dioxide. The oxygen vacancy defects (OVDs) present in cerium oxide nanoparticles also help absorb CO molecules and convert them into carbon dioxide or intermediate bidentate carbonate, which then further oxidizes into carbon dioxide. Additionally, cerium oxide nanoparticles are found to lower the probability of fuel-rich zone formation during secondary atomization, which is one of the common reasons for CO emissions in diesel engines. Similar reductions in CO and HC emissions have been observed when cerium oxide was blended with biodiesel or biodiesel-diesel fuel mixtures. The HC emissions also decrease with increasing engine speed and higher dosages of cerium oxide nanoparticles. This is because the cerium oxide (+4 state) can be beneficially transformed to the cerous oxide (+3 state) during the oxidation of hydrocarbons, promoting more complete combustion.

2.2.3. Copper oxide

Unlike the more extensively studied nanoparticles like aluminum oxide and cerium oxide, the research on copper oxide nanoparticles as fuel additives is relatively limited. However, copper oxide nanoparticles have the potential to act as effective anti-oxidants, stabilizers, and most importantly, as surfactants in fuel-based systems. These properties can contribute to significant reductions in engine emissions. The thermal heat carrying capacity of the copper oxide transition metal oxide is also believed to play a major role in curtailing emissions when used as a fuel additive. While aluminum oxide and cerium oxide nanoparticles have been more extensively investigated for their effects on diesel and biodiesel engine performance and emissions, the body of work focused on copper oxide nanoparticles as fuel additives is relatively smaller in comparison.

2.2.4. Zinc oxide

Zinc oxide nanoparticles possess several appealing properties that make them a useful additive for compression ignition engines. Zinc oxide acts as an antioxidant, providing protective benefits, and is relatively easy to manufacture at a lower cost compared to other nanoparticle options. Additionally, the anti-wear and corrosion inhibiting characteristics of zinc oxide further enhance its utility as a fuel additive in CI engine applications. Overall, the combination of antioxidant, cost-effective, anti-wear, and corrosion inhibiting properties makes zinc oxide nanoparticles a favorable choice for incorporation into CI engine fuels and lubricants.

The addition of zinc oxide nanoparticles to diesel fuel has been found to enhance the brake thermal efficiency of the engine, with higher BTE achieved as the dosage of the nanoparticles is increased. This is due to the improved combustion properties provided by the zinc oxide (Selvaganapthy et al., 2013). In the case of blending zinc oxide with biodiesel or biodiesel-diesel mixtures, the BTE is lower than standard diesel, but higher than the blend without the nanoparticle additive. While the inherently higher viscosity, lower calorific value, and higher molecular weight of biodiesel negatively impact BTE, the zinc oxide nanoparticles provide additional oxygen to promote more complete combustion and help form a more homogeneous fuel-air mixture (Sravani & Ravindra Reddy, 2016). Similarly, the brake-specific fuel consumption is lower for zinc oxide blended diesel compared to standard diesel, and decreases further as the nanoparticle dosage increases. The zinc oxide increases the overall calorific value of the fuel and reduces ignition delay due to the higher surface area-to-volume ratio (Hamadi et al., 2016). For biodiesel blends, the zinc oxide addition is able to significantly lower the BSFC compared to standard diesel, by compensating for the less favorable physical properties of the biodiesel fuel (Karthikeyan et al., 2014).

Zinc oxide nanoparticles act as a catalyst when added to diesel fuel. The inherent oxygen content of the zinc oxide supports the combustion in fuel-rich zones, helping to complete the oxidation process. This results in lower carbon monoxide emissions compared to standard diesel, with the CO levels decreasing further as the nanoparticle dosage is increased (Hamadi et al., 2016). Similar effects are observed when zinc oxide is blended with biodiesel or biodiesel-diesel mixtures, where the nanoparticles help form a more stoichiometric air-fuel mixture within the engine cylinder (Sirajuddin & Siddeswara, 2016). HC emissions are also lower for zinc oxide blended diesel, biodiesel, and biodiesel-diesel fuels, and the HC levels decrease as the nanoparticle concentration increases. This is attributed to the increased spray length and improved fuel atomization provided by the higher surface area-to-volume ratio of the zinc oxide nanoparticles, which enhances the combustion process and prevents fuel wetting on the cylinder walls. The addition of zinc oxide nanoparticles reduces the premixed burn fraction in the combustion chamber by decreasing the ignition delay. This helps lower the peak combustion temperatures, resulting in reduced NOx emissions (Vellaiyan & Amirthagadeswaran, 2016b). Similarly, smoke emissions are lower for zinc oxide blended fuels compared to standard diesel, as the nanoparticles improve fuel atomization, spray characteristics, and rapid evaporation within the cylinder, leading to more complete combustion (Prabakaran & Udhoji, 2016).

2.2.5. Other Metal Oxide Nanoparticles

Amirabedia et al. conducted experiments involving the blending of two different types of nanoparticles into spark-ignition gasoline in combination with ethanol. The researchers utilized an ultrasonicator to blend 10 ppm of Mn_2O_3 and 20 ppm of Co_3O_4 nanoparticles into the gasoline-ethanol fuel. The results indicated that higher BP values were achieved with increasing dosing levels of nanoparticles. Specifically, for dosing levels of 10 and 20 ppm of Mn_2O_3, the BP values increased by 14.38% and 19.56%, respectively (Amirabedia et al., 2019). Similarly, the BP values for dosing levels of 10 and 20 ppm of Co_3O_4 increased by 7.96% and 11.5%, respectively. Additionally, the inclusion of ethanol mixed with the nanoparticles resulted in a reduction in carbon monoxide and unburned hydrocarbon emissions, along with an increase in carbon dioxide emissions. Based on the results, the gasoline-ethanol fuel blend with 20 ppm of Mn_2O_3 nanoparticles exhibited the best combustion and emission performance. These findings align with a previous study conducted by Ananda et al. where the addition of ethanol and nanoparticle additives to gasoline fuel improved engine performance and exhaust emissions (Ananda Srinivasan et al., 2018).

Devarajan et al. (2019) conducted a study to examine the impact of different mass fractions (5 and 10 ppm) and particle sizes (10 and 20 nm) of AgO nano-additive on the performance, emission, and combustion behavior of palm stearin biodiesel. Under peak load conditions, the biodiesel fuel blend containing nanoparticles with a particle size of 20 nm and a concentration level of 10 ppm exhibited higher BTE and lower BSFC emissions. The addition of AgO nanoparticles to the biodiesel resulted in a reduction of harmful emissions. The biodiesel fuel with 10 ppm of 20 nm AgO nanoparticles demonstrated the best engine performance. In comparison to pure biodiesel, the in-cylinder pressure decreased by 2.2%, while the net heat release rate value improved by 4.7% (Devarajan et al., 2019).

Tamilvanan et al. (2019) conducted a study to analyze the performance, combustion, and emission characteristics of *Calophyllum inophyllum* seed oil biodiesel with the addition of 30 ppm of copper nanoparticles in a single-cylinder diesel engine, with varying loads. The results showed that the biodiesel blend with Cu additives achieved a higher BTE compared to the biodiesel without additives at all load conditions. However, the BTE value was slightly lower than that of diesel fuel. The decrease in BTE value for biodiesel can be attributed to its lower heat of combustion. Nevertheless, the inclusion of Cu nanoparticles in the biodiesel fuel blend enhanced the combustion properties of the engine and significantly reduced emissions (Tamilvanan et al., 2019).

Venu and Appavu (2021) conducted an experiment where they introduced Zr nanoparticles into jatropha biodiesel for use in a CI engine. The study revealed that the biodiesel blended with Zr nanoparticles exhibited the lowest BSFC value and the highest BTE value compared to both diesel fuel and biodiesel without Zr nanoparticles. Furthermore, a significant reduction in HC, CO, and smoke emissions was observed, accompanied by a slight increase in NOx and CO_2 emissions (Venu & Appavu, 2021). These findings share similarities with the research conducted by Yogaraj et al. who utilized Ag-TiO_2 nanoparticles as fuel additives. In both studies, the addition of nanoparticles resulted in incomplete combustion, leading to lower BSFC, CO_2, and HC emissions. However, it should be noted that higher NOx emissions were observed in all cases (Yogaraj et al., 2021)

2.3. Instability of Nanoparticles and Its Effects on Engine Components

Adding nanoparticles to diesel, alcohol, or biodiesel blends can lead to common issues like creaming, flocculation, amalgamation, and phase separation. The affinity of the nanoparticles to the base fuel is a crucial factor in determining the stability of these blends (Mehta et al., 2012). The prolonged operation of a diesel engine using alternative fuel blends can be severely impacted by the instability of alcohol-diesel blends. Therefore, it is important to systematically assess factors like the type of surfactant, water quantity, and viscosity of the blends during the preparation stage (Ithnin et al., 2014). Proper mechanical agitation is needed to suspend the nanoparticles in the liquid sample and promote mass transfer. It has been observed that adding nanoparticles can improve the miscibility of lower carbon-content alcohols with diesel (Ampah et al., 2022). Standard sedimentation techniques and centrifugation are commonly used to examine the instability and phase separation issues in nanoparticle-added diesel/alcohol blends (El-Seesy & Hassan, 2019). Nanofluids, where the nanoparticles are properly dispersed in the base fuel, are a viable approach to doping diesel/alcohol blends. Carbon nanomaterials have shown remarkable improvements in blend stability when used this way (Auffan et al., 2017). Ultrasonication is an effective method to dissolve nanoparticles in the base fluid, which can help minimize phase separation problems.

Common surfactants like sodium dodecyl sulfate, sorbitan oleate, acetyl trimethyl ammonium bromide, and oleic acid have been widely used to improve the dispersion of nanoparticles in diesel/higher alcohol blends (Soudagar et al., 2018). The selection of carbon nanotubes as nanoparticles is influenced by their high surface-to-volume ratio and catalytic reactivity, which can help reduce sedimentation in the blends. The hybridization of carbon-carbon bonds in the nanoparticles can strengthen their miscibility in water, which ultimately improves the stability of the diesel/alcohol blends (Hosseinzadeh-Bandbafha et al., 2019).

While there have been many studies on the stability of nanoparticle-containing diesel/alcohol blends (nanofluids), the effects of these nanoparticles on engine components have not been thoroughly investigated yet. Some studies have shown that adding nanoparticles to these fuel blends does not lead to carbon deposition in engine components. However, more critical analysis is needed on the specific type, quantity, and size of nanoparticles used. Further research is required to understand the material compatibility of engine components when using various nanoparticle additives in diesel, biodiesel, and alcohol fuel blends (Mei et al., 2019). Experimental research should also be extended to study the impact of nanoparticles on the tribological behavior of lubricating oils contaminated with these fuels.

2.4. Engine Performance

2.4.1. Brake Specific Fuel Consumption (BSFC)

Brake-specific fuel consumption (BSFC) is the measure of fuel consumption relative to the brake power produced by the engine. Rakopoulos et al. (2019) experimented using a six-cylinder, turbocharged direct injection (DI) engine with a power output of 177 kW at 1500 rpm and 3.56 bar brake mean effective pressure (BMEP). They tested blends containing 5%, and 10% ethanol to assess performance and emission levels. The results showed that BSFC increased when using ethanol blends compared to pure diesel fuel for the same power output. Furthermore, BSFC rose progressively as the ethanol content in the blends increased. This indicates that the engine consumes more ethanol-blended fuel than pure diesel to achieve the same performance. These findings align with observations made by numerous researchers. The increase in fuel consumption is expected due to the lower calorific value of ethanol-blended fuel.

2.4.2. Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency is defined as the ratio of the mechanical brake power produced by the engine to the fuel energy consumed per unit time. It is a critical parameter that reflects the engine's ability to convert the chemical energy of fuel into useful mechanical work (Wang et al., 2021).

Janakiraman et al. (2021) conducted experiments on a single-cylinder, four-stroke, direct injection (DI) engine operating at a constant speed of 1600 rpm and a power output of 5.2 kW. The tests were performed using pure diesel and various ethanol-diesel blends. Their findings revealed that the BTE for a 5% ethanol blend (E05) increased compared to pure diesel. However, as the ethanol concentration in the blend was further increased, the BTE decreased, though it remained higher than that of pure diesel. Additionally, they observed that the difference in BTE between pure diesel and ethanol-diesel blends became more pronounced as the engine load increased. This indicates that while ethanol blends can improve thermal efficiency at lower concentrations, higher ethanol content may lead to a reduction in efficiency due to the lower calorific value of ethanol.

2.4.3. Brake torque and brake power

Brake power is closely linked to brake torque at a specific engine speed, with changes in fuel composition influencing both (Raji et al., 2024). In a study by Kumar and Chaurasia (2019), experiments conducted on a six-cylinder direct injection (DI) engine with 82 kW power, 150 bar injection pressure, and 1600 rpm demonstrated that both brake torque and brake power increased with the addition of ethanol (E%) in the fuel blend, with a maximum improvement of 3.8% observed at a 6% ethanol fuel mix (D94E6). This enhancement was attributed to improved combustion efficiency due to the oxygenated nature of ethanol. Furthermore, engine power, which is influenced by compression ratio, was also found to increase with ethanol blending, as it positively impacted volumetric efficiency, which is a key factor in brake torque production (Chansauria & Mandloi, 2018).

In contrast, a study by Algayyim et al. (2024), focusing on a four-cylinder, 4-stroke turbocharged DI diesel engine with 150 bar injection pressure and operating at 2000 rpm, revealed that brake torque and brake power decreased when 5% ethanol was blended with diesel. This reduction in engine performance persisted as the ethanol concentration increased. These findings suggest that while ethanol blends can improve performance in certain engine types, their effects may vary significantly depending on engine configuration, fuel composition, and operational parameters. The differences observed in these studies underline the complexity of fuel-blend interactions and highlight the need for tailored solutions for optimizing engine efficiency.

2.5. Engine Emissions

Exhaust emissions such as particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO2), oxides of nitrogen (NOx), and total unburned hydrocarbons (THC) are heavily influenced by the oxygen content and combustion conditions of the fuel. Bessagnet et al. (2022) emphasized that emissions are affected by the local oxygen factor of oxygenated fuels, regardless of the oxygen improvement method. However, emissions are also shaped by several other factors beyond fuel composition, including the fuel metering method, engine maintenance, age, emissions control technology, and test conditions (Agarwal & Mustafi, 2021).

2.5.1. NOx Emissions

NOx emissions are among the most concerning pollutants from CI engines, primarily influenced by in-cylinder temperatures and oxygen concentration (Ashok et al., 2022). Kumar and Chaurasia (2019) investigated NOx emissions in a single-cylinder, 4-stroke, water-cooled, naturally aspirated open chamber direct injection (DI) Kirloskar TVI diesel engine operating at 3 kW brake power (BP) and 1500 rpm. Their findings indicated that NOx emissions were either the same or slightly lower for ethanol-blended fuels compared to pure diesel. Similarly, Rakopoulos et al. (2021) observed that NOx emissions decreased with increasing ethanol concentration in diesel-ethanol emulsified fuels. The reduction in NOx levels can be attributed to the lower calorific value of ethanol, which reduces combustion temperatures inside the engine cylinder, thereby limiting the formation of NOx. The presence of oxygen in ethanol blends also plays a role in mitigating NOx emissions by enhancing combustion efficiency.

However, the effects of ethanol blending on NOx emissions are complex and depend on several factors, including ignition delay and combustion temperature. Ethanol, with its lower cetane number, leads to a longer ignition delay, which can cause higher temperatures during the premixed combustion phase, ultimately promoting NOx production. While the oxygenated nature of ethanol may reduce overall NOx emissions due to its lower energy content, the increased temperature during ignition delay can counterbalance this effect. Thus, the relationship between ethanol blending and NOx emissions is influenced by a combination of factors, such as fuel composition, combustion timing, and engine operating conditions.

2.5.2. CO Emissions

Carbon monoxide CO is a harmful engine emission resulting from incomplete combustion of hydrocarbon fuels. Its formation is influenced by factors such as fuel composition, combustion efficiency, and engine operating conditions. Due to its toxic nature, controlling CO emissions is a critical environmental and regulatory concern (Ashok et al., 2022).

Several studies have investigated CO emissions from diesel engines operating on neat diesel and ethanol-blended fuels. Al-Harbi et al. (2022) observed that CO emissions were higher for pure diesel fuel compared to ethanol-blended fuels. The increase in ethanol content in the fuel blend led to a leaner mixture, promoting more complete combustion and enhancing the conversion of CO to CO_2. This improvement in combustion efficiency is attributed to ethanol's oxygenated nature, which facilitates better oxidation of CO. The higher CO emissions in ethanol blends were linked to ethanol’s higher latent heat of vaporization and the resultant lower combustion temperature of the cycle. The cooling effect of ethanol may lead to incomplete oxidation of CO under certain operating conditions, thereby increasing CO emissions (Usman et al., 2023).

2.5.3. HC Emissions

Hydrocarbon emissions consist of unburned fuel that has not undergone complete combustion. Several studies have analyzed HC emissions for different ethanol blends, including E0, E05, E10, and E15. Annamalai et al. (2024) examined HC emissions from a four-stroke single-cylinder direct injection CI engine at 5.2 kW and 1500 rpm. Their findings indicated that HC emissions were higher for ethanol-containing fuels compared to neat diesel, with higher ethanol concentrations in the blend leading to increased HC emissions. This trend has been consistently observed across multiple studies on various engine types and operating conditions.

The increase in HC emissions with ethanol blends is attributed to the lower cycle temperature caused by ethanol’s higher latent heat of vaporization, which results in incomplete fuel combustion (Iodice & Cardone, 2021). Additionally, HC emissions were observed to rise with increasing engine speed, suggesting that engine operating conditions play a crucial role in emission characteristics.

2.6. Exhaust Gas Temperature

Exhaust gas temperature is a key indicator of combustion performance inside the cylinder. Various researchers have studied the effects of ethanol-diesel blends on exhaust gas temperature and concluded that increasing the ethanol concentration in the blend leads to a reduction in exhaust gas temperature. This decrease is attributed to ethanol’s lower heating value (LHV) and its higher latent heat of vaporization, which absorb more heat during fuel evaporation, thereby reducing the overall combustion temperature (Martins et al., 2024). The continuous reduction in exhaust gas temperature with higher ethanol percentages suggests that ethanol blends contribute to cooler combustion conditions, which may impact overall engine efficiency and emissions.

2.7. Taguchi and Analysis of Variance

In recent years researchers have increasingly turned to computer-based optimization methods due to the time-consuming and laborious nature of traditional experimental procedures. The Taguchi design method is a popular Design Experiments technique, as it requires fewer tests, thereby reducing the time and cost associated with optimization studies. Unlike traditional methods where each factor is examined individually, Taguchi analysis allows for optimization by evaluating combinations of factor levels within a carefully designed array. Sharma et al. (2020) investigated the application of the Taguchi design method to optimize the performance and emissions of a diesel engine using methyl esters.
Ansari et al. (2018) also employed the Taguchi technique to optimize the performance and exhaust emissions of a diesel engine fueled with a blend of biodiesel and diesel. Biodiesel proportion, injection timing, and injection pressure were identified as the key variables influencing these parameters. Wu et al. (2021) also utilized Taguchi's design to determine the optimal operating conditions for a diesel engine fueled with a blend of biodiesel, diesel, and liquefied petroleum gas. Their study demonstrated that the Taguchi method significantly reduced the number of experimental tests required for optimization and that the predictions made by the Taguchi design were in good agreement with the actual experimental results.

Uslu and Aydın (2020) also demonstrated the effectiveness of Taguchi's design in rapidly assessing the impact of various operating characteristics, such as diesel engine efficiency (DEE), palm oil ratio, injection timing, and engine load. Feroskhan and Ismail (2020) employed an L_{16} orthogonal array to evaluate the performance of a diesel engine operating on biogas under dual-fuel conditions. They analyzed four key intake characteristics at four different stages. Chaudhary and Gakkhar (2020) utilized the L_{16} orthogonal array of the Taguchi method to optimize fuel blends consisting of neem methyl esters and diesel on a single-cylinder diesel engine.

Patil and Desai (2020) employed an L_{25} orthogonal array to design experiments for optimizing the blend percentage and engine load to minimize brake power and brake-specific fuel consumption when using jatropha biodiesel in a single-cylinder variable compression ratio (VCR) engine. Palanisamy (2014) utilized an L_9 orthogonal array of the Taguchi technique to investigate the influence of three factors (at three levels each) on engine performance. The factors studied were injection pressure, biodiesel proportion, and engine load, to optimize brake thermal efficiency and BSFC in a single-cylinder diesel engine fueled with rubber seed methyl esters. Yadav et al. (2015) optimized the performance of a Tata Indica 4-cylinder engine using groundnut methyl esters. They employed an L_{16} orthogonal array design of experiments within the Taguchi framework.

Ganesan et al. (2020) optimized the addition of CeO_2 nanoparticles to biodiesel-diesel blends to improve engine efficiency and reduce emissions. They employed an L_{16} orthogonal array for experimentation, utilizing the average grey grade and signal-to-noise (S/N) ratio as performance metrics. Modi (1997) investigated the influence of various factors, including injection pressure, load, and compression ratio, on the performance of a diesel engine fueled with a blend of palm biodiesel and diesel. They utilized the L_9 orthogonal array of the Taguchi design method, employing the signal-to-noise (S/N) ratio to optimize the blend. Wilson (2012) utilized the L_{16} orthogonal array method to optimize NOx emissions and BSFC in a 5.2 kW diesel engine. They considered five key engine parameters: valve opening pressure, clearance volume, static injection timing, nozzle-hole diameter, and engine load. The study demonstrated that the predicted optimum values obtained from the Taguchi method closely matched the experimental results, with less than 10% deviation.

2.8. Optimization

Numerous research scholars have employed various optimization techniques to compare and validate experimental results with statistical findings. The Taguchi-Grey relational analysis is widely used for addressing challenges involving multi-response optimization, enabling the identification of the optimal process parameters with minimal experimental trials (Natarajan et al., 2018). For instance, Kumar and Dinesha (2018) employed the Taguchi-Grey approach to optimize diesel engine's performance and emission parameters fueled with biodiesel blends, finding that the method effectively reduced emissions and improved thermal efficiency. For a diesel engine operating with either WCO-based pure biodiesel (B100) or a 20% biodiesel-diesel blend (B20), the Taguchi L_9 orthogonal array design is utilized to optimize the combination of fuel type, engine speed, and load for optimal performance. According to the ANOVA, the fuel type is identified as the most influential factor, contributing 44.28% to the variation in output parameters (Gul et al., 2022). In another study, Gomaa et al. (2021) confirmed the robustness of the L_9 orthogonal array in reducing experimental runs while achieving reliable optimization of combustion parameters in engines using alternative fuels. Moreover, hybrid optimization methods have gained attention in recent years. The incorporation of nanoparticles into fuel blends has also been studied extensively, as highlighted by Pullagura et al. (2024), who demonstrated the efficacy of Al_2O_3 nanoparticles in reducing particulate matter and improving combustion characteristics. These findings underscore the critical role of fuel composition and optimization techniques in advancing engine performance and sustainability.

