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Research Article

Experimental investigation of methyl-ester soybean biodiesel: performance and emission characteristics as an alternative diesel fuel

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ABSTRACT

Due to the higher demand for renewable and sustainable energy sources, it is very important to investigate fuels such as soybean biodiesel. This study focuses on a compression ignition diesel engine's performance characteristics and emissions when running on soybean biodiesel (B100 with 5% ethanol) in comparison to normal diesel fuel. The hypothesis is based on soybean being a biodiesel that can perform reasonably close to normal diesel engine with low emissions. Key performance variables such as indicated power, brake horse power, frictional power, thermal efficiencies, mechanical efficiency and specific fuel consumption were obtained during the experimental analysis as depicted in the research methodology. Emissions of CO, HC, CO_2, O_2, and NO_x for the diesel fuel and for various biodiesel blends (B25, B50, B75) were also studied. Findings indicated that soybean biodiesel had comparative fuel economy and power generation as diesel, and CO emission was reduced by 40, while NO_x emissions increased by 48 percent at full load condition. This studies clearly show that it is easy to use soybean oil based biodiesel as a renewable eco-friendly alternative biodiesel for compression ignition engines with much more improvement opportunities in terms of emissions performance. The originality of this work resides in the broader scope to evaluate the performance, emissions and trade-offs of soybean biodiesel blends and prospects that the literature on the sustainability of biodiesel is expanding by bringing in such new perspectives on it. Through the integration of experimental results, relevant performance as well as environmental assessments, this study extends previous endeavors and provides concrete recommendations for researchers, industry players and policy-makers willing to contribute to the advancement of alternative fuels.

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INTRODUCTION

Background and Importance of Soybean Biodiesel

Due to its convenience and a great source of lipids, soybean oil has become an excellent feedstock for biodiesel production. The use and the production of biodiesel from soybeans increases energy independence and pushes for environmental friendly policies through less emissions of greenhouse gases (GHGs). According to recent estimates, U.S. soybean oil production's carbon footprints have been reduced by 22% demonstrating that the oil is a suitable low-carbon feedstock for clean fuels [1-3]. Comparative life-cycle studies demonstrate that with reasonable estimates based on production practices and geographical location, biodiesel from soybean oil is expected to emit 40% to 69% fewer GHGs until 2040 [4]. Further, as new technologies in biofuel production are being developed such as superior transesterification processes and better catalysts, soybean biodiesel is being made more efficient and sustainable all the time. This enables wider acceptance since it leads to increased outputs and decreased costs of production [5]. In addition, the rising interest in biodiesel has led to increased soybean growing and it is anticipated that 14 billion pounds of soybean oil will be used in biofuel production during the period of 2024 to 2025 [6]. But on the other hand, it is also important to think about the land-use change and the GHG emitting consequences that ever increasing soybean farming may have. Such studies show that unless sustainable agricultural practices are put in place, increased production of soybeans will result in more emissions [7]. This study thus aims at investigating the effects of differing reaction times on oil yields when using non-edible oils such as waste cooking oil, rubber seed oil and jatropha curcas linn seed oil in biodiesel synthesis. Looking at these issues will bring forth a revelation concerning why soybeans can stand out as a food security crop even in areas where other food crops cannot grow properly, let alone produce enough to be sold or consumed by people living in those regions [8]. The soybean bio-diesel is one possible solution towards achieving this goal, provided it ends up replacing petroleum diesel fully since it would not burn sulfur-containing compounds in our atmosphere like does ordinary diesel fuel. We strive for a cleaner energy future; soybean biodiesel stands out as a promising contender within this transition period for a more earth-friendly and greener power landscape.

