TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

THESIS NO: M-97-MSMDE-2023-2025

Effect of Al_2O_3 Nanoparticles on Performance and Emission Characteristics of Diesel Engine Fueled with B20 Pine Oil-Diesel Biodiesel Blends

by
Ganesh Rawal

A THESIS
REPORT SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN MECHANICAL SYSTEM DESIGN AND ENGINEERING

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING LALITPUR,NEPAL

December, 2025

Copyright

TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled **"Effect of Al_2O_3 Nanoparticles on Performance and Emission Characteristics of Diesel Engine Fueled with B20 Pine Oil-Diesel Biodiesel Blends"** submitted by Ganesh Rawal for the Final Thesis Report in partial fulfillment of the requirements for the degree of Master of Science in Mechanical System Design and Engineering.

....
Supervisor
Surya Pd. Adhikari, PhD
Associate Professor
Department of Mechanical and Aerospace Engineering

....
External Examiner
Daniel Tuladhar, PhD
Professor
Department of Mechanical Engineering,
Kathmandu University

....
Committee Chairperson
Sudip Bhattrai, PhD
Assistant Professor/Head of the Department
Department of Mechanical and Aerospace Engineering

Tribhuvan University
Institute of Engineering
Department of Mechanical and Aerospace Engineering
Pulchowk Campus

Date : 1st, December, 2025

Abstract

This study examines the effects of Al_2O_3 nanoparticles on the performance and emission characteristics of a diesel engine fueled with a blend of 20% pine oil and 80% diesel (B20). The Al_2O_3 nanoparticles were synthesized using a sol-gel method and characterized by XRD, UV-visible absorption, and FTIR analysis to confirm the crystalline nature of the particles. Later, Al_2O_3 nanoparticles at different concentrations of 25 ppm, 50 ppm, and 75 ppm were added into the B20 blend by using an ultrasonication method for homogeneous dispersion. Experimental tests were conducted on a VCR single-cylinder engine at compression ratios of 15:1 and 17:1 under various load conditions. The results revealed that the addition of Al_2O_3 nanoparticles improved some physicochemical properties of the fuel, including calorific value, viscosity, and cetane number.The brake thermal eficiency increased up to 4.42% for the B20+75 ppm fuel blends compared with commercial diesel at maximum load at CR 17. The brake power improved while BSFC decreased with increasing loading condition, which demonstrates improved energy conversion and better fuel economy. The emission test results indicated a significant reduction in CO (up to 25%) and HC (up to 13%) for the B20+50 ppm blend compared with diesel fuel. However, NO_2 emission increased due to the increased combustion temperature. A slight increase in the emission of CO_2 was also observed, indicating more complete combustion.

Keywords: *Al_2O_3 nanoparticles, Diesel engine, Pine -Diesel Biodiesel, Performance, Emission*

Acknowledgment

I would like to express my heartfelt gratitude to Associate Professor Surya Parsad Adhikari, PhD for his invaluable guidance, encouragement and insightful suggestions which greatly contributed to the successful completion of this thesis work.

I am also sincerely thankful to all faculty members from the Department of Mechanical and Aerospace Engineering,Pulchowk Campus for their support and valuable feedback throughout this thesis work. I am also grateful to my classmate and senior Er. Bhuwesh Pant for offering me advice and moral support. I am deeply grateful to the Armed Police Force, Nepal for providing the necessary guidelines and support without which this thesis work would not have been possible throughout the study.

My special thanks to my senior from the Armed Police Force, Nepal , Ssp .Er. Naniram Humagain and my junior Insp. Er. Suyash Acharya for his invaluable support, motivation and guidance during this thesis work. Finally, I would like to express my deepest gratitude to my family members for their unwavering love, patience, and encouragement. Their constant belief in my abilities has been a source of strength and motivation throughout this journey.

Contents

List of Figures

List of Tables

List of Abbreviations

$\mathbf{AL_2O_3}$	Alumonium oxide
CI	Compression Ingnition Engine
B20	Diesel fuel Blends with 20% Pine Oil
PPM	Parts Per Million
IP	Indicated Power
BP	Break Power
SFC	Specific Fuel Consumption
IMEP	Indicated Mean Effective Pressure
ME	Mechanical Efficiency
BTE	Break Thermal Efficiency
VE	Volumetric Efficiency
UV	Ultra Voilet
XRD	X-ray Diffraction
FTIR	Fourier Transform Infrared Spectroscopy
CO	Carbon Monoxide
$\mathbf{CO_2}$	Carbon Dioxide
$\mathbf{NO_x}$	Nitrogen Oxide
IC	Internal Combustion
$^0\mathbf{C}$	Celcius

1. Introduction

1.1 Background

Biofuel refers to solid, liquid, gaseous fuels that can extracted from sustainable biological supplies, such as plant, algae, animal waste, treated municipal and industrial waste. As global energy demand continuous to rise, the importance of bio-fuel has grown because they offer a more sustainable and eco-friendly alternative to traditional fossil fuels, supporting both energy security and economic development. Researchers from all over the world are sincerely trying to identify a suitable diesel fuel substitute that doesn't require significant engine modifications.[1].For the past seven decades emission such as hydrocarbons(HCs),particulates,nitrogen oxide(NO_x), sulfur oxide(SO_x), carbon monoxide(CO) and carbon dioxide(CO_2) are important reasons behind global warming and acid rain[2].A 1998 study by the USDA and US DOE found that using pure biodiesel in urban buses "results in substantial reduction in life cycle emissions of total particulate matter, carbon monoxide and sulfur oxides (32%, 35% and 8% reductions, respectively, relative to petroleum diesel's life cycle). In recent decades, researchers have focused on addressing these issues using various means such as exploring alternative sources, replacing fossil fuels with alternative fuels, or improving the energy efficiency of the system and combustion by using nanoparticles as fuel additives.

Rajan parajuli analyzes the cost of producing biodiesel in the context of mixing 20% with pure diesel in Nepal. Their research found that the production of biodiesel is economically feasible with crops yielding more than 100 kg / plant and the price of the oil is below 0.45 USD / kg has a positive return on investment. With a yield below 2 kg/plant, the production cost of biodiesel cannot be competitive with the current price of diesel. In recent years, the energy demand is increasing day by day since the energy sector plays a vital role in the world economy. From crude oil, consumption of total primary energy is nearly 29.45%[3].As the world's population continues to grow and economies develop, the demand for energy is indeed increasing. This trend is driven by various factors, including urbanization, industrialization, and the adoption of energy-intensive technologies. The projection of a 6% increase in global oil demand from 2022 to 2028, as mentioned in the IEA oil report (2023), underscores the continued reliance on fossil fuels. This can pose challenges in terms of both supply and environmental sustainability.

Environmental concerns associated with fossil fuels and the finite nature of these resources, there's a growing need to transition to alternative and renewable energy sources. This transition is vital for mitigating climate change and reducing greenhouse gas emissions. The blending biodiesel in diesel fuel improves the calorific value and good solubility due to it's inherent oxygen content as compared to diesel fuel. Biofuel is one of the renewable energy fuels produced from biomass, which can be used as an alternative greener energy substitute for petroleum based fuels. Methanol and ethanol are two accepted alternative fuels, which possess the potential to replace diesel fuel.[4] Due to its oxygen content, biofuel produces more complete combustion than that of conventional diesel fuel. Normally, plants yields two types of oils, i.e. triglyceride oil (TG oils) and turpene oil (light oil) among them, triglyceride oil is obtained from plant seeds, whereas turpene oil is obtained from plant parts[5].Pine oil is pale yellow in color having a fresh forest smell, alcoholic compounds and watery in viscosity. It is obtained from oleoresin of pine tree and contains terpineol, which is a tertiary alcohol, along with pinene[6].

Over time, investigations have shown that biodiesel may be blended with other additives and diesel fuel in various ratio to enhance both the fuel's characteristics and the efficiency of diesel engines however, there have been some difficulties especially with the viscosity of the fuel. CI engines, at the forefront of alternative technology, are viable candidates for biodiesel and its mixes. As a result, the general public is becoming more interested in these eco-friendly fuels. Diesel engines can run on vegetable oils as fuel. They are frequently referred to as pure plant oil (PPO) or straight vegetable oil (SVO) when used as fuel, regardless of whether the engine has been modified. Injection systems in contemporary engines are designed to deliver and efficiently atomize diesel fuel. SVO must first be heated before being used in diesel engines. In the majority of contemporary engines, the heating system consist of glow plug that use battery power to heat the oil or a heater installed inside the vegetable oil tank that transfer heat to the cooling engine[7].

Numerous substances, including edible and non-edible oils, animal fat, and microalgae, have been used in the production of biodiesel. Among them, pine oil is also best option for biodiesel due to its comparable properties, pine oil, a renewable biomass source of fuel can be blended with petroleum- based diesel fuel .[8]Pine oil, synthesized from pine oleoresin, is recently being viewed as a potential renewable source of fuel for diesel engine application. Significantly, the estimated physical and thermal properties of pine oil are suited for its use in diesel engine, with the notable advantages of lower viscosity, boiling point and comparable calorific value with diesel.

1.2 Statement of the problem

The growing dependence on fossil fuel and the increasing environmental concerns associated with diesel engine emissions have increased the search for sustainable and clean alternatives. For such reasons, pine oil–diesel biodiesel blends have gained attention as a good replacement for conventional diesel because it is renewable and has very encouraging combustion properties. However, biodiesel–pine oil blends often exhibit limitations in terms of lower thermal efficiency, higher fuel consumption, and increased emission at certain operating conditions.

Recent investigations have indicated that metal-oxide nanoparticles, especially alumina (Al_2O_3), improve fuel-air mixture, enhance combustion quality, and possibly even reduce emissions when applied as additives in fuel. In spite of this, there is still limited research on how the combined effect of Al_2O_3 nanoparticles influences the performance and emission characteristics of a diesel engine running on pine-diesel biodiesel blends. The optimum nanoparticle concentration, the influence of compression ratio, and the overall impact on the behavior of the engine are not well-understood.

Therefore, a deep investigation will be necessary to ascertain whether the addition of Al_2O_3 nanoparticles will effectively enhance the performance, fuel economy, and emission profile of pine-diesel biodiesel blends without engine modification. This research, therefore, tries to fill these knowledge gaps and provides scientific evidence to inform the development of efficient and environmentally friendly biofuel-nanoadditive combinations for compression-ignition engine.

1.3 Novelty of work

Based on the literature's published so far, it was found that there is a significant gap in research on Pine oil biodiesel with metal oxide nano particles as a substitute fuel for diesel engines. Although there are several literature relating to Al_2O_3 as nano additives in other types of biodiesel and pine oil biodiesel with other metal oxide nano additives, there is no literature that has come to systematic study of the application of aluminium oxide additives with pine oil biodiesel yet. Aluminium oxide proves to be a prospective nano additive in biodiesel with improved engine performance and emission characteristics, as found from thorough study of previous work published. Within this context , this research work solely focuses on exploration of engine performance and emission characteristics of pine oil biodiesel blends with aluminium oxide additives without any engine modifications.

1.4 Research objectives

1.4.1 Main objective

The main objective of this research work is to experimentally investigate the effect of Al_2O_3 on performance and Emission Characteristics of diesel engine fueled with Diesel-pine biodiesel blends.

1.4.2 Specific objectives

The specific objectives are:

- To synthesize Aluminium oxide nanoparticles using sol-gel method followed by its characterization through X –ray diffraction techniques and UV-absorption test.
- To prepare biodiesel form diesel blend with 20% pine oil(B20) and doze nanoparticles on fuel blend in concentration of 25 ppm, 50 ppm and 75 ppm through the ultrasonication process for achieving adequate mixing and adsorption on the fuel.
- To characterize the nanoparticles blended fuel and operate it in single cylinder water cooled CI engine.
- To compare the performance and emission parameters of test fuels with conventional diesel.

1.5 Scope of the work

This study opens the gateway on investigating the effect of incorporating aluminium oxide nano-additive in powder form at 25 ppm, 50 ppm and 75 ppm. Additionally, the application of neat pine oil biodiesel blend as a potential alternative to fossil fuel was also explored. Nano-additive in nano powder form will be mixed with pine oil biodiesel blend at 20% by volume at 25, 50 and 75 ppm on mass basis using bath sonicator and the engine performance and emission characteristics of an unmodified diesel engine was studied. This study on the field of alternative fuel holds significant importance for the following reasons:

- Investigating the role of Al_2O_3 nanoparticles in reducing emissions like CO, CO_2, NO_x and particulate matter, the study could help in the promotion of cleaner energy solutions and sustainable fuel alternatives.
- Results could give a strategy to optimize and reduce fuel consumption with improvement in overall performance in diesel engines for automotive and industrial benefits.
- This could be useful data for policy makers and regulators in the drafting of more strict standards on emissions and the promotion of alternative fuels.

1.6 Limitation of the work

While the study offers valuable insights into how Al_2O_3 nanoparticles affect pine-diesel biodiesel blends, it is important to acknowledge some limitations in order to comprehend the limitations of the results.

- Equipment available up till now in our country doesn't provide complete parameters.
- In the blend of pine, after a month storage, a small white precipitate accumulates at the bottom, which needs to be filtered before use in the diesel engine.
- Synthesis of nanoparticle in laboratory is complicated job due to limited infrastructures.
- As pine oil is extracted in limited quantity in our country, at present it is more expensive than diesel oil.

2. Literature Review

2.1 Earlier Work

The utilization of pine oil as a blending component in diesel fuel has been shown to significantly influence engine performance and emissions. Studies indicate that the addition of pine oil improves specific fuel consumption (SFC) and brake thermal efficiency (BTE), while key performance parameters such as brake power (BP), indicated power (IP), and brake mean effective pressure (BMEP) remain comparable to those of conventional diesel fuel. Research findings suggest that diesel-pine oil blends can be effectively used in compression ignition (CI) engines without requiring any modifications [9].The increasing reliance on fossil fuels as a non-renewable energy source poses severe environmental and health concerns. Excessive fossil fuel consumption contributes to greenhouse gas emissions, which negatively impact plant and animal life, as well as human health. According to the Lancet Countdown on Health and Climate Change[10] the continued use of fossil fuels has led to a significant rise in global temperatures, with current average temperatures exceeding pre-industrial levels by more than four degrees. Consequently, there is an urgent need to explore renewable and sustainable fuel alternatives that can serve as viable substitutes for fossil fuels.

Despite ongoing advancements in alternative energy sources, internal combustion engines (ICEs) will likely remain the dominant power source for transportation in the near future. Therefore, enhancing the efficiency of diesel engines while reducing emissions remains a critical research focus. The development and optimization of renewable fuels, such as pine oil blends, offer a promising solution for improving engine performance while mitigating the environmental impact of fossil fuel usage. Many researchers have experimentally evaluated the performance of CI engines fueled with biodiesel and its blends. An et al. [11]conducted experiments on in-line four-cylinder, four-stroke, turbocharged, direct injection diesel engines using waste cooking oil and found that brake specific fuel consumption of B10 was similar to that of diesel fuel. For B50 and B100, an increase in BSFC was observed. This is due to the less calorific value of biodiesel and reduced thermal efficiency. The thermal efficiencies of biodiesel at 50% and 100% loads are higher than that of diesel. This is due to a higher oxygen content in the bio diesel that enhances combustion. CO_2 and HC emissions are significantly reduced by using biodiesel.

The emissions and performance of the CI engine powered with the water-alumina-diesel emulsion were investigated in another experimental investigation[12].According to the findings, alumina fuel blends improved engine performance while also lowering pollution emissions. Rapid expansion in the transport industry as a result of modernization and industrialization boosts the consumption of energy and raises emissions from engines, which harm the environment worldwide. IC (internal combustion) engines are primarily utilized in the automotive, power generation, and agricultural industries due to their poorer fuel efficiency. Fossil fuel consumption results in increased levels of HC, CO, and NOx emissions, which contribute to global climate change[13].As a result, numerous academic researches has been working on the search for diesel fuel alternatives, such as vegetable oils, and their derivatives. Vegetable oils are biodegradable and non-toxic; but they possess low volatility and high viscosity that lead to poor atomization resulting in to incomplete combustion, engine deposits, excessive smoke emissions, and poor brake thermal efficiency when utilized in CI (compression ignition) engines[14].

An experimental research was performed to determine performance characteristics of 5%,15% and 20% pine oil mixed with diesel fuel in single cylinder four stroke compression ignition(CI) engine by[15] .In this research showed better brake specific fuel consumption (BSFC) i.e 18.75% lower than diesel fuel and brake thermal efficiency (BTE) increases to 13.5% mainly on 50% loading condition. Also brake power (BP) and brake mean effective pressure (BMEP) found nearer to diesel. [16] concludes the alumina nanoparticles were mixed with crude diesel oil at different weight ratios of 20, 30 and 40 mg/L. Engine testing has shown that the addition of 40 ppm Nano-alumina to commercial diesel oil improves thermal efficiency by up to 5.5% compared to pure diesel fuel. The average reductions in specific fuel consumption for pure diesel fuel were found to be 3.5%, 4.5% and 5.5% at dosage levels of 20, 30 and 40 ppm respectively when fully charged. Smoke, HC, CO and NOx emissions were found to be reduced by approximately 17%, 25%, 30% and 33% respectively with 40ppm of Nano-additives for diesel engine operation.

[17] performed an experimental investigation on the performance of a CI engine fueled with waste cooking Oil biodiesel blends and results of the experiments show that IP and SFC of mixed biodiesel were marginally better. Likewise, it was discovered

that BP and BMEP were comparable to diesel fuel. Similarly, performance analysis and testing of diesel with ferric oxide (Fe_2O_3) nanomaterial and pine oil in internal combustion engine by[18] and conclude that sample 90 PPM (Fe_2O_3) in B20 fuel were compared with different compression ratio 15 and 16 which shows the improvement of IP by 9.92%, BP by 4.39%, BTE by 4.64%, ITE by 13.49%, ME by 12.83%, VE by 2.89% and SFC by 17.14%. The impact of zinc oxide nanoparticles as fuel additives blend with rice bran oil and diesel fuel at doze level of 25, 50, 75 ppm of nanoparticles studied by[19] . The test fuel with 75 ppm of zinc oxide additive at 17.5 compression ratio resulted in an overall improvement at full load: brake thermal efficiency increased by 2.45%, brake specific fuel consumption reduced by 5.45%, cylinder peak pressure increased by 3.27% and net heat release increased by 10.32% in comparison with base fuel. The influence of nano AL_2O_3 on compression ignition engine characteristics fueled with mahua biodiesel conducted by[20], the result conclude that BTE was improved and the emission of smoke,HC,CO and NO_x was reduced significant percent.

[21] studied the performance and exhaust emissions investigation of a diesel engine using γ-Al_2O_3 nanoparticle additives to biodiesel. The results showed that the brake thermal efficiency was improved by 8% when nanoparticle additive dosage level was varied from 25 to 100 ppm and a maximum improvement was observed at dosing levels of 25 and 75 ppm. Specific fuel consumption was reduced up to 0.05 kg/kWh at 80%load with the addition of 25 ppm. Also carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x) and hydrocarbon (HC) emissions were reduced to a greater extent with the addition of γ-Al_2O_3 nanoparticle additive, compared to the biodiesel without γ-Al_2O_3 nanoparticle at all load conditions of the engine.

The combustion and emission characteristics of pine oil–diesel blends were investigated in a high-speed turbocharged diesel engine under varying loads and exhaust gas recirculation (EGR) rates. Four fuel blends were tested: pure diesel (P0) and diesel mixed with pine oil at 20% (P20), 40% (P40), and 50% (P50)[22]. Key findings includes equivalent brake specific fuel consumption (BSFC) of P50 was 2.08–3.5% higher than P0 under 40–100% load, while P20 showed minimal (<1%) increase compared to pure diesel and increasing EGR rate from 0% to 24.6% significantly reduced NO_x emissions, with minimal impact on soot, CO, and THC emissions.

Similarly, explore the impact of adding Fe_2O_3, Al_2O_3, and Fe_2O_3–Al_2O_3 hybrid nanoparticles (at concentrations of 30, 60, and 90 ppm) to pure diesel fuel on the combustion, performance and emission characteristics of a diesel engine[23] and results illustrated that Fe_2O_3 blends showed greater improvements in brake power (7.40%) and brake thermal efficiency (BTE) (14%) compared to Al_2O_3 blends and Al_2O_3 blends were more effective in reducing NO_x (23.9%) and SO_2 (23.4%) emissions compared to Fe_2O_3 blends. The effects of adding Al_2O_3 nanoparticles to 'Mesua ferrea Linn' (MFL) vegetable oil-diesel blends on the emission characteristics, performance, and combustion of a diesel engine. Two test fuels were examined namely MFL20D80(20% MFL + 80% diesel) and MFL20D80A50(20% MFL + 80% diesel + 50 ppm) Al_2O_3nanoparticles[24].The addition of Al_2O_3 nanoparticles improved combustion efficiency and emission characteristics, making MFL20D80A50 a promising alternative fuel for diesel engines.

