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A Review On Alternative Fuels in Internal Combustion Engine and Its Characterization & Performance Analysis

Mr. Santhosh Kumar S.[1], Dr.Anix joel singh[2]
[1]Assistant Lecturer, Mechanical Engineering Department,
St. Joseph University in Tanzania, Dar es salaam, Tanzania
East Africa
[2]Senior lecturer,Mechanical engineering department
St.joseph college of engineering & Technology, Tanzania

Abstract- The increasing demand for sustainable energy resources, along with growing environmental concerns related to fossil fuel consumption, has accelerated research into alternative fuels for internal combustion engines. This study focuses on the experimental investigation and performance analysis of an internal combustion engine operated with alternative fuel as a potential replacement for conventional diesel fuel. The experimental investigation was conducted to evaluate the effects of alternative fuel usage on engine performance and exhaust emission characteristics under different operating conditions. The performance evaluation was carried out based on key parameters, including brake power, torque, brake thermal efficiency (BTE), and brake-specific fuel consumpion (BSFC). In addition, the emission characteristics were analyzed by measuring exhaust gases such as carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NOx), carbon dioxide (CO_2), and smoke opacity. The results demonstrated that alternative fuel operation produced comparable engine performance with conventional diesel fuel. Variations in brake power, torque, thermal efficiency, and fuel consumption were observed due to differences in fuel properties, combustion behavior, and energy content. The alternative fuel showed a slight increase in fuel consumption due to its lower calorific value; however, it provided improved emission characteristics by reducing CO, HC, and smoke opacity emissions. A minor change in NOx emissions was observed, which was mainly associated with variations in combustion temperature and oxygen availability during the combustion process. Overall, the experimental findings indicate that alternative fuels can be effectively utilized in internal combustion engines while maintaining satisfactory performance and reducing harmful exhaust emissions. The study highlights the potential of alternative fuels as sustainable energy solutions for cleaner and more efficient engine operation.

Keywords- Alternative fuel, Internal combustion engine, Engine performance, Brake thermal efficiency, Brake-specific fuel consumption, Emission characteristics, Sustainable energy.

I. INTRODUCTION

The global energy sector is undergoing a significant transition driven by the rapid depletion of fossil fuel reserves, increasing energy demand, and growing concerns about climate change and air pollution. The transportation sector remains one of the largest consumers of petroleum-based fuels and is a major contributor to greenhouse gas (GHG) emissions and urban air pollution. Conventional fuels such as gasoline and diesel release substantial quantities of carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM), all of which negatively affect environmental quality and human health. Consequently, governments, researchers, and industries have intensified efforts to develop and adopt cleaner and more sustainable alternative fuels.

Alternative fuels are fuels derived from renewable, low-carbon, or non-conventional energy resources that can partially or completely replace petroleum-based fuels in transportation and power generation systems. These fuels include biodiesel, bioethanol, methanol, hydrogen, compressed natural gas

(CNG), liquefied petroleum gas (LPG), dimethyl ether (DME), renewable natural gas, electricity, synthetic fuels, and solar-derived fuels. Their application in spark ignition (SI) and compression ignition (CI) engines has attracted considerable attention because they can reduce dependence on fossil fuels while improving energy security and mitigating environmental pollution (Singh & Mercer, 2024).

The adoption of alternative fuels offers numerous environmental, economic, and social benefits. Environmentally, they contribute to lower greenhouse gas emissions and reduced emissions of NO_x, CO, HC, and PM, thereby improving air quality and supporting global climate change mitigation efforts. Economically, alternative fuels diversify the energy supply, reduce reliance on imported petroleum products, encourage the utilization of locally available renewable resources, and stimulate technological innovation and employment opportunities. Furthermore, alternative fuels enhance national energy security by reducing vulnerability to fluctuations in global oil prices and supply disruptions (Pustějovská et al., 2023).

Recent technological advancements have expanded the range of alternative fuels available for transportation applications. Biofuels, hydrogen, electricity, methanol, ammonia, renewable natural gas, and synthetic fuels are increasingly being investigated for passenger vehicles, heavy-duty transportation, aviation, and maritime applications. These technologies are considered essential components of global decarbonization strategies because they offer pathways to significantly reduce life-cycle carbon emissions while maintaining transport efficiency. However, their large-scale deployment remains constrained by challenges including production costs, feedstock availability, infrastructure limitations, storage requirements, and technological readiness (Vishnuram et al., 2025).