The literature highlights the significance of Taguchi-Grey and RSM techniques in optimizing parameters that influence engine performance. Recent studies have applied these methods to analyze engine input parameters to enhance thermal and exergy efficiency, reduce NOx emissions, and minimize cost variations in a CI diesel engine.

A critical research gap identified in the existing literature is the limited exploration of the combined effects of hybrid nanoparticles (Al_2O_3 and CeO_2) and ethanol-diesel blends on the performance, combustion, and emission characteristics of CI engines under varying loading conditions. While previous studies have individually investigated the impact of ethanol-diesel blends or nanoparticle additives, there is a lack of comprehensive research that systematically evaluates the synergistic effects of these factors. Additionally, most studies focus on single performance metrics or emissions, with limited emphasis on optimizing multiple parameters simultaneously. This study addresses these gaps by employing a Taguchi orthogonal array design and Grey-Taguchi method to optimize multiple-performance and emission parameters, while also assessing combustion characteristics and engine durability. By bridging these gaps, this research aims to provide a holistic understanding of the potential of hybrid nanoparticles in enhancing the efficiency and sustainability of diesel-ethanol-powered CI engines.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Materials

For the study, commercially available diesel fuel and ethanol suitable for the specific diesel-ethanol-powered CI engine were purchased from the market. These fuels were sourced from reputable suppliers to ensure their quality and compatibility with the engine. Additionally, Aluminum oxide (Al_2O_3) and Cerium Oxide (CeO_2) nanoparticles were purchased from Sigma Aldrich, a well-known supplier of research chemicals and materials. All the chemicals and raw materials needed for experimentation are shown in Table 3.1.

Table 3.1. Raw materials and chemicals are needed for experimentation.

No	Chemicals
1	Aluminum oxide
2	Cerium Oxide
3	Ethanol
4	Fuel

The experimental study was conducted at Addis Ababa Science and Technology University using various laboratory equipment. The equipment and instruments used are listed in Table 3.2 and Table 3.3.

Table 3.2. list of equipment and instruments needed for blend preparation

No	Item
1	Glassware
2	Thermometer
3	Hot plate magnetic stirrer
4	Digital balance
5	Beakless
6	Flow meter
7	Graduated glass cylinder for measurement
8	Burette
9	Ultrasonic cleaner

Table 3.3. list of equipment and instruments required for engine testing experiment

No	Item	Specification
1	Single-cylinder, four-stroke, air-cooled diesel engine	TBM3-02 diesel engine
2	Engine dynamometer	AM-1 electric motor control unit
3	Exhaust gas analyzer	MQ550-4

3.2. Generalized Process Description

Fuel for diesel engines was prepared by blending ethanol-diesel, aluminum oxide, and cerium oxide nano-additive. The prepared blends were fueled in the CI engine, and their sustainable performance characteristics were experimentally investigated. The selection of input parameters and their respective levels was determined by a comprehensive review of prior literature on diesel engines. The study considered feasible experimental ranges that had an apparent impact on outcomes, excluding ranges where no notable changes were observed. Taguchi's design of experiment was used to conduct experiments and for each experiment, multiple sustainable performance characteristics of the engine were measured and recorded. Taguchi's approach including S/N ratio, ANOM, and ANOVA was used to determine the optimal setting of the input parameters that resulted in the optimum multiple performance characteristics. The results of the study were validated using a confirmation test. The detailed aspect of the methodology is described in the subsequent sections. The complete procedure adopted in the present study is shown in the flowchart depicted in Figure. 3.1.

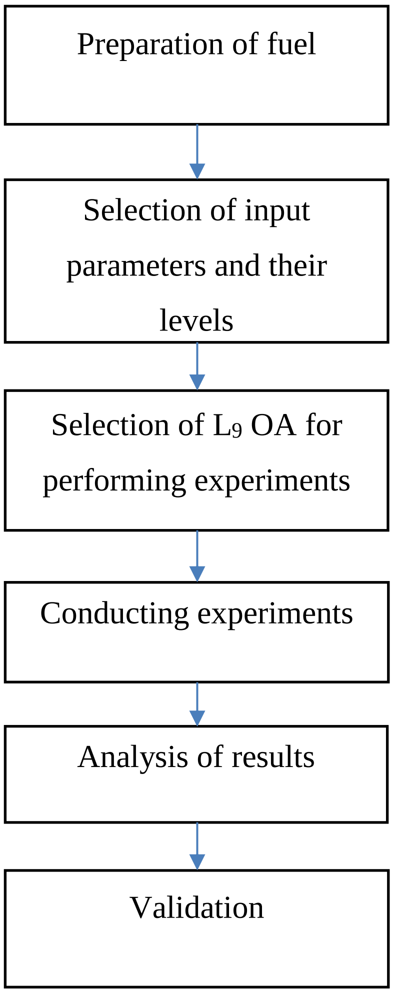


Figure 3.1 flowchart showing the procedure adopted during the study

3.1. Methods

3.2.1. Experimental Design

The experiment in this study was designed using the Taguchi orthogonal array approach. This method’s main benefit is its capacity to methodically choose a subset of tests that accurately reflect the entire range of factors and levels, yielding the most information with the minimum number of trials. Orthogonal arrays were used to evaluate all possible component-level combinations. This made it possible to identify the most important variables and the best conditions for them, which enhanced performance and decreased variability. The experiments were thoughtfully planned to record the interplay of variables and offer important new information about the system being studied.

In this method, in a design Process Y was not only stay within the specifications but also be centered always at the target i.e., within the process capability Y was always try being at the mean value. This is so because according to Taguchi, whenever there is a variation of the process from the target a loss is incurred even though it is within specifications. The larger the deviation, the larger is the loss. In this method not only, the conventional DOE factors are modeled, but noise factors are also considered which helps in building a sustainable model having less variance in the response are modeled, noise actors are also considered which helps in building a sustainable model having less variance in response.

Table 3.4 L_9 orthogonal array test layout (source: Minitab Statistical Software)

Ethanol/Diesel Ratio	**Aluminum Oxide (Al_2O_3) in ppm**	**Cerium Oxide (CeO_2) in ppm**	**Load (%)**
E10D90	15	15	25
E10D90	30	30	50
E10D90	45	45	80
E20D80	15	30	80
E20D80	30	45	25
E20D80	45	15	50
E30D90	15	45	50
E30D90	30	15	80
E30D90	45	30	25

Table 3.4 outlines the L_9 orthogonal array employed in the experimental design. This design matrix facilitated the investigation of four key parameters: ethanol-diesel ratio, aluminum oxide content, cerium oxide content, and engine load. Each of these parameters was systematically evaluated at three distinct levels. The ethanol-diesel ratio was varied across E10D20, E20D80, and E30D70. Aluminum oxide content was tested at 15 ppm, 30 ppm, and 45 ppm. Similarly, cerium oxide content was assessed at 15 ppm, 30 ppm, and 45 ppm. Finally, engine load was varied between 25%, 50%, and 80%. This experimental approach allowed for a structured examination of the influence of each parameter and its potential interactions on the observed response variables.

The ethanol ratio was selected based on its alignment with previous studies focusing on E10, E20, and E30 blends, providing a clear progression in increasing ethanol content (Ramos & Wallace, 2018). The range allows for a comprehensive evaluation of how varying ethanol concentrations influence engine performance, combustion efficiency, and emissions. By testing these blends the research contributes to the existing body of knowledge on biofuel blends and their effects on diesel engines.

The selection of Al_2O_3 and CeO_2 nanoparticles was guided by their catalytic properties and impact on combustion and emissions reduction (Bhan et al., 2024). The tested concentrations of 15 ppm, 30 ppm, and 45 ppm were chosen based on their effectiveness in optimizing combustion efficiency without excessive wear. Similarly, varying engine loadings (25%, 50%, and 80%) were selected to represent typical operational scenarios and assess the nanoparticle's impact under different engine conditions. The L_9 orthogonal array with four parameters checked at three levels is shown in Table 3.5.

Table 3.5 L_9 orthogonal array 4 parameters checked at 3 levels.

Parameter	**Ethanol/ diesel (Ratio)**	**Aluminum oxide (ppm)**	**Cerium oxide (ppm)**	**Load (%)**
level 1	E10D20	15	15	25
Level 2	E20D80	30	30	50
Level 3	E30D70	45	45	80

S/N ratio is the signal-to-noise ratio, which is the log function of desired output and considers both the average and variation, which can also be the amount of energy for the intended function divided by the amount of energy wasted. The signal-to-noise (S/N) ratio, as introduced by Taguchi, is a critical metric used to evaluate the robustness and quality of a system by comparing the desired output (signal) to the unwanted variation (noise). It is expressed as a logarithmic function that considers the average performance and the variation in the output. The S/N ratio can be interpreted as the ratio of energy used for the intended function to the energy wasted, making it a valuable tool for optimizing processes and improving quality. As stated in equation 3.1, the S/N ratio for the Smaller-the-Better (STB) scenario is calculated as (Srihari & Thirumalini, 2017):

$$s/n = -10\log 1/10 \left\{ \sum_{i=1}^{n} {y_{ij}}^2 \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq3.1$$

This formula is applied when the goal is to minimize the output, such as reducing defects, noise, or other undesirable characteristics. Here, Y_{ij} represents the observed data, and the objective is to reduce its magnitude. Conversely, for the Larger-the-Better (LTB) scenario, where the goal is to maximize a certain outcome (e.g., strength, efficiency), the S/N ratio is calculated using equation 3.2 (Srihari & Thirumalini, 2017):

$$s/n = -10\log 1/10\left\{\sum_{i=1}^{n}\left(\frac{1}{{y_{ij}}^2}\right)\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. eq3.2$$

Where;

S/N signal-to-noise ratio,

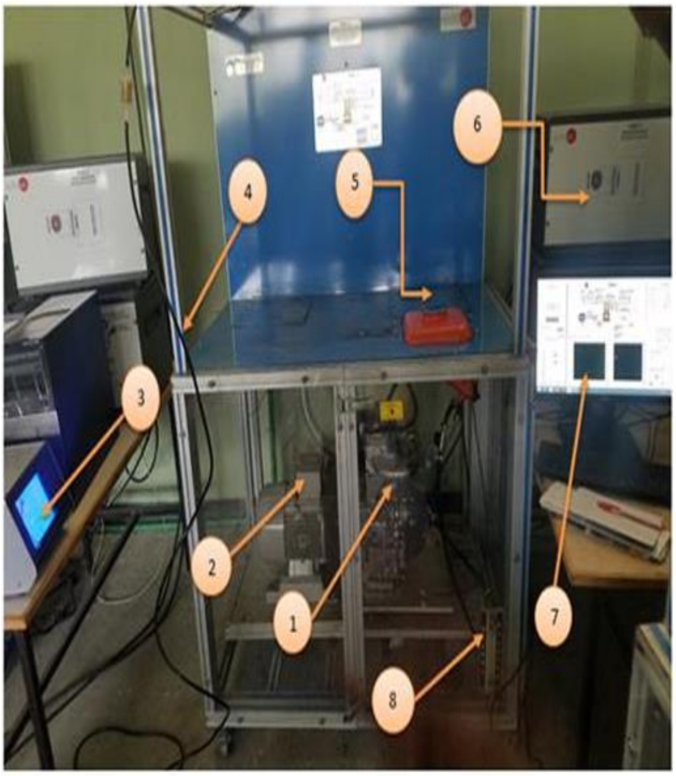
n is the number of measurements taken in a trial,

y_{ij} is i^th^ response in j^th^ test

In this study, the criteria of larger are the better, which was applied to brake power, brake torque, and brake thermal efficiency as the goal was to maximize these parameters. On the other hand, the 'smaller is better' criterion is suitable for exhaust gas recirculation, carbon monoxide, hydrocarbons, nitrogen oxides, carbon dioxide, and brake-specific fuel consumption, as the objective is to minimize these values. However, the Taguchi method can only optimize problems with a single desired outcome. Since the study involves the optimization of multiple responses, the Grey-Taguchi method was employed to integrate various performance parameters into a single unified response. The Minitab software was used for the analysis, and the measured responses are presented in Table 4.1.

3.2.2. Experimental setup

The experiment was carried out using a single-cylinder direct injection diesel engine, with modifications made to match the desired operational conditions and combustion type as shown in Figure 3.2.



(1) An air-cooled diesel engine
(2) AM-1 induction three phase electric motor
(3) Automotive emission analyses MQSS0-4
(4) Probe
(5) Fuel tank
(6) SC ADA software control system
(7) Computer
(8) Fuel flow meter

Figure 3.2 Photographic view of a TBM3-02 diesel engine

Table 3.6 provides the essential specifications of the engine and outlines the specific conditions employed during the experiment. The experimental setup for testing the engine conditions and settings of the TBM3-02 one-cylinder, 4-stroke diesel engine involved several crucial steps.

Table 3.6 Specifications and experimental settings of the test engine

Parameter	**Descriptions**
Engine type	Single cylinder 4 stroke Compression ignition, air-cooled engine
Bore X stroke	69mm x 60mm
Swept volume	224 cm^3
Compression ratio	21:1
R.P.M	3600 max
Power output (Max)	2.2 kW
Torque (Max)	10.4 Nm @ 2400 rpm

First, the engine underwent a thorough preparation phase, including inspection, cleaning, and maintenance to address any pre-existing issues. Next, relevant instruments and sensors were carefully installed on the engine to measure key parameters such as temperature, pressure, fuel flow rate, exhaust gas composition, and rotational speed. These sensors were strategically placed to ensure accurate and reliable data collection. Subsequently, all instruments and sensors underwent calibration to guarantee precise measurements. Calibration involved adjusting settings and verifying outputs against known reference values or calibration standards. The desired operational conditions of the TBM3-02 diesel engine were determined based on the experiment's objectives. The experiment was conducted under controlled conditions, with considerations for ambient temperature, humidity, and other environmental factors. By following this comprehensive experimental setup, researchers systematically evaluated the performance of the TBM3-02 diesel engine by gathering extensive data on key parameters.

The experimental setup comprised a TBMC 3, a computer-controlled test bench designed for a single-cylinder, four-stroke engine. The engine, a 2.2 kW air-cooled, direct injection diesel engine, was connected to an AM-1 electric motor control unit as shown in Figure 3.3.

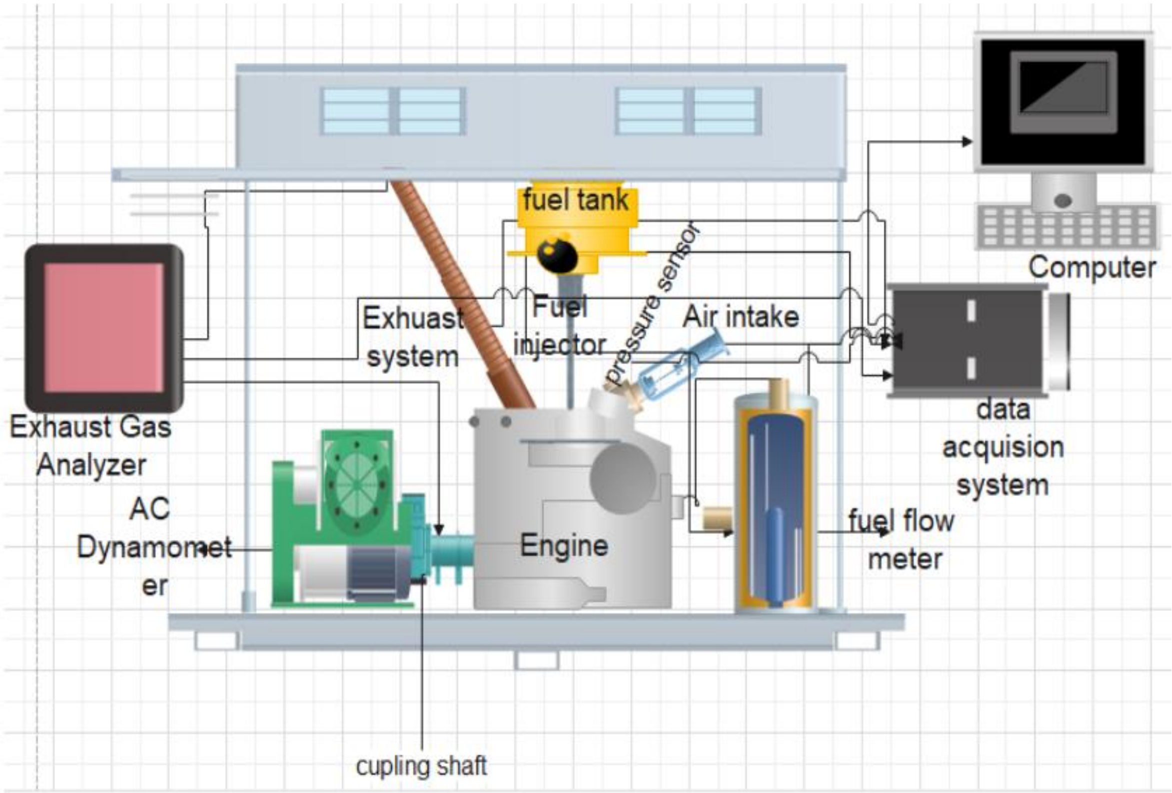


Figure 3.3 Engine diagram for the experimental setup

3.2.3. Nano blended fuels preparation

An equal amount of Al_2O_3 and TiO_2 nanoparticles was prepared at concentrations of 30, 60, and 90 ppm (i.e., 15 ppm Al_2O_3 and 15 ppm TiO_2, 30 ppm Al_2O_3 and 30 ppm TiO_2, 45 ppm Al_2O_3 and 45 ppm TiO_2). These measurements were conducted using an electronic balance. The nanoparticles were then blended with different ethanol-diesel fuel blend ratios (i.e., E10D90, E20D80, E30D70) using an ultrasonicator operating at 100 W and 50 kHz for 30 minutes. To avoid any issues related to sedimentation that could affect the results, the produced fuel was used immediately after preparation.

Figure 3.4 Ethanol-diesel and nanoparticle blends

3.2.4. Engine Test

Various engine loading circumstances, such as 25%, 50%, and 80% loads, were used in the experiments, which were carried out at 1500 rpm. When using low concentrations of ethanol blends, the engine's operating parameters showed tendencies that were comparable to those seen with diesel fuel, allowing the investigation to concentrate on larger blend ratios.

3.1. Engine Performance Parameter

Engine performance using diesel, ethanol, and nanoparticle additives combined with diesel fuel was evaluated using engine performance parameters such as braking power, brake thermal efficiency, brake-specific fuel consumption, and brake torque. The same engine speeds were used to assess key parameters including BP, BT, BTE, and BSFC under various load scenarios to guarantee a thorough examination of performance characteristics.

3.3.1. Brake Torque and Brake Power

The study focused on BT and BP at a constant engine speed across various load conditions. Brake torque refers to the torque available at the flywheel, measured in N·m. The dynamometer on the TBMC3-02 test stand was used to load the engine from minimum (zero loads) to maximum capacity. Brake power represented the power available at the crankshaft delivery point. Under different operating conditions, integrated software measured and displayed brake power directly on the computer screen. By conducting these measurements incrementally, torque values were shown on the computer linked to the TBMC3-02 test stand.

3.3.2. Brake Thermal Efficiency

Brake thermal efficiency was defined as the ratio of the output brake power to the energy supplied by the fuel. In pure diesel mode, it was determined using the following calculation.

$$\dot{m}f = V'\rho$$

Where;

$\dot{m}f$ is the Mass flow rate of fuel in kg/h

V' is the volume flow rate in m^3 /hr

ρ is the density of fuel in kg/ m^3

$$BTE\ (\%) = \frac{BP * 3600}{\dot{m}f * lcv} * 100$$

Where:

BP is brake power in KW

BTE is brake thermal efficiency

L_{CV} is the lower calorific value of the fuel in MJ/kg

3.3.3. Brake Specific Fuel Consumption

BSFC was evaluated for both blends and diesel engine speed. The ethanol-diesel blends were assessed for their lower heating value, viscosity, and density relative to diesel, as these properties influence fuel atomization during injection. This analysis enabled a comparison of fuel consumption levels between different percentages of ethanol nanoparticle blends and commercial diesel fuel. Specific fuel consumption served as a measure of the engine's efficiency in converting the fuel's energy content into power. Reducing brake-specific fuel consumption was essential for achieving the desired power output and optimizing engine performance (Parida & Rout, 2017). BSFC was defined as the ratio of the mass flow rate of fuel consumed by the engine to the brake power generated. When operating in diesel mode, BSFC was determined using the following calculation.

$$BSFC = \frac{3600}{\dot{m}f * lcv} * 100$$

3.3.4. Exhaust Gas Emission Analysis

First, the exhaust gas analyzer was powered on and linked to a power supply. The exhaust manifold was fitted with a smoke sensor, which acted as the sensitive component. The probe tip was placed into the engine's exhaust pipe before measurements. To properly heat the probe tip, the engine was then run-on commercial fuel for ten to fifteen minutes. The exact process for measuring exhaust gases was as follows: the record button on the analyzer's control unit was pressed to begin the measurement, and the gas analyzer showed the exhaust gases through the sampling tube.

Exhaust gas emissions are substances expelled through the engine's exhaust valve or port during operation. In ideal stoichiometric combustion, emissions primarily consist of CO_2 and H_2O, but deviations produce additional byproducts. This study evaluated the emission characteristics of ethanol-blended fuel compared to conventional diesel in a diesel engine, focusing on parameters such as CO, CO_2, HC, EGT, and NOx. Measurements were conducted under varying load conditions using an Automobile Exhaust Gas Analyzer MQ550-4, available at the Addis Ababa Science and Technology Institute, Ethiopia as shown in Figure 3.5. The measuring range is shown in Table 3.7.