According to the various literature reviews, there have been no studies focusing on the use of a mixture of pine oil and Al_2O_3 nanoparticles in diesel engines; therefore, the aim of this study is to present a comprehensive study investigating and comparing the effects of different concentrations of Al_2O_3 nanoparticles, as well as their blending in diesel engines. Finally, Al_2O_3 nanoparticles and pine oil mixtures at different concentrations were mixed in the diesel fuel and their effects on combustion (cylinder pressure and heat release rate), performance (BP, IMEP, AF, BSFC, BTE and ME) and emission (opacity) of a CI (diesel) engine parameters at different loads were studied.

2.2 Pine oil biodiesel

The inventor of the first Diesel engine in 1895 was Dr. Rudolf Diesel, who used the only biofuel in his engine. He once stated where he indicates the importance of oil in the future. Biodiesel is an alternative fuel that is made from several renewable natural fuels such as edible and nonedible vegetable oils. According to ASTM standards, biodiesel is a fuel composed of the long chain of mono-alkyl ester. There are several problems encountered while using biodiesel compared to petroleum products.

Pine oil is used as biodiesel due to its impressive fuel properties such as lower viscosity ,flash point, boiling point and comparable calorific value to diesel fuel[25].Pinus roxburghii sarg is a species of several evergreen trees belonging to the pinaceae and is inhabitant to the himalayas and dispersedall through Pakistan, India, Nepal and Bhutan[26].Pine oil is derived through distillation of pine tree resins and consists primarily of cyclic monoterpenes, i.e., α-pinene, β-pinene, and limonene. Owing to these components, it has low viscosity, high volatility, and moderate cetane number, making it a suitable candidate for being used as biodiesel. Studies indicate that pine oil has lower energy density compared to diesel but high oxygen content, which enhances combustion efficiency and reduces emissions[27].Pine oil is usually blended with diesel rather than being transesterified like in the case of conventional biodiesel. Its performance at various blend levels, normally ranging from 5% to 30% (P5–P30) with diesel, has been examined by a number of researchers. Blending is simple due to the high miscibility of pine oil with diesel fuel.

This study investigated the feasibility of using pine oil as an alternative fuel for diesel engines by analyzing its spray characteristics, combustion, performance and emission characteristics [28]. It concluded that Pine oil blends exhibit similar spray and combustion characteristics to diesel, with comparable power output and reduced soot emissions. Similarly performance, combustion and emission characteristics of a compression ignition engine operating on pine oil investigated experimentally by[9] and result showed viscosity ,flash point and cetane index of pine are lower than diesel and calorific value is higher than that of diesel, which is shown in table 2.1.

Table 2.1: Fuel Properties of Diesel and Pine Oil

Properties	**Diesel**	**Pine Oil**
Density (kg/m^3)	830	846.3
Kinematic viscosity (mm^2/s) @ 40°C	3.2	1.8
Flash point (°C)	63	46
Calorific value (kJ/kg)	42,500	43,012
Cetane index	49	14

2.3 Selection of Al_2O_3 nanoparticle

When selecting Al_2O_3 (alumina) nanoparticles for use in diesel-turpentine fuel blends in a compression ignition (CI) engine, consider the following key factors:

High thermal conductivity:Thermal conductivity of Al_2O_3 (aluminium oxide) nanoparticles are high compared to many other materials, making them effective for improving the thermal properties of base fluid. Al_2O_3 nanoparticles enhance the evaporation rate of nanofuel droplets and shift the maximum flame temperature to the upstream region[29].

Chemical stability:Al_2O_3 is chemically inert and stable, ensuring that it does not react with the base fuel or corrode the system components. This stability is crucial for maintaining the long-term performance of the biofuel[30].

Cost effective: :Al_2O_3 nanoparticles are relatively inexpensive compared to other high-performance nanoparticles like gold or carbon nanotube, making them a cost-effective choice for large-scale applications.

Availability and ease of production :Al_2O_3 nanoparticles can be effectively dispersed in common base fuel with appropriate surfactants or ultrasonic agitation, ensuring a stable suspension[31].

Research and application history :Al_2O_3 has been extensively studied and used in various biofuel applications. This wealth of research provides a solid foundation of knowledge and data, facilitating the design and optimization of experiments.

2.4 Synthesis of nanoparticles

A nanoparticle is a particle or a structure that has at least one dimension at the nanoscale. The nanoscale ranges from 1 to 100 nanometers. At the nanoscale, materials have unique and often improved physical and chemical properties over their bulk counterparts. This is due to the high surface area to volume ratio and the quantum size effects. Types of nanoparticles Metal nanoparticles, metal oxides nanoparticles, polymers, carbon-based materials, etc.There are numerous ways to create nanoparticles, each having benefits and drawbacks. The preferred approach is determined by the desired nanoparticle properties, size, shape, and application. Some typical techniques for creating nanoparticles are as follows:

1. **Chemical Precipitation:** This technique produces nanoparticles by combining a solution containing precursor salts with a reducing agent or a precipitating agent. Using sodium borohydride as a reducing agent, silver nitrate is used to synthesize silver nanoparticles

2. **Sol-Gel Technique:** This technique involves through a series of condensation and hydrolysis reactions, a precursor solution (often a metal alkoxide) is transformed into a gel, which is then dried and calcined to produce nanoparticles. This technique is commonly applied to metal oxide nanoparticles such as aluminum oxide,iron oxide, copper oxide nanoparticles.

3. **Electrochemical Deposition:** This technique involves through the use of an electric current; nanoparticles are deposited onto a substrate using electrochemical techniques. This technique is used for preparing electrode and thin film materials.

4. **Hydrothermal Synthesis:** This technique involves high-temperature, high-pressure aqueous solutions or organic solvents are used to create nanoparticles, enabling controlled growth and crystallization. This technique is frequently used to create complex, high-quality nanoparticles, such as nanowires and nanorods

2.5 X-ray crystallography

X-ray crystallography is a scientific technique for ascertaining the structure of atom in a crystal[32]. It is made up of the X-ray irradiation of a crystal and interpretation of the resulting diffraction patterns to deduce the three-dimensional structure of atoms in the crystal lattice.The principle of X-ray crystallography is based on how X-rays interact with the electrons within a crystal lattice[33]. When X-rays pass through a crystal, they engage with the atoms' electrons, leading to an important phenomenon called diffraction. Diffraction happens when waves encounter periodic structures, causing them to scatter in specific directions. In X-ray crystallography, the crystal lattice serves as such a periodic structure, causing the X-rays to undergo diffraction.

X-rays are electromagnetic radiation of wavelength about 1 Å (0.01-10nm), which is about the same size as an atom[34].They occupy the part of the electromagnetic spectrum between gamma rays and ultraviolet light. Discovered in 1895, X-rays allowed scientists to examine the atomic structure of crystalline materials.

When X-rays interact with a crystalline substance, they produce a diffraction pattern. Approximately 95% of solid materials are crystalline and each crystalline solid has a unique X-ray diffraction (XRD) pattern, serving as a distinctive "fingerprint" for identification. To date, around 50,000 inorganic and 25,000 organic single-component crystalline phases and their diffraction patterns have been cataloged and stored on magnetic or optical media as reference standards.

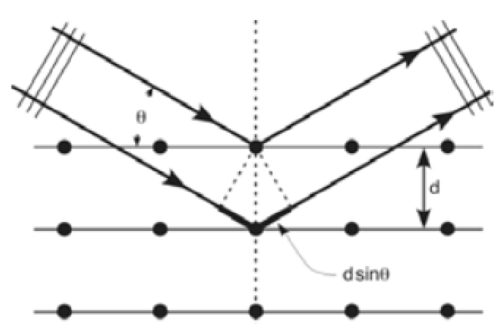

Figure 2.1: Reflection of X rays from two lattice planes of solid

Figure 2.1 illustrates how X-rays are reflected from two adjacent atomic plane in a solid. A crystal lattice, which is the orderly, three-dimensional arrangement of atoms in a crystal, includes forms such as cubic or rhombic lattices. These atoms are arranged in repeated, parallel layers with a distance between them called d, and this distance depends on the material. Each set of planes in a crystal can have a different orientation, thus a different inter planar spacing. If a monochromatic X-ray beam of wavelength λ strikes these planes at an angle θ, diffraction occurs only if there is constructive interference. Constructive interference occurs when the extra path taken by X-rays reflected from successive planes is an integral multiple n of λ. This condition describes Bragg's Law

$$n\lambda = 2d\sin(\theta) \tag{2.1}$$

In Bragg's Law, n is an integer (1, 2, 3, ...), although it is generally taken as 1. The symbol λ represents the wavelength of the X-rays in angstroms. For example, the wavelength of copper radiation is 1.54 Å. The term d is the spacing between atomic planes in angstroms, and θ is the diffraction angle in degrees. For a polycrystalline sample, different sets of lattice planes satisfy the Bragg condition for different angles θ, and a series of diffraction peaks is obtained. The position and intensity of the peaks constitute a characteristic pattern of the material. If there are several phases in a sample, the resultant diffractogram is the sum of the patterns of each phase.

XRD is one of the most powerful analytical techniques that yields detailed information on material structural, chemical, and physical parameters. It is normally used for two important purposes: the identification of crystalline substances by their unique diffraction pattern and the detailed atomic arrangement in such materials. Once the material is identified, X-ray crystallography gives information on how the atoms are arranged in a crystal, including distances between atoms and angles of bonds. Because it is precise and reliable, XRD has maintained itself as one of the prime techniques for material characterization. X-ray diffraction is one of the most important characterization tools used in solid state chemistry and materials science. We can determine the size and the shape of the unit cell for any compound most easily using the diffraction of x-rays.

Table 2.2: Al_2O_3(Corundum)-major XRD reflections (JCPDS-ICDD File No 46-1212)

Peak Position (2θ)	**Miller Indices (h,k,l)**	**d-spacing (Å)**
25.59	(012)	3.48
35.14	(104)	2.551
37.78	(110)	2.379
43.36	(113)	2.085
52.55	(024)	1.740
57.52	(116)	1.601
66.55	(214)	1.405
68.20	(300)	1.374

2.6 Properties of fuel

2.6.1 Density

Density is defined as the mass of a material per unit volume, and it is strongly affected by temperature. In fuels, it is normally measured at 15 °C as a standard quality reference. It is one of the most relevant fuel properties in the combustion process and in fuel atomization. The main applications of this property involve the design and operation of fuel handling systems, such as manufacturing, storage, and distribution installations. Moreover, this property affects different related fuel characteristics: cetane number, viscosity, and heating value. Since density and viscosity are directly related, increased density increases the energy content of the fuel, which could help reduce leakage[35]. It may also enhance atomization efficiency[36]. On the other hand, an excessively high density leads to an increase in viscosity, which might be responsible for incomplete combustion and deterioration of engine performance and emissions

2.6.2 Viscosity

The fuel flow behavior, spray formation, and atomization efficiency are strongly dependent on the kinematic viscosity of the fuel. With high viscosity, more energy is needed to transport the fuel through the injection system; this leads to higher power consumption of the fuel pump and causes poor spray and atomization[36, 37] and also increases the fuel consumption[38].The fuel viscosity should be within acceptable limits for good engine performance. If the viscosity is too low, fuel droplets become very tiny and travel with low momentum, which produces an overly fine spray that may cause black smoke and poor penetration. On the other hand, if fuel viscosity is too high, it can disrupt the combustion process, which often leads to blue smoke, reduction in engine power, and increased deposit formation. Furthermore, a change in temperature also alters the fuel viscosity: at low temperature, viscosity rises, which may present several operational problems at engine start-up and during fuel flow.

2.6.3 Cetane number

The cetane number, or CN, is a significant parameter reflecting the ignition quality of fuels for compression-ignition engines. It is a dimensionless quantity directly related to the ignition delay period, which refers to the time between fuel injection and the beginning of combustion. A fuel with a higher cetane number is ignited faster, thus giving a shorter ignition delay, while a lower CN means slower ignition. In general, higher cetane numbers are desirable in CI engines to ensure proper and efficient combustion[39].

2.6.4 Flash point

The flash point of any fuel is the lowest temperature at which the fuel is able to generate enough vapor to be ignited. A higher flash point improves the safety of the fuel both in its handling and storage, since it reduces the risk of accidental ignition during normal operating conditions[39].

2.6.5 Pour point

The pour point is the temperature below which the liquid loses its current characteristics and it presents very important property can be applied to assess the activity of fuel to flow[40]. It tells about flow property under gravity and degree of pumping of fuel at low temperature. It helps to understand performance of fuel during winter. The pour point of crude oil is 278-288 K. The fuel cannot be stored at temperature below pour point. The higher paraffin content in a fuel leads to higher pour point.

2.6.6 Cloud point

Cloud point is defined as the temperature at which the first crystal is formed[41].The cloud point is the temperature at which the wax in the fuel forms a cloudy appearance.

Above this temperature, the fuel turns to be turbid. This is important for the fuel consumption at winter. This formation of wax results in clogging of engine filters. It is also known as wax appearance point (WAP).

2.6.7 Calorific value

The calorific value of any fuel defines the quantity of heat produced by the complete combustion of the unit mass of that fuel. Fuels of higher calorific values are desirable because during combustion they are able to release more energy, hence giving better efficiency and performance to the engine[42, 43]. Commercial diesel usually has a calorific value of about 45.5 MJ/kg. Biodiesel generally exhibits a lower calorific value than commercial diesel due to its molecular structure, which contains a greater proportion of oxygenated compounds instead of long-chain hydrocarbons.

2.7 Performance parameter

2.7.1 Indicated power

The power actually developed inside the engine cylinder by the combustion of the fuel is called indicated horsepower. It is given by the relation.

$$I.P = \frac{P \times L \times A \times N}{4500} \text{for 2- stroke engine} \tag{2.2}$$

$$I.P = \frac{(P \times L \times A \times N)}{2 \times 4500} \text{for 4-stroke engine} \tag{2.3}$$

Where,

P = Mean effective pressure in kg/cm^2

L = Stroke length in meters

A = Cross-section area of the piston in cm^2

N = Number of revolutions of the crankshaft

For different engine types:

In a 2-stroke engine: number of revolutions = number of r.p.m of the crankshaft.

In a 4-stroke engine: number of revolutions = $\frac{1}{2}\times$ number of r.p.m of the crankshaft.

2.7.2 Brake power

Brake power is the useful power available at the engine output shaft for performing mechanical work. It is typical ranges 70-85% of the indicated power. This power is measured using devices such as a prony brake or dynamometer and can be calculated using the following relationship:

$$B.P = \frac{2\pi NR(W-S)}{4500} = \frac{\pi DN(W-S)}{4500} \tag{2.4}$$

Where,

D = Diameter of the brake drum

N = Number of revolutions per minute of the crankshaft

W = Brake load in kg

S = Reading of the spring balance in kg

2.7.3 Mechanical efficiency

Mechanical efficiency refers to the measure of how effectively power generated inside the engine cylinder is transmitted to the output shaft . Which is also expressed as the proportion of power divided by indicated power.

$$\eta_m = \frac{\text{Brake Power}}{\text{Indicated Power}} \tag{2.5}$$

2.7.4 Volumetric efficiency

Volumetric efficiency is defined as the proportion of the volume of air-fuel mixture inducted into the engine cylinder at atmospheric conditions at the time of intake stroke to the total volume of cylinder.

$$\eta_v = \frac{\text{Volume of air drawn into the cylinder}}{\text{Maximum possible volume in the cylinder}} \tag{2.6}$$

For an engine operating at relatively high speed, the volumetric efficiency is typically around 80%. However, in some engines, it may drop at 50% at very high speed due to incomplete filling of cylinder during intake stroke.

2.7.5 Indicated thermal efficiency

Indicated thermal efficiency represents the proportion of the fuel's energy that is converted into indicated power produced inside the engine cylinder.

$$\eta_{it} = \frac{\text{Indicated Power}}{\text{Fuel Energy}} \tag{2.7}$$

$$\eta_t(\%) = \frac{\text{Indicated Power (kW)} \times 3600}{\text{Fuel Flow (kg/hr)} \times \text{Calorific Value (kJ/kg)}} \times 100 \tag{2.8}$$

2.7.6 Brake thermal efficiency

Brake thermal efficiency is the ratio between break power to fuel energy termed as break thermal efficiency.

$$\eta_{bth} = \frac{\text{Brake Power}}{\text{Fuel Energy}} \tag{2.9}$$

$$\eta_{bth}(\%) = \frac{\text{Brake Power (kW)} \times 3600}{\text{Fuel Flow (kg/hr)} \times \text{Calorific Value (kJ/kg)}} \times 100 \tag{2.10}$$

Different types of engine efficiency are shown in Figure 2.2

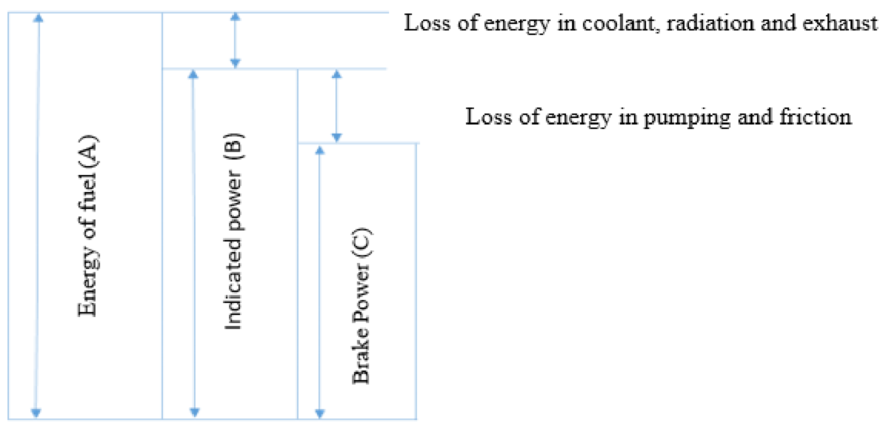

Figure 2.2: Schematic diagram represent different types of efficiency

2.8 Emission parameter

Evaluation of emission characteristics is an essential aspect of assessing the performance and impact on the environment of diesel engines operated on conventional diesel and biodiesel blends.The major exhaust emission parameters of interest include carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), nitrogen oxide (NO_x) and particulate matter (PM).

2.8.1 Carbon monoxide (CO)

Carbon monoxide (CO) is one of the most critical pollutants emitted from compression ignition engine. It is primarily formed as a result of incomplete combustion of fuel, occurring when there is insufficient oxygen, poor atomization or inadequate mixing of the air-fuel mixture inside combustion chamber[44]. Diesel engines typically generate measurable amounts of CO under rich or transient operating conditions, especially at low loads. However, the use of biodiesel significantly influences CO emissions due to its inherent oxygen content. Biodiesel molecules generally contains about 10-12% oxygen by weight which enhances combustion efficiency and facilitates the major complete conversion of carbon into carbon dioxide rather than CO[45].Numerous experimental studies have reported that biodiesel blends consistently reduce CO emission in comparison with pure diesel.

2.8.2 Carbon dioxide (CO_2)

Biodiesel with nano-additives typically exhibits improved combustion and slightly higher exhaust CO_2, reflecting more complete fuel burning, it remains environmentally favorable due to its renewable origin and overall reduction in life cycle greenhouse gas emissions. The nanoparticles act as oxygen-donating catalysts that enhance the oxidation process and improve combustion efficiency. As a result, a slight increase in CO_2 emission is typically observed compared to the base biodiesel blend, which indicates more complete combustion of fuel mixture rather than higher total carbon output. Studies have shown that the use of Al_2O_3 nanoparticles in concentration from 25 ppm to 100 ppm can improve atomization and reduce ignition delay, leading to better oxidation of carbon compounds and consequently increased CO_2 formation with reduced CO and unburnt hydrocarbon (HC) emissions[46].

2.8.3 Hydrocarbon (HC)

The major pollutants generated from fuel that does not undergo proper combustion are unburned hydrocarbons. Various authors have reported that biodiesel-diesel blends, in general, emit fewer hydrocarbons since the higher oxygen content in biodiesel promotes better combustion. Besides, the addition of nanoparticles in fuel leads to lower HC emissions[47].The influence of the addition of 20 ppm of cerium oxide nanoparticles in Cymbopogon flexuosus biofuel has been reported by [48].They detected a 3.63% reduction in the emissions of hydrocarbon compared to biodiesel-diesel blends without nanoparticles. They believe that the oxygen vacancy properties of the cerium oxide nanoparticles are responsible for such improvement.Kataria et al. [49] have conducted tests using waste cooking oil biodiesel doped with 5 wt% zinc-doped calcium oxide nanoparticles in a single cylinder, water-cooled, variable compression ratio diesel engine. According to their results, a biodiesel blend containing nanoparticles emitted lower hydrocarbons compared to the conventional diesel, indicating that nanoparticles improve the combustion processes and thus yield cleaner exhaust.