Among the emerging clean-energy technologies, hydrogen fuel cells and battery-electric systems represent promising long-term alternatives to conventional internal combustion engines. Fuel cells convert the chemical energy of hydrogen directly into electrical energy through electrochemical reactions without combustion, resulting in higher energy conversion efficiencies, quieter operation, and near-zero tailpipe emissions. Similarly, battery-electric vehicles eliminate direct exhaust emissions and contribute significantly to transportation decarbonization when powered by renewable electricity. Nevertheless, continued investments in renewable energy generation, charging and refueling infrastructure, and supportive government policies are necessary to accelerate their widespread adoption (Vishnuram et al., 2025).

Despite these challenges, alternative fuels are widely recognized as one of the most effective strategies for achieving sustainable transportation and reducing the environmental impacts of conventional fossil fuels. Continued research and development, together with supportive policies and technological innovation, will play a critical role in improving fuel production technologies, enhancing engine compatibility, and increasing the commercial viability of alternative fuel systems. As nations strive to achieve carbon neutrality and meet international climate commitments, alternative fuels are expected to become an increasingly important component of future transportation and energy systems (Sustainability, 2024).

II. TYPES OF ALTERNATIVE FUELS

Alternative fuels are energy sources that can replace conventional petroleum-based fuels in transportation and power generation. They are generally classified according to their source, chemical composition, and method of energy conversion. The major types of alternative fuels are discussed below.

Biodiesel
Biodiesel is a renewable fuel produced through the transesterification of vegetable oils, animal fats, waste cooking oils, or algae-derived oils. It consists mainly of fatty acid methyl esters (FAME) and can be used in compression ignition (CI) engines either in pure form (B100) or blended with conventional diesel (e.g., B5, B20). Biodiesel offers several advantages, including biodegradability, high lubricity, and reduced emissions of carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and greenhouse gases. However, it may increase nitrogen oxide (NO_x) emissions under certain operating conditions and has lower energy content than conventional diesel.

Bioethanol
Bioethanol is an alcohol-based renewable fuel produced through the fermentation of biomass feedstocks such as sugarcane, corn, cassava, wheat, and lignocellulosic materials. It is primarily used in spark ignition (SI) engines either as pure ethanol or blended with gasoline (e.g., E10, E20, and E85).

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Bioethanol has a high octane number, promotes cleaner combustion, and reduces carbon monoxide and hydrocarbon emissions. However, its lower heating value results in higher fuel consumption compared to gasoline.

Methanol

Methanol is a simple alcohol that can be produced from natural gas, coal, biomass, or captured carbon dioxide using renewable hydrogen. It has excellent combustion characteristics, a high octane rating, and lower soot formation than gasoline or diesel. Methanol can be used directly in modified internal combustion engines or as a feedstock for producing other clean fuels such as dimethyl ether (DME).

Hydrogen

Hydrogen is considered one of the cleanest alternative fuels because its oxidation produces water as the primary by-product. It can be used directly in internal combustion engines or in fuel cells to generate electricity. Hydrogen offers high energy conversion efficiency and eliminates carbon dioxide emissions at the point of use. However, challenges such as storage, transportation, production costs, and limited refueling infrastructure continue to hinder its widespread commercialization.

Natural Gas

Natural gas is available in two main forms: compressed natural gas (CNG) and liquefied natural gas (LNG). It consists primarily of methane and burns more cleanly than gasoline and diesel. Natural gas significantly reduces emissions of particulate matter, sulfur oxides (SO_x), and carbon monoxide while providing relatively high engine efficiency. However, methane leakage during production and distribution remains an environmental concern due to its high global warming potential.

Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas is composed mainly of propane and butane. It is widely used in spark ignition engines because of its high octane rating and clean combustion characteristics. LPG-powered vehicles generally produce lower emissions of carbon monoxide, hydrocarbons, and particulate matter than gasoline vehicles while offering lower operating costs. The main limitation is the need for specialized storage tanks and refueling infrastructure.

Dimethyl Ether (DME)

Dimethyl ether is a clean-burning oxygenated fuel that can be produced from natural gas, coal, or biomass. Due to its high cetane number and soot-free combustion, DME is considered an attractive substitute for diesel fuel in compression ignition engines. However, its low viscosity requires modifications to conventional diesel fuel systems.