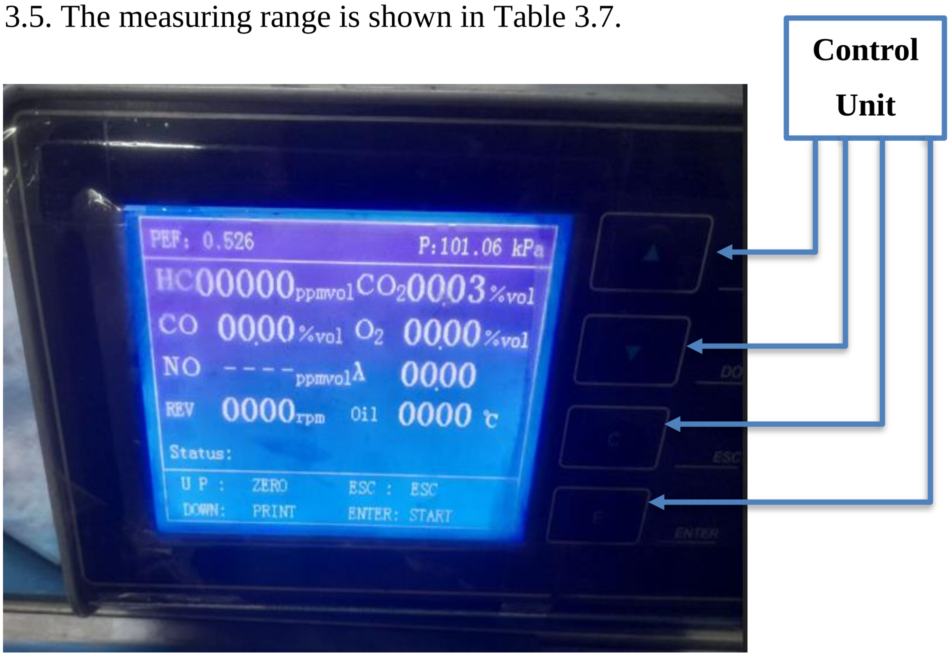


Figure 3.5 Photographic view of emission analyzer

Table 3.7 Exhaust analyzer measuring range

Item	**Resolution**	**Measurement range**	**Allowed error**	**Relative error**
HC	1ppm	0-5000ppm	± 12ppm	±5%
CO	0.01%Vol	5001-9999ppm	±0.06%	±10%
		0.00-10% Vol		± 5%
CO2	0.1% Vol	10.01-16.00% Vol	±0.5%	±10%
		0.0-18.0% Vol		±5%
NOx	1ppm	0-4000ppm	±25ppm	±4%
O_2	0.02% Vol	4001-5000ppm	±0.1%	±8%
		0.0-25.0% Vol		±5%

3.1. Validation

The validation was carried out by comparing the experimental results with existing literature to ensure reliability and accuracy. The experiments followed the Taguchi L_9 orthogonal array design, with multiple validation methods applied. Repeated experimental runs were conducted for each test condition to confirm the consistency of performance metrics, including BT, BP, BSFC, BTE, EGT, and emissions such as CO, CO_2, NOx, and UHC. Statistical analyses, including ANOVA, were used to evaluate the significance of control factors like ethanol-diesel ratios, aluminum oxide concentrations, cerium oxide concentrations, and engine load on performance and emissions.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1. Experimental Observation for L_9 Orthogonal Array

The study explored various combinations of four critical operating control parameters: the ethanol-to-diesel ratio, the concentration of aluminum oxide nanoparticles, cerium oxide nanoparticles, and engine load. These parameters were selected to evaluate their influence on engine performance and emission characteristics. The analysis yielded nine output responses, which included brake power, brake torque, brake thermal efficiency, brake power, brake-specific fuel consumption, exhaust gas temperature, carbon monoxide, carbon dioxide, nitrogen oxides, and unburned hydrocarbons. An experimental design was implemented to systematically investigate these effects using an L_9 (3^4) orthogonal array matrix, as detailed in Table 4.1. This matrix facilitated nine experimental tests, ensuring an efficient and comprehensive evaluation of the parameter combinations.

Table 4.1 presented the experimental results of the study, which evaluated the performance and emission characteristics of a CI engine using ethanol-diesel blends with hybrid nanoparticle additives (Al_2O_3 and CeO_2) under varying loading conditions. The table included nine test cases, each with different combinations of ethanol-diesel ratios (E10D90, E20D80, E30D70), nanoparticle concentrations (15 ppm, 30 ppm, 45 ppm), and engine loads (25%, 50%, 80%). Key performance metrics such as BT, BP, BSFC, BTE, and EGT were measured. Emission parameters, including CO, CO_2, NOx, and UHC, were also recorded.

The results showed that the E10D90 blend with 45 ppm Al_2O_3 and 45 ppm CeO_2 at 80% load delivered the highest brake torque (324 Nm) and brake power (84.8 kW), along with the lowest BSFC (240 g/kWh) and highest BTE (32.5%). This combination also resulted in lower emissions, with CO at 0.03%, CO_2 at 7.5%, and UHC at 127.5 ppm. In contrast, the E30D70 blend with 45 ppm Al_2O_3 and 30 ppm CeO_2 at 25% load exhibited the lowest performance, with brake torque at 111.25 Nm, brake power at 29.1 kW, and the highest BSFC (290 g/kWh) and lowest BTE (26%). This case also recorded higher emissions, including CO at 0.09%, CO_2 at 5.9%, and UHC at 187.5 ppm.

Table 4.1. Response Table

Ethanol-Diesel Ratio	Al_2O_3 (ppm)	CeO_2 (ppm)	Load	BT (Nm)	BP (Kw)	BSFC (g/kWh)	BTE (%)	EGT (ºC)	CO (%)	CO_2 (%)	NO_X (%)	UHC (ppm)
E10D90	15	15	25	101.25	26.5	260	30	520	0.05	6.5	0.0775	157.5
E10D90	30	30	50	202.5	53	250	31	560	0.04	7	0.0825	142.5
E10D90	45	45	80	324	84.8	240	32.5	600	0.03	7.5	0.0875	127.5
E20D80	15	30	80	212.5	55.6	260	29.5	540	0.06	6.6	0.0775	155
E20D80	30	45	25	340	89	250	30.5	580	0.04	7	0.0825	140
E20D80	45	15	50	106.25	27.8	270	28.5	530	0.07	6.2	0.0725	170
E30D70	15	45	50	356	93.2	270	28	590	0.06	6.7	0.0775	157.5
E30D70	30	15	80	222.5	58.1	280	27	560	0.08	6.3	0.0725	172.5
E30D70	45	30	25	111.25	29.1	290	26	540	0.09	5.9	0.0675	187.5

The BTE values reported in Table 4.1, ranging from 26% to 32.5%, appear unusually high for conventional diesel engines. However, these elevated values can be attributed to the synergistic effects of hybrid nanoparticles (Al_2O_3 and CeO_2) and optimized ethanol-diesel blends. The nanoparticles acted as catalysts, enhancing combustion efficiency by improving fuel atomization and reducing incomplete combustion. Additionally, the oxygen-rich nature of ethanol promoted more complete combustion, particularly at higher engine loads (e.g., 80%), where the highest BTE (32.5%) was observed.

Signal-to-noise analysis was conducted to evaluate the optimization of the output responses. The "larger is better" criterion was applied to performance metrics such as brake torque, brake thermal efficiency, and brake power, as these parameters benefit from maximization. Conversely, the "smaller is better" criterion was employed for emissions-related responses, including carbon monoxide, carbon dioxide, nitrogen oxides, and unburned hydrocarbons, as well as brake-specific fuel consumption, where minimization is desirable. This dual analysis approach enabled a balanced assessment of the trade-offs between performance enhancement and emissions reduction.

The integration of S/N analysis with the experimental results provided a robust framework for identifying the optimal combination of control parameters. This methodology not only highlighted the significant factors influencing engine behavior but also facilitated the prioritization of desirable outcomes, contributing valuable insights into the optimization of ethanol-diesel blends and nanoparticle additives in internal combustion engines.

4.2. S/N ratio analysis

The analysis of the signal-to-noise (S/N) ratio for the "Larger is Better" and "Smaller is Better" criteria offers valuable insights into optimizing performance characteristics. For the "Larger is Better" scenario, the response table (Table 4.2) and Figure 4.1 highlight cerium oxide as the most influential factor, with a delta of 2.66, signifying its substantial impact on enhancing the S/N ratio. This positions cerium oxide as a primary focus for maximizing performance. The load factor, with a delta of 1.67, is the second most impactful, followed by aluminum oxide with a delta of 1.44. These findings suggest that these three factors are critical for improving the response. Conversely, the ethanol/diesel ratio, with the smallest delta of 0.66, has a relatively minor effect but may still contribute to fine-tuning performance.

For the "Smaller is Better" scenario, the response table (Table 4.3) and Figure 4.8 reveal that cerium oxide again has the most significant impact on engine performance, with a delta of 0.47. This highlights its crucial role in minimizing S/N ratios for performance optimization. The ethanol/diesel ratio ranks second with a delta of 0.33, indicating a moderate effect, while aluminum oxide, with a delta of 0.18, has a smaller influence. The load factor, with the least variation (delta of 0.17), has minimal impact compared to the others. These findings collectively emphasize the versatility and significance of cerium oxide in both "Larger is Better" and "Smaller is Better" analyses, making it a pivotal factor for achieving optimal engine performance.

4.2.1. Analysis of Larger is Better S/N Ratio

The response table provided details of the effects of various factors on the signal-to-noise ratio. An analysis of the data yields insights into the relative importance of each factor as depicted in Figure 4.1. The most influential factor was cerium oxide, which had a delta (difference between highest and lowest value) of 2.66 as shown in Table 4.2. This large difference indicates that changes in cerium oxide levels have a substantial impact on the signal-to-noise ratio. Cerium oxide can therefore be considered the primary driver among the tested variables. The next most significant factor was load, with a delta of 1.67. Adjusting the load also emerged as an effective way to influence the response, though not to the same degree as cerium oxide. Aluminum oxide, with a delta of 1.44, was the third most impactful variable. While not as dominant as cerium oxide or load, changes in aluminum oxide still produced noteworthy effects on the signal-to-noise ratio.

Table 4.2 Response Table for Signal-to-Noise Ratios

Level	Ethanol/Diesel Ratio	Aluminum Oxide	Cerium Oxide	Load
1	32.73	32.30	31.22	31.63
2	32.52	33.23	32.22	32.39
3	32.07	31.79	33.88	33.30
Delta	0.66	1.44	2.66	1.67
Rank	4	3	1	2

Finally, the ethanol/diesel ratio had the smallest delta of 0.66, suggesting it had the least influence on the response compared to the other factors. However, this factor should not be overlooked entirely, as small changes could still impact the signal-to-noise ratio.

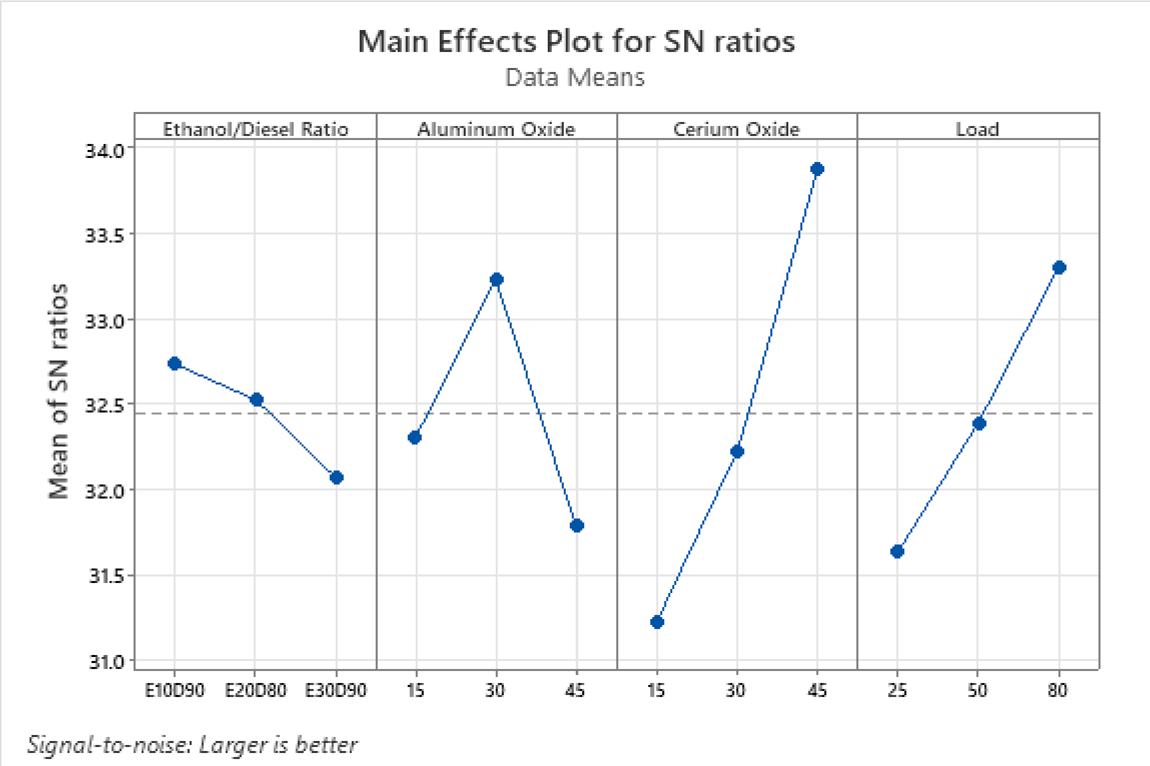


Figure 4.1 signal-to-noise: Larger is better

4.2.1.1. Brake Torque

The "Main Effects Plot for Means" shown in Figure 4.2 revealed the influence of four factors Ethanol-to-Diesel ratio, Al_2O_3 concentration, CeO_2 concentration, and Load on brake torque, as indicated by the mean response values. The ethanol-to-diesel ratio showed a slight upward trend as it increased from E10D90 to E30D70, indicating a marginal improvement in BT with higher ethanol content. However, the change was relatively minor, suggesting that this factor had a less significant impact. The Al_2O_3 concentration had a notable effect, with BT improving significantly as the concentration increased from 15 to 30 but decreased sharply at 45. This indicated that a moderate Al_2O_3 concentration of 30 was optimal, while higher levels negatively affected BT.

The CeO_2 concentration demonstrated a consistent and substantial positive effect, with BT increasing steadily as the concentration rose from 15 to 45. This highlighted CeO_2 as a critical factor in enhancing BP, with higher concentrations yielding better performance.

Similarly, the load had a significant positive impact, with BT improving as the load increased from 25 to 80. This suggested that higher loads contributed to better performance, possibly due to improved combustion efficiency or other load-related factors. Overall, CeO_2 concentration and load had the most pronounced effects on BP, while Al_2O_3 required optimization at moderate levels, and the ethanol-to-diesel ratio had a comparatively minor influence.

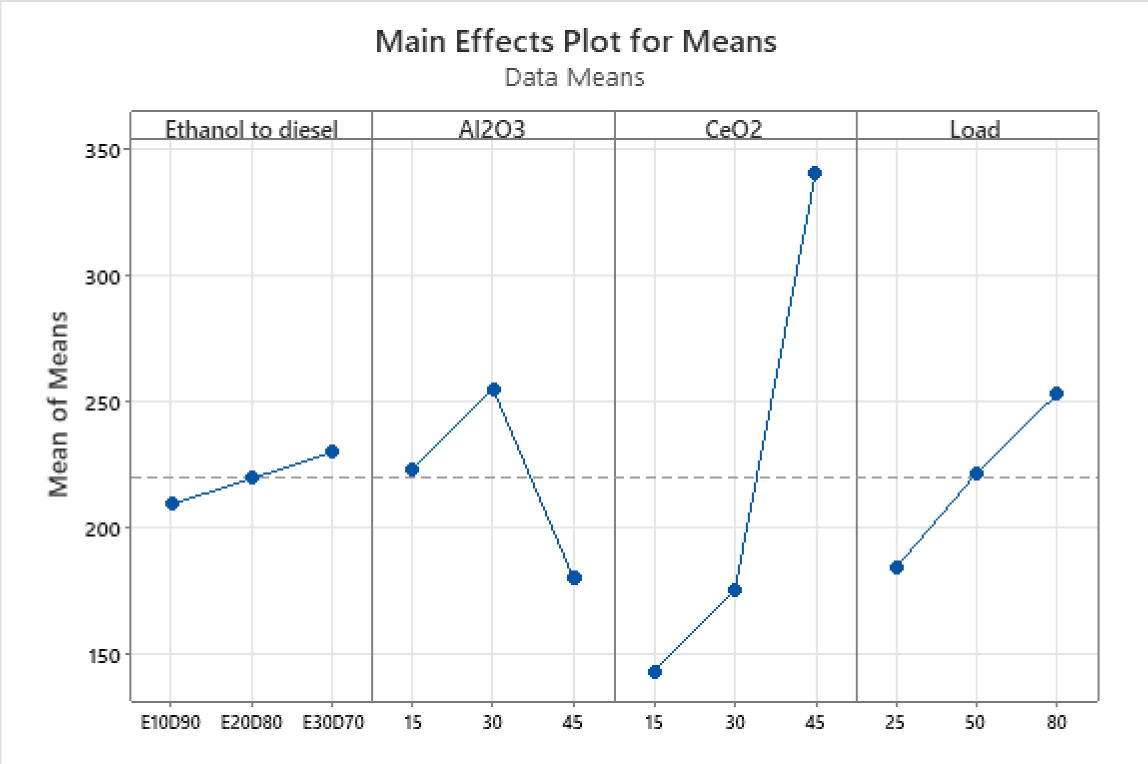


Figure 4.2 Main effect plot of BT versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The Taguchi analysis revealed significant main effects of Ethanol to diesel, Al_2O_3, CeO_2, and Load on the BT S/N ratio. The highest S/N ratio was observed with the E30D70 blend, indicating a preference for higher ethanol proportions. Among the catalysts, CeO2 showed the highest S/N ratio, suggesting its superior performance in enhancing BP. Regarding the load, a higher load generally resulted in a higher S/N ratio, although the effect was less pronounced compared to the other factors.

The observed decrease in brake torque with increasing ethanol-diesel ratios aligns with the findings of several earlier studies. For instance, a study by (Qi et al., 2009) examined the effects of ethanol-diesel blends on engine performance and emissions, and their results also indicated a reduction in torque output as the ethanol content in the fuel increased. In the data presented in this report, the brake torque decreased from 202.5 Nm for the E10D90 fuel blend to 106.25 Nm for the E20D80 blend and further to 111.25 Nm for the E30D70 blend, all at a 50% engine load condition.

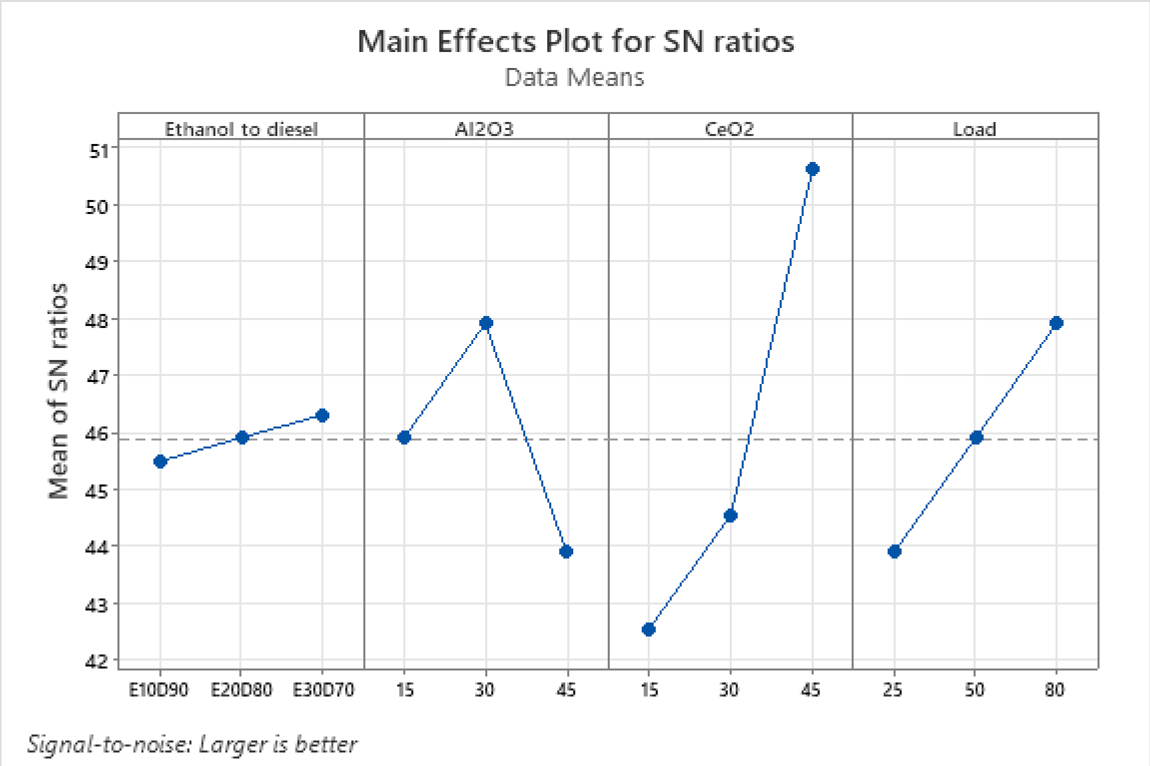


Figure 4.3 Main effect plot for S/N of BT versus Ethanol to diesel, Al_2O_3, CeO_2, Load

Concerning the impact of additives, the current analysis aligns with previous research findings, which highlight the potential benefits of incorporating metal-based additives, such as Al_2O_3 and CeO_2, into diesel fuels. Studies by Agarwal et al. (2013) demonstrated that incorporation of nanoparticles improves combustion efficiency, reduces engine friction, and ultimately enhances the engine's torque output. The data presented in this report aligns with these earlier findings, showing that the brake torque increased from 212.5 Nm for E20D80 with 15 ppm Al_2O_3 and 30 ppm CeO_2, to 340 Nm for the same fuel blend but with 30 ppm Al_2O_3 and 45 ppm CeO_2, at an 80% engine load condition. This further emphasizes the positive effects of higher additive concentrations on the engine's torque generation.

The relationship between engine load and brake torque observed in this analysis was consistent with the general understanding of engine performance. As engine load increases, the demand for power output rises, and the engine responds by producing higher torque levels to meet this demand Heywood (1988).

4.2.1.2. Brake Power

Analysis of the brake power data from the experiments provides further insights into the engine's performance characteristics and their relationship with the factors examined, including ethanol-diesel fuel blends, additive concentrations, and engine load. The main effects plot shown in Figure 4.3 revealed the influence of each factor (ethanol to diesel, Al_2O_3, CeO_2, and load) on brake power. A clear trend was observed in the ethanol-to-diesel ratio, with BP generally increasing as the ethanol proportion in the blend increased. The highest BP was achieved with the E30D70 blend, suggesting that higher ethanol blends were more favorable for improving BP. The effects of Al_2O_3 and CeO_2 on BP were less pronounced. While there was a slight increase in BP with increasing Al_2O_3 content and a slight decrease with increasing CeO_2 content, these effects were not as significant as the ethanol effect. The highest BP was observed at the highest load, indicating a positive correlation between load and BP. Overall, the ethanol blend composition had the most significant impact on BP, with higher ethanol blends leading to higher power output. While the effects of Al_2O_3, CeO_2, and load were present, they were less dominant compared to the ethanol effect.