Scope of the Study

As the demand for biodiesel rises, there is an ongoing development of quality standards and specifications that impose restrictions on permissible levels of contaminants in biodiesel. Key elements influencing the economic feasibility of biodiesel production comprise plant capacity, feedstock oil prices, and glycerine and biodiesel yields. An operation with an annual capacity of 100,000 tons demonstrates economic viability, displaying increased ARR and NNP alongside a reduced BBP. Enhancing capacity using soybean oil or waste cooking oil maintains economic feasibility, supporting the future promotion of biodiesel production by reducing feedstock oil costs and increasing valuable product yields in large-scale plants [9]. Biodiesel indicated a lower exhaust emissions but CO2 emission slightly higher with the exception of NOx according to M. Canakci [10]. The potential for lower oxidation stability and lower performance in cold weather due to higher cloud and pour points needs to be improved [11-12]. The improvement can be done by using some additive for cold flow improvement, a slight blend of petro-diesel during winter, the winterization process, hydrotreating technology, or the use of ethanol or methanol blends [13-14].

Soybean Biodiesel is derived from the chemical reaction between soybean oil, methanol, and a catalyst, resulting in the biodiesel manufacturing process (fatty acid methyl esters) and glycerin as a secondary product. Its compatibility with unmodified diesel engines and potential substitution for petroleum-based diesel addresses the growing demand for alternative, biodegradable, and economically viable fuel sources [15-19]. Amid global apprehensions regarding the exhaustion of petroleum reserves, the intensification of global warming, and environmental challenges, there exists an urgent requirement for sustainable alternatives. Recognized as a clean, green, and renewable fuel, biodiesel emerges as a prime substitute for traditional diesel, aiming to reduce dependence on pollution-inducing fossil fuels and mitigate environmental impact. The agricultural soybean yield serves as a valuabel protein source as well as the primary feedstock in the production of biodiesel. The use of soybean oil, an abundant renewable resource, makes up 73% of biodiesel and finds applications across various industries [20-21]. Additionally the use of soybean oil as a biodiesel feedstock is novel in the sense that methyl esters are prepared from the oil on a large level. Lapin described the problematic clarification processes of unevenly heated biodiesel produced from the microalgae Spirulina in a novel ans simple way. Most microalgae lipids that can convert to methyl esters, are thermally stable. Therefore, external heating gently and evenly solves the heating issue, while microalgae that remain unutilized can solve the lack of heating.

Diluting with hexane improves the separation of crystals from liquid methyl esters, offering potential benefits for biodiesel production [22]. In contrast to other oil crops, soybeans exhibit greater harvest and contain approximately 19% of oil content.

The rising demand for energy compels the investigation of alternative energy sources such as biofuels and methods for energy conservation. Chand et al. present a diesel engine-driven combined heat and power system utilizing various blends of biodiesel as fuel [23]. The findings indicate that Eureka Sativa oil biodiesel exhibits the highest brake thermal efficiency and the lowest brake specific fuel consumption compared to all other biodiesel blends. Sekharraj et al. investigate the application of algae-derived biodiesel, including microalgae oil, in the production of biodiesel [24]. The study also compares Bi2O3 nanoparticles with additives to biodiesel fuel blends which have better results in terms of performance and emissions. The study conducted by Rangasamy and co-workers and Ahmadbeigi et al. presents the use of Chlorella emersonii methyl ester (CEME) which is a common fresh water green algae growing in Indian subcontinent. Biodiesel presents considerable potential as an energy source, attributed to its renewable characteristics, lower emissions, and versatility in production from diverse materials [25-26]. Sonawane et al. discussed different ethanol-diesel blends, including those close to 5%, noting emission benefits like reductions in particulate matter and smoke [27]. According to Salmani and the work of, 5% ethanol blends offers increased combustion efficiency driven by combustion and emission reduction [28].

Through the use of lipases as biocatalysts, Lloyd and other authors demonstrated the ease and accuracy of the conversion of triglycerides to alkyl esters. Assessments on the efficiency of various lipase biocatalysts revealed a significant difference in conversion potency. These results provide fundamental insight towards building green pathways to large-scale biodiesel production [29]. Schumacher and other authors observed a reduction to the total amount of hydrocarbons emitted, together with the particulate matter and carbon monoxide but more NOx [30].