Biogas

Biogas is produced through the anaerobic digestion of organic materials such as agricultural waste, livestock manure, municipal solid waste, and sewage sludge. It mainly consists of methane and carbon dioxide and can be upgraded to biomethane for vehicle applications. Biogas contributes to waste management while reducing greenhouse gas emissions and dependence on fossil fuels.

Electricity

Electricity is increasingly used as an alternative energy source for battery electric vehicles (BEVs). Unlike conventional fuels, electric vehicles produce zero tailpipe emissions and offer high energy efficiency. The environmental benefits of electric vehicles depend largely on the source of electricity generation, with renewable electricity providing the greatest reductions in lifecycle emissions.

Ammonia

Ammonia has recently emerged as a promising carbon-free fuel because it contains no carbon atoms and therefore does not produce carbon dioxide during combustion. It can be used directly in modified internal combustion engines or as a hydrogen carrier for fuel cell applications. Current research focuses on improving combustion characteristics and reducing nitrogen oxide emissions associated with ammonia combustion.

Synthetic Fuels (E-fuels)

Synthetic fuels, commonly known as e-fuels, are produced by combining green hydrogen with captured carbon dioxide using renewable electricity. These fuels possess properties similar to conventional gasoline or diesel and can be used in existing engines with minimal modifications. E-fuels offer a potential pathway for decarbonizing sectors where battery electrification is difficult, although their production remains energy-intensive and expensive.

Fuel Cells

Fuel cells are electrochemical devices that convert the chemical energy of hydrogen directly into electricity without combustion. Compared with conventional internal combustion engines, fuel cells provide higher energy efficiency, near-zero pollutant emissions, quiet operation, and improved reliability. Proton Exchange Membrane Fuel Cells (PEMFCs) are the most widely used technology in automotive applications due to their high power density and rapid start-up characteristics.

Summary of alternative fuels

The selection of an appropriate alternative fuel depends on factors such as engine type, fuel availability, production cost, infrastructure, environmental impact, and energy efficiency. Biodiesel, bioethanol, hydrogen, natural gas, LPG, DME, biogas, electricity, ammonia, synthetic fuels, and fuel cells each offer unique advantages and challenges. Continued technological advancements and supportive policies are expected to accelerate the adoption of these alternative fuels, contributing to reduced emissions, enhanced energy security, and a more sustainable transportation sector.

Fuel Properties and Characterization Analysis

The characterization of fuel properties is a crucial step in determining the suitability of alternative fuels for internal combustion engine applications. The physical, chemical, and thermal properties of fuels directly influence fuel injection behavior, combustion characteristics, engine performance, and exhaust emission formation. Therefore, a detailed analysis of alternative fuel properties is necessary to understand their effects on engine operation and to compare their performance with conventional fuels.

The important fuel properties considered in characterization analysis include density, kinematic viscosity, calorific value, flash point, fire point, cetane number, oxygen content, and chemical composition. These properties determine the quality of fuel combustion, energy release rate, ignition behavior, and overall engine compatibility.

Density is an important parameter that affects the quantity of fuel injected into the combustion chamber and influences spray formation and atomization characteristics. Variations in fuel density can affect the air–fuel mixing process and combustion efficiency.

Kinematic viscosity plays a significant role in fuel atomization and injection performance. Higher viscosity fuels may result in poor spray characteristics, larger fuel droplets, and incomplete combustion, which can increase exhaust emissions. Lower viscosity fuels generally improve atomization and promote better combustion.

Calorific value represents the amount of energy released during complete combustion of the fuel. It has a direct effect on engine power output and fuel consumption. Alternative fuels with lower calorific values may require a higher fuel supply rate to achieve similar power output compared with conventional diesel fuel.

Cetane number indicates the ignition quality of compression ignition fuels. A higher cetane number improves ignition characteristics by reducing ignition delay and providing stable combustion. The flash point and fire point represent the safety characteristics of fuels and indicate their resistance to ignition during storage and handling.

The oxygen content present in many alternative fuels improves combustion by enhancing oxidation reactions inside the combustion chamber. This can contribute to lower carbon monoxide (CO), unburned hydrocarbon (HC), and smoke emissions. However, changes in fuel composition may also influence combustion temperature and nitrogen oxide (NOx) formation.

The chemical composition of alternative fuels, such as fatty acid composition in biodiesel or alcohol concentration in blended fuels, significantly affects their combustion behavior and emission characteristics. Proper characterization helps in selecting suitable fuel blends and optimizing engine operating parameters.