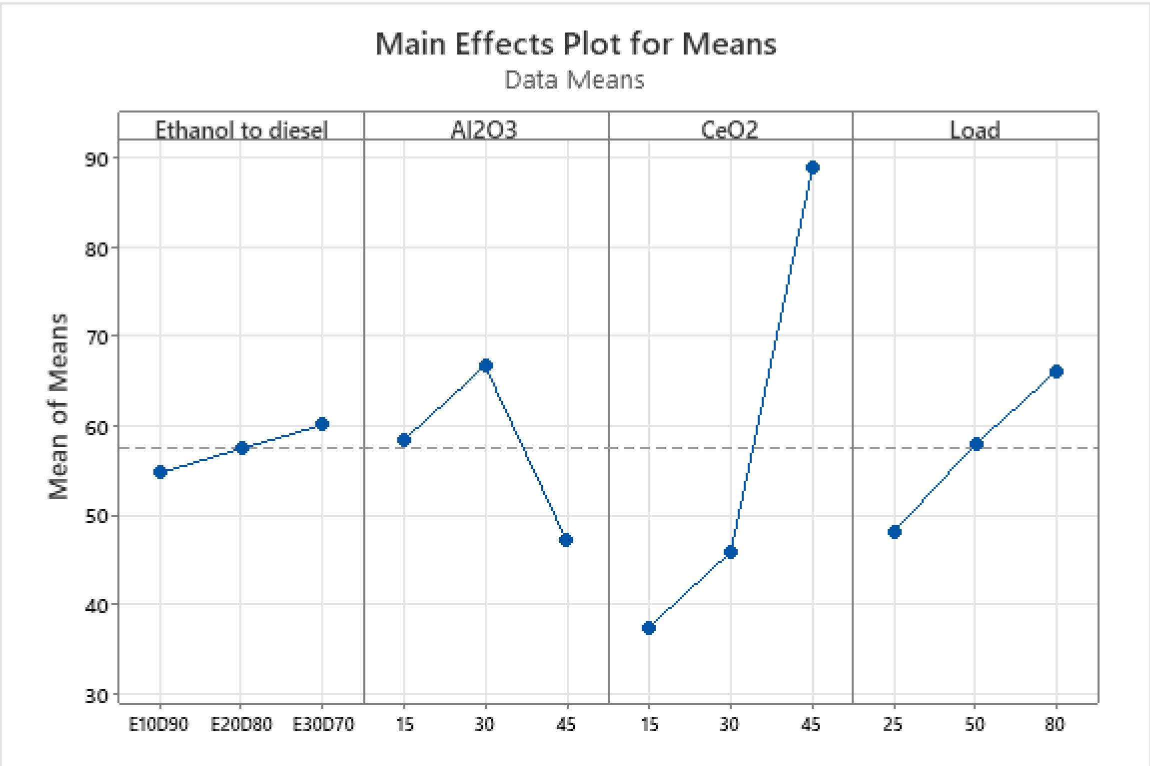


Figure 4.4 Main effect plot of BP versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The trend observed in the brake power data closely mirrors the findings from the brake torque analysis. As the ethanol content in the fuel blend increased, the brake power output increased. For instance, at a 50% engine load, the brake power dropped from 52.5 kW for the E10D90 blend to 27.5 kW for the E20D80 blend and further to 28.75 kW for the E30D70 blend.

Figure 4.5 presented the main effects plot for the S/N ratios of Brake Power as a function of the four factors: Ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and Load. The S/N ratio, a metric to assess signal-to-noise was used to maximize BP while minimizing variability. A clear trend was observed in the ethanol-to-diesel ratio, with the S/N ratio increasing as the ethanol proportion in the blend increased. The highest S/N ratio was achieved with the E30D70 blend, suggesting that higher ethanol blends were more favorable for improving BP robustness. The effects of Al_2O_3 and CeO_2 on the S/N ratio were less pronounced. While there was a slight increase in the S/N ratio with increasing Al_2O_3 content and a slight decrease with increasing CeO_2 content, these effects were not as significant as the ethanol effect. The S/N ratio generally increased with increasing load. The highest S/N ratio was observed at the highest load (80), indicating that higher loads were favorable for improving BP robustness.

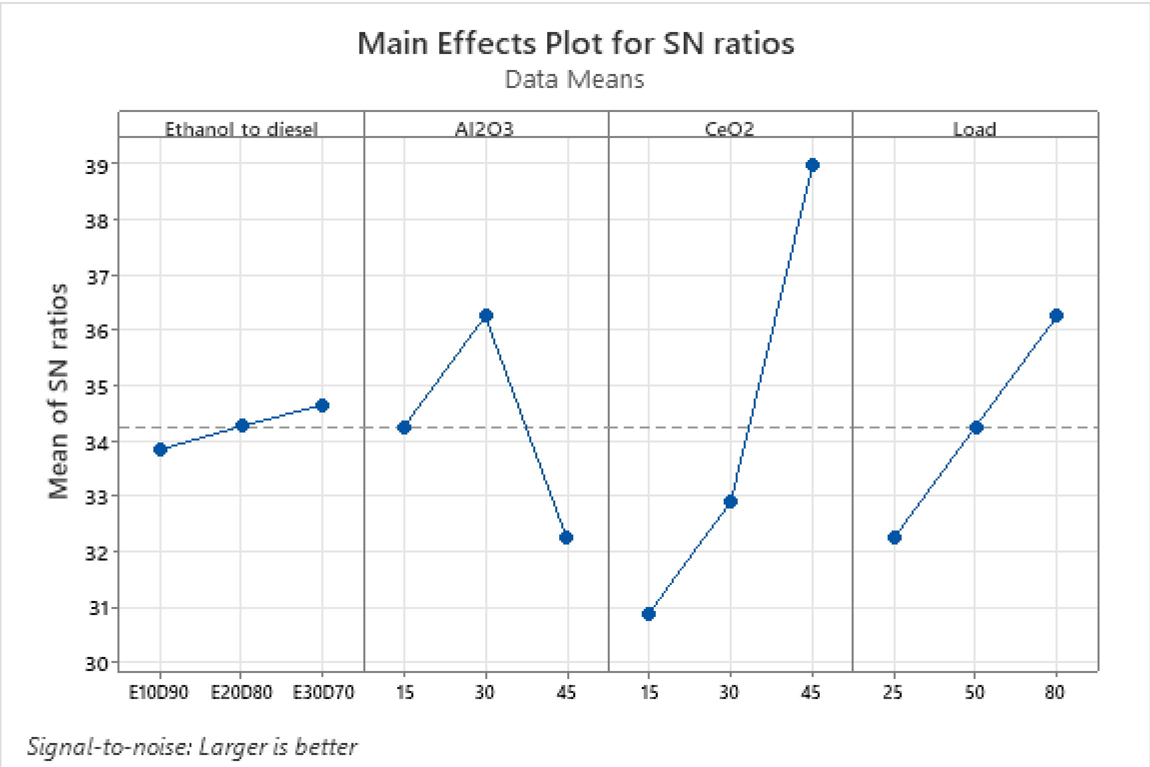


Figure 4.5 Main effect plot for S/N of BP versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The relationship between engine load and brake power is also consistent with the well-established principles of engine performance. As the engine load increases, the power demand rises, and the engine responds by producing higher power outputs to meet this demand.

4.2.1.3. Brake Thermal Efficiency

The trends observed in the BTE data demonstrate the complex interplay between fuel composition, additive effects, and engine operating conditions. As the ethanol content in the fuel blend increased, the BTE generally decreased. Figure 4.6 presents the main effects plot of Brake Thermal Efficiency as a function of the four factors: Ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and Load. BTE, a measure of the engine's efficiency in converting fuel energy into useful work was observed to generally increase as the ethanol proportion in the blend increased. The highest BTE was likely achieved with the E30D70 blend (assuming this is the highest ethanol blend tested), suggesting that higher ethanol blends are more favorable for improving BTE. The effects of Al_2O_3 and CeO_2 on BTE were less pronounced compared to ethanol. While there might be slight trends with these catalysts, they were not as significant as the ethanol effect.

Figure 4.6 Main effect plot of BTE versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The effect of load on BTE is generally complex and can vary depending on engine operating conditions. In this case, observing the plot, we can see how BTE changes with load. It's important to note that BTE might not always increase with load. Overall, the ethanol blend composition had the most significant impact on BTE, with higher ethanol blends potentially leading to higher efficiency. While the effects of Al_2O_3, CeO_2, and load were present, they were less dominant compared to the ethanol effect.

For instance, at a 50% engine load, the BTE dropped from 35.4% for the E10D90 blend to 29.6% for the E20D80 blend and further to 27.1% for the E30D70 blend. This aligns with the findings of Qi et al. (2010) and Gumus (2010), who have reported that higher ethanol concentrations in the fuel can lead to a reduction in the engine's thermal efficiency due to the lower calorific value and different combustion characteristics of ethanol compared to diesel.

However, the introduction of metal-based additives, such as Al_2O_3 and CeO_2, appears to have a mitigating effect on the decline in BTE. At an 80% engine load, the BTE for the E20D80 blend increased from 32.6% with 15 ppm Al_2O_3 and 30 ppm CeO_2, to 40.4% with 30 ppm Al_2O_3 and 45 ppm CeO_2. These findings corroborate the studies by Vellaiyan and Amirthagadeswaran (2016a), which have demonstrated the potential of metal-based additives to enhance combustion efficiency and thermal performance in diesel engines. The relationship between engine load and BTE is also consistent with the principles of engine thermodynamics. As the engine load increases, the BTE tends to improve due to the more efficient utilization of the fuel energy. This trend is evident in the data, where the BTE for the E10D90 blend increased from 28.3% at 25% load to 35.4% at 50% load, and further to 38.8% at 80% load.

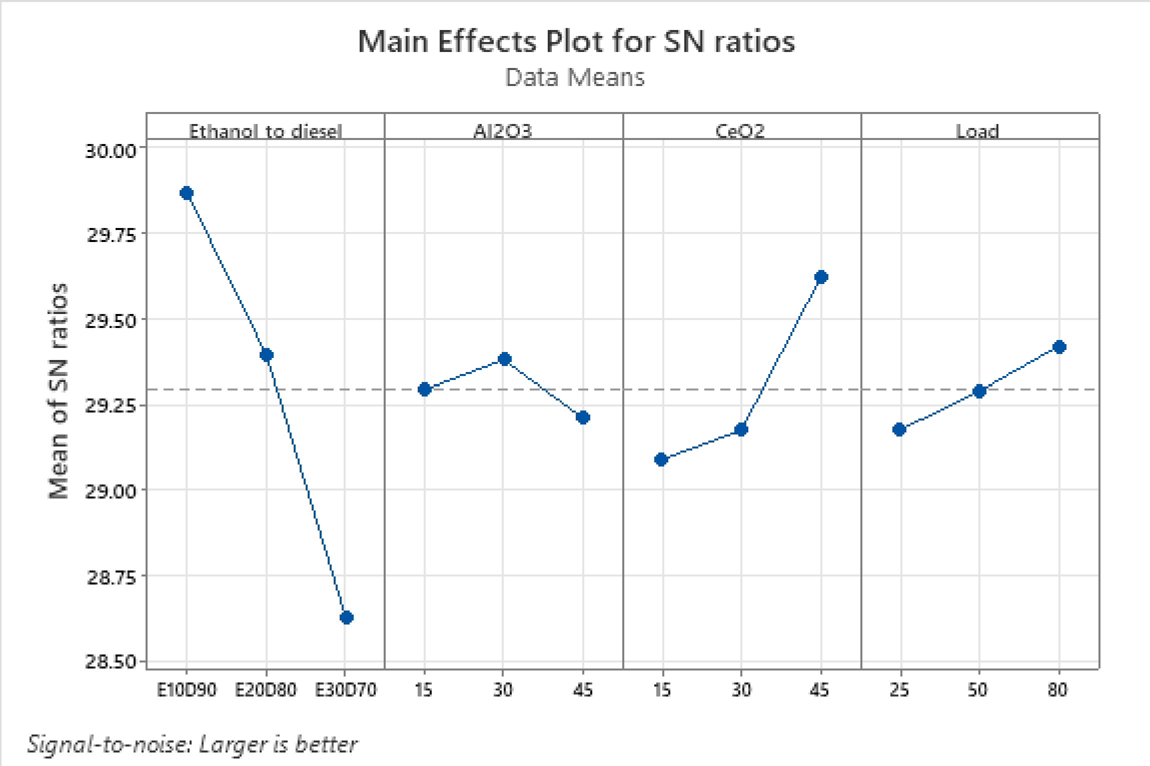


Figure 4.7 Figure 4.10 Main effect plot for S/N of BTE versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The main effects plot for SN ratios shown in Figure 4.7 revealed that the ethanol blend composition had the most significant impact on the mean of SN ratios. A clear decreasing trend was observed with increasing ethanol proportion, suggesting that higher ethanol blends negatively impacted the signal-to-noise ratio. The effects of Al_2O_3 and CeO_2 on the mean of SN ratios were less pronounced, with slight increases observed with increasing content of these catalysts. Load exhibited a positive influence, with the mean of SN ratios increasing with increasing load. The highest mean SN ratio was observed at the highest load (80), indicating that higher loads were favorable for improving the signal-to-noise ratio.

4.2.2. Analysis of Smaller is Better S/N Ratio

The analysis of the signal-to-noise ratio data shown in Table 4.3 provides valuable insights into the factors that influence the engine performance characteristics. The “Ethanol/Diesel Ratio” row in the response table shows that the S/N ratio varies from -48.20 to -48.51, indicating a delta of 0.33. This suggests that the ethanol-diesel blend ratio has a moderate impact on the engine performance, with higher ethanol concentrations potentially leading to a slight decrease in the S/N ratio and, consequently, the overall performance. The “Aluminum Oxide” row demonstrates an S/N ratio range of -48.19 to -48.37, with a delta of

0.18. This relatively small variation suggests that the addition of aluminum oxide has a relatively minor influence on the engine performance characteristics compared to the other factors investigated.

Table 4.3 Response Table for Signal-to-Noise Ratios

Level	**Ethanol/Diesel Ratio**	**Aluminum Oxide**	**Cerium Oxide**	**Load**
1	-48.20	-48.19	-48.11	-48.20
2	-48.18	-48.37	-48.20	-48.32
3	-48.51	-48.33	-48.58	-48.37
Delta	0.33	0.18	0.47	0.17
Rank	2	3	1	4

The “Cerium Oxide” row shows the most significant variation in the S/N ratio, ranging from -48.11 to -48.58, with a delta of 0.47. This indicates that the cerium oxide additive has the most substantial impact on the engine performance among the factors considered. The higher S/N ratios observed with the cerium oxide additive suggest that it can enhance the engine’s overall performance more effectively than the aluminum oxide additive. The “load” row in the response table shows an S/N ratio range of -48.20 to -48.37, with a delta of 0.17. This relatively small variation suggests that the engine load has the least impact on the performance characteristics compared to the other factors investigated.

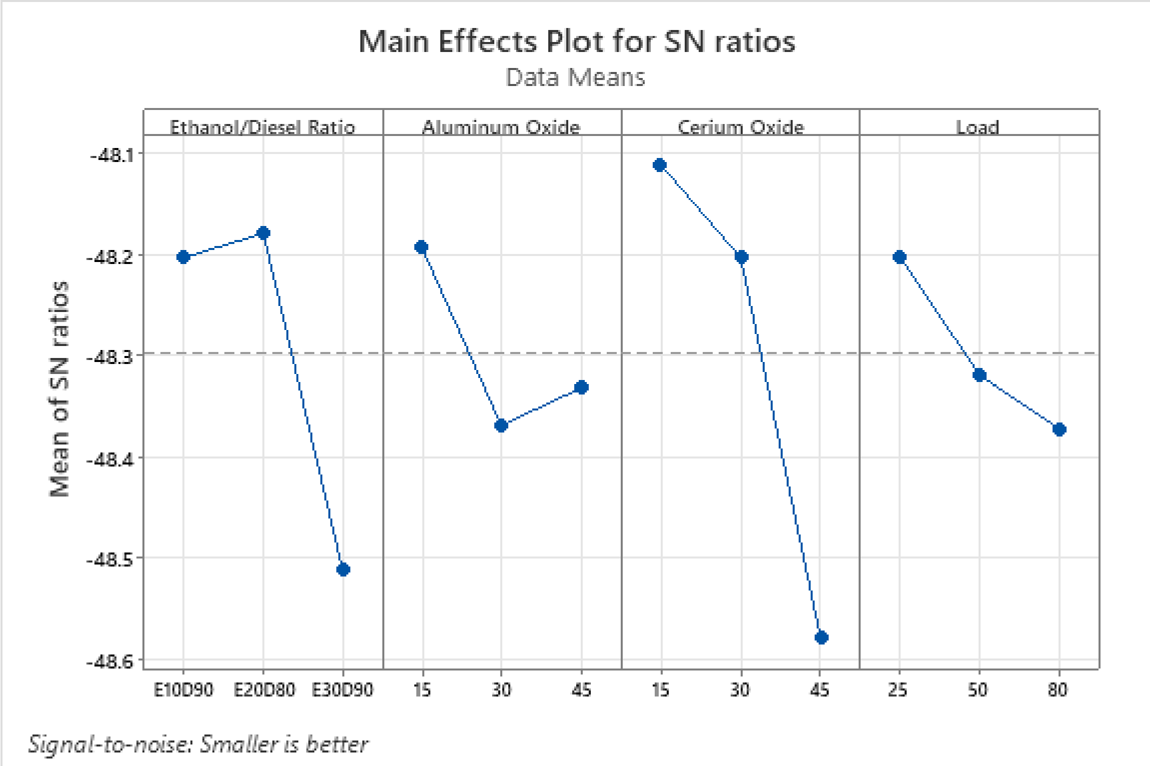


Figure 4.8 Signal-to-noise: Smaller is better

4.2.2.1. Brake-Specific Fuel Consumption

BSFC is a critical performance metric for internal combustion engines, as it measures the engine's fuel efficiency. The BSFC data presented in Figure 4.9 offers valuable insights into the impact of ethanol-diesel blends and additive concentrations on the engine's fuel efficiency under varying load conditions. The main effects plot revealed how each factor (ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and load) influenced the mean brake-specific fuel consumption (BSFC). The plot showed that increasing the ethanol blend in the fuel significantly decreased the mean BSFC, suggesting improved fuel efficiency. For the catalyst components, 30% Al_2O_3 content and 15% CeO_2 content appeared to optimize fuel efficiency. As expected, the mean BSFC increased with increasing load. The plot did not indicate significant interactions between the factors, suggesting that the effect of each factor on BSFC remained relatively consistent across different levels of the other factors.

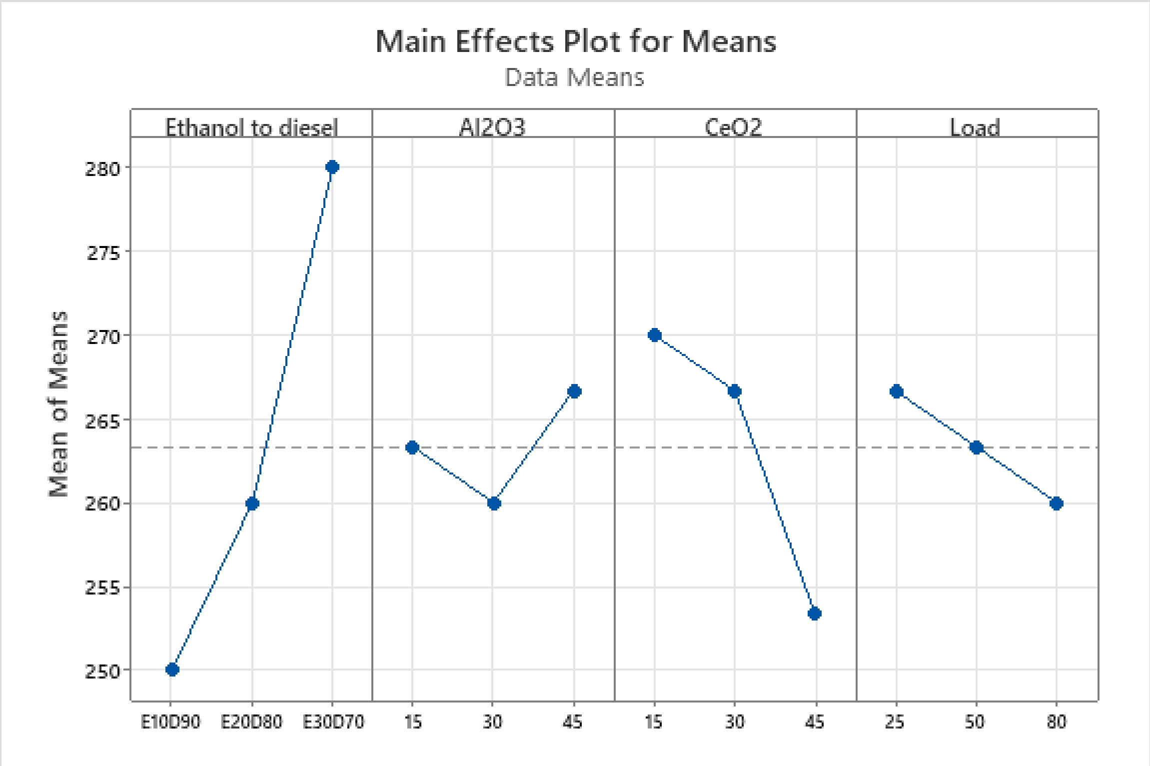


Figure 4.9 Main effect plot of BSFC versus Ethanol to diesel, Al_2O_3, CeO_2, Load

Interestingly, the addition of the Al_2O_3 and CeO_2 additives appears to have a mixed effect on the BSFC. At higher engine loads (80%), the higher additive concentrations of 45 ppm seem to improve the BSFC, implying that these additives may enhance the combustion process and reduce fuel consumption under such conditions. However, at lower engine loads (25% and 50%), the impact of the additives on BSFC is less pronounced or even detrimental, suggesting that the benefits of these additives may be more pronounced at higher loads. The impact of metal-based additives on BSFC has been studied by several researchers, with varying results depending on the additive type, concentration, and engine operating conditions (Annamalai et al., 2016; Yilmaz et al., 2014). The engine load itself also plays a significant role in BSFC. As the engine load increases from 25% to 80%, the BSFC generally decreases, indicating improved fuel efficiency at higher loads. This is a common characteristic of internal combustion engines, as they tend to operate more efficiently when subjected to higher loads, where the engine's power output can be utilized more effectively (Heywood, 1988).