Alcantara et al., explored three fatty materials—soybean oil, used frying oil (a 50% mixture of olive and sunflower oil), and tallow. These materials were subjected to transesterification with methanol to generate biodiesel. The cetane indices, determined by ASTM methods based on density and atmospheric distillation, matched those of conventional petrochemical diesel. Utilizing biodiesel like Soygold utilized as a blending component for middle distillate fuels offers numerous advantages. Compliant with or exceeding of ASTM specifications, it provides beneficial synergistic effects when combined with stable and unstable middle distillate fuels. Blended insoluble at 10-20% show stability in storage for at least one year and pass the ASTM filterability test [31]. While the failure of the ASTM filterability test in pure soy-derived diesel is attributed to the presence of polar species, it's important to note their tendency to clog such filters. Additionally, esters in biodiesel enhance lubricity, foster positive synergies, act as an additional oxygen source and interact with fuel system components [32].

Candeia et al. identified that the blend ratios of soybean biodiesel with diesel depended on the biodiesel proportion and the primary alcohol size in the ester. Careful consideration should be taken with diesel engines as increasing concentrations of biodiesel may impact engine performance and operation. All in all, biodiesel-diesel blends are a practical and reasonable alternative to fossil fuels [33]. Additionally, Ozener et al. analyzed the combustion, performance and emissions of conventional diesel and blends with soybean oil derived biodiesel (B10, B20, B50, B100). They showed that lower heating value of biodiesel could be responsible for the 1-4% decrease in torque and 2-9% increase in brake-specific fuel consumption (BSFC). They noted significant reductions in carbon monoxide (CO) and unburned total hydrocarbons (THC) emissions but higher emissions of NOx and CO2 [34]. They found that biodiesel decreases the diesel ignition delay time and the premixed combustion phase duration, which means, it's a promising alternative fuel for the engine which is less harmful to the environment. Improved sustainability practices, such as crop rotation and reduced tillage, are necessary for environmentally responsible biodiesel. Addressing NO_x emissions may require new injection strategies. Bioenergy production, especially biodiesel, faces sustainability challenges. Despite being a crucial energy resource for global fuel diversification, increased efficiency, and pollution reduction, concerns arise. According to the eligible content, the caused concerns can include sustainability, socio economics, and environment impacts such as deforestation, biodiversity loss, and health-related concerns in the case of soybean, which is one of the key biodiesel feedstock. South American soybean production schemes, mainly in Argentina and Brazil, sound the alarm about soil fertility exhaustion, agrochemical poisoning, and negative burdens for the society. Improved sustainability practices, such as crop rotation and reduced tillage, are necessary for environmentally responsible biodiesel.

Nevertheless, the current projection indicates the extinction of soy biodiesel by 2050, pointing towards the necessity of the range of feedstock crops to support the biodiesel industry sustainably [35]. Can et al, showed that incorporating diesel with soybean biodiesel and EGR used in a diesel engine improves the combustion characteristics of the diesel and helps in the reduction of NOx emission while maintaining the engine performance [36]. These results demonstrate soybean biodiesel's advantage as a renewable substitute for diesel engines and its role in protecting the environment.