2.8.4 Nitrogen oxide (NO_x)

One of the main pollutants released by CI engines is NO_x. The interaction between oxygen and nitrogen at high temperatures in the cylinder is the primary cause of NO_x formation, according to thermal mechanism.The oxidation process during combustion would be enhanced by the nanoparticles, increasing NO_x emissions. In order to compare the emission characteristics of diesel and diesel-soy biodiesel [50] investigated the addition of nanoparticles to a modified fuel blend. The findings demonstrated a significant decrease in CO and UHC emissions while a slight increase in NOx emissions at full load. This is due to the fact that alumina nanoparticles can more effectively utilize the oxygen present in soybean biodiesel.

3. Methodology

3.1 Flow chart

The research methodology is illustrated through the provided flow chart shown in Figure 3.1

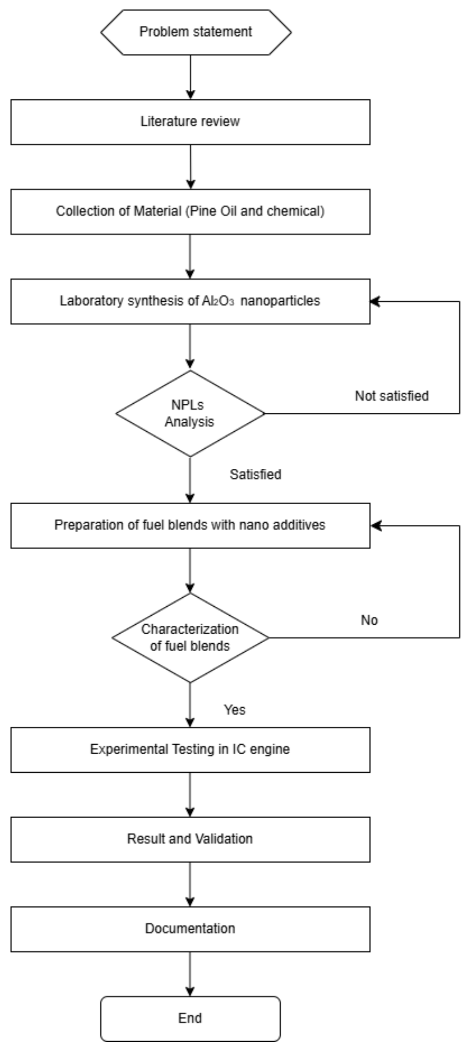

Figure 3.1: Research methodology flow Chart

3.2 Collection of pine oil

Pine trees reach 40 meters tall, with a flat-topped crown and reddish-brown bark that becomes deeply fissured. Leaves are needle-like, gray-green, and often in pairs. Flowers are orange-yellow, and cones brown, pointed, and oval. Most species are valued for their commercial timber all over the world. Oil from the tree is extracted by steam distillation from the fresh needles, twigs, and cones of pinus sylvestris. The crude oil is pale yellow and forest-scented with alcoholic odor, alcohol-based compounds, and water-like consistency. The major constituents are α -terpinene and 3-carene. The pine oil selected for this project was purchased from Divya Rosin and Turpentine Pvt. Ltd., Attariya, Kailali, and used as fuel in a compression ignition engine. Table 2.1 shows some fuel properties of pine oil compared to conventional diesel fuel. From the table, the pine oil has more calorific value than diesel oil, whereas its kinematic viscosity and flash points are relatively lower than conventional mineral diesel fuel. The overall fuel properties of pine oil are fairly comparable to those of commercial diesel fuel, therefore, pine oil may serve as an appropriate substitute as an alternative fuel.

3.3 Synthesis of Al_2O_3 by Sol-gel method

Aluminum Oxide nanoparticles was synthesized using the Sol-Gel process in the chemistry lab in Department of Applied Sciences and Chemical Engineering, Pulchowk Campus. [51] carried out similar process. Procedure followed is mentioned below. It was conducted through the following steps as shown in figure 3.2.

- 10 gm of Aluminum Nitrate Nonahydrate ($Al(NO_3)_3 .9H_2O$) was weighed in the analytical balance and dissolved in 100 ml of water with the help of magnetic stirrer in a beaker.
- After that, 3.35 gm of ethanol was added in 50 ml of distilled water and mixed with Aluminum Nitrate Nonahydrate solution.
- The solution was placed in hot plate magnetic stirrer for one hours maintaining temperature of 80 °C, transparent solution was formed.
- Then gel was again heated in the muffle furnace at 350 °C for 45 minutes.
- Then the material obtained product was grounded and heated at 1000 degree Celsius for 1 hour resulting in the formation of Al_2O_3nanoparticles.

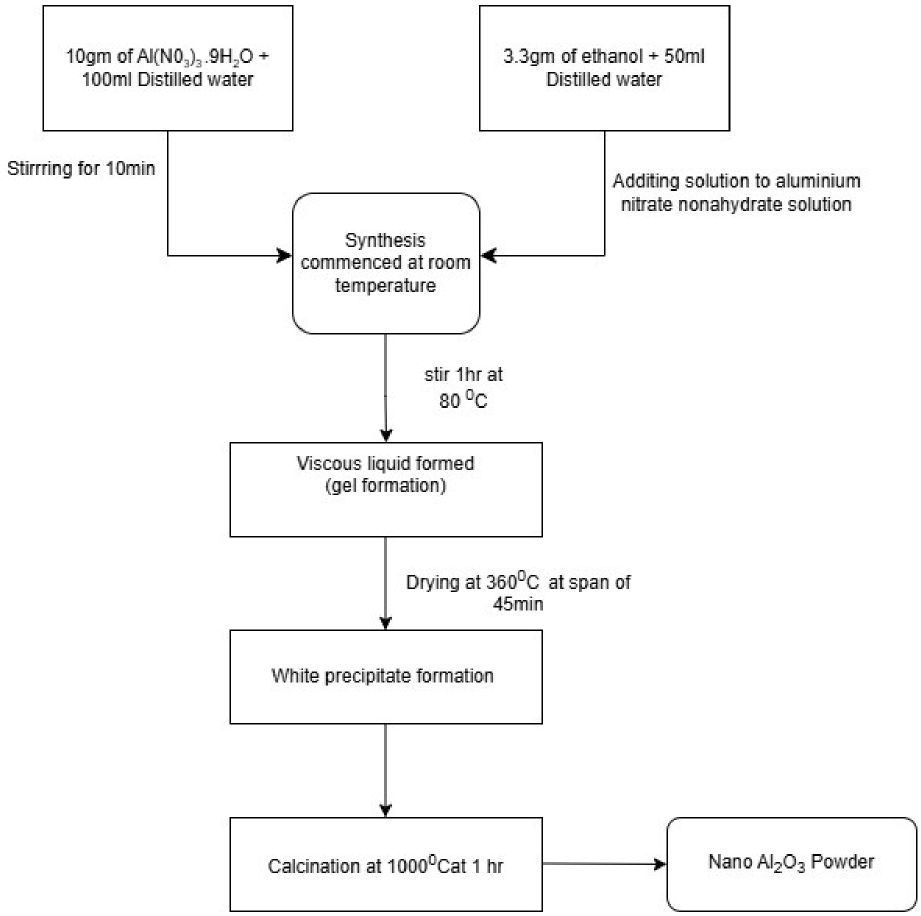

Figure 3.2: Synthesis of nanoparticle

3.4 Characterization of nanoparticles

Characterization of prepared Al_2O_2nanoparticles is a significant step in confirming their applicability as additives into diesel–pine biodiesel blends. This allows us to understand their main physical and chemical characteristics, like particle size, shape, purity, and structural features that are very important for their mixing and staying dispersed in fuel. In turn, their behavior in the blend directly influences the combustion quality, performance of the engine, and emission performance.

3.4.1 X-ray diffraction

The XRD technique was used to investigate the phase purity and crystalline structure of synthesized Al_2O_3nanoparticles. The XRD patterns were obtained from a Bruker D8 Advance diffractometer running at 40 kV and 40 mA, using a Cu-Kα radiation source and graphite monochromator. Intensity for diffraction peaks was recorded

20-70°(2θ) range with a step size of 0.03.The analysis confirmed that the alumina beads contain mainly α-phase.The XRD result of Al_2O_3 power[52] shown in figure 3.3 . It can be seen that the XRD result obtained peaks of Al_2O_3 sample close to the standard ICDC 46-1212 for aluminum oxide material.Peak-peak shown conforms the pure Al_2O_3. since similarities found at 2θ of 8.12, 15.92,25.59, 35.45, 38.07, 41.94, 43.94, 43.63, 52.83, 57.79, 61.59, 66.78, 77.13 and 77.47°[52].

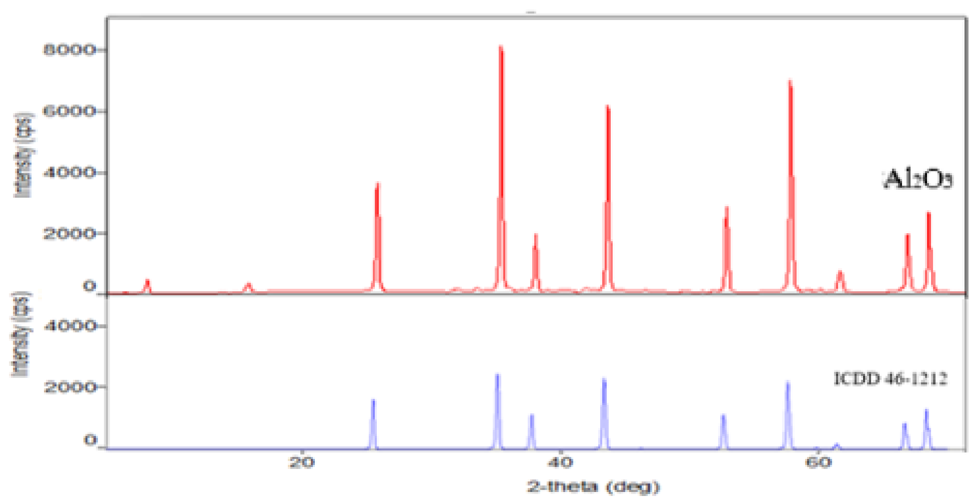

Figure 3.3: XRD graph of Al_2O_3 as per ICDD 46-1212.

XRD raw data included values of diffraction peak intensity with increasing 2θ from 10° to 90° with step increment of 0.02°. This resulted in a blur and fuzzy XRD spectrum when intensity was plotted against 2θ, causing difficulty in determining the clear peak width, peak position and corresponding intensity. So, data smoothing was carried out using ORIGIN 2018 software.A new set of smoothed data of peak intensity at increasing 2θ was obtained, which when plotted, produced clear XRD graph for synthesized Al_2O_3. During smoothing, values of peak intensities and peak positions varied slightly when compared to original raw data.

Recalling Debye-Scherrer equation, grain size for the synthesized Al_2O_3 was calculated as follows

$$D = \frac{k\lambda}{\beta \cos\theta} \tag{3.1}$$

Where:
K = Scherrer constant = 0.94

λ = wavelength of radiation = 0.154
β = FWHM in radian
Full width at half maximum (β) was obtained for each peak position using ORIGIN 2018 software.

3.4.2 UV-spectrometry

Ultraviolet (UV) spectrometry, also known as UV-visible (UV-Vis) spectroscopy, is an analytical technique used to measure the absorbance of ultraviolet and visible light by a substance. It is based on the principle that molecules absorb light at specific wavelengths, leading to electronic transitions in the molecule. This technique is widely used for qualitative and quantitative analysis of compounds in various fields, including chemistry, pharmaceuticals, environmental science, and nanotechnology[53].A UV-Vis spectrophotometer directs light of varying wavelengths through a sample, and a detector measures the amount of light absorbed by the sample. The absorbance is governed by Beer-Lambert's Law, which states that absorbance (A) is proportional to the concentration (C) of the absorbing species and the path length (L):

$$A = \varepsilon C L \tag{3.2}$$

where ε is the molar absorptivity (specific for each compound).
Wavelength Range :Ultraviolet region: 200–400 nm and Visible region: 400–700 nm. Al_2O_3nanoparticles exhibit strong absorption primarily in the UV region, with a significant absorption band typically occurring between 200 and 350 nm. This range corresponds to the electronic transitions within the material.A study by [54] demonstrated that Al_2O_3 nanoparticles synthesized via the sol-gel method exhibited a strong UV absorption peak around 250–300 nm, which is consistent with the absorption characteristics observed for nanoparticles.

3.5 Preparation of different fuel blends

Commercial Diesel was taken from the Armed Police Force, Nepal petrol pump and the pine oil was collected from Divya Rosin and Turpentine Pvt.Ltd,Attariya, Kailali. Which was manufactured from from raw product of tree is given naturally by pine trees available in the middle range of mountains region of Nepal.It is then transported from jungle to the factory and then processed to make Gum Rosin and Turpentine oil its state of art and modern steam plant.

The experimental test fuel samples were prepared by a two-step procedure with the aim of achieving stable and uniform nanoparticles dispersion. First, the base fuel blend (B20) was prepared by mixing 20% refined pine oil volumetrically, which is selected for its renewable nature and known ignition characteristics improvements, at 80% conventional diesel, as shown by[55]. In this base fuel blend aluminum oxide (Al_2O_3) nanoparticles were added at three concentration levels: 25 ppm, 50 ppm and 75 ppm by mass. For the present work, the required amount of (Al_2O_3) nanoparticles was prepared by sol-gel method in the laboratory followed by[51] and their size, purity and crystalline structure were verified by using XRD analysis.

Following established nanofluid preparation procedures, the Nano additives were initially mixed in the fuel using a magnetic stirrer for 30 minute to break up an early agglomeration. This step was followed by a 60 minute controlled ultrasonication treatment, during which the sample container was placed an ice bath to minimize thermal evaporation[29]. Ultrasonication ensured that the nanoparticles were evenly distributed and remained stable meaning they resisted settling or clustering over time. The fuel mixtures prepared for engine testing included B20 blended with 25 ppm, 50 ppm and 75 ppm of Al2O3 nanoparticles.

3.6 Characterization of biodiesel blends

To evaluate the basic fuel properties of the biodiesel samples, B20 and the nanoparticle-enhanced fuel blends (B20+25 ppm, B20+50 ppm, and B20+75 ppm) were characterized before engine testing. The essential properties of the biodiesel were subsequently studied to verify its suitability and to enable comparison with commercial diesel fuel. The evaluated properties are presented in Table 3.1.

Table 3.1: ASTM diesel fuel properties

Properties	**Mearured Value**	**Test Description**
Kinematic viscosity measured at 40 °C	1.9 - 4.1 cSt	ASTM D445
Heating value	43200 Kj/kg	ASTM D2382
Density determined at 15 °C	830 Kg/m^3	ASTM D1298
Cetane rating	30 - 65	ASTM D613
Flash point	52 °C	ASTM D3828

3.7 Fourier transform infrared spectroscopy (FTIR) test

FTIR is one of the common analytical techniques in the identification of different materials, such as organic compounds, polymers, and some inorganic substances. The basis of this technique involves shining infrared light onto a sample to analyze its chemical properties. Infrared radiation from the instrument ranges between approximately 10,000 to 100 cm^{-1}, some of which is absorbed and others pass through the sample. The absorbed energy induces rotational and vibrational changes within the molecules.These interactions are recorded by the detector as a spectrum, typically between 4000 to 400 cm^{-1} ; this acts as a finger print for the molecule in sample. Since each compound has its own unique spectral pattern, FTIR is very good at chemical identification. In this work, FTIR analysis of the B20 + 50 ppm fuel blend sample was carried out at the Banaspati Bivag, Kathmandu.

3.8 Engine specification

The studying engine performance and emission characteristics of pine-oil-based biofuel were carried out on a single-cylinder, four-stroke, direct-injection, water-cooled Kirloskar diesel engine. Tests were carried out under various loads applied on the dynamometer. The detailed test engine specifications are presented in Table 3.2.The fuel consumption was measured by a glass burette and a stopwatch, and the exhaust emissions were analyzed by a calibrated gas analyzer The pressure in the cylinder was measured by a pressure transducer fitted on the cylinder head. A crank-angle encoder attached to the crankshaft of the engine provided the means of recording the position of the crank at any instant during combustion. All the tests for the fuel blends of Diesel + Pine Oil + Aluminum Oxide (Al_2O_3) nanoparticles were conducted at the TU, IOE, Thapathali Campus, ,Kathmandu.

Table 3.2: Technical specifications of diesel engine

S. N	Parameters	Specification
1	Manufacturer	Kirloskar Diesel Engine
2	Engine	Liquid Cooled Diesel Engine
3	No. of Strokes	4
4	No. of cylinders	1
5	Starting	Electric Motor cranking
6	Combustion Principle	CI
7	Loading	Eddy Current dynamometer
8	Compression Ratio	15:1 – 18:1
9	Crank Radius	55 mm
10	Connecting Rod Length	300 mm
11	Maximum Operating Speed (RPM)	1500

3.9 Experimental setup and procedure

The engine was first run with standard diesel for approximately 15–20 min until the engine attained a state of steady operation. Once all the parameters related to the running of the engine attained a state of stability, the experiment was continued with the pine–biodiesel blend (B20) and with Al_2O_3 nanoaddtives fuel blends. Water as the coolant was passed through the engine at a pressure of about 1 atm during the experiment, as measured with the inbuilt pressure gauge.The load levels were applied using an eddy current dynamometer: 1 , 3 , 6 , and 9 kg, while the constant engine speed was maintained to 1500 rpm as possible. Fuel consumption was measured using a burette and stopwatch arrangement, recording the volume of fuel consumed over 60 seconds for each test run. The compression ratios applied were 17:1 and 15:1 for the nanoparticle-enhanced fuel blends. The same procedure was repeated using standard diesel to enable proper comparison between diesel and the nano-blended fuels. Figure 3.4 shows the block diagram of the experimental setup with all the sensors used in the system.

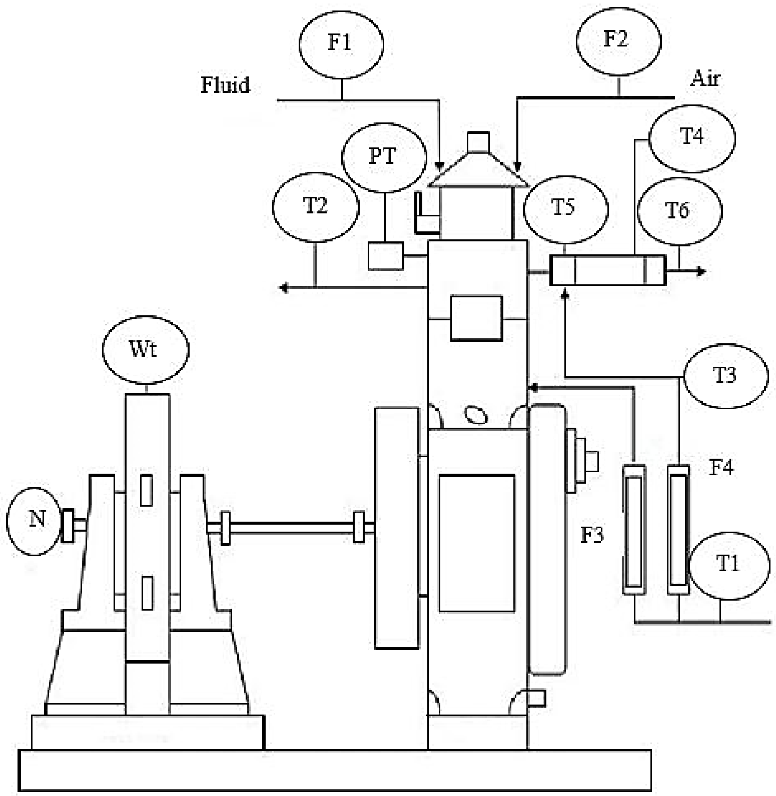

Figure 3.4: Test engine block diagram

The symbols in the block diagram are defined as follows:

$$PT = \text{Pressure sensor}$$
$$T = \text{Temperature sensor}$$
$$F = \text{Mass flow sensor}$$
$$N = \text{Speed sensor}$$
$$Wt = \text{Load sensor}$$

Based on experimental data, an assessment was carried out to identify the optimal fuel blends. Engine performance parameters such as BP, BSFC, BTE along with emissions level of CO, CO_2, NO_x and HC were examined.