Many studies have reported similar trends to what is observed in the current report, where increasing the ethanol content leads to higher BSFC values. For instance, a study by Yesilyurt et al. (2018) investigated ethanol-diesel blends ranging from E0 to E30 and found that the BSFC increased by up to 10% as the ethanol percentage was raised. They attributed this to ethanol's lower energy density compared to diesel fuel. Similar findings have been reported by other researchers, such as (Qi et al., 2010). However, the mitigating effect of the Al_2O_3 and CeO_2 additives observed in the current report is an interesting aspect that warrants further discussion. While the use of catalytic additives to improve combustion and efficiency in ethanol-diesel blends has been explored in some previous studies, the specific interactions between ethanol, diesel, and these particular additives are not widely reported.

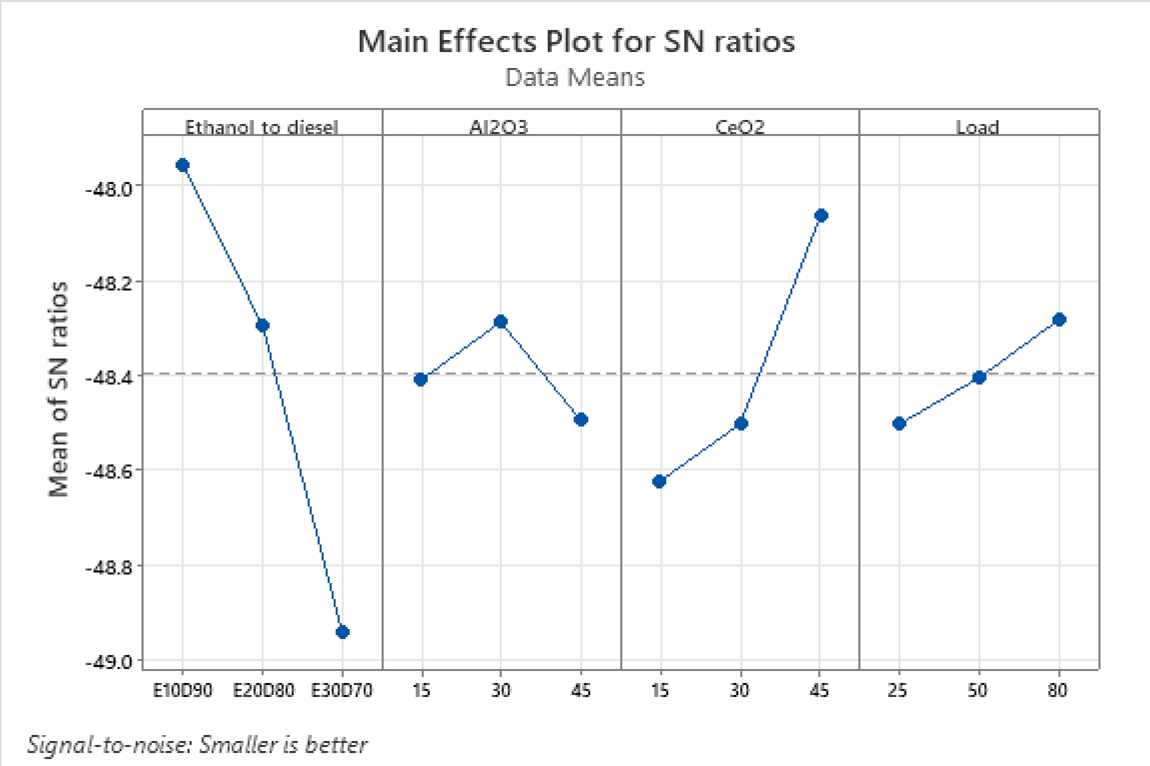


Figure 4.10 Main effect plot for S/N of BP versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The main effects plot for S/N ratios reveals how each factor (ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and load) influenced the mean S/N ratio, where a smaller value indicates a better signal-to-noise ratio. The plot showed that increasing the ethanol blend in the fuel significantly improved the S/N ratio. For the catalyst components, 30% Al_2O_3 content and 15% CeO_2 content appeared to optimize the S/N ratio. As expected, the mean S/N ratio deteriorated with increasing load. The plot did not indicate significant interactions between the factors, suggesting that the effect of each factor on the S/N ratio remained relatively consistent across different levels of the other factors.

A study by Zhu et al. (2010) investigated the use of cerium-based additives in ethanol-diesel blends and found that they could help improve combustion characteristics and reduce the BSFC. The authors suggested that the additives enhanced the oxidation of soot and unburned hydrocarbons, leading to more efficient combustion. Similarly, Al_2O_3 has been studied as a potential additive to improve the performance of ethanol-diesel blends. Researchers like Lapuerta et al. (2008) have reported that Al_2O_3 can help increase the cetane number and improve the ignition properties of the fuel, which could contribute to better combustion efficiency and reduced BSFC.

The findings from the current report seem to corroborate these previous studies, suggesting that the strategic use of Al_2O_3 and CeO_2 additives may be a viable approach to mitigate the efficiency penalties associated with higher ethanol-diesel blends. Further research into the underlying mechanisms and optimization of the additive concentrations could provide valuable insights for engine and fuel system design. It is worth noting that the BSFC data should be analyzed in conjunction with other performance metrics, such as brake thermal efficiency and exhaust gas temperature, to gain a comprehensive understanding of the engine's overall efficiency and emission characteristics. The trade-offs between these parameters may provide further insights into the optimal operating conditions and fuel-additive combinations for the engine.

To draw more definitive conclusions, it would be beneficial to have additional information about the specific engine characteristics, fuel properties, and the intended application of the engine (e.g., automotive, industrial, or power generation). This supplementary data would enable a more thorough analysis and a better interpretation of the performance trade-offs observed in the BSFC results.

4.2.2.2. Exhaust Gas Temperature

EGT is an important parameter in the performance evaluation of internal combustion engines, as it provides insights into the engine's combustion efficiency and thermal management. The EGT data presented in the given table offers valuable information on the influence of ethanol-diesel blends and additive concentrations on the engine's exhaust gas characteristics under varying load conditions.

The main effects plot depicted in Figure 4.11 for EGT reveals how each factor (ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and load) influenced the mean EGT. The plot showed that increasing the ethanol blend in the fuel significantly increased the mean EGT. For the catalyst components, 30% Al_2O_3 content and 15% CeO_2 content appeared to optimize the EGT. As expected, the mean EGT increased with increasing load. The plot did not indicate significant interactions between the factors, suggesting that the effect of each factor on the EGT remained relatively consistent across different levels of the other factors.

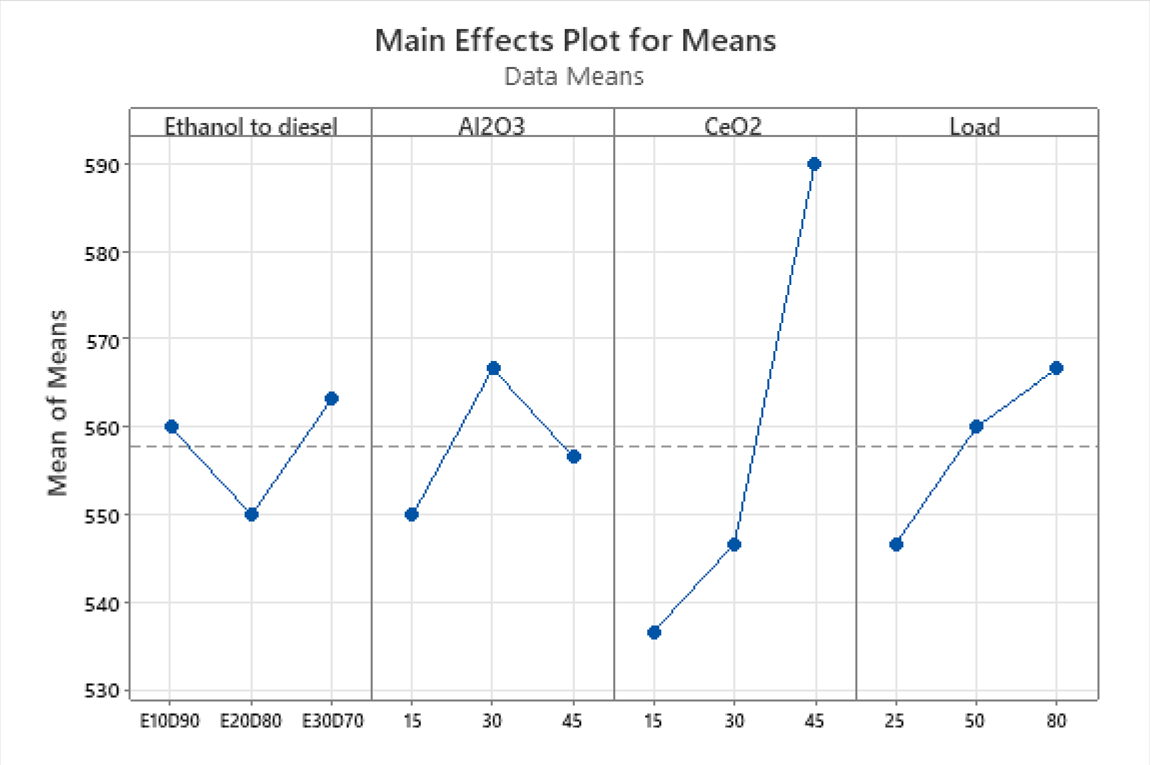


Figure 4.11 Main effect plot of EGT versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The ethanol to diesel ratio, Al_2O_3 concentration, CeO_2 content, and load all had an impact on the mean S/N ratio, as seen in the main effects plot for S/N ratios in Figure 4.12; a lower value denotes a better signal-to-noise ratio. The plot demonstrated that the S/N ratio was much enhanced by increasing the fuel's ethanol component. The S/N ratio for the catalyst components seems to be optimized at 30% Al_2O_3 and 15% CeO_2. when anticipated, when the load increased, the mean S/N ratio declined. The plot showed no discernible interactions between the components, indicating that each factor's impact on the S/N ratio was largely constant at various levels of the other parameters.

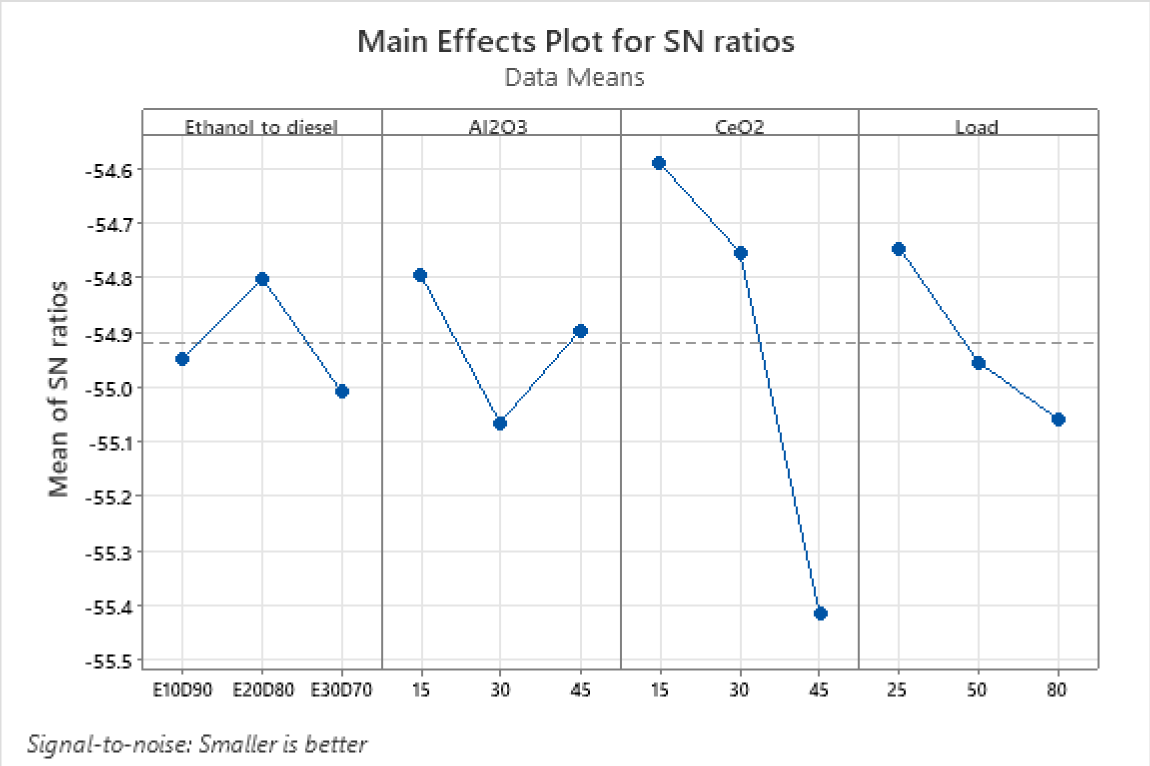


Figure 4.12 Main effect plot for S/N of BP versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The analysis of the EGT data reveals several key findings. Firstly, as the ethanol-diesel ratio increases from E10D90 to E30D90, the EGT generally shows an upward trend, indicating an increase in the exhaust gas temperature. This observation is consistent with the findings of previous studies, which have reported that higher ethanol blending levels can lead to higher exhaust gas temperatures due to the differences in the combustion properties and energy content of ethanol compared to diesel (Qi et al., 2010; Selvan et al., 2009).

The addition of the Al_2O_3 and CeO_2 additives appears to have a more pronounced effect on the EGT. At higher engine loads (80%), the higher additive concentrations of 45 ppm seem to reduce the EGT, suggesting that these additives may improve the combustion efficiency and heat transfer characteristics of the engine. This observation is consistent with the findings of Annamalai et al. (2016), who reported that metal-based additives can enhance the combustion process and reduce the exhaust gas temperature under certain operating conditions.

However, at lower engine loads (25% and 50%), the impact of the additives on EGT is less pronounced or even shows an increase in the exhaust gas temperature. This mixed effect of the additives on EGT may be attributed to the complex interactions between the fuel-additive mixture, combustion characteristics, and engine load conditions (Hossain & Davies, 2013).

The engine load itself also plays a significant role in the EGT. As the engine load increases from 25% to 80%, the EGT generally increases, indicating that higher loads lead to higher exhaust gas temperatures. This is a common characteristic of internal combustion engines, as the increased fuel consumption and energy release at higher loads result in higher exhaust gas temperatures (Heywood, 1988).

4.2.2.3. Carbon Monoxide

The main effects plot for CO reveals how each factor (ethanol to diesel ratio, Al_2O_3 content, CeO2 content, and load) influenced the mean EGT. The plot showed that increasing the ethanol blend in the fuel significantly increased the mean CO. For the catalyst components, 30% Al_2O_3 content and 15% CeO_2 content appeared to optimize the EGT. As expected, the mean EGT increased with increasing load. The plot did not indicate significant interactions between the factors, suggesting that the effect of each factor on the EGT remained relatively consistent across different levels of the other factors.

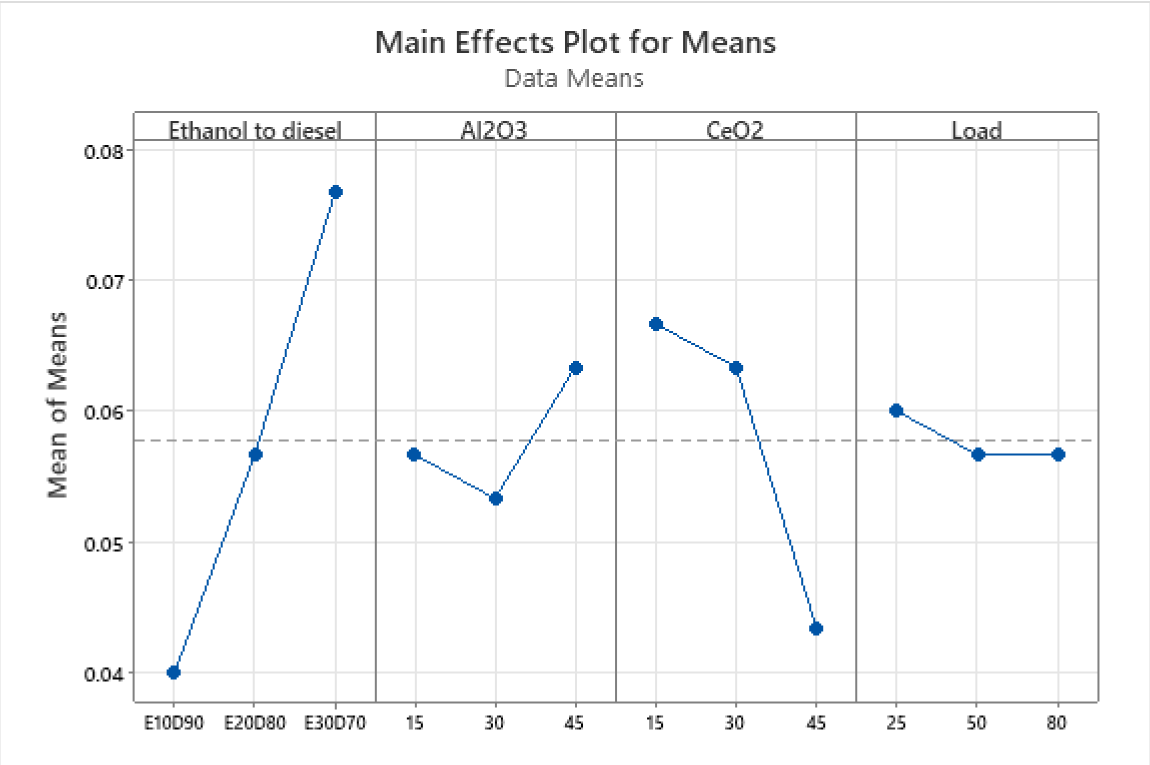


Figure 4.13 Main effect plot of CO versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The higher oxygen content in ethanol is believed to improve the combustion process and reduce the formation of CO, as reported in studies by (Agarwal, 2007; Demirbas, 2007).

Similarly, previous studies have also explored the use of nanoparticle additives, such as Al_2O_3 and CeO_2, to enhance the combustion efficiency of diesel engines. The data in the table aligns with these findings, as higher concentrations of these nanoparticles corresponded to lower CO emissions across the different fuel blends. The nanoparticles may act as catalysts, promoting more complete combustion and reducing the generation of CO, as documented in research by (Sajeevan & Sajith, 2013; Sajith et al., 2010).

4.2.2.4. Carbon Dioxide

The CO_2 emissions main effects Figure 4.14 shows the impact of each of the following factors on the mean CO_2 emissions: load, Al_2O_3 content, CeO_2 content, and ethanol-diesel blend. Plotting revealed that the mean CO_2 emissions rose dramatically as the fuel's ethanol concentration rose. The catalyst's most efficient combination for reducing CO_2 emissions appears to be 30% Al_2O_3 content and 15% CeO_2 content, which seemed to provide the lowest CO_2 emissions. CO_2 emissions increased as the engine load increased, as was to be expected. The plot did not show any significant interactions between the components, which is noteworthy since it suggests that the impact of each factor on CO_2 emissions was mostly independent of the other element's values.

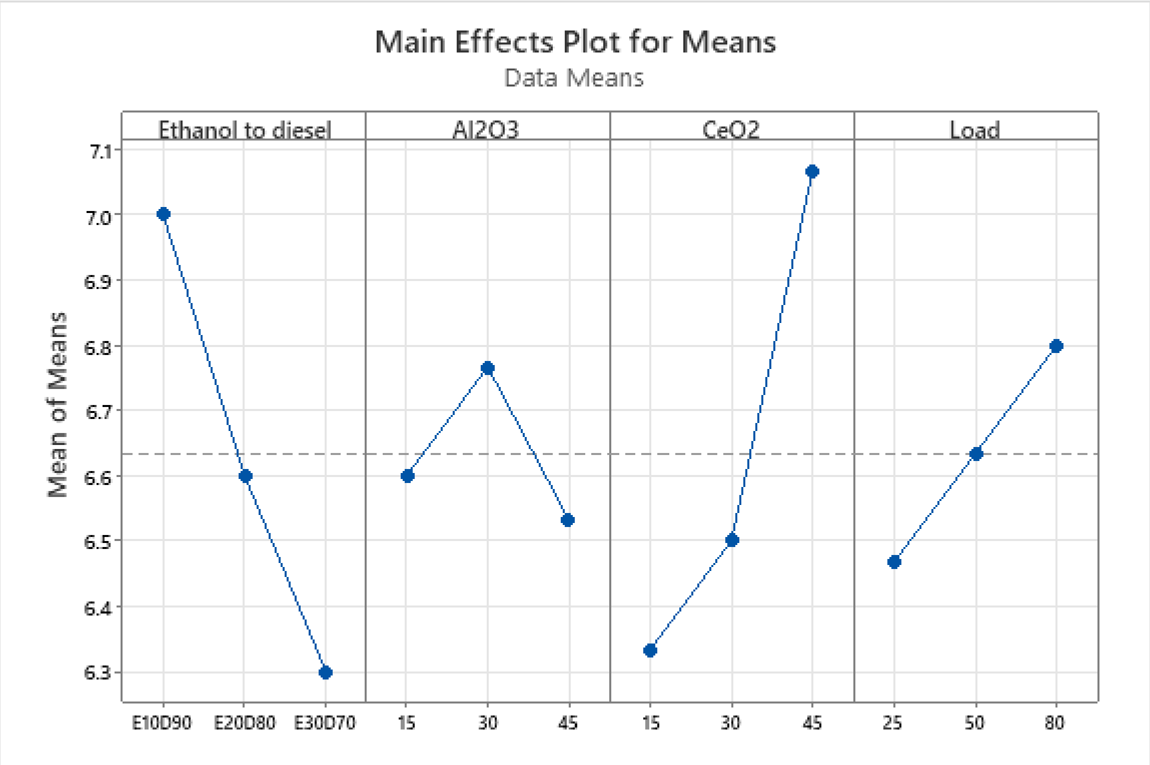


Figure 4.14 Main effect plot of CO_2 versus Ethanol to diesel, Al_2O_3, CeO_2, Load

Figure 4.14 shows that increasing the ethanol content in the fuel blend led to a decrease in CO_2 emissions. This aligns with previous studies, which have reported that the higher oxygen content and lower carbon content of ethanol results in reduced CO_2 outputs compared to neat diesel fuel (Demirbas, 2009a). The magnitude of CO_2 reduction observed here, from around 6.5% to 5.9%, is consistent with trends reported in these earlier review papers.