Cesar et al discusses the competitiveness of 'social soybeans' for biodiesel production in Brazil. It explores the social, economic, and political factors impacting the supply chain and offers strategies to strengthen the position of subsistence farmers [37]. While Zhu et al. [38] analyze the socio-economic consequences of biodiesel and the potential of biodiesel for inclusive growth. Zhu et al introduces a CaO/Ag nano-catalyst for the transesterification of soybean oil and proves that it has better catalytic activity than the isolated catalysts. With optimized conditions, this catalyst reaches a very high biodiesel yield of 90.95 ± 2.56%, which is a substantial improvement compared to only using CaO. Improved reaction kinetics, thermodynamics, and economics as articulated in the kinetic and thermodynamic studies, demonstrate the growing potential of CaO/Ag for biodiesel catalyst and the catalyst's promise for the industry biodiesel production. The studies were conducted with fresh and used soybean oils into biofuel free of the wax compounds. The new oil had a higher oleic acid content, and the results indicated variations in peroxide values and free fatty acid concentrations [39]. A green heterogeneous catalyst was developed by transesterifying soybean oil to produce biodiesel. Transesterification was sped up by the catalyst, which was made from Parkia speciosa biomass and exhibited strong active sites for calcium and potassium. The catalyst was a good substitute for traditional homogeneous catalysts since it maintained its heterogeneity even after five cycles and produced the maximum biodiesel production of 96.4% at 40 °C [40]. Agbulut et al., produced alternative diesel engine fuels from waste soybean oil. Through a transesterification method, hybrid catalysts such as Ni-doped ZnO, Alkyl-celite, Poly-acrylonitrile nano-fibrous, and Ironoxide are used to make the biodiesel. Blends with diesel were made using the waste soybean oil (BDWSBO) with the highest yields. With 30.85% BTE and 17.96% less smoke opacity than the 25% diesel fuel with 75% IO-II-used BDWSBO blend, it is advised as an alternate fuel for diesel engines [41].

Research Gap and Novelty

So far, existing literature reveals limited investigations on soybean biodiesel, with only a few researchers exploring its performance parameters in four-stroke diesel engines. Some aspects remain unclear, such as the few low content biodiesel blends with petroleum diesel studies. To fill these gaps, the current work examines performance curves, power variation exhaust emissions, and fuel consumption fuel using four blends of soybean biodiesel and 5% (V/V) ethanol, knows as B25, B50, B75 and B100. This investigation aims at updating this information by examining the technological features of soybean biodiesel production and analyzing its performace as well as its environmental sustainability. This study, by examining of soybean biodiesel, could present an insightful side for researchers, policy makers and industry that want to produce the sustainable and a cleaner substitution energy.

MATERIALS AND METHODS

Preparation of Soybean Biodiesel: Transesterification Process

FAME, or fatty acid methyl esters, are long-chain mono alkyl esters that are created when oils and fats are converted to biodiesel is justified for bio-diesel blends production. In such process 100 parts of oil or fat and 10 parts of a short-chain alcohol such as methanol yare reacted in the presence of a catalyst. Sugar glycerin is generated as a co-product. A common process for making biodiesel from vegetable and animal fats is transesterification. Different methods, including as solvent extraction, supercritical fluid extraction, transesterification, and mechanical presses, are used in the conventional biodiesel production process to extract and convert oil from soybeans. It includes lowering the viscosity of fats or oils by reacting them with alcohol to create glycerol and alky esters. Selecting the right alcohol and catalyst is essential; methanol is a common option because of its low cost and several chemical and physical benefits such as low viscosity (0.54 cP at 25 °C), high reactivity, and low carbon emissions (20-50%) with congenital fuels [42]. Triacylglyceryl esters of fatty acids with glycerol make up the majority of vegetable oils.

Description of the Transesterification Process

The transesterification process covers the following procedures:

(a) Reaction Mechanism: In this process, soybean oil which contains triglycerides is reacted with methanol with the use of an alkali catalyst such as sodium or potassium hydroxide. Such a process produces methyl esters (biodiesel fuel) and glycerol as a byproduct.

(b) Optimal Reaction Conditions:

- **Temperature:** The process is usually performed under a temperature of 60 ºC which is sufficient to ensure that optimal yield results, while energy requirements are minimized.
- **Time of Reaction:** A time period extending between 1-2 hours is sufficient for the conversion of the triglyceride oils to methyl esters.
- **Alcohol-to-oil:** In most cases a ratio of alcohol-to-oil of 6:1 (methanol to oil) is used to complete the reaction.

(c) Purification: After the reaction, the closely mixed solution is allowed to sediment. The layer containing biodiesel is separated from the glycerol layer. The biodiesel obtained is then washed with water to remove remaining catalyst or impurities, followed with a drying process until the required level of purity is achieved.