4. Results & Discussion

4.1 Characterization of nanoparticles

The required specification of Al_2O_3 nanoparticles has been prepared by sol-gel method were characterized to conform their physical and structural properties before blending with biodiesel-diesel fuel mixture.The phase and crystalline structure of Al_2O_3 were examined using X-ray diffraction (XRD) ,which confirmed the presence of sharp peaks corresponding to Al_2O_3 nanoparticles, indicating a high degree of crystallinity. To further evaluate the functional groups and bonding characteristics , Fourier Transform Infrared Spectroscopy(FTIR) was performed , which showed absorption bands typical of Al-O vibrations.

4.1.1 UV-absorption analysis

UV-Visible spectroscopy is an important technique used for the characterization of nanoparticles. Its principal is chased an absorption of UV-Visible radiation. The absorbance peak from 200 nm to 400 nm show presence of nano particles[56].The UV test was carried out at Nano-Material laboratory, IOE, Pulchwok Campus, Pulchwok, Lalitpur, showed a peak value observed at 260 nm within the range of 200-400 nm and, indicating that the sample contains Al_2O_3 nanoparticles shown in figure 4.1.

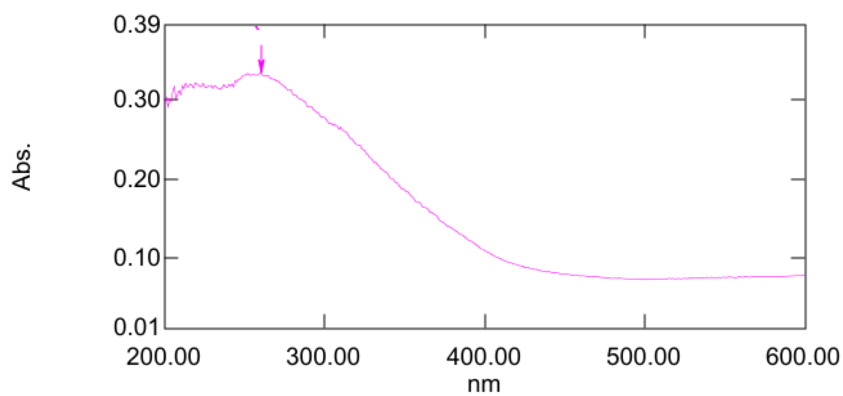

Figure 4.1: Uv-absorption test of Al_2O_3 nanoparticle

4.1.2 XRD analysis

X-ray powder diffraction method, as detailed in section 3.4, was used to quantify crystallinity, phase purity and particle size of Al_2O_3 nanoparticles synthesized. Incident X-ray is diffracted by the Al_2O_3 nanoparticles, as per Bragg's law, resulting in peak intensities and related peak position values. XRD plot, given in figure 4.2, displayed eight major peaks, one of them being the result of diffraction by a set of lattice planes of crystal with orientation in 3-dimensional space. X-rays have wavelength of order Angstroms (Å), similar to inter-planar spacing within Al_2O_3 crystals being used as diffraction gratings to produce multiple diffraction pattern. Nine distinct peaks signified presence of nine sets of lattice planes, each within a constant 3-dimensional co-ordinates system and direction characterized by miller indices. The 2θ angular positions of observed peaks were 25.42°, 34.83°,37.44°,43.05°,57.27°,66.28°,67.89°. All the diffraction peaks, as shown in Table 4.2, were in good concordance with standard JCPDS-ICDD File No 46-1212 data of Al_2O_3 with reasonable $\pm$ 0.10 peak variation. No other peaks were seen, which indicates the formation of pure Al_2O_3 nanoparticle.Each diffraction peaks were indexed as the same as Al_2O_3 nanoparticles miller indices (h, k, l) .i.e. (012). (104), (110), (113), (024), (116), (214) and (300) respectively. By applying the Scherer formula, the obtained size represents the average or apparent crystalline/grain size for the material. The size of the grain size of nanoparticles was found to be 35 nm .

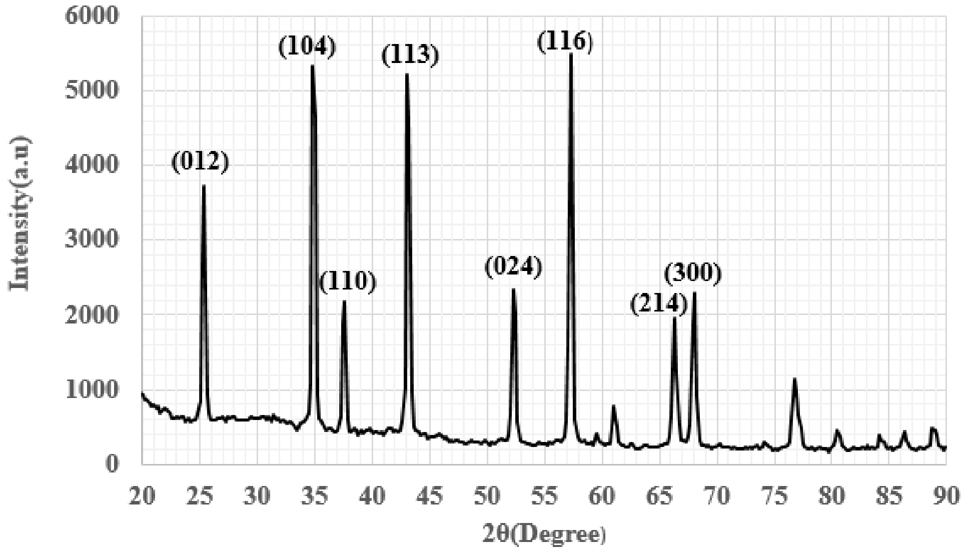

Figure 4.2: XRD spectrum of synthesized Al_2O_3 nanoparticles

4.1.3 FTIR analysis

FTIR (Fourier Transform Infrared Spectroscopy) graph compares the transmittance spectra of pure diesel and B20+50 ppm nanoparticle blend over a wavenumber range of 500–4500 cm^{-1} as shown in figure 4.3. Both diesel and B20+50 ppm blends exhibit strong peaks in the region 2800–3000 cm^{-1} indicating the presence of alkanes(CH_3, CH_2, CH groups) from hydrocarbons in diesel and biodiesel [57].The B20+50 ppm blend shows a slightly higher transmittance, suggesting minor compositional changes due to biodiesel and nanoparticles.The B20+50 ppm blend has a more prominent peak compared to diesel in range of C=O Stretching (1700–1800 cm^{-1}).

C-O stretching in the range of (1000–1300 cm^{-1}) stronger peaks in this region for B20+50 ppm suggest a higher presence of oxygenated functional groups, likely due to oxygenated compounds in biodiesel[58].The presence of Al_2O_3 nanoparticles can be confirmed by absorption bands in the region 500–800 cm^{-1}corresponding to Al-O stretching vibrations.

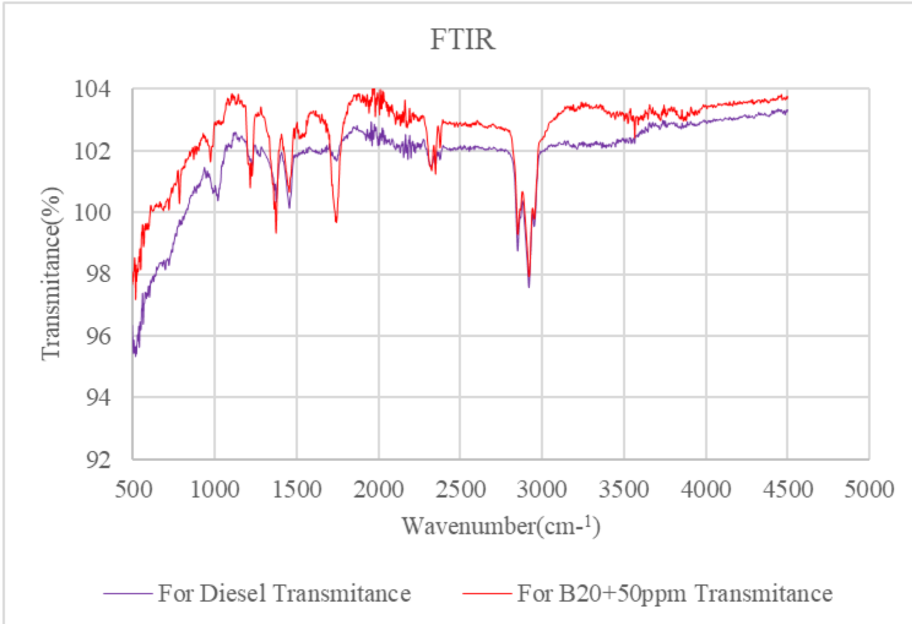

Figure 4.3: FTIR graph

4.2 Physicochemical property of test fuel

Among the prepared test fuels, pine oil , B20 and B20+25ppm fuel blends were characterized for their physicochemical properties such as density, kinematic viscosity, cetane number, calorific value, pour point and flash point as shown in table 4.1.

Table 4.1: Physicochemical property

S.N	Characteristics	Test	Diesel	B20	B20+50ppm
1	Density at 15°C,kg/m^3	ASTM D1298	810-845	840	842
2	Flash Point °C (Min)	IP170	57	42	44
3	Cetane Number (Min)	IP 380/NS 237	46	51	52
4	Pour Point °C (Max)	ASTM D5949	-25	-10	-15
5	Kinematic Viscosity @40°C, Cst	ASTM D445	2 - 4.5	2.268	2.15
6	Calorific Value (Kcal/Kg)	IS 1448	11110	11214	11300

4.3 Effect of biodiesel blends with nano Al_2O_3 additive on engine performance

The engine performance characteristics were evaluated by fueling conventional diesel fuel , biodiesel (B20) and blends with different concentration of nano additives. The experiment was conducted at different compression ratios 15 and 17 for different fuel blends and compared the results with commercial diesel, which are discussed below:

4.3.1 Brake power at varying load condition and different compression ratio

The brake power of the engine is always less than that of indicated power of an engine.The brake power versus load characteristics for diesel, B20, B20 blended with Al_2O_3 nanoparticles at different concentration 25 ppm, 50 pppm and 75 ppm were evaluated at compression ratios of 17 and 15 illustrates in figure 4.4 and 4.5 respectively. At CR 17, B20 showed a slightly higher BP compared to commercial diesel, despite B20 having lower calorific value than diesel can be attributed to the presence of inherent oxygen in pine oil, which improves combustion efficiency and heat release rate. Similar findings were reported by[59].

The addition of Al_2O_3 nanoparticles further enhanced brake power, with the maximum value observed for B20+75 ppm of 2.74 KW at 9 kg load, which was higher than both diesel and B20. This enhancement is explained by the catalytic role of Al_2O_3 nanoparticles, which promote atomization, accelerate oxidation reactions and improve the combustion rate due to their high surface to volume ratio. Similar trend were reported by[60], who noted that Al_2O_3 nanoparticles increased brake power when dispersed in biodiesel blends, and by[61] who conformed improved engine performance with nanoparticle-assisted combustion.

At CR 15, a comparable trend was observed B20 again delivered slightly higher BP than diesel and further improvements were achieved with Al_2O_3 addition. The maximum brake power was recorded for B20+75 ppm of 2.67 Kw at a load of 9 kg. When comparing compression ratios, CR 17 consistently produced higher brake power than CR 15 across all blends. This can be validated by thermodynamic principles, as a higher compression ratio increase peak temperature and pressure during combustion, thus improving thermal efficiency and brake power. Similar results reported by[62] and [63] who found that higher compression ratios yield better engine performance for biodiesel blends.

Figure 4.6 illustrates the variation of BP of B20 test fuel at different compression ratios (CR) 17 and 15.For B20 BP increases linearly with load. At CR 17 BP is consistently higher than CR 15, with improvements of about 3.8% at 1 Kg load (0.26 to 0.27 Kw), 2.2% at 3 Kg load (0.89 to 0.91 Kw), 1.2% at 6 Kg load (1.73 to 1.75 Kw) and 1.6% at 9 Kg load (2.54 to 2.58 Kw). This shows that the effect of higher compression ratio on BP is more significant at lower load. Similarly in Figure 4.7 shows variation of BP of B20+25 ppm test fuel with varying load condition at compression ratios (CR) 17 and 15. With 25 ppm nano-additives, BP improves further at CR 17 compared to CR 15. The increment are about 7.1% at 1 Kg load (0.28 to 0.30 Kw), 6.7% at 3 Kg load (0.90 to 0.96 Kw), 1.1% at 6 Kg load (1.75 to 1.77 Kw) and 2.7% at 9 Kg load (2.61 to 2.68 Kw). The largest relative gain is observed at low load indicating better combustion stability with nano-additives under lean conditions.

In Figure 4.8 shows variation of BP of B20+50 ppm test fuel with varying load condition at different compression ratios(CR) 17 an 15. For the 50 ppm additives blend at CR 17 yields slightly higher BP than 15. The improvements are 6.7% at 1 kg load (0.30 to 0.32 Kw), 5.4% at 3 Kg load (0.92 to 0.97 Kw) , 1.1% at 6 Kg load (1.76 to 1.78 Kw) and 3% at 9 Kg load (2.63 to 2.71 Kw). Again the enhancement is more noticeable at low and high loads. Also in Figure 4.9 shows variation of BP of B20+75 ppm test fuel with varying load condition at different CR. At the highest additives 75 ppm nano-additives the benefit of CR 17 is most pronounced. BP increments over CR 15 are 10% at 1 Kg load (2.67 to 2.74 Kw), 1% at 3 kg load (0.96 to 0.97 Kw), 1.1% at 6 Kg load (1.77 to 1.79 Kw) and 2.6% at 9 Kg load (2.67 to 2.74 Kw). This indicates that the synergistic effect of nano-additives and higher compression ratio results in the maximum improvement at very low load while the difference narrows at higher loads.