The impact of the Al_2O_3 and CeO_2 nanoparticle additives on CO_2 emissions is less clear from the data provided. Some studies have found that certain hydrogen-generating additives like sodium borohydride can help reduce diesel engine emissions, including CO_2 (Sajeevan & Sajith, 2013; Sajith et al., 2010). However, the effects of the metal oxide nanoparticles in this dataset do not demonstrate a consistent trend, which contrasts with findings from Sajith et al. (2010) and Selvan et al. (2009) who reported improvements in combustion efficiency with cerium oxide additives in biodiesel blends.

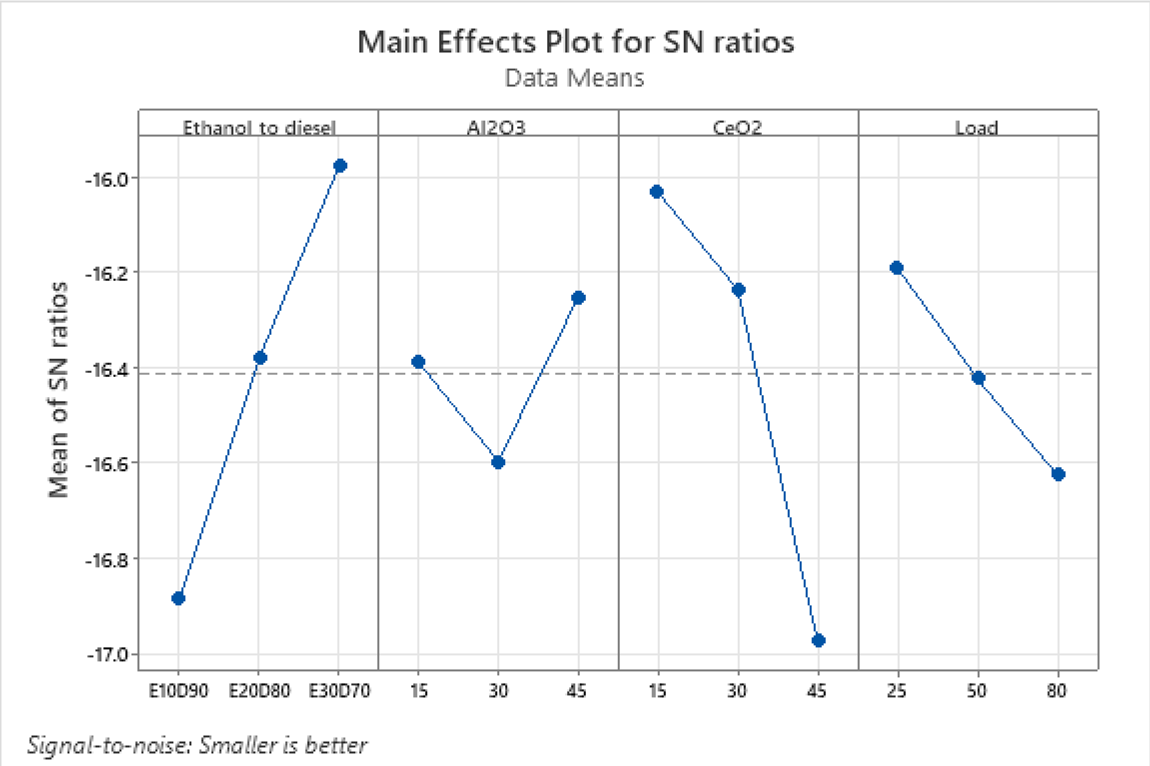


Figure 4.15 Main effect plot for S/N of CO_2 versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The main effects graphic for S/N ratios show how the load, Al_2O_3 concentration, CeO_2 content, and ethanol-to-diesel ratio all affected the mean S/N ratio; a lower value denotes a better signal-to-noise ratio. Increasing the fuel's ethanol blend considerably enhanced the S/N ratio, according to the plot. 30% Al_2O_3 and 15% CeO_2 concentration seems to maximize the S/N ratio for the catalytic components. The mean S/N ratio declined with increasing load, as was to be predicted. Each factor's impact on the S/N ratio appeared to be fairly constant across varying levels of the other components since the plot did not show any significant interactions between them.

As the engine load increased from 25% to 50% to 80%, the CO_2 emissions generally increased across the different fuel blends and additive levels. This aligns with the expected trends, as higher engine loads typically result in more complete combustion and higher CO_2 outputs (Giakoumis, 2012). The magnitudes of CO_2 increase from low to high load are also consistent with findings reported in previous studies on the impact of engine operating conditions.

4.2.2.5. Nitrogen oxides

The main effects plot depicted in Figure 4.16 for NOx emissions demonstrates how each factor (ethanol-diesel blend, Al_2O_3 content, CeO_2 content, and load) influenced the mean NOx levels. The plot revealed that increasing the ethanol content in the fuel significantly reduced NOx emissions. Regarding the catalyst components, 30% Al_2O_3 and 15% CeO_2 content appeared to yield the lowest NOx levels, suggesting the most effective combination for minimizing NOx emissions. As expected, increasing the engine load led to an increase in NOx emissions.

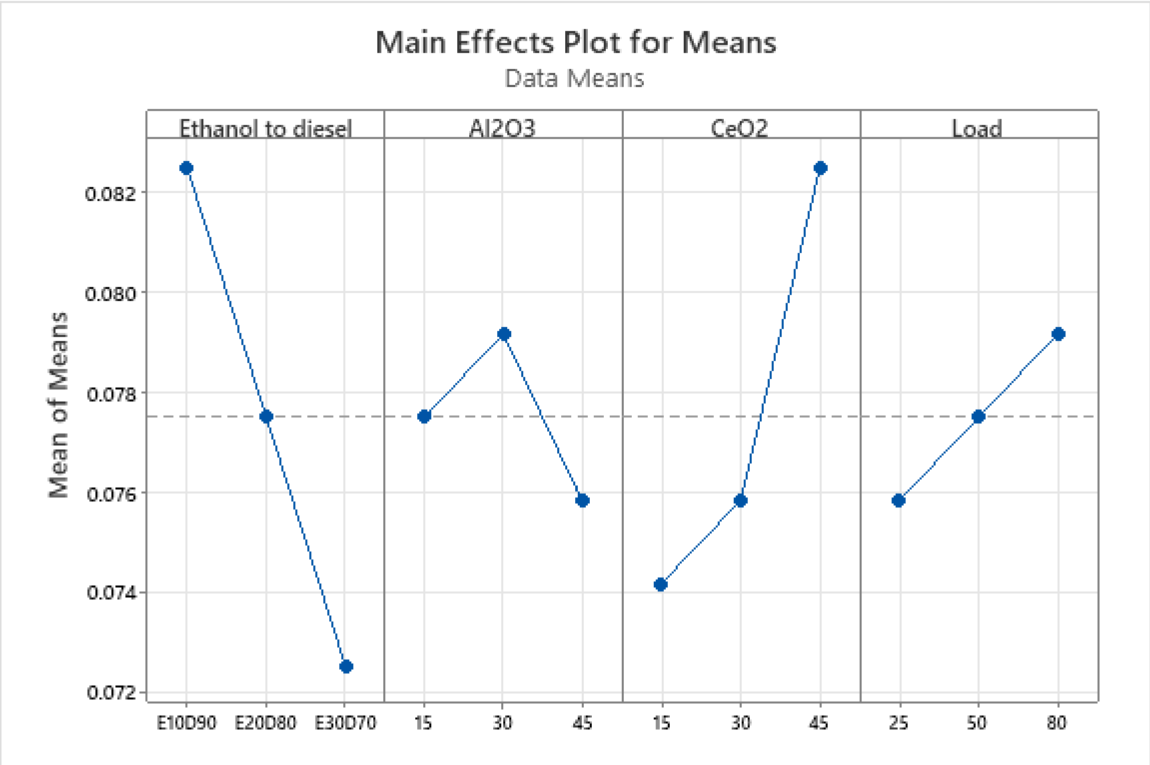


Figure 4.16 Main effect plot of NOx versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The main effects plot for S/N ratios shown in Figure 4.17 reveals how each factor (ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and load) influenced the mean S/N ratio, where a smaller value indicates a better signal-to-noise ratio. The plot showed that increasing the ethanol blend in the fuel significantly improved the S/N ratio. For the catalyst components, 30% Al_2O_3 content and 15% CeO_2 content appeared to optimize the S/N ratio. As expected, the mean S/N ratio deteriorated with increasing load. The plot suggests that increasing the ethanol blend in the fuel was the most effective way to improve the signal-to-noise ratio for NOx emissions, indicating a reduction in NOx emissions variability.

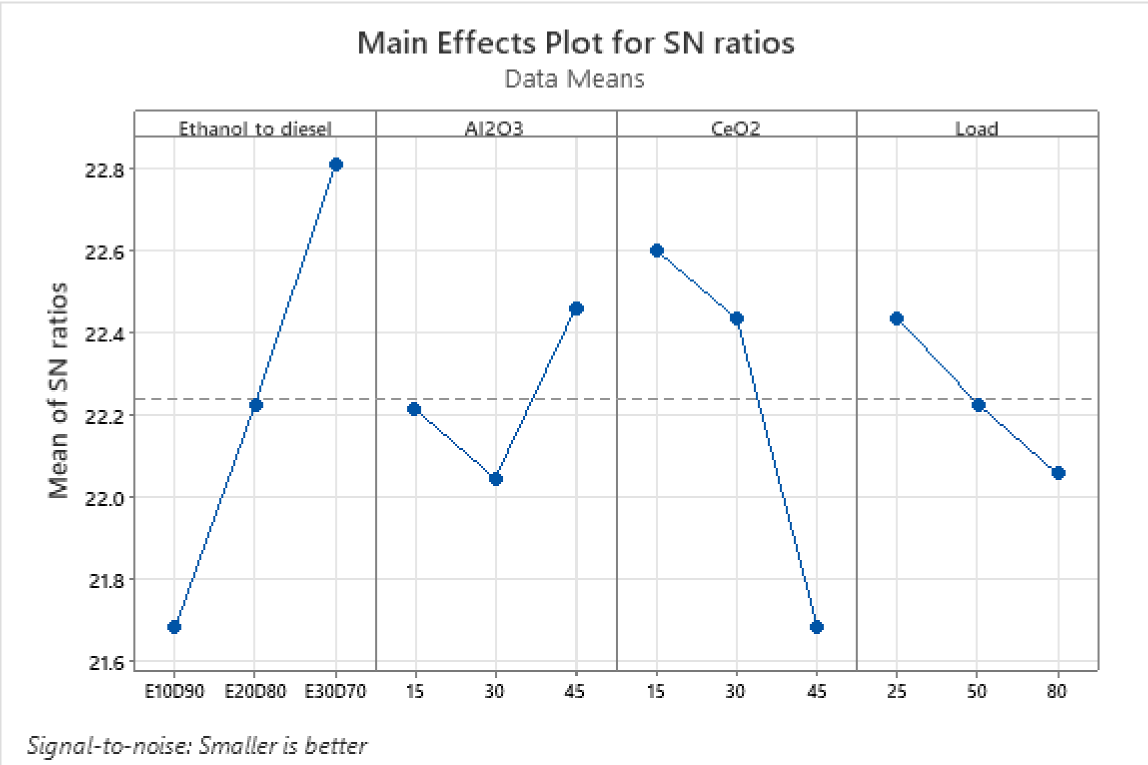


Figure 4.17 Main effect plot for S/N of NOx versus Ethanol to diesel, Al_2O_3, CeO_2, Load

This trend aligns with findings from previous studies, which have demonstrated that the higher oxygen content and combustion temperatures associated with ethanol-diesel blends can lead to elevated NOx outputs compared to neat diesel fuel (Buyukkaya, 2010). The magnitude of the NOx increase observed, ranging from approximately 0.0675% to 0.0875%, is consistent with the ranges reported in these earlier review articles. In contrast, the addition of alumina and cerium oxide nanoparticle additives had a more pronounced effect of reducing NOx emissions. Several prior studies have found that certain metal oxide additives can help mitigate NOx formation by improving combustion efficiency and limiting local hot spots (Manigandan et al., 2020). Congruent with these previous findings, the data shows that incorporating Al_2O_3 and CeO_2 nanoparticles led to reductions in NOx output, with the CeO_2 additive being particularly effective.

As the engine load was increased from 25% to 50% to 80%, the NOx emissions generally trended upwards across the different fuel blends and additive levels. This alignment with expected trends is supported by literature, which has shown that higher engine loads typically result in increased in-cylinder temperatures and pressures, which are conducive to NOx formation (Giakoumis, 2012).

4.2.2.6. Unburned Hydrocarbons

The main effects plot shown in Figure 4.18 for UHC reveals how each factor (ethanol to diesel ratio, Al_2O_3 content, CeO_2 content, and load) influenced the mean UHC emissions. The plot showed that increasing the ethanol blend in the fuel significantly increased the mean UHC emissions. For the catalyst components, 30% Al_2O_3 content and 15% CeO_2 content appeared to optimize the UHC emissions by minimizing them. As expected, the mean UHC emissions increased with increasing load. The plot did not indicate significant interactions between the factors, suggesting that the effect of each factor on the UHC emissions remained relatively consistent across different levels of the other factors.

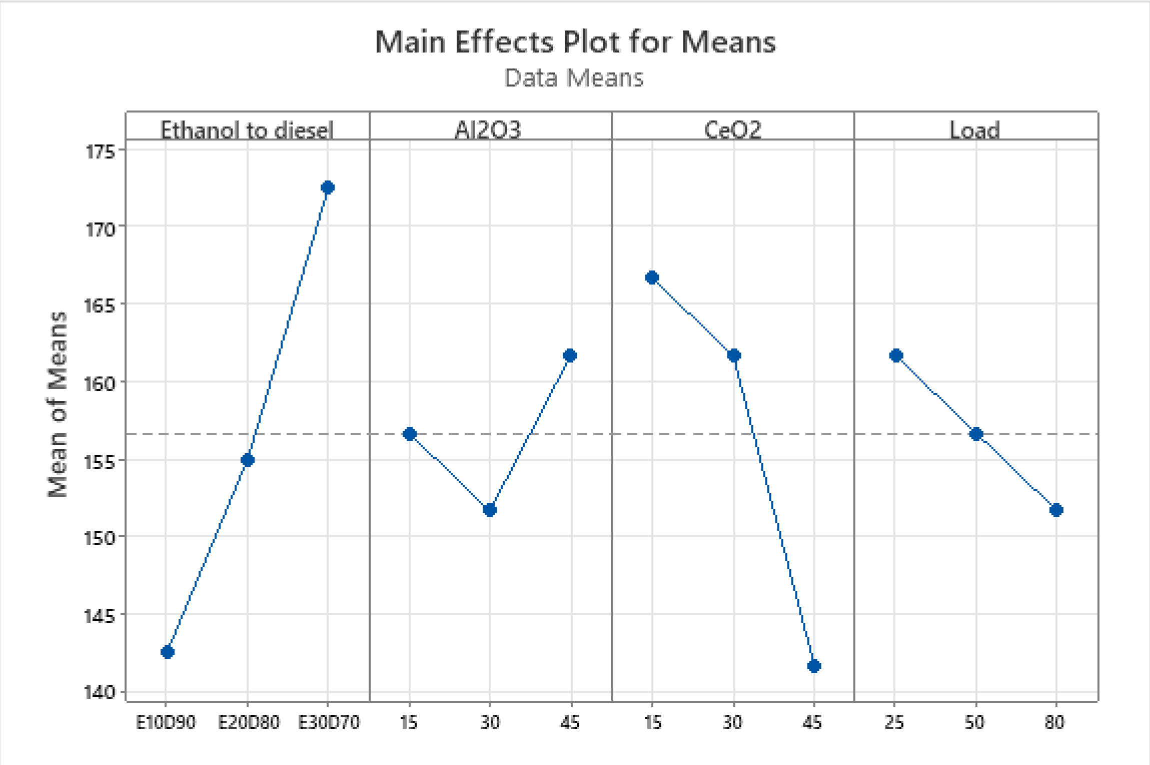


Figure 4.18 Main effect plot of UHC versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The main effects plot for the S/N ratios of UHC emissions demonstrates how each factor (ethanol-diesel blend, Al_2O_3 content, CeO_2 content, and load) influenced the overall signal-to-noise ratio. Lower S/N values indicate better performance in minimizing UHC emissions. The plot revealed that increasing the ethanol content in the fuel significantly improved the S/N ratio, suggesting a reduction in UHC emissions. Regarding the catalyst components, 30% Al_2O_3 and 15% CeO_2 content appeared to yield the optimal S/N ratios, suggesting the most effective combination for minimizing UHC emissions. As expected, increasing the engine load led to a deterioration in the S/N ratio, indicating an increase in UHC emissions. Notably, the plot did not reveal any significant interactions between the factors, implying that the effect of each factor on the S/N ratio remained relatively consistent regardless of the levels of the other factors.

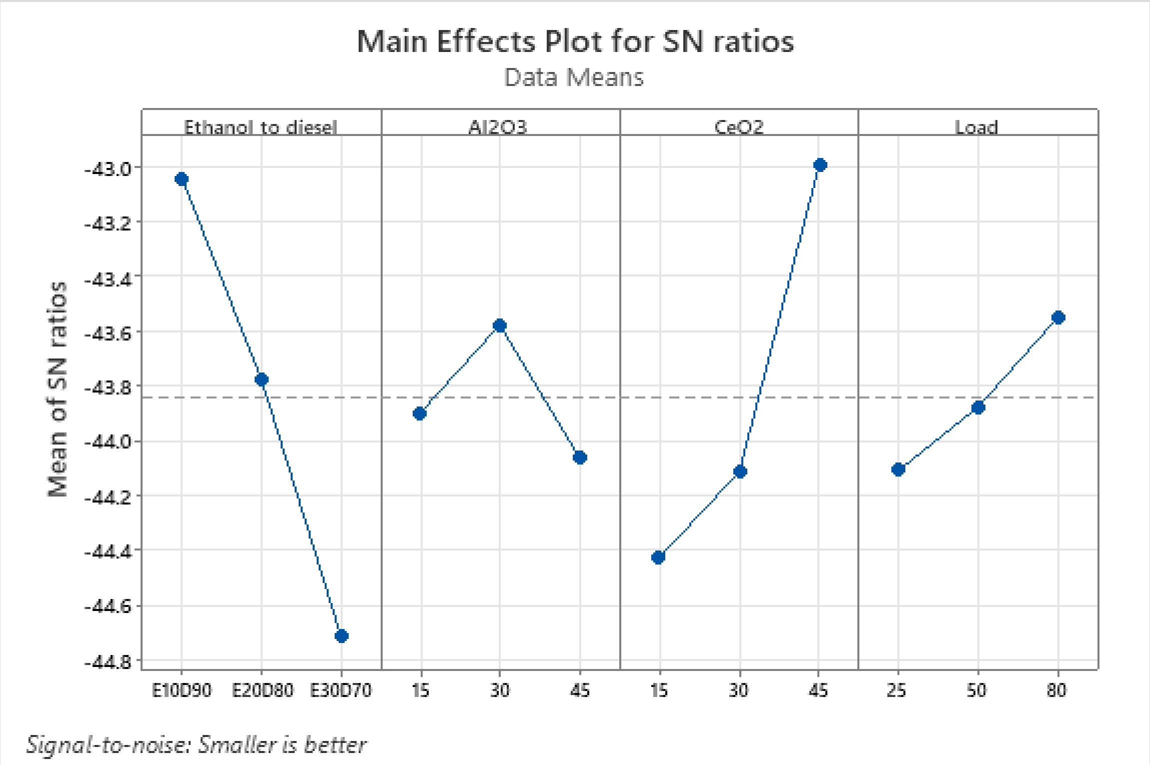


Figure 4.19 Main effect plot for S/N of UHC versus Ethanol to diesel, Al_2O_3, CeO_2, Load

The data reveals some interesting trends regarding unburned hydrocarbon emissions for the different ethanol-diesel fuel blends and nanoparticle additive concentrations. For the E10 blend, the UHC levels ranged from 157.5 ppm to 127.5 ppm as the Al_2O_3 and CeO_2 nanoparticle concentrations were varied. This demonstrates that increasing the nanoparticle content from 15 ppm to 45 ppm had a moderating effect on UHC emissions for the E10 blend. Similar reductions in UHC with nanoparticle additives have been reported in other studies (Imtenan et al., 2014).

When the ethanol proportion was increased to the E20 blend, the UHC values decreased further, ranging from 155 ppm down to 140 ppm. This suggests that the higher ethanol content plays a more significant role in reducing unburned hydrocarbon emissions compared to the nanoparticle additives. The increased oxygen availability from the ethanol allows for more complete combustion, resulting in fewer unburned fuel molecules escaping the engine (Karabektas & Hosoz, 2009).

For the E30 blend, the UHC levels ranged from 157.5 ppm to 187.5 ppm as the nanoparticle concentrations were varied. Interestingly, this represents a slight increase in UHC compared to the E20 blend, indicating that the benefits of higher ethanol content may start to plateau or even reverse at very high ethanol proportions, as reported in some previous studies (Parlak et al., 2006). Examining the impact of the nanoparticle additives, the data shows that increasing the Al_2O_3 and CeO_2 concentrations from 15 ppm to 45 ppm decreased UHC emissions by around 15-20 ppm for both the E10 and E20 blends. This suggests the nanoparticles help enhance overall combustion efficiency, but their impact is more modest compared to the gains achieved by raising the ethanol content (Khalife et al., 2017).

4.3. Validation

The results obtained from this study exhibit strong agreement with existing literature, reinforcing their reliability and accuracy. The experimental findings, derived from the Taguchi L9 orthogonal array, were validated through multiple approaches, with repeated experimental runs confirming the consistency of key performance metrics, including BT, BP, BSFC, BTE, EGT, and emissions such as CO, CO_2, NOx, and UHC. Statistical analyses, including ANOVA presented in the Appendix, demonstrated that ethanol-diesel ratios, aluminum oxide (Al_2O_3), cerium oxide (CeO_2) concentrations, and engine load significantly influenced these metrics.

The observed trends in the "larger-is-better" and "smaller-is-better" S/N ratios closely aligned with theoretical expectations and previous studies, reinforcing the credibility of the results. For instance, higher ethanol blends, such as E30D70, enhanced braking power and torque while reducing CO and NOx emissions, consistent with ethanol's known combustion-enhancing properties.

Confirmatory runs conducted under predicted optimal conditions E30D70 with 30 ppm Al_2O_3 and 15 ppm CeO_2 at high loads validated the accuracy of the Taguchi model, with the experimental results closely matching predicted values and showing minimal deviations. Sensitivity analysis further confirmed the robustness of the experimental setup, demonstrating reliability under varying conditions. Additionally, the interaction effects of Al_2O_3 and CeO_2 were evident, with CeO_2 playing a significant role in optimizing combustion efficiency and reducing emissions.