Figure 1 displays the basic flowchart of the entire manufacturing process.

Formulation of Blends (B25, B50, B75, B100)

After preparation of soybean biodiesel from the transesterification process, four different blends are prepared in the laboratory. These blends are, namely, B25 (25% biodiesel + 70% petro-diesel + 5% ethanol), B50 (50% biodiesel + 45% petro-diesel + 5% ethanol), B75 (75% biodiesel + 20% petro-diesel + 5% ethanol), and B100 (with 5% ethanol). An additive of 5% ethanol is mixed to keep the charge temperature lower than its usual level and to drop the temperature of the combustion chamber, as higher temperature enhances NO_x production in the exhaust [28]. A 5% ethanol blend strikes a balance by improving properties like viscosity and flash point without significantly compromising the fuel's energy content or causing phase separation issues [43].

Experimental Setup

The experimentation targeted a four-stroke, 5 H.P single-cylinder diesel engine, shown in Figure 2(a), which underwent trying out with various fuel combos. These included petroleum-derived diesel, B100 (with a 5% ethanol

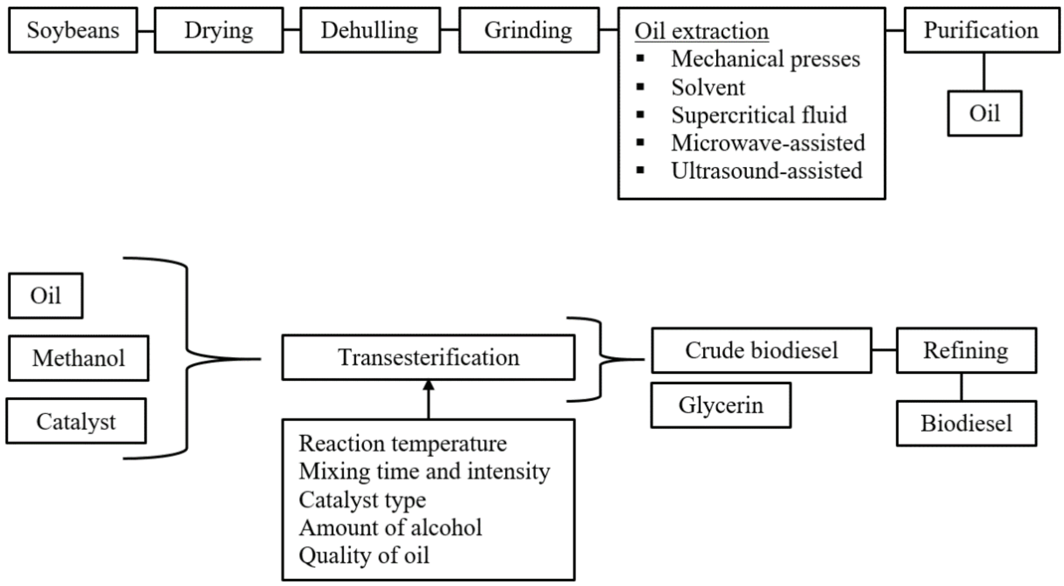

Figure 1. Basic flowchart of the overall manufacturing process of soybean biodiesel.

addition), and various biodiesel blends, namely B25, B50, and B75. In such process 100 parts of oil or fat and 10 parts of a short-chain alcohol such as methanol yare reacted in the presence of a catalyst. Sugar glycerin is generated as a co-product. To control the charge temperature and to reduce the combustion chamber temperature, a 5% ethanol+diesel blend was homogeneouslymixed into all the biodiesel blends. This tactical action was to avoid the charge temperature becoming higher than the norm and to reduce the chamber temperature. The higher temperatures in the combustion chamber are one of the causes for higher NOx production in the exhaust. The biodiesel blends used in the experimental section were carefully prepared, and have the following mixtures: B25 (25% biodiesel, 70% petro-diesel and 5% ethanol), B50 (50% biodiesel, 45% petro-diesel and 5% ethanol) and B75 (75% biodiesel, 20% petro-diesel and 5% ethanol).