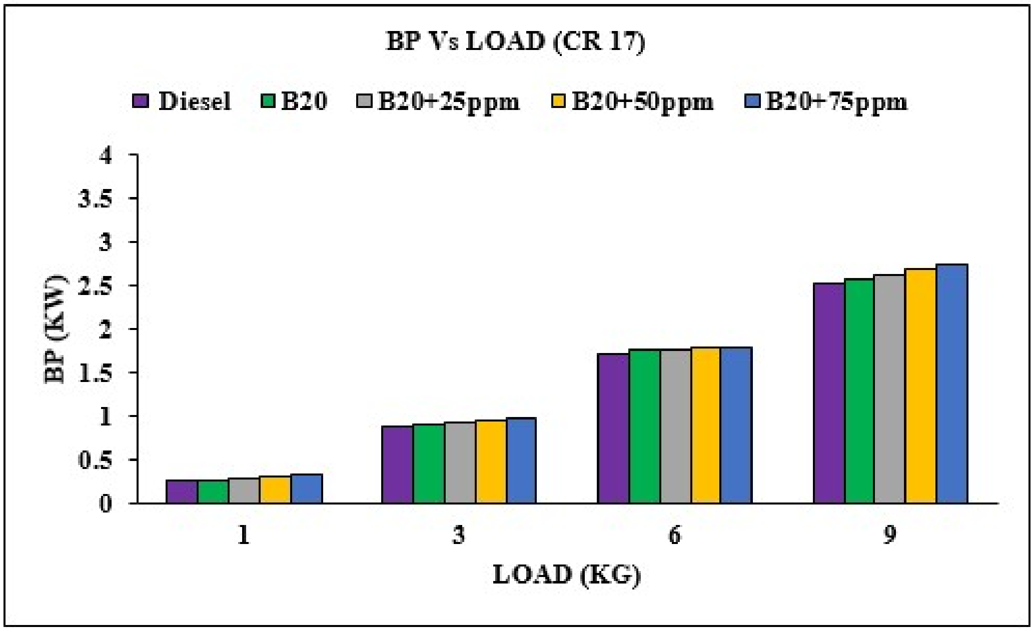

Figure 4.4: BP with varying load condition at CR 17

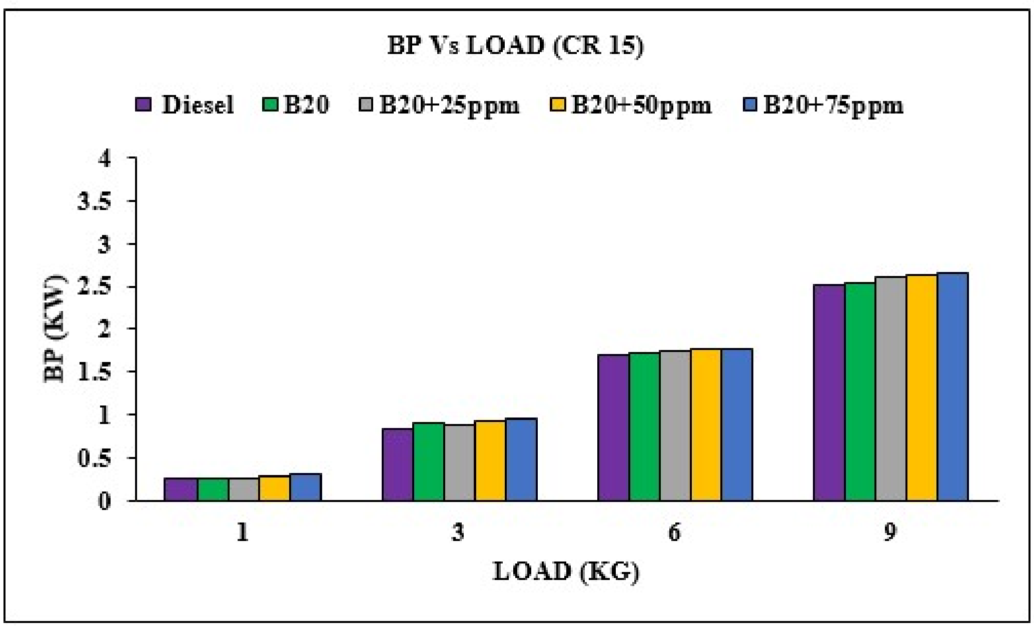

Figure 4.5: BP with varying loading condition at CR 15

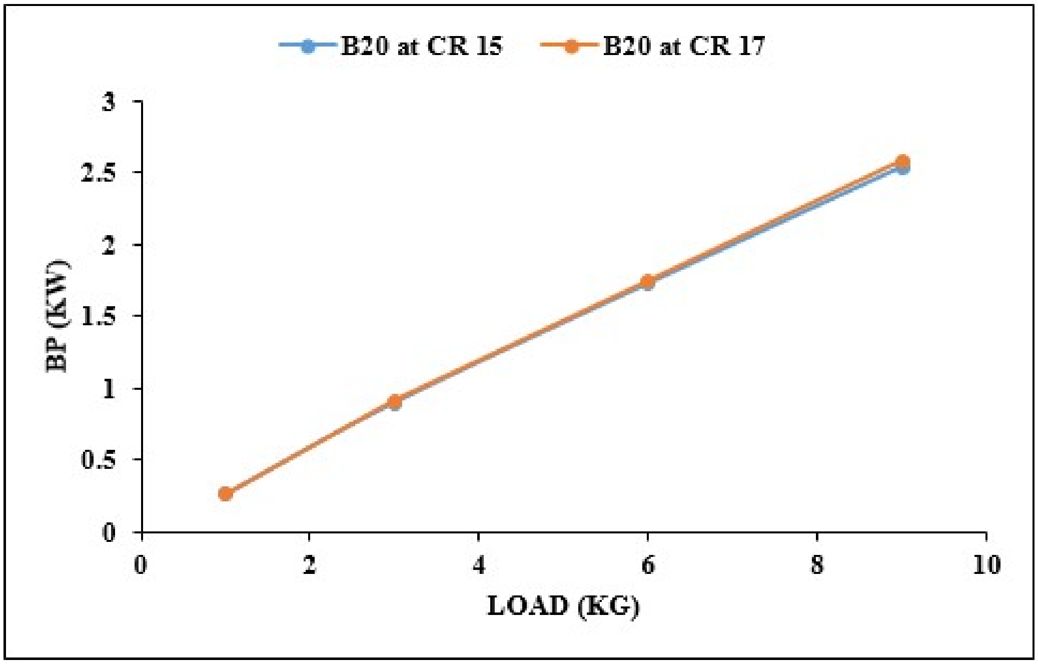

Figure 4.6: Variation of BP of B20 at different CR

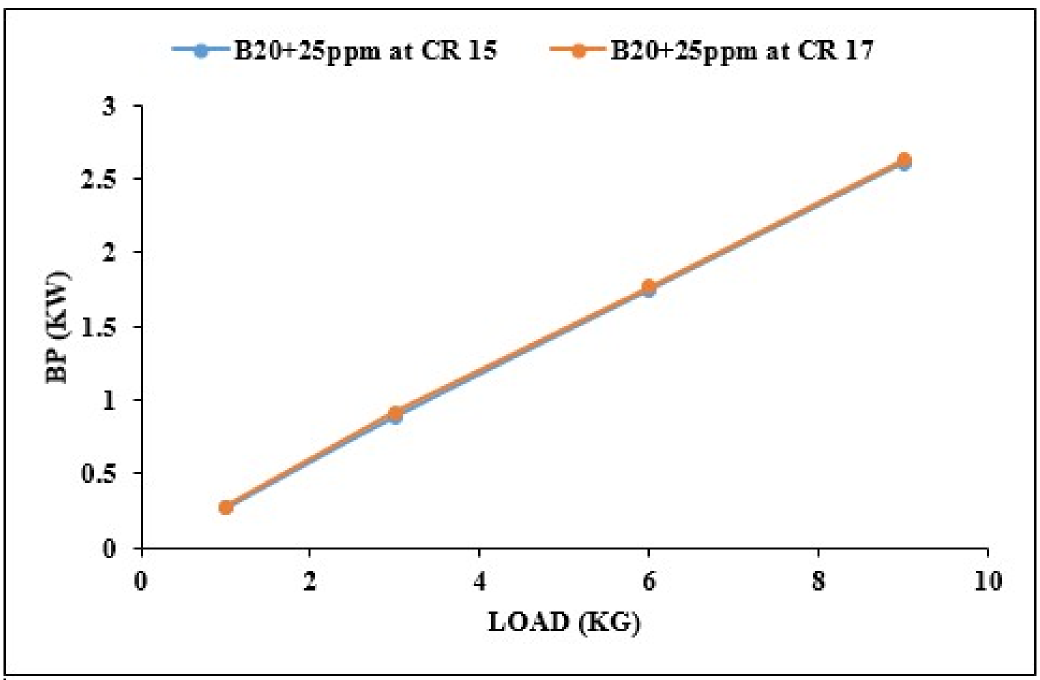

Figure 4.7: Variation of BP of B20+25 ppm at different CR

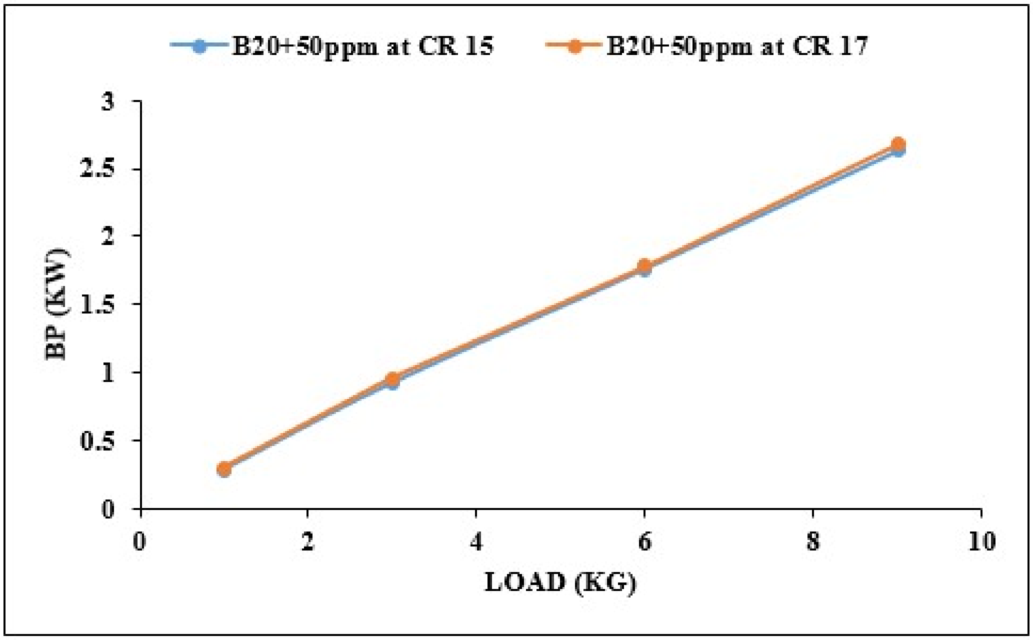

Figure 4.8: Variation of BP of B20+50 ppm at different CR

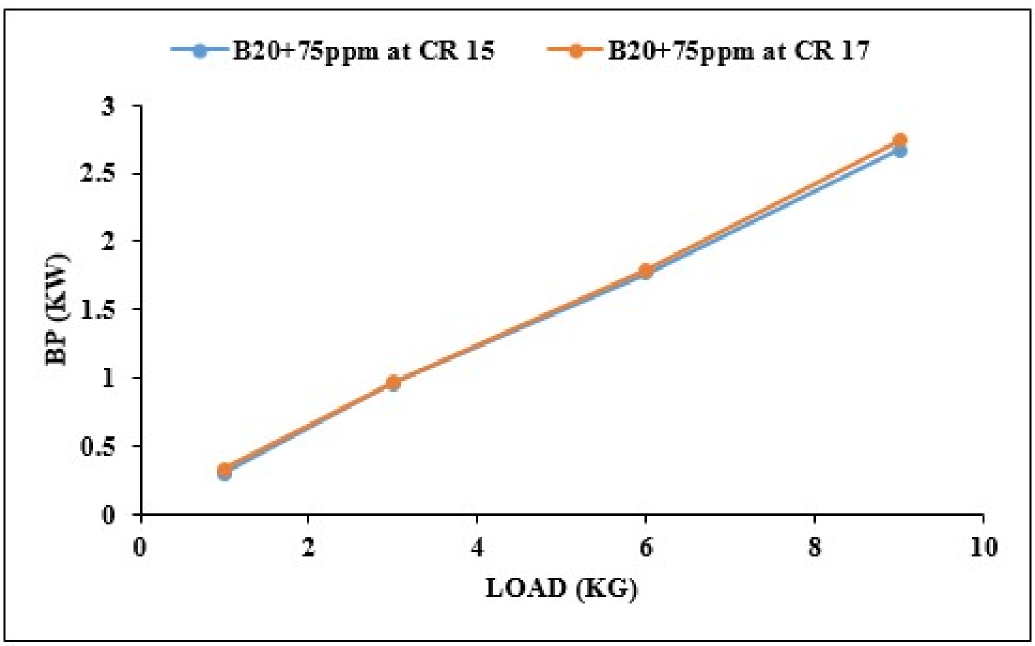

Figure 4.9: Variation of B20+75 ppm at different CR

4.3.2 Brake specific fuel consumption at varying load condition and different compression ratio

The brake specific fuel consumption (BSFC) variation with engine load at compression ratios 17 and 15 are shown in figures 4.10 and 4.11. It is one of the key indicators of fuel economy in an engine. The lower value of BSFC means better fuel economy. At the higher compression ratio , the engine exhibited lower fuel consumption. The addition of nanoparticles further reduced the BSFC because of improved combustion characteristics. An increase in the compression ratio increases the combustion temperature, which reduces the viscosity of the fuel and improves its physical properties. This leads to finer atomization and more complete combustion, ultimately reducing BSFC [64].

Figures 4.12, 4.13, 4.13 and 4.15 shows that when the load was increased, the BSFC decreased for both diesel and the nano additives fuel blends. Furthermore, when Al_2O_3 nano concentration was increased from 25 to 75 ppm BSFC was also reduced. This is attributed to the reduced ignition delay of the nanoparticles, which can attributed to their increased surface to volume ratio. Additionally, when the nanoparticles mass fraction was increased, BSFC went down at any given load. At CR 17, the base fuel B20 and addition of Al_2O_3 nanoparticles of concentration 25, 50 and 75 ppm resulted in decreased of 3.14%, 6.28%, 8.8% and 11.32% in BSFC compared to diesel fuel at lower load. Correspondingly at higher load resluted in decreased of 5.26%, 10.52%, 18.42% and 21.05% in BSFC respectively.This result showed reduction of BSFC in higher load is more significant than lower load due to the cylinder temperature and pressure are relatively low, so that additional oxygen does not greatly enhance combustion at lower load, the combustion temperature rises significantly, allowing the oxygen fuel to burn more complete , this combustion efficiency results in greater reduction in BSFC at higher load.[65]. The decreased in BSFC at CR 15 for test fuel blends for B20, B20+25 ppm, B20+50 ppm and B20+75 ppm compared with commercial diesel by 2.56%, 7.69%, 10.25% and 15.38%, at higher load, corresponding test fuel blends decreased in BSFC at lower load by 2.12%, 3.82%, 5.53% and 6.82% respectively.

At CR 15, Brake specific fuel consumption of base fuel B20 and nano- enriched fuel B20+25ppm, B20+50 ppm and B20+75 ppm test fuel varies from 0.38 to 2.3 Kg/kWh, 0.36 to 2.26 kg/kWh, 0.35 to 2.22 kg/kWh and 0.33 to 2.19 kg/kWh respectively at higher load and lower load.Corresponding values of BSFC at CR 17 varies from 0.36 to 1.54 kg/kWh, 0.34 to 1.49 kg/kWh, 0.31 to 1.45 kg/kWh and 0.3 to 1.41 kg/kWh.

The addition of Al_2O_3 resulted in lower BSFC illustrating reducing trend of BSFC with increasing in nanoparticles in fuel blend, which is in well agreement with previous studies for Al_2O_3 as fuel additive[46]. The Al_2O_3 nanoparticles provides better atomization of fuel and helps in better combustion. This enhances combustion after a fuel droplet gets injected inside combustion chamber by breaking it into fine secondary fuel droplets, augmenting air-fuel mixing and lowering BSFC. In addition of Al_2O_3 increases the surface area to volume ratio of fuel blends, which leads to better combustion and reduces BSFC.

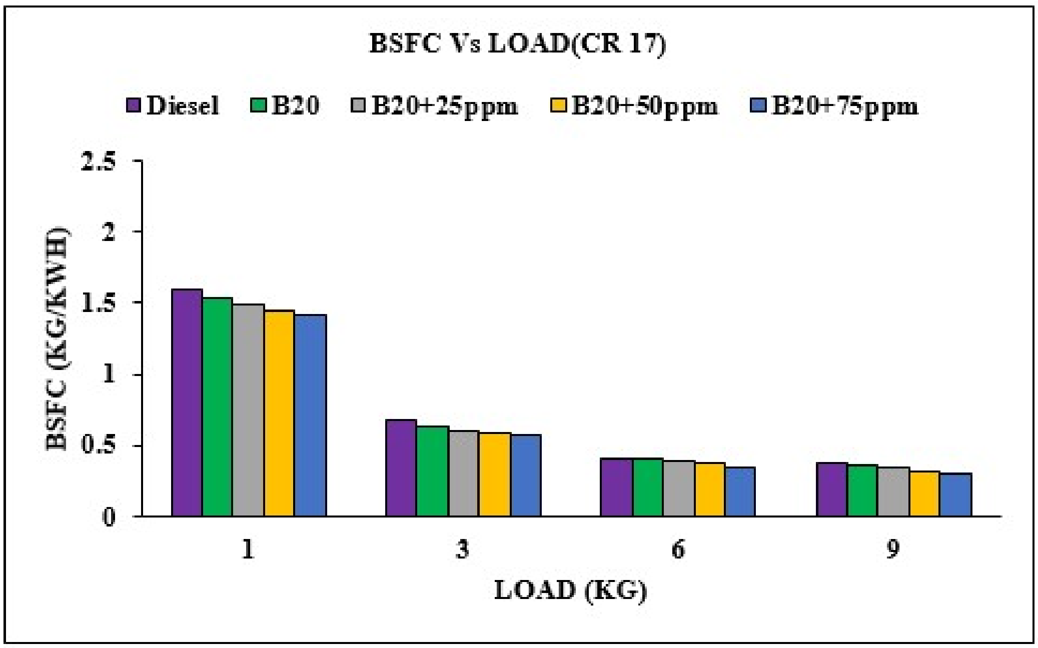

Figure 4.10: BSFC with varying load at CR 17

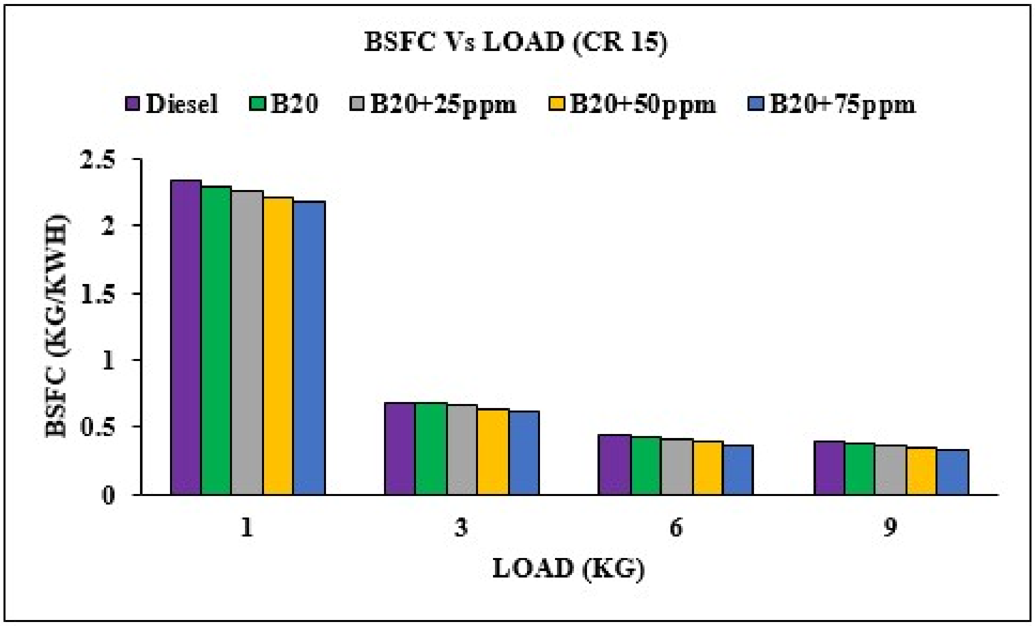

Figure 4.11: BSFC with varying load at CR 15

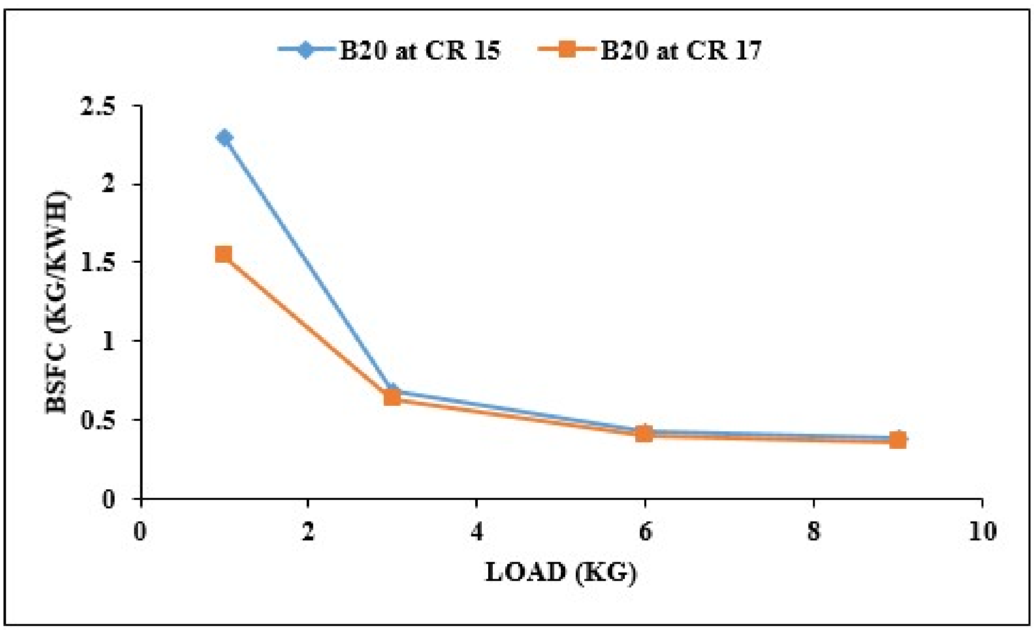

Figure 4.12: Variation of BSFC of B20 at different CR

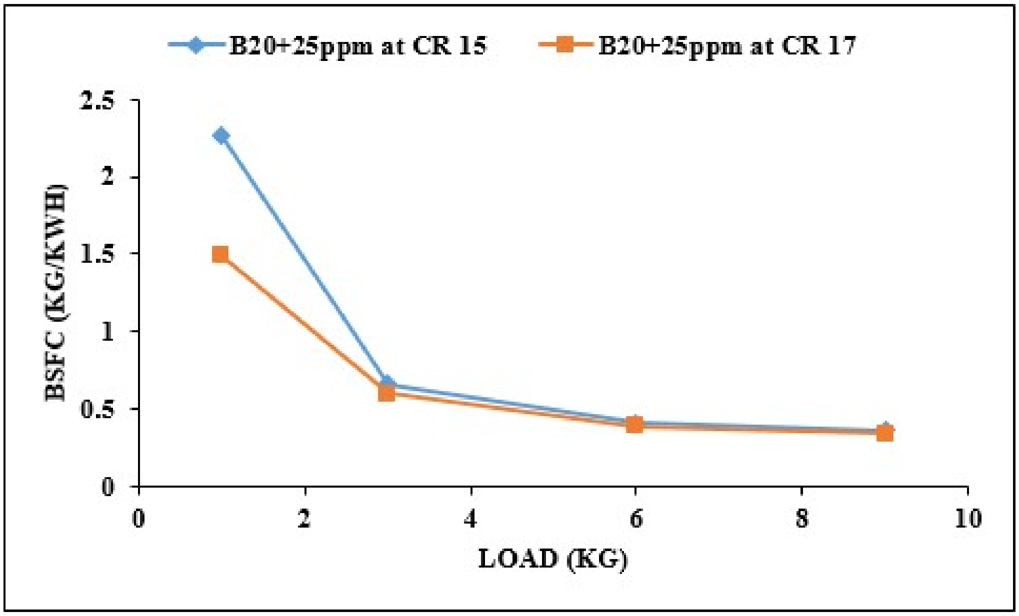

Figure 4.13: Variation of BSFC of B20+25 ppm at different CR

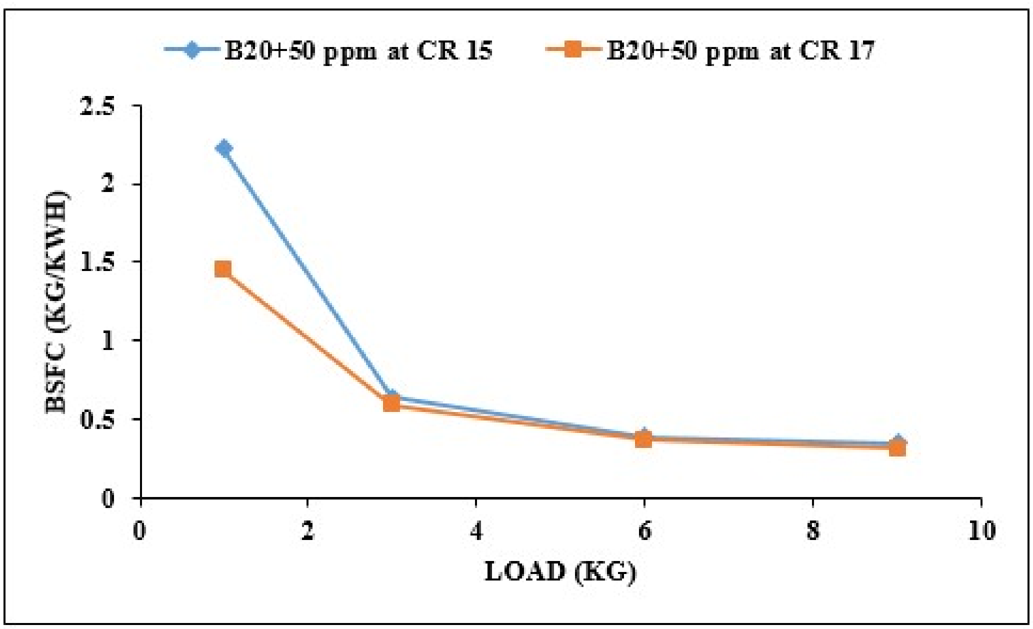

Figure 4.14: Variation of BSFC of B20+50 ppm at different CR

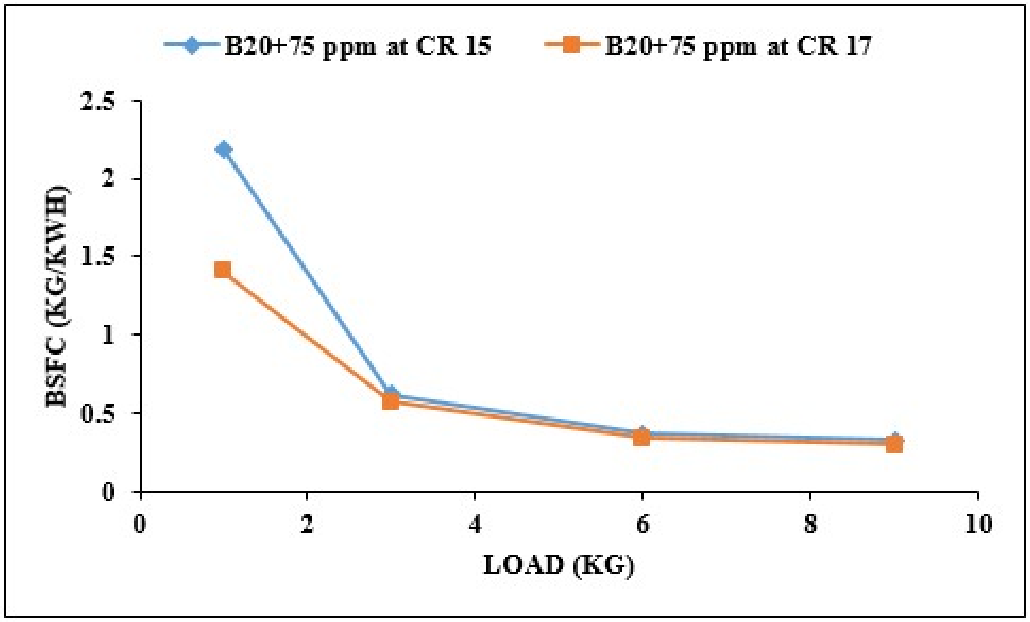

Figure 4.15: Variation of BSFC of B20+75 ppm at different CR

4.3.3 Brake thermal efficiency at varying load condition and different compression ratio

Brake thermal efficiency (BTE) gives the amount of heat energy supplied by fuel, which an engine successfully converts into useful brake power. The variation of BTE versus engine load for compression ratios 17 and 15 is shown in figures 4.16 and 4.17, respectively. For all the fuel blends tested under these two compression ratios, BTE was observed to increase with increasing load. The trend seen may be attributed to the combined effects of an overall increase in brake power output and a reduction of heat loss through the cooling system at higher load conditions.