III. ALTERNATIVE FUEL ENGINE PERFORMANCE ANALYSIS

The evaluation of engine performance under alternative fuel operation is essential for determining the potential of these fuels as substitutes for conventional petroleum-based fuels. Engine performance is commonly assessed using key parameters such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), brake power, and torque. These parameters provide valuable information about the efficiency of energy conversion, fuel consumption characteristics, and the capability of an engine to generate useful mechanical power.

Brake Thermal Efficiency (BTE)
Brake thermal efficiency (BTE) indicates the ability of an engine to convert the chemical energy available in the fuel into useful brake power output. It is influenced by various factors, including fuel properties, combustion characteristics, air–fuel mixing quality, ignition or injection timing, and combustion temperature. Alternative fuels containing higher oxygen content and exhibiting better combustion characteristics can improve BTE by promoting more complete combustion and reducing energy losses.

However, differences in fuel properties, such as heating value, viscosity, volatility, and ignition characteristics, can significantly affect thermal efficiency. Alternative fuels with lower calorific values may require increased fuel consumption to achieve the same power output, which can result in variations in the overall efficiency of engine operation.

Brake-Specific Fuel Consumption (BSFC)
Brake-specific fuel consumption (BSFC) represents the quantity of fuel consumed to produce a unit of brake power over a given period. It is an important parameter for evaluating engine fuel economy and is generally expressed as the mass of fuel consumed per unit power output per hour.

The BSFC of an alternative fuel engine is affected by fuel energy content, combustion efficiency, and operating conditions. Fuels with lower heating values typically result in higher BSFC because a larger amount of fuel is required to produce equivalent power output. In contrast, fuels with improved combustion properties can reduce BSFC by enhancing combustion efficiency and minimizing energy losses.

Brake Power
Brake power represents the useful mechanical power delivered by the engine at the output shaft. It is a significant indicator of engine performance and is influenced by engine speed, torque generation, combustion pressure, and the rate of heat release during combustion.

The brake power output of an engine operating with alternative fuels depends on factors such as fuel injection characteristics, combustion duration, oxygen availability, and in-cylinder pressure development. Fuels that promote efficient combustion and higher cylinder pressure can improve brake power performance and provide output levels comparable to conventional fuels.

Torque
Torque is the rotational force produced by the engine crankshaft and represents the engine's ability to perform mechanical work. It is mainly affected by combustion pressure, fuel energy release characteristics, and engine operating conditions.

The torque output of alternative fuel engines may vary due to differences in ignition delay, flame propagation rate, fuel atomization, and combustion efficiency. Improved fuel–air mixing and increased oxygen availability can enhance combustion and increase torque production, whereas unfavorable fuel properties may reduce torque performance.

Overall Performance Evaluation
The overall performance of an alternative fuel engine is determined by the combined effects of fuel properties and engine operating parameters. An effective alternative fuel should achieve high brake thermal efficiency, low brake-specific fuel consumption, and satisfactory brake power and torque output compared with conventional fuels. Therefore, a comprehensive analysis of these performance parameters is necessary to identify suitable alternative fuels for sustainable, efficient, and reliable engine operation.

IV. EXPERIMENTAL ENGINE PERFORMANCE TEST

Engine Test Conditions:
- Engine type: Single-cylinder, four-stroke diesel engine
- Rated speed: 1500 rpm
- Fuel tested: Diesel and alternative fuel blend
- Load range: 0–100

Table 4.1: Experimental Readings for Diesel Fuel Operation

Load (%)	Fuel Consumption (kg/h)	Speed (rpm)	Torque (N·m)	Brake Power (kW)	BTE (%)	BSFC (kg/kWh)
0	0.42	1500	0.0	0.00	0.00	-

25	0.65	1495	8.5	1.33	18.5	0.49
50	0.88	1490	16.8	2.62	24.7	0.34
75	1.15	1485	25.4	3.95	28.9	0.29
100	1.48	1480	33.2	5.15	31.6	0.28

Table 4.2: Experimental Readings for Alternative Fuel Blend Operation

Load (%)	Fuel Consumption (kg/h)	Speed (rpm)	Torque (N·m)	Brake Power (kW)	BTE (%)	BSFC (kg/kWh)
0	0.45	1500	0.0	0.00	0.00	-
25	0.70	1493	8.2	1.28	17.8	0.55
50	0.96	1488	16.2	2.52	23.5	0.38
75	1.26	1482	24.8	3.85	27.4	0.33
100	1.62	1478	32.5	5.02	30.2	0.32

Table 4.3: Comparative Performance Summary

Fuel Type	Maximum Brake Power (kW)	Maximum Torque (N·m)	Maximum BTE (%)	Minimum BSFC (kg/kWh)
Diesel	5.15	33.2	31.6	0.28
Alternative Fuel Blend	5.02	32.5	30.2	0.32

Final Result and Discussion

The experimental investigation of alternative fuel engine performance was carried out by analyzing key performance parameters, including brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), brake power, and torque under different engine load conditions.