Engine Specifications and Testing Conditions

The diesel engine employed in this case study is a single cylinder four stroke engine commonly used and well-accepted in research due to the reliability, low cost, and availability. Such engine allows for the precise parameters to be controlled and measured such as torque, fuel intake, and emissions of the engine. Moreover, its small scale and standardized design ensure reliability of replication and comparison.

Taking into account the small-scale industries, the engine's capacity of 5 H.P can be ideal for them, thus making the results applicable for real time scenarios. The testing conditions alongside fuel blend and variable loads were practical and useful for the analysis of the engine in different scenarios. Moreover, a rope brake dynamometer is being utilized in this case for the accurate measurements of the brake horse power.

Experimental Procedures

Before beginning the experiments on the four-stroke, 5-horsepower single-cylinder diesel engine, we fill the engine fuel tank with the necessary amount of fuel and check its level. The lubricating oil level is checked. The cooling water is supplied to the calorimeter. We start the engine and then supply the cooling water. It is loaded slowly using the brake drum dynamometer, and respective quantity values are noted during testing, such as brake drum loading, engine speed, and time taken for 10 cc of fuel consumption. The parameters are obtained by using a set of calculations that are explained in the result and discussion part. The engine's specifications are as follows:

Equipment Used (Saybolt Viscometer, AVL Gas Analyzer)

The essential fuel characteristics, encompassing Fire and Flash points, as well as Kinematic viscosity, were evaluated using the Saybolt viscometer, as shown Figure 2(b)

Table 1. Engine specifications

Number of cylinders: Single
Cooling system: Water-cooled
Loading device: Rope brake dynamometer
Brake power: 5 horsepower (H.P)
Bore diameter: 80 millimeters
Stroke length: 110 millimeters
Engine speed: 1500 revolutions per minute (rpm)
Compression ratio: 16:1
Air orifice diameter: 24 millimeters
Brake drum radius: 165 millimeters

Figure 2(a). Experimental setup: four stroke, 5 H.P single cylinder diesel engine. (It was drawn by the author).

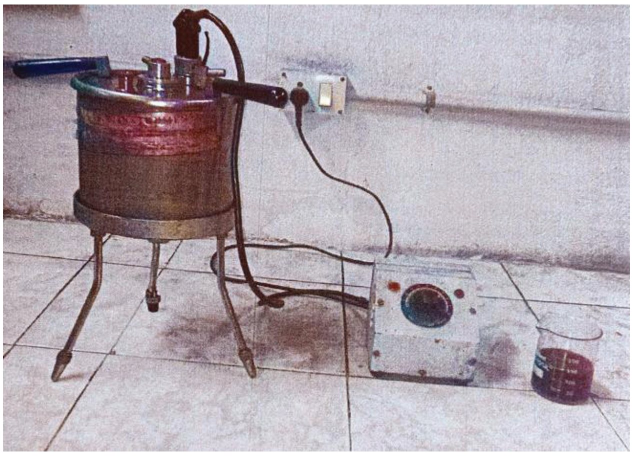

Figure 2(b). Saybolt Viscometer.

Figure 2 (c). AVL gas Analyzer readings.

and the Pensky-Martin apparatus for various fuels, including biodiesel and its blends. The rationale for performing experiments on the flash and fire point lies in the chemical decomposition of fuel when exposed to elevated temperatures. This process results in the breakdown of hydrocarbons, leading to the formation of volatile combustible gases. "The flash point of a substance is the lowest temperature at which it can vaporize to form an ignitable mixture in the air. "Fire point is the point which is the lowest temperature at which the vaporized substance may keep on burning if the fire is ignited," on the opposite of the flash point. These features are necessary for the explanation of flammability and safety aspects of the application so the fuels are suitable for use in other fields [44-45].