CHAPTER FIVE

5. CONCLUSION AND RECCOMENDATIONS

5.1. Conclusions

In conclusion, the experimental study using the L_9 orthogonal array provided critical insights into the effects of ethanol-diesel ratios, aluminum oxide (Al_2O_3) and cerium oxide (CeO_2) nanoparticle concentrations, and engine load on the performance and emissions of a CI engine. The results demonstrated that the E10D90 blend with 45 ppm Al2O3 and 45 ppm CeO_2 at 80% load delivered the best performance, achieving the highest brake torque (324 Nm), brake power (84.8 kW), and brake thermal efficiency (32.5%), along with the lowest brake-specific fuel consumption (240 g/kWh) and reduced emissions (CO: 0.03%, CO_2: 7.5%, UHC: 127.5 ppm). In contrast, the E30D70 blend with 45 ppm Al_2O_3 and 30 ppm CeO_2 at 25% load exhibited the poorest performance, with lower efficiency and higher emissions.

The analysis of signal-to-noise (S/N) ratios revealed clear trends, with higher ethanol blends (e.g., E30D70) increasing brake power and torque but reducing brake thermal efficiency due to ethanol's lower calorific value. The "larger is better" S/N ratio for performance metrics like brake power and brake thermal efficiency highlighted the positive influence of higher engine loads and optimal nanoparticle concentrations. Conversely, the "smaller is better" S/N ratio for emissions and brake-specific fuel consumption (BSFC) demonstrated that higher ethanol content significantly reduced CO, NOx, and CO_2 emissions, though it increased unburned hydrocarbons (UHC). Among the additives, CeO_2 showed a more substantial impact on improving combustion efficiency and reducing emissions compared to Al_2O_3, particularly at higher concentrations. Engine load played a pivotal role, with higher loads improving fuel efficiency but increasing emissions such as NOx and UHC.

These findings underscore the importance of optimizing ethanol-diesel ratios, nanoparticle concentrations, and engine load to achieve a balance between performance and emissions. The study provides valuable insights for advancing sustainable CI engine technologies, with the S/N ratio analysis offering a robust framework for identifying optimal parameter combinations. Further research is recommended to validate these results and explore long-term engine durability under these conditions.

5.1. Recommendations

To optimize engine performance and emissions using ethanol-diesel blends and nanoparticle additives, several recommendations can be made based on the analysis of the Smaller is Better S/N ratio. First, ethanol content should be maintained at moderate levels, such as E10 to E30, to balance the improvements in brake-specific fuel consumption and reductions in emissions like carbon monoxide and nitrogen oxides, while minimizing increases in unburned hydrocarbons and exhaust gas temperature. Exploring ethanol-diesel blends beyond E30 under varying engine conditions is recommended to evaluate their potential benefits. Additionally, the incorporation of catalytic additives such as 30% aluminum oxide (Al_2O_3) and 15% cerium oxide (CeO_2) has proven effective in enhancing combustion efficiency, reducing emissions, and improving the S/N ratio. Further research into alternative metal oxide additives or combinations could yield even better results.

Engine load management is another critical factor. Operating engines at higher loads, such as 80%, has been shown to optimize BSFC and fuel efficiency. However, strategies must be implemented to mitigate the associated increase in emissions like NOx and UHC, which can be achieved by adjusting fuel blends and additive concentrations. Regular monitoring of key performance indicators, including BSFC, EGT, and emissions, is essential to ensure optimal engine operation. Real-time adjustments to fuel and additive levels based on engine conditions can further enhance performance.

Lastly, additional research is necessary to investigate the long-term effects of ethanol-diesel blends and nanoparticle additives on engine durability and maintenance. Studies focusing on the interaction between ethanol content, additives, and varying engine loads can refine our understanding of their combined impact. Practical applications of these findings in automotive, industrial, and power generation engines will help validate laboratory results and facilitate commercial adoption. By implementing these strategies, engines can achieve greater efficiency and environmental sustainability while maintaining high performance standards.

References

Abd Alla, G., Soliman, H., Badr, O., & Abd Rabbo, M. (2002). Effect of injection timing on the performance of a dual fuel engine. *Energy conversion and Management*, *43*(2), 269-277.

Agarwal, A. K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in energy and combustion science*, *33*(3), 233-271.

Agarwal, A. K., & Mustafi, N. N. (2021). Real-world automotive emissions: Monitoring methodologies, and control measures. *Renewable and Sustainable Energy Reviews*, *137*, 110624.

Agarwal, A. K., Srivastava, D. K., Dhar, A., Maurya, R. K., Shukla, P. C., & Singh, A. P. (2013). Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. *Fuel*, *111*, 374-383.

Al-Harbi, A. A., Alabduly, A. J., Alkhedhair, A. M., Alqahtani, N. B., & Albishi, M. S. (2022). Effect of operation under lean conditions on NOx emissions and fuel consumption fueling an SI engine with hydrous ethanol–gasoline blends enhanced with synthesis gas. *Energy*, *238*, 121694.

Algayyim, S. J. M., Saleh, K., Wandel, A. P., Fattah, I. M. R., Yusaf, T., & Alrazen, H. A. (2024). Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review. *Fuel*, *362*, 130844.

Amirabedia, M., Jafarmadar, S., Khalilarya, S., & Kheyrollahi, J. (2019). Experimental comparison the effect of Mn2O3 and Co3O4 nano additives on the performance and emission of SI gasoline fueled with mixture of ethanol and gasoline. *International Journal of Engineering*, *32*(5), 769-776.

Amiri, M., & Shirneshan, A. (2020). Effects of air swirl on the combustion and emissions characteristics of a cylindrical furnace fueled with diesel-biodiesel-n-butanol and diesel-biodiesel-methanol blends. *Fuel*, *268*, 117295.

Ampah, J. D., Yusuf, A. A., Agyekum, E. B., Afrane, S., Jin, C., Liu, H., Fattah, I. M. R., Show, P. L., Shouran, M., & Habil, M. (2022). Progress and recent trends in the application of nanoparticles as low carbon fuel additives—a state of the art review. *Nanomaterials*, *12*(9), 1515.

Ananda Srinivasan, C., Saravanan, C., & Gopalakrishnan, M. (2018). Emission reduction on ethanol–gasoline blend using cerium oxide nanoparticles as fuel additive. *Particulate Science and Technology*, *36*(5), 628-635.

Annamalai, B., Murugesan, P., Le, T. T., & Nguyen, P. Q. P. (2024). Behavior analysis of Low-Heat Rejection engine powered by biodiesel under varied exhaust gas recirculation ratios. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *46*(1), 3546-3569.

Annamalai, M., Dhinesh, B., Nanthagopal, K., SivaramaKrishnan, P., Lalvani, J. I. J., Parthasarathy, M., & Annamalai, K. (2016). An assessment on performance, combustion and emission behavior of a diesel engine powered by ceria nanoparticle blended emulsified biofuel. *Energy Conversion and Management*, *123*, 372-380.

Ansari, N. A., Sharma, A., & Singh, Y. (2018). Performance and emission analysis of a diesel engine implementing polanga biodiesel and optimization using Taguchi method. *Process Safety and Environmental Protection*, *120*, 146-154.

Ashok, B., Kumar, A. N., Jacob, A., & Vignesh, R. (2022). Emission formation in IC engines. In *NOx Emission Control Technologies in Stationary and Automotive Internal Combustion Engines* (pp. 1-38). Elsevier.

Atmanli, A. (2016). Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine. *Fuel*, *176*, 209-215.

Atmanlı, A., Ileri, E., & Yüksel, B. (2014). Experimental investigation of engine performance and exhaust emissions of a diesel engine fueled with diesel–n-butanol–vegetable oil blends. *Energy conversion and Management*, *81*, 312-321.
Atmanlı, A., Yüksel, B., & Ileri, E. (2013). Experimental investigation of the effect of diesel–cotton oil–n-butanol ternary blends on phase stability, engine performance and exhaust emission parameters in a diesel engine. *Fuel*, *109*, 503-511.
Atmanlı, A., Yüksel, B., Ileri, E., & Karaoglan, A. D. (2015). Response surface methodology based optimization of diesel–n-butanol–cotton oil ternary blend ratios to improve engine performance and exhaust emission characteristics. *Energy conversion and Management*, *90*, 383-394.
Auffan, M., Tella, M., Liu, W., Pariat, A., Cabié, M., Borschneck, D., Angeletti, B., Landrot, G., Mouneyrac, C., & Giambérini, L. (2017). Structural and physical–chemical behavior of a CeO 2 nanoparticle based diesel additive during combustion and environmental release. *Environmental Science: Nano*, *4*(10), 1974-1980.
Bafghi, A. A. T., Bakhoda, H., & Chegeni, F. K. (2015). Effects of cerium oxide nanoparticle addition in diesel and diesel-biodiesel blends on the performance characteristics of a CI engine. *International Journal of Mechanical and Mechatronics Engineering*, *9*(8), 1507-1512.
Balamurugan, T., & Nalini, R. (2014a). Effect of blending alcohol with diesel on performance, combustion and emission characteristics of four stroke diesel engine-an experimental study.
Balamurugan, T., & Nalini, R. (2014b). Experimental investigation on performance, combustion and emission characteristics of four stroke diesel engine using diesel blended with alcohol as fuel. *Energy*, *78*, 356-363.
Balamurugan, T., & Nalini, R. (2016). Experimental investigation on the effect of alkanes blending on performance, combustion and emission characteristics of four-stroke diesel engine. *International Journal of Ambient Energy*, *37*(2), 192-200.
Balasubramanian, D., Venugopal, I. P., & Viswanathan, K. (2019). *Characteristics investigation on Di diesel engine with nano-particles as an additive in lemon grass oil* (0148-7191).
Basha, J. S., Al Balushi, M., Soudagar, M. E. M., Safaei, M. R., Mujtaba, M., Khan, T. Y., Hossain, N., & Elfasakhany, A. (2022). Applications of nano-additives in internal combustion engines: a critical review. *Journal of Thermal Analysis and Calorimetry*, *147*(17), 9383-9403.
Bessagnet, B., Allemand, N., Putaud, J.-P., Couvidat, F., André, J.-M., Simpson, D., Pisoni, E., Murphy, B. N., & Thunis, P. (2022). Emissions of carbonaceous particulate matter and ultrafine particles from vehicles—a scientific review in a cross-cutting context of air pollution and climate change. *Applied Sciences*, *12*(7), 3623.
Bhan, S., Gautam, R., & Singh, P. (2024). Analyzing the impact of adding aluminum oxide and cerium oxide nanoparticles to waste cooking biodiesel on engine performance, combustion and emissions characteristics. *Petroleum Science and Technology*, *42*(6), 706-734.
Buyukkaya, E. (2010). Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel*, *89*(10), 3099-3105.
Carneiro, M. L. N., Pradelle, F., Braga, S. L., Gomes, M. S. P., Martins, A. R. F., Turkovics, F., & Pradelle, R. N. (2017). Potential of biofuels from algae: Comparison with fossil fuels, ethanol and biodiesel in Europe and Brazil through life cycle assessment (LCA). *Renewable and Sustainable Energy Reviews*, *73*, 632-653.
Chansauria, P., & Mandloi, R. (2018). Effects of ethanol blends on performance of spark ignition engine-a review. *Materials Today: Proceedings*, *5*(2), 4066-4077.

Chaudhary, V., & Gakkhar, R. (2020). Parametric optimisation of exergy destruction in small DI diesel engine fuelled with neem biodiesel using the Taguchi method. *International Journal of Ambient Energy*, *41*(3), 274-284.
Chen, H., Shi-Jin, S., & Jian-Xin, W. (2007). Study on combustion characteristics and PM emission of diesel engines using ester–ethanol–diesel blended fuels. *Proceedings of the Combustion institute*, *31*(2), 2981-2989.
Cheng, X., Li, S., Yang, J., & Liu, B. (2016). Investigation into partially premixed combustion fueled with N-butanol-diesel blends. *Renewable Energy*, *86*, 723-732.
Ciniviz, M., Köse, H., Canli, E., & Solmaz, O. (2011). An experimental investigation on effects of methanol blended diesel fuels to engine performance and emissions of a diesel engine. *Scientific Research and Essays*, *6*(15), 3189-3199.
Debbarma, S., & Misra, R. D. (2018). Effects of iron nanoparticle fuel additive on the performance and exhaust emissions of a compression ignition engine fueled with diesel and biodiesel. *Journal of Thermal Science and Engineering Applications*, *10*(4), 041002.
Deep, A., Kumar, N., Gupta, D., Sharma, A., Patel, J. S., & Karnwal, A. (2014). *Potential utilization of the blend of orange peel oil methyl ester and isopropyl alcohol in CI Engine* (0148-7191).
Demirbas, A. (2007). Progress and recent trends in biofuels. *Progress in energy and combustion science*, *33*(1), 1-18.
Demirbas, A. (2009a). Biofuels securing the planet's future energy needs. *Energy conversion and management*, *50*(9), 2239-2249.
Demirbas, A. (2009b). Progress and recent trends in biodiesel fuels. *Energy conversion and management*, *50*(1), 14-34.
Devarajan, Y., Munuswamy, D. B., & Mahalingam, A. (2019). Investigation on behavior of diesel engine performance, emission, and combustion characteristics using nano-additive in neat biodiesel. *Heat and Mass Transfer*, *55*, 1641-1650.
Dhahad, H. A., & Chaichan, M. T. (2020). The impact of adding nano-Al2O3 and nano-ZnO to Iraqi diesel fuel in terms of compression ignition engines' performance and emitted pollutants. *Thermal science and Engineering progress*, *18*, 100535.
Dinesha, P., Kumar, S., & Rosen, M. A. (2021). Effects of particle size of cerium oxide nanoparticles on the combustion behavior and exhaust emissions of a diesel engine powered by biodiesel/diesel blend. *Biofuel Research Journal*, *8*(2), 1374-1383.
El-Seesy, A. I., Attia, A. M., & El-Batsh, H. M. (2018). The effect of Aluminum oxide nanoparticles addition with Jojoba methyl ester-diesel fuel blend on a diesel engine performance, combustion and emission characteristics. *Fuel*, *224*, 147-166.
El-Seesy, A. I., & Hassan, H. (2019). Investigation of the effect of adding graphene oxide, graphene nanoplatelet, and multiwalled carbon nanotube additives with n-butanol-Jatropha methyl ester on a diesel engine performance. *Renewable Energy*, *132*, 558-574.
El-Seesy, A. I., Hassan, H., & Ookawara, S. (2018). Effects of graphene nanoplatelet addition to jatropha Biodiesel–Diesel mixture on the performance and emission characteristics of a diesel engine. *Energy*, *147*, 1129-1152.
Elbanna, A. M., Xiaobei, C., Can, Y., Elkelawy, M., Bastawissi, H. A.-E., & Panchal, H. (2022). Fuel reactivity controlled compression ignition engine and potential strategies to extend the engine operating range: A comprehensive review. *Energy Conversion and Management: X*, *13*, 100133.
Elkelawy, M., Alm ElDin Mohamad, H., Abo-Samra, S., & Abd-Elhay Elshennawy, I. (2023). Nanoparticles Additives for Diesel/Biodiesel Fuel Blends as a Performance

and Emissions Enhancer in the Applications of Direct Injection Diesel Engines: A comparative Review. *Journal of Engineering Research*, *7*(1), 112-121.

Farkade, H., & Pathre, A. (2012). Experimental investigation of methanol, ethanol and butanol blends with gasoline on SI engine. *International Journal of Emerging Technology and Advanced Engineering*, *2*(4), 205-215.

Farrell, J. T., Johnston, R., & Androulakis, I. (2004). Molecular structure effects on laminar burning velocities at elevated temperature and pressure. *SAE transactions*, 1404-1425.

Fayad, M. A., & Dhahad, H. A. (2021). Effects of adding aluminum oxide nanoparticles to butanol-diesel blends on performance, particulate matter, and emission characteristics of diesel engine. *Fuel*, *286*, 119363.

Fazliakmetov, R., & Shpiro, G. (1997). Selection and manufacture technology of antismoke additives for diesel fuel and boiler fuels oils. *Izdetal Stvo Neft I Gaz*, *4*, 43-55.

Feroskhan, M., & Ismail, S. (2020). Evaluating the effect of intake parameters on the performance of a biogas–diesel dual-fuel engine using the Taguchi method. *Biofuels*, *11*(4), 441-449.

Ganesan, S., Raja, J., Kumar, N. B., Hemanandth, J., Senthilkumar, G., Sreenivasan, K., & Rajasekar, R. (2020). Influence of nano catalyst on performance of di diesel engine with blends of Citronella oil using Taguchi approach. AIP Conference Proceedings,

Ghareeb, H. O., & Anjal, H. A. A.-W. (2023). An Investigation of the Impacts of Ethanol-Diesel Blends on Emission and Combustion Parameters of Diesel Engine. *International Journal of Heat & Technology*, *41*(3).

Giakoumis, E. G. (2012). A statistical investigation of biodiesel effects on regulated exhaust emissions during transient cycles. *Applied Energy*, *98*, 273-291.

Gomaa, H. E., Alotaibi, A. A., Gomaa, F. A., Bajuayfir, E., Ahmad, A., & Alotaibi, K. M. (2021). Integrated ion exchange-based system for nitrate and sulfate removal from water of different matrices: Analysis and optimization using response surface methodology and Taguchi experimental design techniques. *Process Safety and Environmental Protection*, *153*, 500-517.

Gul, M., Shah, A. N., Aziz, U., Husnain, N., Mujtaba, M., Kousar, T., Ahmad, R., & Hanif, M. F. (2022). Grey-Taguchi and ANN based optimization of a better performing low-emission diesel engine fueled with biodiesel. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *44*(1), 1019-1032.

Gumus, M. (2010). A comprehensive experimental investigation of combustion and heat release characteristics of a biodiesel (hazelnut kernel oil methyl ester) fueled direct injection compression ignition engine. *Fuel*, *89*(10), 2802-2814.

Gürü, M., Koca, A., Can, Ö., Çınar, C., & Şahin, F. (2010). Biodiesel production from waste chicken fat based sources and evaluation with Mg based additive in a diesel engine. *Renewable Energy*, *35*(3), 637-643.

Haigh, K. F., Saha, B., Vladisavljević, G., & Reynolds, J. C. (2012). Kinetics of the pre-treatment of used cooking oil using Novozyme 435 for biodiesel production. *Procedia Engineering*, *42*, 1106-1113.

Hamadi, A. S., Dhahad, H. A., Noaman, R., Kidher, T., Suhail, S., & Abass, Q. (2016). An experimental investigates to study the effect of zinc oxide nanoparticles fuel additives on the performance and emissions characteristics of diesel engine. *Chemical and Petrochemical Research Centre, Ministry of Industry and Minerals, Baghdad, Iraq*.

Heywood, J. B. (1988). Internal combustion engine fundamentals. *(No Title)*.

Hossain, A., & Davies, P. (2013). Pyrolysis liquids and gases as alternative fuels in internal combustion engines–A review. *Renewable and sustainable energy reviews*, *21*, 165-189.

Hosseinzadeh-Bandbafha, H., Khalife, E., Tabatabaei, M., Aghbashlo, M., Khanali, M., Mohammadi, P., Shojaei, T. R., & Soltanian, S. (2019). Effects of aqueous carbon nanoparticles as a novel nanoadditive in water-emulsified diesel/biodiesel blends on performance and emissions parameters of a diesel engine. *Energy conversion and Management*, *196*, 1153-1166.

Ichikawa, S. (1997). Photoelectrocatalytic production of hydrogen from natural seawater under sunlight. *International journal of hydrogen energy*, *22*(7), 675-678.

Imtenan, S., Varman, M., Masjuki, H., Kalam, M., Sajjad, H., Arbab, M., & Fattah, I. R. (2014). Impact of low temperature combustion attaining strategies on diesel engine emissions for diesel and biodiesels: A review. *Energy conversion and management*, *80*, 329-356.

Iodice, P., & Cardone, M. (2021). Ethanol/gasoline blends as alternative fuel in last generation spark-ignition engines: a review on CO and HC engine out emissions. *Energies*, *14*(13), 4034.

Ithnin, A. M., Noge, H., Kadir, H. A., & Jazair, W. (2014). An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study. *Journal of the Energy Institute*, *87*(4), 273-288.

Janakiraman, S., Lakshmanan, T., & Raghu, P. (2021). Experimental investigative analysis of ternary (diesel+ biodiesel+ bio-ethanol) fuel blended with metal-doped titanium oxide nanoadditives tested on a diesel engine. *Energy*, *235*, 121148.

Kao, M.-J., Ting, C.-C., Lin, B.-F., & Tsung, T.-T. (2008a). Aqueous aluminum nanofluid combustion in diesel fuel. *Journal of testing and evaluation*, *36*(2), 503.

Kao, M.-J., Ting, C.-C., Lin, B.-F., & Tsung, T.-T. (2008b). Aqueous aluminum nanofluid combustion in diesel fuel. *Journal of testing and evaluation*, *36*(2), 186-190.

Karabektas, M., & Hosoz, M. (2009). Performance and emission characteristics of a diesel engine using isobutanol–diesel fuel blends. *Renewable Energy*, *34*(6), 1554-1559.

Karthikeyan, S., Elango, A., & Prathima, A. (2014). Performance and emission study on zinc oxide nano particles addition with pomolion stearin wax biodiesel of CI engine.

Keskin, A., Gürü, M., & Altıparmak, D. (2007). Biodiesel production from tall oil with synthesized Mn and Ni based additives: effects of the additives on fuel consumption and emissions. *Fuel*, *86*(7-8), 1139-1143.

Khalife, E., Tabatabaei, M., Demirbas, A., & Aghbashlo, M. (2017). Impacts of additives on performance and emission characteristics of diesel engines during steady state operation. *Progress in energy and Combustion Science*, *59*, 32-78.

Khond, V. W., & Kriplani, V. (2016). Effect of nanofluid additives on performances and emissions of emulsified diesel and biodiesel fueled stationary CI engine: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *59*, 1338-1348.

Kim, D. (2010). The status and outlook for biobutanol technology. *Auto Journal*, *8*, 36-44.

Kishore, K., Pandey, A., Wagri, N. K., Saxena, A., Patel, J., & Al-Fakih, A. (2023). Technological challenges in nanoparticle-modified geopolymer concrete: A comprehensive review on nanomaterial dispersion, characterization techniques and its mechanical properties. *Case Studies in Construction Materials*, e02265.

Krishna, S. M., Salam, P. A., Tongroon, M., & Chollacoop, N. (2019). Performance and emission assessment of optimally blended biodiesel-diesel-ethanol in diesel engine generator. *Applied Thermal Engineering*, *155*, 525-533.

Küçükosman, R., Yontar, A. A., & Ocakoglu, K. (2022). Nanoparticle additive fuels: Atomization, combustion and fuel characteristics. *Journal of Analytical and Applied Pyrolysis*, *165*, 105575.