The results showed that engine performance improved with an increase in load for both conventional diesel and alternative fuel operation. Brake power and torque increased progressively with increasing load due to higher fuel supply and improved energy release during combustion. The maximum brake power obtained with diesel fuel was approximately 5.15 kW, while the alternative fuel blend produced a comparable value of 5.02 kW.

The brake thermal efficiency increased with engine load because a greater proportion of the fuel energy was converted into useful mechanical output at higher loads. The maximum BTE achieved for diesel fuel was 31.6%, whereas the alternative fuel blend recorded 30.2%. The slightly lower efficiency of the alternative fuel blend was mainly attributed to its lower calorific value and different combustion characteristics.

The brake-specific fuel consumption decreased as the load increased for both fuels, indicating improved fuel utilization at higher operating conditions. The minimum BSFC values obtained were 0.28 kg/kWh for diesel and 0.32 kg/kWh for the alternative fuel blend. The higher BSFC of the alternative fuel was associated with the increased fuel requirement due to differences in energy content.

Overall, the alternative fuel demonstrated satisfactory engine performance with only a small reduction in brake power, torque, and thermal efficiency compared with conventional diesel fuel. The results indicate that alternative fuel blends have the potential to replace a portion of fossil fuels while maintaining acceptable engine performance and contributing to reduced dependence on petroleum-based fuels.

Table 4.5 Final Performance Summary

Parameter	Diesel Fuel	Alternative Fuel Blend
Maximum Brake Power (kW)	5.15	5.02
Maximum Torque (N·m)	33.2	32.5
Maximum BTE (%)	31.6	30.2
Minimum BSFC (kg/kWh)	0.28	0.32

V. EMISSION CHARACTERISTICS ANALYSIS

The emission characteristics of the engine operated with conventional and alternative fuels were evaluated by measuring exhaust gas emissions under different engine load conditions. The major emission parameters considered were carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NOx), carbon dioxide (CO_2), and smoke opacity. These emissions provide an indication of combustion quality and the environmental impact of alternative fuel utilization.

Table 5.1: Emission Characteristics for Diesel Fuel Operation

Load (%)	CO (% vol.)	HC (ppm)	NOx (ppm)	CO_2 (% vol.)	Smoke Opacity (%)	Load (%)

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0	0.08	35	420	2.1	8	0
25	0.12	42	560	3.5	18	25
50	0.16	48	680	5.2	30	50
75	0.20	55	790	6.8	42	75
100	0.24	62	880	8.1	55	100

Table 5.2: Emission Characteristics for Alternative Fuel Blend Operation

Load (%)	CO (% vol.)	HC (ppm)	NOx (ppm)	CO_2 (% vol.)	Smoke Opacity (%)	Load (%)
0	0.06	28	450	2.3	6	0
25	0.09	35	590	3.8	14	25
50	0.12	40	720	5.6	24	50
75	0.15	46	830	7.1	34	75
100	0.18	52	920	8.5	45	100

Table 5.3: Comparative Emission Summary at Full Load

Emission Parameter	Diesel Fuel	Alternative Fuel Blend
CO (% vol.)	0.24	0.18
HC (ppm)	62	52
NOx (ppm)	880	920
CO_2 (% vol.)	8.1	8.5
Smoke Opacity (%)	55	45

Emission Analysis Discussion

The emission results indicate that carbon monoxide (CO), unburned hydrocarbons (HC), and smoke opacity decreased when the engine was operated with the alternative fuel blend compared with diesel fuel. This reduction can be attributed to the presence of oxygen in the alternative fuel, which promotes better combustion and reduces incomplete combustion products.

However, NOx emissions showed a slight increase with the alternative fuel blend due to higher combustion temperature and improved oxygen availability during the combustion process. Carbon dioxide emissions were slightly higher because of more complete fuel oxidation.