At both compression ratios, B20 blend showed better thermal efficiency than standard diesel. The main reason for this improvement is due to the high oxygen content in biodiesel, which facilitates more complete and efficient combustion inside the engine. Furthermore, the addition of nano-additives enhances efficiency even further with B20+75 ppm consistently achieving the maximum values at all load conditions. For instance at full load diesel records 22.43% efficiency at CR 15 and 22.85% at CR 17 whereas B20+75 ppm improves this to 22.86% and 23.86% respectively corresponding to 4.23% improvement over diesel at CR 17 and 1.91% improvement in BSFC was observed at CR 15 .

The comparison between compression ratios shows that CR 17 consistently produces higher BTE than CR 15 across all fuels and loads. The improvement is most pronounced at low load and medium loads, where the effect of higher in-cylinder temperature and reduced ignition delay has a great influence on combustion quality. At high loads, the relative improvement between CR 17 and 15 becomes smaller but remains positive. These results are consistent with earlier studies, where biodiesel blends were found to achieve better thermal efficiency[66], while inclusion of nano-additives further enhanced performance through catalytic effects and improved fuel atomization[67]. In addition, higher compression ratios are known to improve thermal efficiency by increase peak pressures, reducing ignition delay and improving thermodynamic cycle efficiency[68].

At higher load, compression ratio of 17, the observed values of BTE for commercial diesel, B20 fuel and B20 blends containing 25 ppm, 50 ppm and 75 ppm additives were 22.85%, 23.52%, 23.62%, 23.71% and 23.86% respectively. At lower load corresponding fuel blends, the observed BTE values were 5.39%, 5.48%, 5.61%, 5.76% and 5.87%. Similarly at compression ratio of 15 the decreased BTE was observed, when compared with CR 17.

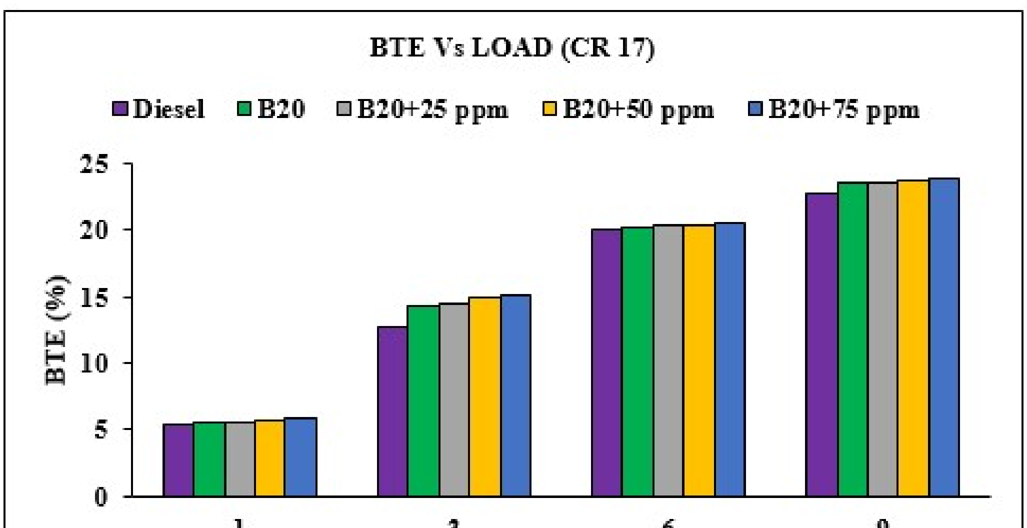

Figure 4.16: BTE with varying load at CR 17

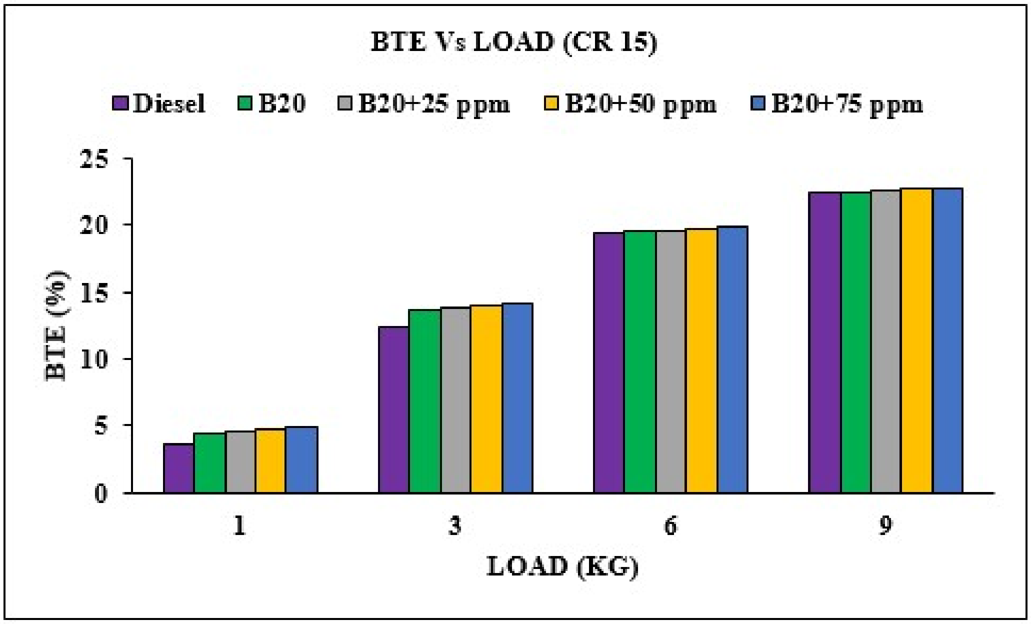

Figure 4.17: BTE with varying load at CR 15

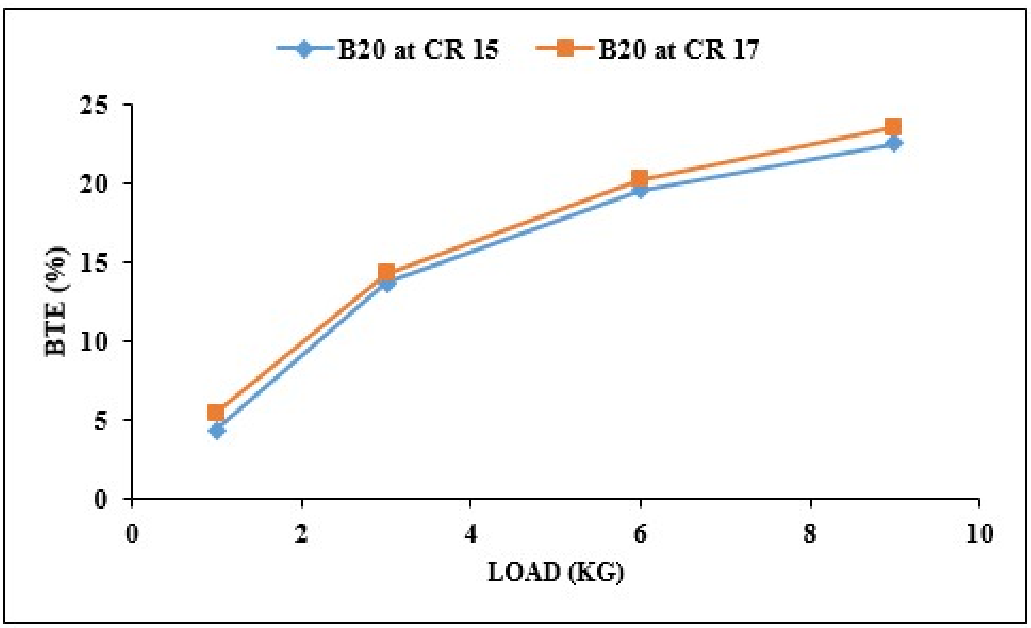

Figure 4.18: Variation of BTE of B20 at different CR

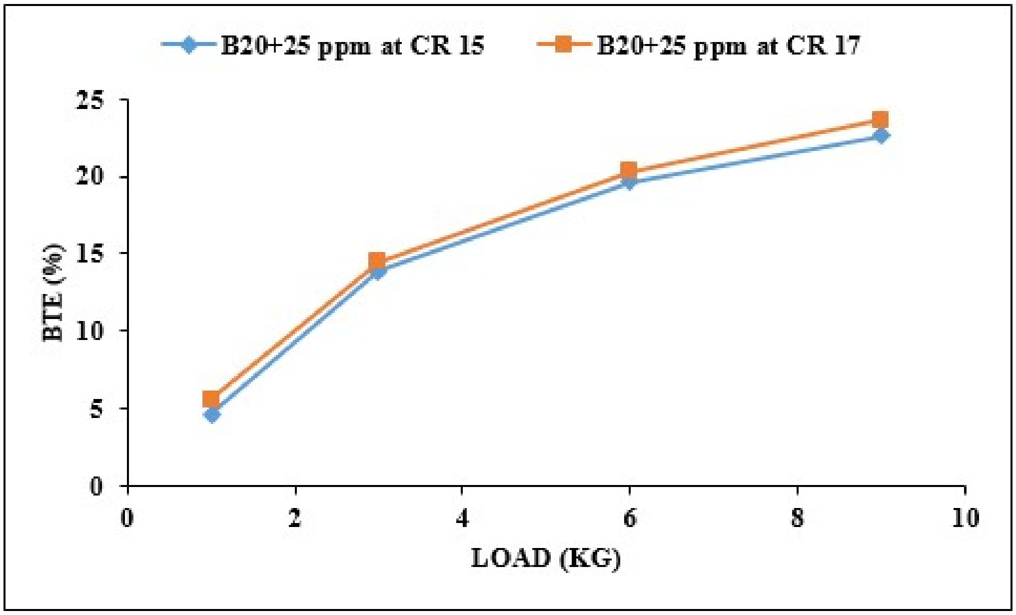

Figure 4.19: Variation of BTE of B20+25 ppm at different CR

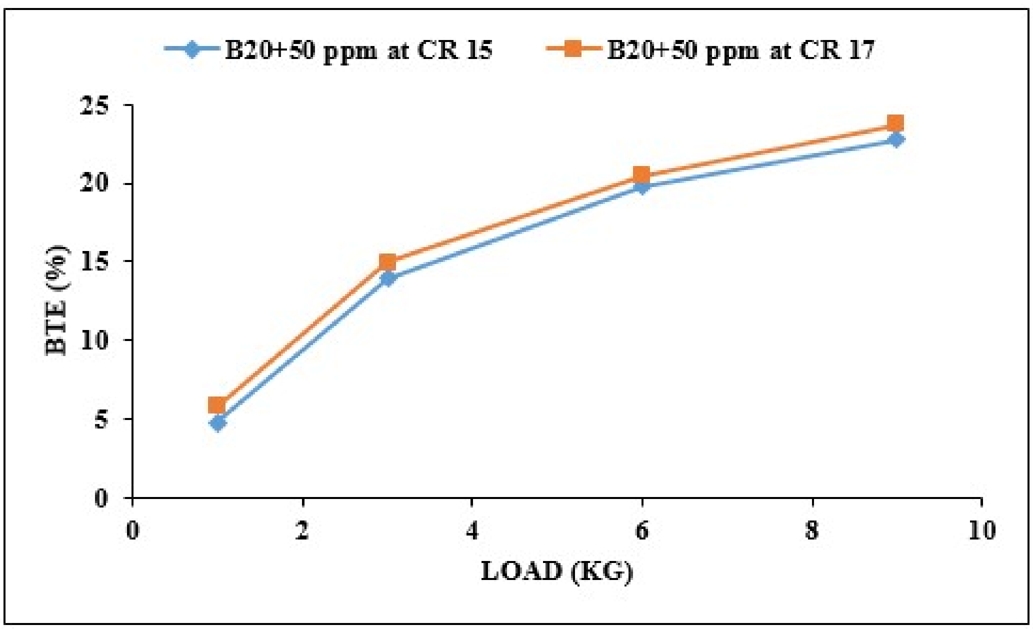

Figure 4.20: Variation of BTE of B20+50 ppm at different CR

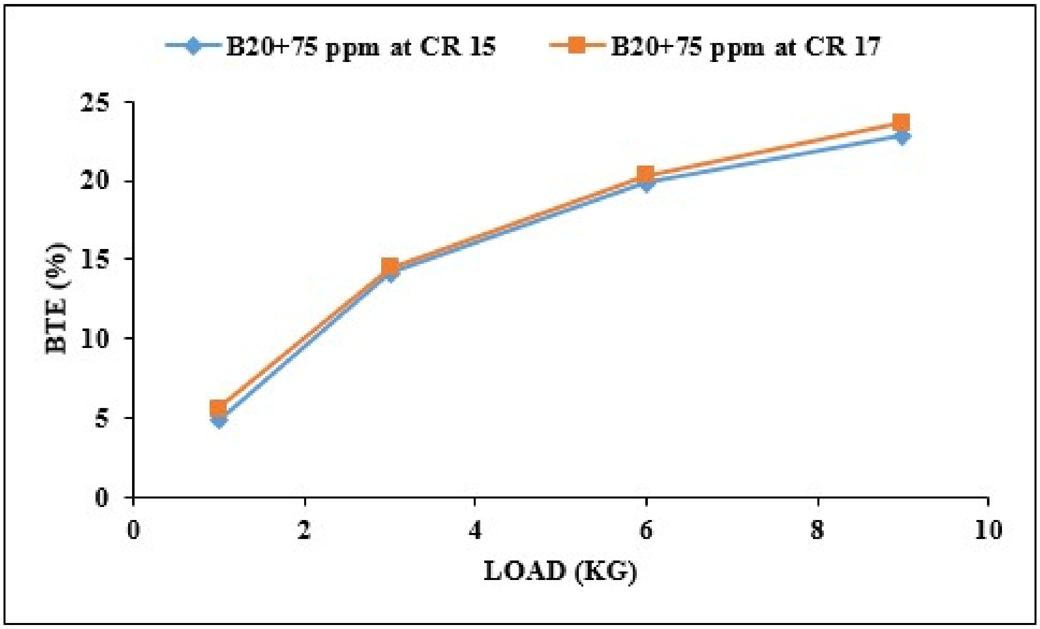

Figure 4.21: Variation of BTE of B20+75 ppm at different CR

4.4 Effect of biodiesel blends with nano Al_2O_3 addition on engine emissions

4.4.1 Carbon Monoxide Emission (CO)

Figure 4.22 shows the variation of CO emission with respect to the increase in engine load for various fuel blends and pure diesel at a compression ratio of 15. In general, CO emissions decrease with increased load on the engine. The addition of biodiesel (B20) and 50 ppm of Al_2O_3 nanoparticles improves combustion so that CO emissions are considerably lower. At medium and high loads, these fuel blends show a considerable decrease in CO emissions compared with pure diesel. It can be seen from figure 4.22 that CO emissions at full load are reduced by approximately 12.5% for B20 and 25% for B20+50 ppm compared with diesel fuel. Corresponding reductions at low load are about 8.33% and 16.67%, respectively. This may be attributed to the higher thermal conductivity brought in by the nanoparticles, which favors a more complete combustion, besides the additional oxygen carried by the pine oil, which acts in support of converting CO into CO_2[69, 70, 71].

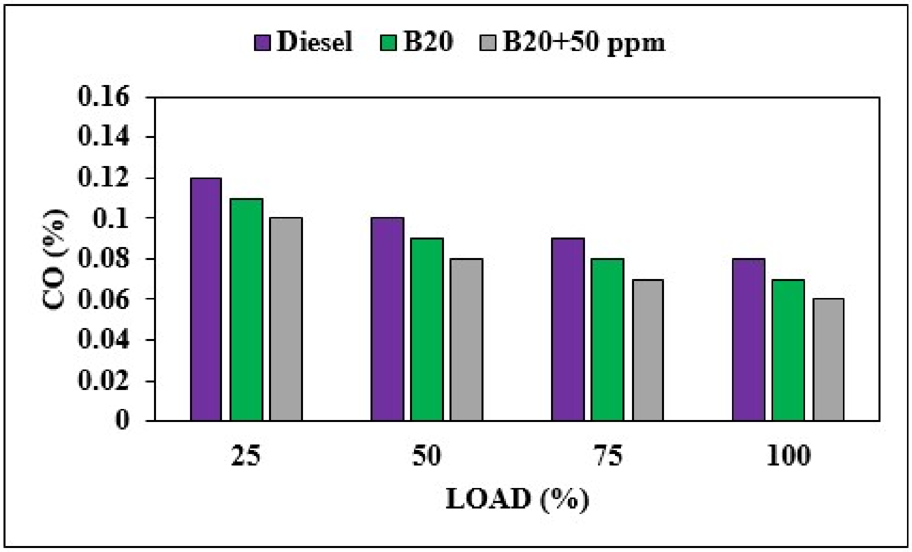

Figure 4.22: Variation of CO emission with load at CR 15

4.4.2 Carbon Dioxide (CO_2) Emission

Figure 4.23 illustrates a comparison of carbon dioxide (CO_2) emissions between diesel and pine oil blends. For all test fuels, CO_2 emissions exhibited a progressive increase with rising engine load.The incorporation of pine oil into the fuel blend with nano-additives resulted in a further elevation of CO_2 emissions. Among the tested fuels, B20+50 ppm blend generated higher CO_2 levels compared to B20 biofuel, while diesel recorded the lowest CO_2 emissions. The elevated CO_2 concentration in the exhaust indicates a more complete combustion process occurring within the engine [72].

At lower load i.e 25% engine load, the biofuel B20 and addition of alumina nanoparticles at 50 ppm shows 4.9% and 23.4% increment in CO_2 emission, respectively, when compared to commercial diesel. This reduction takes place because of the higher oxygen content that is present in biodiesel, which supplies additional oxygen for better combustion of fuel [73]. Adding nanoparticles further tends to homogenize the combustion environment and allows for a more complete burn of fuel, thus reducing CO emissions. Similarly at higher load i.e 100% engine, load B20 and B20+50 ppm biodiesel shows 5.11% and 11.76% increment in CO_2 emission respectively, when compared to the commercial diesel.

This results in generally higher exhaust emission level of CO_2 for B20 compared with commercial diesel under same load conditions and even higher emission level when a combustion enhancing nanoparticles is added to B20, suggesting improved combustion completeness and oxidation chemistry with nanoparticles present. Many research shows that biodiesel's oxygen content and improved combustion often lead to increased exhaust emissions of CO_2 compared to petrol-diesel, even as other pollutants like CO are reduced due to better oxidation of carbon species.

In conclusion, while increased CO_2 in the exhaust with biodiesel blends reflects more complete combustion due to fuel's oxygen content and the action of additives, the overall life-cycle CO_2 impact of biodiesel blends is lower than that of fossil diesel because the carbon originates from recent biological capture rather than long buried fossil carbon. This distinction is crucial exhaust emission CO_2 may be higher but life cycle emissions are reduced making biodiesel a more sustainable fuel choice compared to conventional diesel[74].