Kumar, R., & Chaurasia, O. P. (2019). A review on performance and emissions of compression ignition engine fueled with ethanol-diesel blend. *Journal Européen des Systèmes Automatisés*, *52*(2), 205-214.

Kumar, S., & Dinesha, P. (2018). Optimization of engine parameters in a bio diesel engine run with honge methyl ester using response surface methodology. *Measurement*, *125*, 224-231.

Lapuerta, M., Armas, O., & Rodriguez-Fernandez, J. (2008). Effect of biodiesel fuels on diesel engine emissions. *Progress in energy and combustion science*, *34*(2), 198-223.

Laza, T., & Bereczky, Á. (2011). Basic fuel properties of rapeseed oil-higher alcohols blends. *Fuel*, *90*(2), 803-810.

Loyte, A., Suryawanshi, J., Bhiogade, G., Devarajan, Y., & Subbiah, G. (2022). Recent developments in utilizing hydrous ethanol for diverse engine technologies. *Chemical Engineering and Processing-Process Intensification*, *177*, 108985.

Manigandan, S., Sarweswaran, R., Devi, P. B., Sohret, Y., Kondratiev, A., Venkatesh, S., Vimal, M. R., & Joshua, J. J. (2020). Comparative study of nanoadditives TiO2, CNT, Al2O3, CuO and CeO2 on reduction of diesel engine emission operating on hydrogen fuel blends. *Fuel*, *262*, 116336.

Martins, M., Lanzanova, T., Roso, V., Fagundez, J., Silveira, J., Guilherme, R., Rovai, F., Kersten, T., Garbe, T., & Singer, A. (2024). Performance of anhydrous ethanol and gasoline blends on a SI engine: Decoupling evaporation enthalpy and knock resistance. *Journal of Cleaner Production*, *477*, 143883.

Mehta, R. N., Chakraborty, M., & Parikh, P. A. (2012). Comparative study of stability and properties of alcohol-diesel blends.

Mei, D., Li, X., Wu, Q., & Sun, P. (2016). Role of cerium oxide nanoparticles as diesel additives in combustion efficiency improvements and emission reduction. *Journal of Energy Engineering*, *142*(4), 04015050.

Mei, D., Zuo, L., Adu-Mensah, D., Li, X., & Yuan, Y. (2019). Combustion characteristics and emissions of a common rail diesel engine using nanoparticle-diesel blends with carbon nanotube and molybdenum trioxide. *Applied Thermal Engineering*, *162*, 114238.

Modi, V. (1997). Moving surface boundary-layer control: a review. *Journal of fluids and structures*, *11*(6), 627-663.

Modi, V., Rampure, P. B., Babbar, A., Kumar, R., Nagaral, M., Bhowmik, A., Pandey, S., Hasnain, S. M., Ali, M. M., & Bashir, M. N. (2024). Nanoparticle-enhanced biodiesel blends: a comprehensive review on improving engine performance and emissions. *Materials Science for Energy Technologies*.

Mohanna, H. (2020). *Combustion of pulverized biomass: impact of fuel preparation and flow conditions* Normandie Université].

Murayama, T., Miyamoto, N., Yamada, T., Kawashima, J.-i., & Itow, K. (1982). A Method to Improve the Solubility and Combustion Characteristics of Alcohol—Diesel Fuel Blends. *SAE transactions*, 3485-3494.

Muthaiyan, P., & Gomathinayagam, S. (2016). Combustion characteristics of a diesel engine using propanol diesel fuel blends. *Journal of The Institution of Engineers (India): Series C*, *97*, 323-329.

Nanthagopal, K., Ashok, B., Varatharajan, V., Anand, V., & Dinesh Kumar, R. (2017). Study on the effect of exhaust gas-based fuel preheating device on ethanol–diesel blends operation in a compression ignition engine. *Clean Technologies and Environmental Policy*, *19*, 2379-2392.

Nassir, A. K., & Shahad, H. A. (2018). Experimental study of effect of nanoparticles addition on combustion phasing in diesel engine. *Int J Mech Mechatron Eng*, *18*(1), 87-97.

Natarajan, S., Pitchandi, K., & Mahalakshmi, N. (2018). Optimization of performance and emission characteristics of PPCCI engine fuelled with ethanol and diesel blends using grey-Taguchi method. *Journal of Thermal Science*, *27*, 89-94.

Palanisamy, P. S. (2014). Performance of single cylinder ci engine using blends of rubber seed biodiesel-taguchi method. *UPB Sci Bull Series D*, *76*(4).

Paramashivaiah, B., & Rajashekhar, C. (2016). Studies on effect of various surfactants on stable dispersion of graphene nano particles in simarouba biodiesel. IOP conference series: materials science and engineering,

Parida, M., & Rout, A. (2017). Investigation of performance and emission analysis of Argemone mexicana biodiesel blends as a fuel in a DICI engine at part load conditions. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *39*(6), 623-629.

Parlak, A., Islamoglu, Y., Yasar, H., & Egrisogut, A. (2006). Application of artificial neural network to predict specific fuel consumption and exhaust temperature for a diesel engine. *Applied Thermal Engineering*, *26*(8-9), 824-828.

Patil, A. R., & Desai, A. (2020). Parametric optimization of engine performance and emission for various n-butanol blends at different operating parameter condition. *Alexandria Engineering Journal*, *59*(2), 851-864.

Pinzi, S., Redel-Macías, M., Leiva-Candia, D., Soriano, J., & Dorado, M. (2017). Influence of ethanol/diesel fuel and propanol/diesel fuel blends over exhaust and noise emissions. *Energy Procedia*, *142*, 849-854.

Prabakaran, B., & Udhoji, A. (2016). Experimental investigation into effects of addition of zinc oxide on performance, combustion and emission characteristics of diesel-biodiesel-ethanol blends in CI engine. *Alexandria Engineering Journal*, *55*(4), 3355-3362.

Pullagura, G., Vadapalli, S., Prasad, V., Bikkavolu, J., Chebattina, K., Chava, S. T., & Velisala, V. (2021). Effect of nano additives on fuel properties, engine performance, emission and combustion characteristics of CI engines fuelled with diesel and biodiesel blends: a comprehensive review. *Bulletin Monumental*, *21*(11), 39-50.

Pullagura, G., Vanthala, V. S. P., Vadapalli, S., Bikkavolu, J. R., Barik, D., Sharma, P., & Bora, B. J. (2024). Enhancing performance characteristics of biodiesel-alcohol/diesel blends with hydrogen and graphene nanoplatelets in a diesel engine. *International Journal of Hydrogen Energy*, *50*, 1020-1034.

Qi, D., Bae, C., Feng, Y., Jia, C., & Bian, Y. (2013). Combustion and emission characteristics of a direct injection compression ignition engine using rapeseed oil based micro-emulsions. *Fuel*, *107*, 570-577.

Qi, D., Chen, H., Geng, L., & Bian, Y. Z. (2010). Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends. *Energy Conversion and Management*, *51*(12), 2985-2992.

Qi, D., Geng, L., Chen, H., Bian, Y. Z., Liu, J., & Ren, X. C. (2009). Combustion and performance evaluation of a diesel engine fueled with biodiesel produced from soybean crude oil. *Renewable energy*, *34*(12), 2706-2713.

Raji, N. A., Kuku, R. O., Openibo, A. O., & Owolabi, E. A. (2024). Influence of compression ratio on the performance characteristics of a spark ignition engine. *Journal of Production Engineering*, 5-12.

Rakopoulos, C. D., Rakopoulos, D. C., Kosmadakis, G. M., & Papagiannakis, R. G. (2019). Experimental comparative assessment of butanol or ethanol diesel-fuel extenders impact on combustion features, cyclic irregularity, and regulated emissions balance in heavy-duty diesel engine. *Energy*, *174*, 1145-1157.

Rakopoulos, D., Rakopoulos, C., Papagiannakis, R., & Kyritsis, D. (2011). Combustion heat release analysis of ethanol or n-butanol diesel fuel blends in heavy-duty DI diesel engine. *Fuel*, *90*(5), 1855-1867.

Rakopoulos, D. C., Rakopoulos, C. D., Giakoumis, E. G., & Kosmadakis, G. M. (2021). Numerical and experimental study by quasi-dimensional modeling of combustion and emissions in variable compression ratio high-speed spark-ignition engine. *Journal of Energy Engineering*, *147*(5), 04021032.

Ramos, M. J., & Wallace, J. S. (2018). *Fuel effects on particulate matter emissions variability from a gasoline direct injection engine* (0148-7191).

Reddy, B. V. R., Maity, S. R., & Pandey, K. M. (2019). Characterization of spray formed Al-alloys—A Review. *Reviews on Advanced Materials Science*, *58*(1), 147-158.

Ribeiro, N. M., Pinto, A. C., Quintella, C. M., Da Rocha, G. O., Teixeira, L. S., Guarieiro, L. L., do Carmo Rangel, M., Veloso, M. C., Rezende, M. J., & Serpa da Cruz, R. (2007). The role of additives for diesel and diesel blended (ethanol or biodiesel) fuels: a review. *Energy & fuels*, *21*(4), 2433-2445.

Sadhik Basha, J., & Anand, R. (2013). The influence of nano additive blended biodiesel fuels on the working characteristics of a diesel engine. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *35*, 257-264.

Saeed, M. N., & Henein, N. A. (1989). Combustion Phenomena of Alcohols in C. I. Engines. *Journal of Engineering for Gas Turbines and Power*, *111*(3), 439-444. https://doi.org/10.1115/1.3240273

Sajeevan, A. C., & Sajith, V. (2013). Diesel engine emission reduction using catalytic nanoparticles: an experimental investigation. *Journal of Engineering*, *2013*(1), 589382.

Sajith, V., Sobhan, C., & Peterson, G. (2010). Experimental investigations on the effects of cerium oxide nanoparticle fuel additives on biodiesel. *Advances in Mechanical Engineering*, *2*, 581407.

Saraee, H. S., Taghavifar, H., & Jafarmadar, S. (2017). Experimental and numerical consideration of the effect of CeO2 nanoparticles on diesel engine performance and exhaust emission with the aid of artificial neural network. *Applied Thermal Engineering*, *113*, 663-672.

Sathish Kumar, R., & Suresh Kumar, K. (2015). Effect of methanol blending with Pongamia pinnata biodiesel and diesel blends on engine performance and exhaust emission characteristics of an unmodified compression ignition engine. *International Journal of Ambient Energy*, *36*(2), 70-75.

Savariraj, S., Ganapathy, T., & Saravanan, C. (2012). Performance and emission characteristics of diesel engine using high-viscous vegetable oil. *International Journal of Ambient Energy*, *33*(4), 193-203.

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.

Selvaganapthy, A., Sundar, A., Kumaragurubaran, B., & Gopal, P. (2013). An experimental investigation to study the effects of various nano particles with diesel on DI diesel engine. *ARPN Journal of Science and Technology*, *3*(1), 112-115.

Selvan, V. A. M., Anand, R., & Udayakumar, M. (2009). Effects of cerium oxide nanoparticle addition in diesel and diesel-biodiesel-ethanol blends on the performance and emission characteristics of a CI engine. *J Eng Appl Sci*, *4*(7), 1819-6608.

Shaafi, T., & Velraj, R. (2015). Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel–soybean biodiesel blend fuel: Combustion, engine performance and emissions. *Renewable Energy*, *80*, 655-663.

Shadidi, B., Alizade, H. H. A., & Najafi, G. (2021). The influence of diesel–ethanol fuel blends on performance parameters and exhaust emissions: experimental investigation and multi-objective optimization of a diesel engine. *Sustainability*, *13*(10), 5379.

Sharma, A., Maurya, N. K., Singh, Y., Singh, N. K., & Gupta, S. K. (2020). Effect of design parameters on performance and emissions of DI diesel engine running on biodiesel-diesel blends: Taguchi and utility theory. *Fuel*, *281*, 118765.

Shih, L. K.-L. (1998). *Comparison of the effects of various fuel additives on the diesel engine emissions* (0148-7191).

Sirajuddin, S., & Siddeswara, R. (2016). Utilization of RBO as an Alternative Fuel in CI Engine With Zinc Oxide Nano Fluids as Additives. *Int J Res Mech Eng Technol*, *6*, 51-54.

Sivathanu, N., & Anantham, N. V. (2020). Impact of multi-walled carbon nanotubes with waste fishing net oil on performance, emission and combustion characteristics of a diesel engine. *Environmental Technology*.

Solero, G. (2012). Experimental analysis of the influence of inert nano-additives upon combustion of diesel sprays. *Nanoscience and Nanotechnology*, *2*(4), 129-133.

Soudagar, M. E. M., Nik-Ghazali, N.-N., Kalam, M. A., Badruddin, I., Banapurmath, N., & Akram, N. (2018). The effect of nano-additives in diesel-biodiesel fuel blends: A comprehensive review on stability, engine performance and emission characteristics. *Energy conversion and Management*, *178*, 146-177.

Soudagar, M. E. M., Nik-Ghazali, N.-N., Kalam, M. A., Badruddin, I. A., Banapurmath, N. R., Ali, M. A. B., Kamangar, S., Cho, H. M., & Akram, N. (2020). An investigation on the influence of aluminium oxide nano-additive and honge oil methyl ester on engine performance, combustion and emission characteristics. *Renewable Energy*, *146*, 2291-2307.

Sravani, K., & Ravindra Reddy, G. (2016). Performance and emission characteristics of CI engine when fuelled with Pongamia biodiesel and zinc oxide nano fluid as additive. *Int J Eng Res*.

Srihari, S., & Thirumalini, S. (2017). Investigation on reduction of emission in PCCI-DI engine with biofuel blends. *Renewable energy*, *114*, 1232-1237.

Tamilvanan, A., Balamurugan, K., & Vijayakumar, M. (2019). Effects of nano-copper additive on performance, combustion and emission characteristics of Calophyllum inophyllum biodiesel in CI engine. *Journal of Thermal Analysis and Calorimetry*, *136*, 317-330.

Taneja, S., Singh, P., Sharma, A., & Singh, G. (2021). Use of alcohols and biofuels as automotive engine fuel. *Energy Systems and Nanotechnology*, 161-183.

Uslu, S., & Aydın, M. (2020). Effect of operating parameters on performance and emissions of a diesel engine fueled with ternary blends of palm oil biodiesel/diethyl ether/diesel by Taguchi method. *Fuel*, *275*, 117978.

Usman, M., Ijaz Malik, M. A., Chaudhary, T. N., Riaz, F., Raza, S., Abubakar, M., Ahmad Malik, F., Muhammad Ahmad, H., Fouad, Y., & Abbas, M. M. (2023). Comparative assessment of ethanol and methanol–ethanol blends with gasoline in SI engine for sustainable development. *Sustainability*, *15*(9), 7601.

Vellaiyan, S., & Amirthagadeswaran, K. (2016a). The role of water-in-diesel emulsion and its additives on diesel engine performance and emission levels: A retrospective review. *Alexandria Engineering Journal*, *55*(3), 2463-2472.

Vellaiyan, S., & Amirthagadeswaran, K. (2016b). Zinc oxide incorporated water-in-diesel emulsion fuel: Formulation, particle size measurement, and emission characteristics assessment. *Petroleum Science and Technology*, *34*(2), 114-122.

Venkatesan, S., & Kadiresh, P. (2015). Influence of aluminum oxide nanoparticle additive on performance and exhaust emissions of diesel engine. *Int J Appl Eng Res*, *10*(3), 5741-5749.

Venu, H., & Appavu, P. (2021). Experimental studies on the influence of zirconium nanoparticle on biodiesel–diesel fuel blend in CI engine. *International Journal of Ambient Energy*, *42*(14), 1588-1594.

Venu, H., Subramani, L., & Raju, V. D. (2019). Emission reduction in a DI diesel engine using exhaust gas recirculation (EGR) of palm biodiesel blended with TiO2 nano additives. *Renewable energy*, *140*, 245-263.

Vijayakumar, M., & Mukesh Kumar, P. (2017). Performance enhancement and emissions analysis of diesel engine with biodiesel, n-propanol and 1-butanol blend. *Journal of Applied Fluid Mechanics*, *10*(Special Issue)), 79-84.

Vinayagam, N. K., Hoang, A. T., Solomon, J. M., Subramaniam, M., Balasubramanian, D., EL-Seesy, A. I., & Nguyen, X. P. (2021). Smart control strategy for effective hydrocarbon and carbon monoxide emission reduction on a conventional diesel engine using the pooled impact of pre-and post-combustion techniques. *Journal of Cleaner Production*, *306*, 127310.

Wang, S., Chen, D., Hong, Q., Gui, Y., Cao, Y., Ren, G., & Liang, Z. (2023). Surface functionalization of metal and metal oxide nanoparticles for dispersion and tribological applications-a review. *Journal of Molecular Liquids*, 122821.

Wang, Z., Shuai, S., Li, Z., & Yu, W. (2021). A review of energy loss reduction technologies for internal combustion engines to improve brake thermal efficiency. *Energies*, *14*(20), 6656.

Wilson, V. H. (2012). Optimization of diesel engine parameters using Taguchi method and design of evolution. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *34*, 423-428.

Wu, J., Jiang, Z., Wan, L., Song, H., & Abbass, K. (2021). Robust optimization for precision product using Taguchi-RSM and desirability function. *Arabian Journal for Science and Engineering*, *46*, 2803-2814.

Yadav, A. K., Khan, M. E., Pal, A., & Sharma, D. (2015). Optimisation of biodiesel production from bitter groundnut oil using Taguchi method and its performance and emissions characteristics on a 4-cylinder Tata Indica engine. *International Journal of Sustainable Agricultural Management and Informatics*, *1*(4), 285-300.

Yesilyurt, M. K., Eryilmaz, T., & Arslan, M. (2018). A comparative analysis of the engine performance, exhaust emissions and combustion behaviors of a compression ignition engine fuelled with biodiesel/diesel/1-butanol (C4 alcohol) and biodiesel/diesel/n-pentanol (C5 alcohol) fuel blends. *Energy*, *165*, 1332-1351.

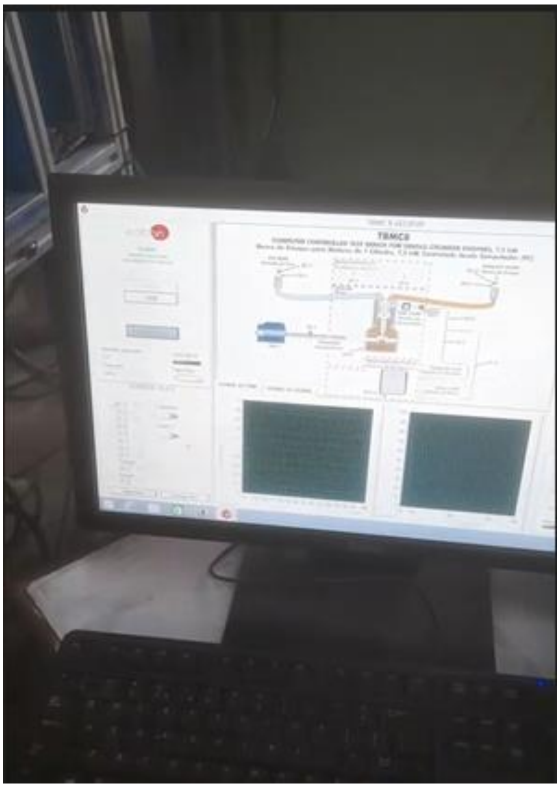
Yetter, R. A., Risha, G. A., & Son, S. F. (2009). Metal particle combustion and nanotechnology. *Proceedings of the combustion institute*, *32*(2), 1819-1838.

Yilmaz, N., Vigil, F. M., Donaldson, A. B., & Darabseh, T. (2014). Investigation of CI engine emissions in biodiesel–ethanol–diesel blends as a function of ethanol concentration. *Fuel*, *115*, 790-793.

Yogaraj, D., Mohamed Iqbal, S., Gokulakrishna, R., & Meikandan, M. (2021). Performance test and emission characteristics of diesel engine with alternate fuel blends and nano additives. *International Journal of Ambient Energy*, *42*(7), 725-729.
Yusaf, T., Hamawand, I., Baker, P., & Najafi, G. (2013). The effect of methanol-diesel blended ratio on CI engine performance. *International Journal of Automotive and Mechanical Engineering*, *8*, 1385-1395.
Zhang, Z.-H., & Balasubramanian, R. (2016). Investigation of particulate emission characteristics of a diesel engine fueled with higher alcohols/biodiesel blends. *Applied energy*, *163*, 71-80.
Zhang, Z., Li, J., Tian, J., Dong, R., Zou, Z., Gao, S., & Tan, D. (2022). Performance, combustion and emission characteristics investigations on a diesel engine fueled with diesel/ethanol/n-butanol blends. *Energy*, *249*, 123733.
Zhong, Y., Zhang, Y., Mao, C., & Ukaew, A. (2022). Performance, combustion, and emission comparisons of a high-speed diesel engine fueled with biodiesel with different ethanol addition ratios based on a combined kinetic mechanism. *Processes*, *10*(9), 1689.
Zhu, L., Zhang, W., Liu, W., & Huang, Z. (2010). Experimental study on particulate and NOx emissions of a diesel engine fueled with ultra low sulfur diesel, RME-diesel blends and PME-diesel blends. *Science of the Total Environment*, *408*(5), 1050-1058.

Appendix

Laboratory work



Larger is better

Table A 1 ANOVA Response Table for Signal-to-Noise Ratios

Level	Ethanol to diesel	Al_2O_3	CeO_2	Load
1	32.73	32.30	31.22	31.63
2	32.52	33.23	32.22	32.39
3	32.07	31.79	33.88	33.30
Delta	0.66	1.44	2.66	1.67
Rank	4	3	1	2

Table A 2 ANOVA Response Table for Means (larger is better)

Level	Ethanol to diesel	Al_2O_3	CeO_2	Load
1	98.39	103.62	69.77	87.07
2	102.18	117.07	83.38	102.92
3	105.68	85.58	153.11	116.28
Delta	7.29	31.49	83.34	29.21
Rank	4	2	1	3

Smaller is better

Table A 3 ANOVA Response Table for Signal-to-Noise Ratios

Level	Ethanol to diesel	Al_2O_3	CeO_2	Load
1	-48.20	-48.19	-48.11	-48.20
2	-48.18	-48.37	-48.20	-48.32
3	-48.51	-48.33	-48.58	-48.37
Delta	0.33	0.18	0.47	0.17
Rank	2	3	1	4

Table A 4 ANOVA Response Table for Means

Level	Ethanol to diesel	Al_2O_3	CeO_2	Load
1	159.9	162.8	163.3	163.6
2	162.0	164.2	163.6	164.5
3	170.4	165.3	165.4	164.2
Delta	10.4	2.5	2.1	0.9
Rank	1	2	3	4