Overall, the alternative fuel blend demonstrated improved exhaust emission characteristics, particularly in reducing CO, HC, and smoke emissions, while maintaining comparable engine performance with conventional diesel fuel.

Results and Discussion of Emission Characteristics

The emission characteristics of the engine operating with diesel fuel and an alternative fuel blend were investigated under different engine load conditions. The exhaust emissions analyzed were carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NOx), carbon dioxide (CO_2), and smoke opacity. The variation in emission levels with increasing engine load provided information regarding combustion behavior and the environmental performance of the alternative fuel.

The results indicated that CO emissions increased with increasing engine load for both fuels due to the higher quantity of fuel supplied at higher loads. However, the alternative fuel blend exhibited lower CO emissions compared with diesel fuel throughout the operating range. This reduction was attributed to the presence of oxygen within the alternative fuel, which improved fuel–air mixing and promoted more complete combustion.

Similarly, HC emissions increased as the engine load increased because of incomplete combustion and reduced oxidation of fuel molecules. The alternative fuel blend produced lower HC emissions than diesel fuel, indicating improved combustion efficiency and better utilization of the supplied fuel.

The NOx emission level increased with increasing load for both fuels due to the increase in combustion temperature and oxygen availability. The alternative fuel blend showed slightly higher NOx emissions compared with diesel fuel, which can be associated with improved combustion intensity, higher peak cylinder temperature, and additional oxygen content in the fuel.

Carbon dioxide (CO_2) emissions increased with increasing load because of the higher fuel consumption and greater carbon oxidation during combustion. The alternative fuel blend produced slightly higher CO_2 emissions, indicating more complete combustion of the fuel.

Smoke opacity showed a significant reduction when the engine was operated with the alternative fuel blend. The lower smoke emission was mainly due to improved atomization, oxygen availability, and reduced formation of soot particles during combustion. The reduction in smoke opacity demonstrates the potential of alternative fuels for minimizing particulate emissions.

Overall Result

The experimental emission analysis revealed that the alternative fuel blend improved several emission characteristics compared with conventional diesel fuel. The alternative fuel reduced CO, HC, and smoke opacity emissions while maintaining comparable engine performance. Although a slight increase in NOx and CO_2 emissions was observed, the overall emission behavior demonstrated improved combustion quality and reduced particulate pollution.

Table 5.5 Summary of Emission Performance at Full Load

Emission Parameter	Diesel Fuel	Alternative Fuel Blend	Performance Observation
CO (% vol.)	0.24	0.18	Reduced emission
HC (ppm)	62	52	Reduced emission
NOx (ppm)	880	920	Slight increase
CO_2 (% vol.)	8.1	8.5	Slight increase
Smoke Opacity (%)	55	45	Significant reduction

VI. CONCLUSION

The experimental investigation of alternative fuel engine performance and emission characteristics was carried out to evaluate the suitability of alternative fuels as a replacement for conventional diesel fuel. The engine performance analysis was conducted based on important parameters such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), brake power, and torque, while the emission analysis was performed by evaluating CO, HC, NOx, CO_2, and smoke opacity levels.

The engine performance results showed that increasing engine load improved brake power, torque, and brake thermal efficiency due to increased fuel energy release and improved combustion conditions. The alternative fuel blend demonstrated comparable performance to diesel fuel, although slight reductions in brake power and thermal efficiency were observed due to differences in fuel properties such as calorific value, viscosity, and combustion characteristics. The BSFC of the alternative fuel was slightly higher than diesel fuel because a greater quantity of fuel was required to produce the same power output.

The emission analysis revealed that the use of alternative fuel significantly reduced carbon monoxide (CO), unburned hydrocarbon (HC), and smoke opacity emissions compared with conventional diesel fuel. These reductions were mainly attributed to the presence of oxygenated compounds in the alternative fuel, which improved fuel–air mixing and enhanced combustion efficiency. However, a slight increase in NOx emissions was observed due to higher combustion temperature and improved oxygen availability during combustion. Carbon dioxide emissions showed minor variations depending on fuel consumption and combustion completeness.

Overall, the experimental results demonstrate that alternative fuels can be successfully utilized in diesel engines while maintaining acceptable performance and improving exhaust emission characteristics. The reduction in harmful pollutants, particularly CO, HC, and smoke emissions, highlights the environmental benefits of alternative fuels. With further optimization of fuel properties, injection parameters, and engine operating conditions, alternative fuels have strong potential for sustainable and cleaner engine operation.

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