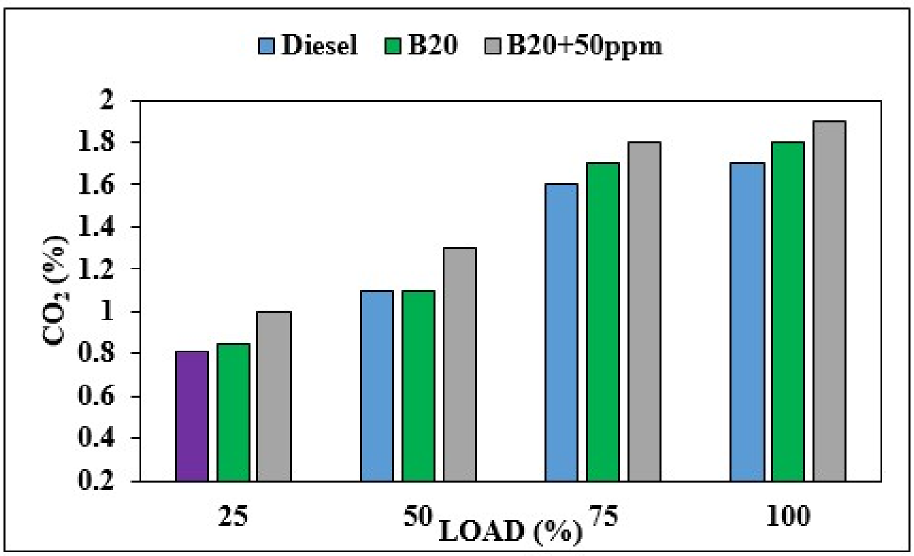

Figure 4.23: Variation of CO_2 emission with load at CR 15

4.4.3 Hydrocarbon (HC) Emission

Incomplete combustion of fuel results in unburned hydrocarbon emissions, which primarily occur due to a lack of sufficient oxygen around the fuel droplets during combustion. The amount of available oxygen varies with the air-fuel mixture, quality of air-fuel mixing, fuel atomization, and temperature of the cylinder walls. As the compression ratio increases for an engine, the temperature of the combustion chamber increases, which in turn improves the combustion process and results in lower HC emissions..

Figure 4.24 illustrates the variation in HC emissions with respect to engine load for diesel, B20 biodiesel, and the B20 blend with 50 ppm of Al_2O_3 nanoparticles. The graph reveals that at full load, the respective HC emissions are 81 ppm for diesel, 72 ppm for B20, and 70 ppm for the nanoparticle-enhanced blend. The presence of nanoparticles promotes better oxidation during combustion and hence reduces HC emissions. Over the entire range of load, the HC values decrease gradually: from 81 to 75 ppm for diesel, from 72 to 67 ppm for B20, and from 70 to 65 ppm for B20+50 ppm. The addition of 50 ppm Al_2O_3nanoparticles further reduces the HC output of B20, since alumina particles behave like oxidation catalysts, promoting better combustion and thereby reducing HC emission [75].

In addition of Al_2O_3 in biofuel , HC emission decreases due to increases in oxygen in the fuel for better combustion, causing reduction in HC emission[76]. At 25% load or at lower load (1 kg engine load) B20 and B20+50 ppm biofuels shows a 11.1% and 13.5% reduction in HC emission, when compared to commercial diesel respectively. Similarly at 100% load i.e higher load (9 kg engine load) tested fuel B20 and B20+50 ppm shows 10.66% and 13.33% reduction in HC emission respectively, when compared to commercial diesel. The reduction in HC emission on the addition of nanoparticles is observed due because of hydrocarbon oxidation and atomization effect due to nanoparticles[77].

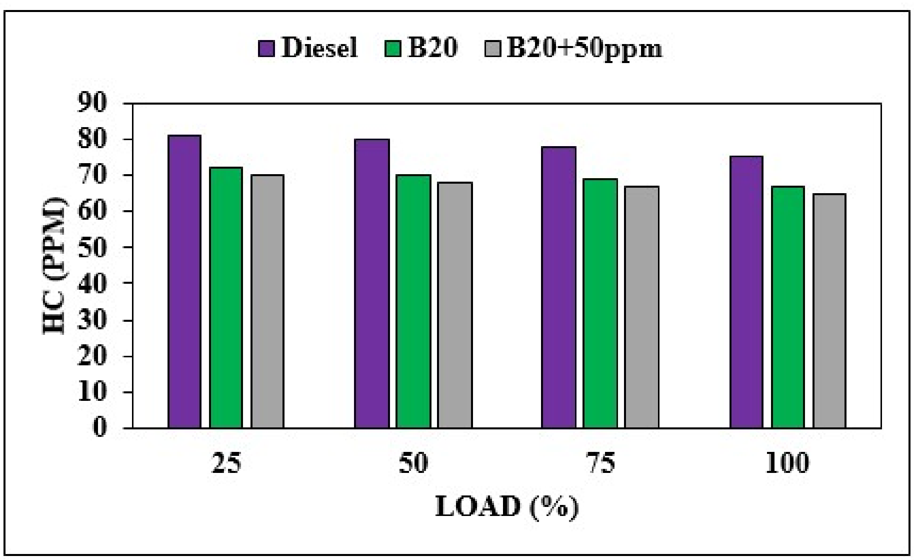

Figure 4.24: Variation of HC emission with load at CR 15

4.4.4 Nitrogen Oxide (NO_x) Emission

The NO_x emissions respond correspondingly to the change in engine load when diesel, biodiesel, and nanoparticle-enhanced fuel blends are used, as observed from Figure 4.25. With an increase in load, NO_x emissions increase because of the higher temperature of combustion created inside the chamber, which is further enhanced by the presence of nanoparticles [46].The addition of nanoparticles to diesel engine cause rise in the amount of heat being generated, which leads to an increase of temperature in the combustion chamber and an increase in NO_x released.

At all loading condition, the diesel fuel emits lower NO_x emission compared to other fuels. This is mainly due to presence of oxygen in biofuel, this leads to more oxidation at higher temperature and responsible for more NO_x emissions[71].The maximum and minimum amount of NO_x produced were 10 and 220 ppm corresponding to Diesel and B20+50 ppm biofuel. From Figure 4.25 , the NO_x emission for diesel was found to be 9.09% and 16.67% reduction than B20 and B20+50 ppm biofuel at 25% load respectively. Similarly at 100% load, for diesel fuel NO_x emission was found to be 9.54% and 18.18% reduction when compared with B20 and B20+50 ppm biofuel. This is mainly due to the catalytic effect of Al_2O_3 nanoparticles.

The addition of 50 ppm nanoparticles to the B20 blend likely enhances atomization or combustion kinetics further promoting higher combustion temperature or uniform oxidation which would explain why the B20 with additives series shows the higher NO_x emissions at each load point in the graph. Additives that enhance combustion efficiency often increase peak flame temperature or lower ignition delay, both of which favour NO_x production mechanism[78].

From life-cycle prospective, these higher engine NO_x emissions do not necessarily undermine the environmental sustainability benefits of biodiesel, these emission combined with after-treatment technologies such as SCR or EGR which can mitigate NO_x emissions post-combustion, biodiesel blends remain a sustainable option that balance greenhouse gas reduction with manageable local emissions through appropriate engine and emission controls[79].

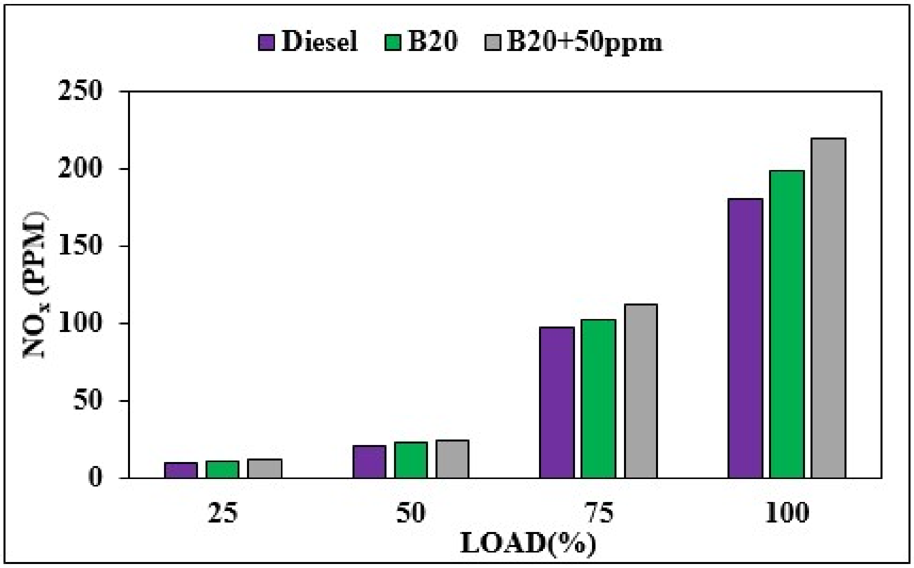

Figure 4.25: Variation of NO_x emission with load at CR 15

5. Conclusions & Recommendations

5.1 Conclusions

The present study focuses on the effect of Aluminium oxide nanoparticles, synthesized by using Sol-gel method and Pine oil biodiesel blend at different loads and varying CRs on a VCR , single cylinder engine and at a constant speed 1500 rpm. In this investigation, the engine was operated at two different compression ratios of 17 and 15. Three nano fuel blends, B20+25ppm, B20+50 ppm and B20+75 ppm were prepared using ultra-sonication process by varying the dosage levels of 25, 50 and 75 ppm of Al_2O_3 nanoparticles. The following conclusions are drawn based on the obtained results.

1. Al_2O_3 nanoparticle was synthesized from an aqueous solution of aluminum nitrate nanohydrate ($Al(NO_3)_3.9H_2O$) solution and subsequently calcined at 1000°C.

2. The crystal size and structural conformation of synthesized nanoparticle were evaluated using XRD analysis and UV characterization, respectively.

3. Incorporating Al_2O_3 nanoparticle into B20 improved several fuel properties, including calorific value, cetane number density, viscosity and flash point.

4. Brake power increased with rising engine load for all tested fuel, at CR 17, the B20+75 ppm fuel blend demontrated superior specific fuel consumption compared to other nanofuel blend under high load condition.

5. At full load diesel records 22.43% brake thermal efficiency at CR 15 and 22.85% at CR 17 whereas B20+75 ppm improves this to 22.86% and 23.86% respectively corresponding to 4.23% improvement over diesel at CR 17 and 1.91% improvement in BTE at CR 15.

6. The CO emission for B20 and B20+50 ppm fuel blends are found to be 12.5% and 25% lower than diesel at full load , similarly at low load CO emission are found to be 8.33% and 16.67% lower than diesel respectively.

7. For all test fuels, CO_2 emissions exhibited a progressive increase with rising engine load.
8. At 25% load , B20 and B20+50 ppm biofuels shows 11.1% and 13.5% reduction in HC emission, and at 100% load tested fuel B20 and B20+50 ppm shows 10.66% and 13.33% reduction in HC emission respectively, when compared to commercial diesel fuel.
9. The NOx emission for diesel was found to be 9.09% and 16.67% reduction than B20 and B20+50 ppm biofuel at 25% load, similarly at 100% load, for diesel fuel NOx emission was found to be 9.54% and 18.18% reduction when compared with B20 and B20+50 ppm biofuels.
10. From the experimental study, it concluded that 20% pine oil and 80% commercial diesel blends with Al_2O_3 nanoadditives could be alternative fuel for CI engine.

5.2 Recommendations

The following recommendations are suggested for future work in this area are as follows:

1. Emissions characteristics of pine oil blends with Al_2O_3 nanoparticles with concentrations higher than 75 ppm.
2. Further study can be carried out using different types of biodiesel with Al_2O_3 nanoparticles additives to examine their effect on engine performance, combustion and emission characteristics.
3. The effect of varying biodiesel blends ratio more than 20% can be analyzed to determine the optimum blend for improved efficiency and reduced emissions.
4. Effect of hybrid nanoparticles with different types of biofuels on the engine performance, combustion and emissions characteristics .
5. Perform detailed cost-benefit analysis of biofuel blends comparing with commercial diesel considering fuel cost, processing and blending expenses for commercial production.

6. Investigate the effect of biofuel usage on engine maintenance requirements and overall operating reliability.

7. Examine the industrial feasibility of large- scale biofuel production, including storage stability and distribution.

8. Perform long-term engine durability studies to evaluate wear characteristics, deposits formation and lubrication oil degradation during continuous biofuel operation.

References

[1] Ambarish Datta and Bijan Kumar Mandal. A comprehensive review of biodiesel as an alternative fuel for compression ignition engine. *Renewable and Sustainable Energy Reviews*, 57:799–821, 2016.

[2] J Venkatesu Naik and K Kiran Kumar. Performance and emission characteristics of diesel engines with al2o3 and cuo nanoparticles as additives. *International Journal of Mechanical Engineering and Technology*, 9(2):791–798, 2018.

[3] Alireza Shirneshan. Hc, co, co2 and nox emission evaluation of a diesel engine fueled with waste frying oil methyl ester. *Procedia-Social and Behavioral Sciences*, 75:292–297, 2013.

[4] K Purushothaman and G Nagarajan. Performance, emission and combustion characteristics of a compression ignition engine operating on neat orange oil. *Renewable Energy*, 34(1):242–245, 2009.

[5] D Tamilvendhan and V Ilangovan. A performance, emission and combustion investigation on hot air assisted eucalyptus oil direct injected compression ignition engine. *Modern Applied Science*, 5(4):53, 2011.

[6] R Vallinayagam, S Vedharaj, WM Yang, CG Saravanan, PS Lee, KJE Chua, and SK Chou. Emission reduction from a diesel engine fueled by pine oil biofuel using scr and catalytic converter. *Atmospheric environment*, 80:190–197, 2013.

[7] Prem Kumar, MP Sharma, and Gaurav Dwivedi. Impact of biodiesel on combustion, performance and exhaust emissions of diesel engines. *Journal of Integrated Science and Technology*, 2(2):57–63, 2014.

[8] R Vallinayagam, S Vedharaj, WM Yang, PS Lee, KJE Chua, and SK Chou. Pine oil–biodiesel blends: A double biofuel strategy to completely eliminate the use of diesel in a diesel engine. *Applied Energy*, 130:466–473, 2014.

[9] P Tamilselvan and N Nallusamy. Performance, combustion and emission characteristics of a compression ignition engine operating on pine oil. *Biofuels*, 6(5-6):273–281, 2015.

[10] Nick Watts, Markus Amann, Sonja Ayeb-Karlsson, Kristine Belesova, Timothy Bouley, Maxwell Boykoff, Peter Byass, Wenjia Cai, Diarmid Campbell-Lendrum, Jonathan Chambers, et al. The lancet countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *The Lancet*, 391(10120):581–630, 2018.

[11] H An, WM Yang, A Maghbouli, J Li, SK Chou, and KJ Chua. Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils. *Applied energy*, 112:493–499, 2013.

[12] J Sadhik Basha and RB Anand. Effects of nanoparticle additive in the water-diesel emulsion fuel on the performance, emission and combustion characteristics of a diesel engine. *International Journal of Vehicle Design*, 59(2/3):164–181, 2012.

[13] Avinash Kumar Agarwal and K Rajamanoharan. Experimental investigations of performance and emissions of karanja oil and its blends in a single cylinder agricultural diesel engine. *Applied energy*, 86(1):106–112, 2009.

[14] AS Ramadhas, C Muraleedharan, and S Jayaraj. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. *Renewable energy*, 30(12):1789–1800, 2005.

[15] Ishwar Joshi and Surya Prasad Adhikari. Performance characteristics of pine oil mixed diesel fueled single cylinder four stroke diesel engine. *Himalayan Journal of Applied Science and Engineering*, 2(1):15–24, 2021.

[16] Mohammed S Gad, Sayed M Abdel Razek, PV Manu, and Simon Jayaraj. Experimental investigations on diesel engine using alumina nanoparticle fuel additive. *Advances in Mechanical Engineering*, 13(2):1687814020988402, 2021.

[17] Lochan Kendra Devkota and Surya Prasad Adhikari. Experimental investigation on the performance of a ci engine fueled with waste cooking oil biodiesel blends. *Himalayan Journal of Applied Science and Engineering*, 2(1):25–31, 2021.

[18] Kiran Poudel, Radha Gautam, and Surya Prasad Adhikari. Performance analysis and testing of diesel with ferric oxide (fe2o3) nanomaterial and pine oil in internal combustion engine. 2023.

[19] Manish Koirala, Amit Kumar Sah, Rabindra Prasad Dhakal, Rupesh Lal Karn, Mukunda Khanal, and Surya Prasad Adhikari. Effect of green synthesized zinc oxide nanoadditives and rice bran oil biodiesel blend on performance and combustion characteristics of a variable compression ratio diesel engine: an experimental study. *Biofuels, Bioproducts and Biorefining*, 17(6):1595–1610, 2023.

[20] A Backiyaraj, M Parthasarathy, N Murugu Nachippan, PB Senthilkumar, and T Kumaran. Influence of nano al2o3 on compression ignition engine characteristics fuelled with mahua biodiesel. *Materials Today: Proceedings*, 72:2238–2244, 2023.

[21] RL Krupakaran, T Hariprasasd, A Gopalakrishna, and Pejjai Babu. The performance and exhaust emissions investigation of a diesel engine using γ-al2o3 nanoparticle additives to biodiesel. *Carbon Management*, 7(3-4):233–241, 2016.

[22] Haozhong Huang, Wenwen Teng, Qingsheng Liu, Chengzhong Zhou, Qingxin Wang, and Xueqiang Wang. Combustion performance and emission characteristics of a diesel engine under low-temperature combustion of pine oil–diesel blends. *Energy Conversion and Management*, 128:317–326, 2016.

[23] Mohammad Nouri, Amir Homayoon Meghdadi Isfahani, and Alireza Shirneshan. Effects of fe2o3 and al2o3 nanoparticle-diesel fuel blends on the combustion, performance and emission characteristics of a diesel engine. *Clean Technologies and Environmental Policy*, 23(8):2265–2284, 2021.

[24] Md S Mujaheed Khan, Pankaj Kumar, Imamuddin Ansari, and Niranjan Sahoo. Experimental analysis of diesel engine characteristics powered with al2o3 doped mesua ferrea linn vegetable oil-diesel blend. *Fuel*, 381:133251, 2025.

[25] CG Saravanan, K Raj Kiran, M Vikneswaran, P Rajakrishnamoorthy, and S Prasanna Raj Yadav. Impact of fuel injection pressure on the engine characteristics of crdi engine powered by pine oil biodiesel blend. *Fuel*, 264:116760, 2020.

[26] Prabodh Satyal, Prajwal Paudel, Josna Raut, Akash Deo, Noura S Dosoky, and William N Setzer. Volatile constituents of pinus roxburghii from nepal. *Pharmacognosy Research*, 5(1):43, 2013.

[27] Magín Lapuerta, Indira Tobío-Pérez, Marianela Ortiz-Alvarez, David Donoso, Laureano Canoira, and Ramón Piloto-Rodríguez. Heterogeneous catalytic conversion of terpenes into biofuels: an open pathway to sustainable fuels. *Energies*, 16(6):2526, 2023.

[28] H. Huang, C. Shi, Q. Liu, P. Zhang, et al. Experiment on spray visualization of pine oil blends and their combustion and emission characteristics. *Neiranji Xuebao/Transactions of CSICE (Chinese Society for Internal Combustion Engines)*, 36(1):37–43, 2018.

[29] SH Pourhoseini and Maryam Ghodrat. Experimental investigation of the effect of al2o3 nanoparticles as additives to b20 blended biodiesel fuel: Flame characteristics, thermal performance and pollutant emissions. *Case Studies in Thermal Engineering*, 27:101292, 2021.

[30] V Shenbaga Muthuraman, Adamya Patel, Vemuluri Shreya, Avinash Vaidyanathan, KNGL Reshwanth, C Karthick, Michal Jan Geca, B Ashok, K Sivagami, and K Nanthagopal. Progress on compatibility issues of alcohols on automotive materials: Kinetics, challenges and future prospects-a comprehensive review. *Process Safety and Environmental Protection*, 162:463–493, 2022.

[31] Xianjun Hou, Haijun Liu, Xiaoxue Li, Hua Jiang, Zekun Tian, and Mohamed Kamal Ahmed Ali. An experimental study and mechanism analysis on improving dispersion stability performance of al 2 o 3 nanoparticles in base synthetic oil under various mixing conditions. *Journal of Nanoparticle Research*, 23:1–16, 2021.

[32] MS Smyth and JHJ Martin. x ray crystallography. *Molecular Pathology*, 53(1):8, 2000.

[33] Li-ling Ooi. *Principles of X-ray Crystallography*. Oxford University Press, USA, 2010.

[34] JF Clauser and MW Reinsch. New theoretical and experimental results in fresnel optics with applications to matter-wave and x-ray interferometry. *Applied Physics B*, 54(5):380–395, 1992.

[35] Seung Bum Lee, Kyong Ho Han, Jae Dong Lee, and In Kwon Hong. Optimum process and energy density analysis of canola oil biodiesel synthesis. *Journal of Industrial and Engineering Chemistry*, 16(6):1006–1010, 2010.

[36] Ertan Alptekin and Mustafa Canakci. Characterization of the key fuel properties of methyl ester–diesel fuel blends. *Fuel*, 88(1):75–80, 2009.

[37] Olawole Abiola Kuti, Jingyu Zhu, Keiya Nishida, Xiangang Wang, and Zuohua Huang. Characterization of spray and combustion processes of biodiesel fuel injected by diesel engine common rail system. *Fuel*, 104:838–846, 2013.

[38] MA Kalam, M Husnawan, and HH Masjuki. Exhaust emission and combustion evaluation of coconut oil-powered indirect injection diesel engine. *Renewable Energy*, 28(15):2405–2415, 2003.

[39] MI Arbab, HH Masjuki, M Varman, MA Kalam, S Imtenan, and H Sajjad. Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel. *Renewable and Sustainable Energy Reviews*, 22:133–147, 2013.

[40] Eliana Weber de Menezes, Rosângela da Silva, Renato Cataluna, and Ricardo JC Ortega. Effect of ethers and ether/ethanol additives on the physicochemical properties of diesel fuel and on engine tests. *Fuel*, 85(5-6):815–822, 2006.

[41] VT Palichev and DI Jordanov. A depressant additive for diesel fuel. *Comptes Rendus de l'Academie Bulgare des Sciences, vol. 54, p. 11: 71*, 54(11):11–71, 2001.

[42] Silvio CA De Almeida, Carlos Rodrigues Belchior, Marcos VG Nascimento, Leonardo dos SR Vieira, and Guilherme Fleury. Performance of a diesel generator fuelled with palm oil. *Fuel*, 81(16):2097–2102, 2002.

[43] Herchel TC Machacon, Seiichi Shiga, Takao Karasawa, and Hisao Nakamura. Performance and emission characteristics of a diesel engine fueled with coconut oil–diesel fuel blend. *Biomass and bioenergy*, 20(1):63–69, 2001.

[44] John B. Heywood. *Internal Combustion Engine Fundamentals*. McGraw-Hill, New York, 1988.

[45] Gerhard Knothe, Jon Van Gerpen, and Jürgen Krahl. *The Biodiesel Handbook*. AOCS Press, Champaign, Illinois, 2005.

[46] Yatendra Kaushik, Vijay Verma, Kuldeep Kumar Saxena, and Saurav Dixit. Effect of al_2o_3 nanoparticles on performance and emission characteristics of diesel engine fuelled with diesel–neem biodiesel blends. *Energies*, 15(9):1–14, 2022.

[47] P. K. Sahoo, L. M. Das, M. K. G. Babu, P. Arora, V. P. Singh, N. R. Kumar, and T. S. Varyani. Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. *Fuel*, 88(9):1698–1707, 2009.

[48] B. Dhinesh, Y. Maria Ambrose Raj, C. Kalaiselvan, and R. KrishnaMoorthy. A numerical and experimental assessment of a coated diesel engine powered by high-performance nano biofuel. *Energy Conversion and Management*, 171:815–824, 2018.

[49] J. Kataria, S. K. Mohapatra, and K. Kundu. Biodiesel production from waste cooking oil using heterogeneous catalysts and its operational characteristics on variable compression ratio ci engine. *Journal of the Energy Institute*, 92(2):275–287, 2019.

[50] S. Vellaiyan. Enhancement in combustion, performance, and emission characteristics of a diesel engine fueled with diesel, biodiesel, and its blends by using nanoadditive. *Environmental Science and Pollution Research*, 26:9561–9573, 2019.

[51] Joseph Owolabi and Pius Ojadi. Synthesis, characterization and x-ray diffraction analysis of aluminum oxide nanomaterials. *FUW Trends in Science & Technology Journal*, 8(3):423–427, 2023.

[52] Gunawan Gunawan, Amir Arifin, Irsyadi Yani, and Muhammad Indrajaya. Characterization of porous hydroxyapatite-alumina composite scaffold produced via powder compaction method. *IOP Conference Series: Materials Science and Engineering*, 620:012107, 2019.

[53] Douglas A. Skoog, F. James Holler, and Stanley R. Crouch. *Principles of Instrumental Analysis*. Cengage Learning, 2017.

[54] L. Zhang, X. Li, Y. Wu, and H. Zhang. Uv-vis spectroscopic study of the optical properties of alo nanoparticles synthesized by the sol-gel method. *Journal of Nanomaterials*, 2018, 2018.

[55] M. Venkataraman and S. Subramanian. An assessment of pine oil as a potential alternative fuel for compression ignition engines: A review on performance, combustion, and emission characteristics. *Renewable and Sustainable Energy Reviews*, 169:112934, 2022.

[56] E. Bibi. Synthesis and characterization of al_2o_3 nanoparticles from *trachyspermum ammi*. *HSOA Journal of Agronomy & Agriculture Science*, 2023.

[57] Ganesh Lamichhane, Sujan Khadka, Sanjib Adhikari, Niranjan Koirala, and Dhruba Prasad Poudyal. Biofuel production from waste cooking oils and its physicochemical properties in comparison to petrodiesel. *Nepal Journal of Biotechnology*, 8(3):87–94, 2020.

[58] R. Patel and K. Sharma. Influence of metal oxide nanoparticles on the functional groups and performance of biodiesel blends. *Renewable Energy*, 180:1123–1135, 2022.

[59] Avinash Kumar Agarwal. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science*, 33(3):233–271, 2007.

[60] S. Karthikeyan, T. Elango, and A. Prathima. Diesel engine performance and emission analysis using canola oil methyl ester with the nano additive cerium oxide. *Thermal Science*, 18(1):217–228, 2014.

[61] C. Nayak, B.P. Pattanaik, and S.K. Nayak. Effect of alumina nanoparticle additive on performance and emission characteristics of a ci engine fuelled with mahua biodiesel blend. *Journal of Thermal Analysis and Calorimetry*, 138(1):403–411, 2019.

[62] C.M. Prasad, T. Srinivas, and K. Rajagopal. Performance and emission characteristics of a diesel engine using biodiesel with varying compression ratio. *International Journal of Applied Engineering Research*, 7(11):2012–2019, 2012.

[63] S.E. Hosseini and M.A. Wahid. Feasibility of biodiesel as a fuel for compression ignition engines: A review. *Renewable and Sustainable Energy Reviews*, 74:439–448, 2017.

[64] O. Nwafor. The effect of elevated fuel inlet temperature on performance of diesel engine running on neat vegetable oil at constant speed conditions. *Renewable Energy*, 28(2):171–181, 2003.

[65] Siti Nurul Akmal Yusof, Nor Azwadi Che Sidik, Yutaka Asako, Wan Mohd Arif Aziz Japar, Saiful Bahri Mohamed, and Nura Mu'az Muhammad. A comprehensive review of the influences of nanoparticles as a fuel additive in an internal combustion engine (ice). *Nanotechnology Reviews*, 9(1):1326–1349, 2020.

[66] A. Demirbas. Progress and recent trends in biodiesel fuels. *Energy Conversion and Management*, 50(1):14–34, 2009.

[67] M. Mofijur, H. H. Masjuki, M. A. Kalam, A. E. Atabani, I. M. Rizwanul Fattah, and H. M. Mobarak. Comparative evaluation of performance and emission characteristics of moringa oleifera and palm oil based biodiesel in a diesel engine. *Industrial Crops and Products*, 53:78–84, 2013.

[68] S. A. Basha. Performance, emission and combustion characteristics of a diesel engine running on nano additive blended biodiesel. *Procedia Engineering*, 64:479–490, 2014.

[69] H. Venu and V. Madhavan. Effect of diethyl ether and Al_2O_3 nano additives in diesel-biodiesel-ethanol blends: Performance, combustion and emission characteristics. *Journal of Mechanical Science and Technology*, 31(1):409–420, 2017.

[70] O. Khan, M. Z. Khan, N. Ahmad, A. Qamer, M. T. Alam, et al. Performance and emission analysis on palm oil derived biodiesel coupled with aluminum oxide nanoparticles. *Materials Today: Proceedings*, 46(1):6781–6786, 2021.

[71] Sharanappa Godiganur, Suryanarayana Ch. Murthy, and Rana Prathap Reddy. Performance and emission characteristics of a kirloskar ha394 diesel engine operated on fish oil methyl esters. *Renewable Energy*, 35:355–359, 2010.

[72] M. Gumus. Evaluation of hazelnut kernel oil of turkish origin as alternative fuel in diesel engines. *Renewable Energy*, 33:2448–2457, 2008.

[73] S. C. A. de Almeida, C. R. Belchior, M. V. G. Nascimento, L. d. S. R. Vieira, and G. Fleuryb. Performance of a diesel generator fueled with palm oil. *Fuel*, 81:2097–2102, 2002.

[74] Cheng Tung Chong, Ting Yu Loe, Kang Yao Wong, Veeramuthu Ashokkumar, Su Shiung Lam, Wen Tong Chong, Aiduan Borrion, Bo Tian, and Jo-Han Ng. Biodiesel sustainability: The global impact of potential biodiesel production on the energy-water-food (ewf) nexus. *Energy Conversion and Management*, 238:114131, 2021.

[75] P. Atarod, E. Khlaife, M. Aghbashlo, M. Tabatabaei, A.T. Hoang, H. Mobli, M.H. Nadian, H. Hosseinzadeh-Bandbafha, P. Mohammadi, T.R. Shojaei, et al. Soft computing-based modeling and emission control/reduction of a diesel engine fueled with carbon nanoparticle-dosed water/diesel emulsion fuel. *Journal of Hazardous Materials*, 407:124369, 2020.

[76] B. Pradipkumar, S. Pohit, and R. Kumar. Biodiesel from jatropha: Can india meet the 20% blending target? *Energy Policy*, 38:1477–1484, 2010.

[77] D. Ganesh and G. Shankar. Effect of nanofluid additive on emission reduction in a biodiesel fueled ci engine. *Electrical Control Engineering*, 9:3453–3459, 2011.

[78] S. M. Palash, M. A. Kalam, H. H. Masjuki, B. M. Masum, I. M. Rizwanul Fattah, and M. Mofijur. Impacts of biodiesel combustion on no_x emissions and their reduction approaches. *Renewable and Sustainable Energy Reviews*, 23:473–490, April 2013.

[79] Kemal Masera and Abul Kalam Hossain. Advancement of biodiesel fuel quality and nox emission control techniques. *Renewable and Sustainable Energy Reviews*, 176:113143, 2023.

Appendices

Figure 5.1: Synthesized Al_2O_3 nanoparticles in laboratory

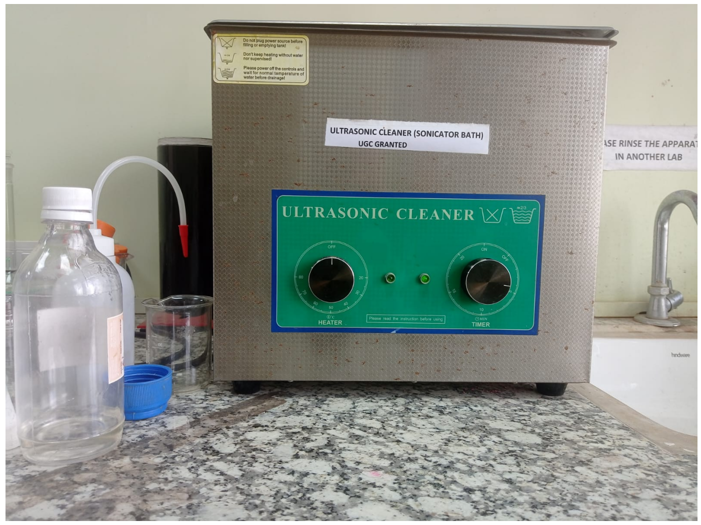

Figure 5.2: Bath sonicator equipment

Figure 5.3: Sonication of nanoparticles with fuel blends

Figure 5.4: Blended biofuel sample

Figure 5.5: Research engine

Figure 5.6: Refueling test engine with biofuel sample

Figure 5.7: Performing performance test

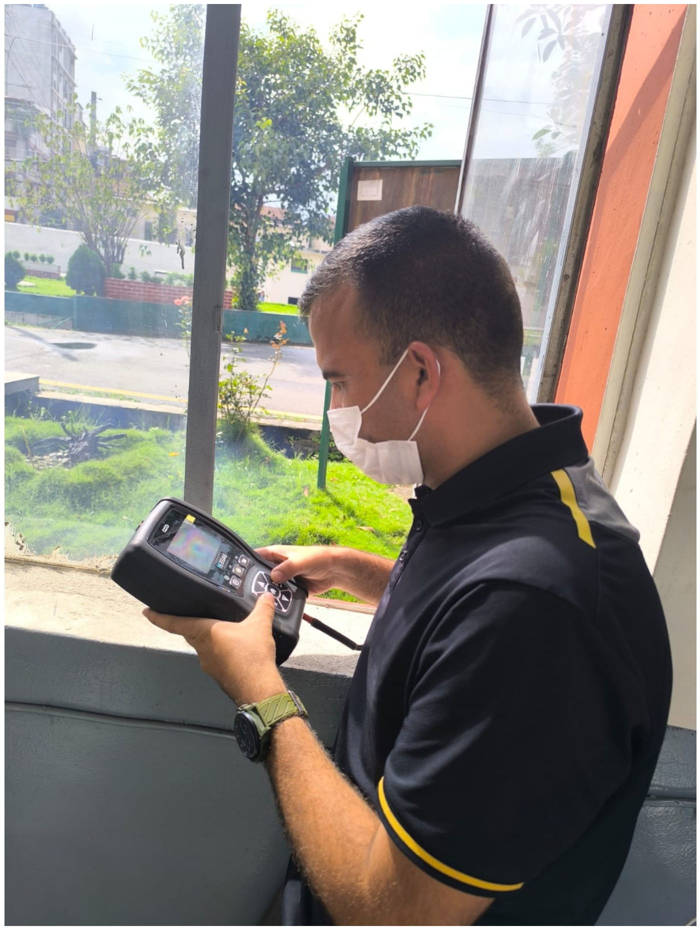

Figure 5.8: Performing emission test

TUTA Pashchimanchal Campus

to me

Fri, Nov 28, 2:18 PM

Dear author(s),

We are pleased to inform you that your manuscript titled "Performance Analysis of Diesel Engine Fueled with Pine-Diesel Blends Enhanced by Al2O3 Nanoparticles" has been accepted after peer review for publication in the 9th Volume of Oodbodhan(ISSN 2091-2676) on 28th November 2025

Regards,

Editorial Board

•••

Final Report for plagarism check-Ganesh - III.pdf

Tribhuvan University

Document Details

Submission ID
trn:oid:::3117:541113841

Submission Date
Dec 16, 2025, 12:13 PM GMT+5:45

Download Date
Dec 16, 2025, 12:14 PM GMT+5:45

File Name
Final Report for plagarism check-Ganesh - III.pdf

File Size
998.4 KB

62 Pages

14,369 Words

75,950 Characters

11% Overall Similarity

The combined total of all matches, including overlapping sources, for each database

Filtered from the Report

- Bibliography
- Quoted Text
- Cited Text
- Small Matches (less than 10 words)

Custom Section Exclusions

{titlesCount} Section Titles, {keywordsCount} Keywords

Section title	No. of Section Starters	Section Starters
"Acknowledgements"	4	Acknowledgements, Acknowledgement, Acknowledgment, Acknowledgments

Match Groups

- **88 Not Cited or Quoted 11%**
  Matches with neither in-text citation nor quotation marks
- **0 Missing Quotations 0%**
  Matches that are still very similar to source material
- **0 Missing Citation 0%**
  Matches that have quotation marks, but no in-text citation
- **0 Cited and Quoted 0%**
  Matches with in-text citation present, but no quotation marks

Top Sources

- 9% Internet sources
- 6% Publications
- 0% Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

88 Not Cited or Quoted 11%
Matches with neither in-text citation nor quotation marks

0 Missing Quotations 0%
Matches that are still very similar to source material

0 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

9% Internet sources
6% Publications
0% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Internet	ebooks.inflibnet.ac.in	<1%
2	Internet	file.techscience.com	<1%
3	Internet	mafiadoc.com	<1%
4	Publication	Manish Koirala, Amit Kumar Sah, Rabindra Prasad Dhakal, Rupesh Lal Karn, Muku...	<1%
5	Internet	docplayer.net	<1%
6	Internet	elibrary.tucl.edu.np	<1%
7	Internet	www.researchgate.net	<1%
8	Internet	www.tandfonline.com	<1%
9	Internet	www.theengineerspost.com	<1%
10	Publication	Tien Duc Pham, Motoyoshi Kobayashi, Yasuhisa Adachi. "Interfacial characterizati...	<1%

11	Internet	
www.heraldopenaccess.us		<1%
12	Internet	
telemetr.io		<1%
13	Internet	
coredifferences.com		<1%
14	Publication	
Tahir Ali Khan, Tasneem Ahmad Khan, Ashok Kumar Yadav, M. Emran Khan, Muk...		<1%
15	Publication	
B. Ashok, K. Nanthagopal, D. Arumuga Perumal, J.M. Babu, Anmol Tiwari, Akhil Sh...		<1%
16	Publication	
Surya Prasad Adhikari, Bhuwesh Pant, Amir Khanal, Lochan Kendra Devkota, Rup...		<1%
17	Internet	
avesis.erciyes.edu.tr		<1%
18	Internet	
www.iuav.it		<1%
19	Publication	
G Balaji, Utkarsh Arora, Saurav Dasgupta, Siddhant Mund. " Individual effects of ...		<1%
20	Publication	
Kehinde Ojeniyi, Chirinda Ngonidzashe, Krishna Devkota, Donald Madukwe. "Opti...		<1%
21	Internet	
www.jetir.org		<1%
22	Publication	
Bhanu Teja Nalla, Ganesan Subbiah, Saroj Kumar Acharya, Sunil Kumar M et al. "I...		<1%
23	Publication	
Laxmikant D. Jathar, Meherunnesa, Sagar Shelare, Kiran Shahapurkar et al. "A Sh...		<1%
24	Internet	
pt.scribd.com		<1%

25 Internet
www.bnhcrc.com.au <1%

26 Publication
Manish Koirala, Amit Kumar Sah, Rabindra Prasad Dhakal, Rupesh Lal Karn, Muku... <1%

27 Internet
text-id.123dok.com <1%

28 Publication
S. Ramkumar, V. Kirubakaran. "Biodiesel from vegetable oil as alternate fuel for C... <1%

29 Publication
Ulrich Cabrel Kenmegne Tebe, Julius Kewir Tangka, Henri Grisseur Djoukeng, Bric... <1%

30 Internet
cdn.techscience.cn <1%

31 Internet
ejournal2.undip.ac.id <1%

32 Internet
ebin.pub <1%

33 Internet
link.springer.com <1%

34 Internet
vdocuments.site <1%

35 Internet
www.clearsign.com <1%

36 Internet
www.qucosa.de <1%

37 Publication
B.S. Utkal Laxmi Pani, Natarajan Chandrasekaran. "Investigating the impact of na... <1%

38 Publication
Mukesh Yadav, Ashok Kumar Yadav, Aqueel Ahmad. "Enhancing combustion and ... <1%

39 Publication
P. Kannan, T. Jayakumar, R. Anandhan, S. Karpagarajan, J. Arunprasad, R. Thirugn... <1%

40 Publication
R. Vallinayagam, S. Vedharaj, W.M. Yang, C.G. Saravanan, P.S. Lee, K.J.E. Chua, S.K.... <1%

41 Publication
Tafsirul Hassan, Md. Mizanur Rahman, Md. Sanaul Rabbi, Md. Arafat Rahman, Re... <1%

42 Internet
etd.aau.edu.et <1%

43 Internet
hal.univ-lorraine.fr <1%

44 Internet
ir-library.egerton.ac.ke <1%

45 Publication
A. Praveen, V. Lakshmi narayana, K. Ramanaiah. "Influence of nanoadditive Chlor... <1%

46 Publication
Medhat Elkelawy, Hagar Alm-Eldin Bastawissi, Khaled Khodary Esmaeil, Ahmed M... <1%

47 Internet
amsdottorato.unibo.it <1%

48 Internet
dspace.unza.zm <1%

49 Internet
worldwidescience.org <1%

50 Internet
www.research.manchester.ac.uk <1%

51 Internet
www.scribd.com <1%

52 Publication
Nagaraja, S., K. Sooryaprakash, and R. Sudhakaran. "Investigate the Effect of Co... <1%