Knowledge of the flash and fire points is important when it comes to fuel handling and storage safety, ensuring the observance of the set safety requirements. It is a must to test the fuel according to the procedures developed by the American Society of Testing Materials (ASTM) before using it in the internal combustion engines. According to the ASTM demands, the flash point of B100 (Biodiesel) shall not exceed 150 °C, except in the case that the oil used for transesterification and the catalyst are employed. In contrast, the typical range for diesel fuel ranges from 60 °C to 80 °C. The index of viscosity refers to the magnitude of the difference in resistance among layers of fluid in motion, and is among the most important parameters. ASTM has set kinematic viscosity at a certain level where the aims are zeroing the possibility of the injector being clogged and measuring the flow rate unambiguously in engines. Be that as it may, compliance to these viscosity standards is absolutely necessary for the utilization of the fuel in the internal combustion engines in an optimal way, thus a probable guarantee of efficient and trouble-free engine performance.

The AVL Gas Analyser, as shown in Figure 2(c), is an auto-calibrated machine that has a series of filters fitted inside and sideways to predict the amount of exhaust gases entering from the exhaust pipe. It has a long tailpipe attachment to the main unit, of which one end has to let through the exhaust passage of the diesel engine and the other to the unit. As the exhaust gases pass through the pipe fitted with filters, they reach the sensors, where each sensor calibrates the presence of different emissions and shows the results on the monitor. The unit is equipped with three types of filters for measuring purposes: one is installed along the tail pipe, a second circular paper filter is fixed to the front of the unit, as shown in Figure 2(c), and a third type filter is fixed to the bottom of the unit. As the gas passes through these series of filters, sensors are fixed along the way to measure different emissive gases.

Engine testing was conducted in accordance with ISO 8178 standards for exhaust emissions and ASTM D6751 standards for biodiesel quality. Key tests were performed in compliance with ASTM D445, D613, and D93. Calibration methods of the instruments were described, as which could guarantee the mesausrements repeated and precisely. These additions provide a clearer context for the reliability and rigor of the experimental approach.

Procedure of Heat Balance Analysis

Engine is supplied with the fuel. The coolant generally water is made to pass through the water jacket of the engine. The engine parameters are noted on the application of the load over it, starting from no load condition till the maximum load that could be applied on it. The parameters such as time for consumption of the 10cc of fuel is noted along with the inlet and outlet temperature of the cooling water, Exhaust gas temperature are noted using the thermal sensors placed at strategic points in the system.

Mathematical formulation involved in tabulation of performance parameters:

1. **Torque produced (T)** = w * r Newton-meter
   Where w = m*g; m = load applied using rope brake; g = acceleration due to gravity taken as 9.81 m/s2;
   r = brake drum radius of 165mm.
2. **Brake Power (B.P)** is the power developed by an engine at the output shaft.
   B. P = 2πNT/60000 Kilowatt
   Where N is speed in rpm; T is torque produced;
3. **Mass fuel consumption (MFC)** = (a*specific gravity)/(1000*t) kg per second
   Where a is 10cc of fuel consumed; t is time taken for consumption of 10cc;
   Specific gravity of biodiesel is 0.88 kg per liter and diesel is 0.85kg per liter.
4. **Specific fuel consumption (SFC)** is mass fuel consumed per brake power produced = MFC/B.P
   Units is kg per second per kilowatt
5. **Indicated power (I.P)** is the total power by the combustion of fuel in the combustion chamber.
   I.P = Brake power + Frictional power
   Frictional power is got by plotting graph between MFC vs. B.P
6. **Mechanical efficiency (ηmech)** = (Brake power/indicated power) *100%
7. **Brake Thermal Efficiency (ηbth):**
   The ratio of the Brake power produced to the total heat supplied by the combustion of fuel.
   Brake thermal efficiency (ηbth) = Brake power/Q;
   Where Q = MFC*CV; CV is the calorific value of the fuel; For Diesel: CV = 44,800KJ/Kg
8. **Indicated Thermal efficiency** is the ratio of the indicated power to the total heat supplied by the fuel.
   Indicated thermal efficiency (η_{ith}) = Indicated power/Q.

Mathematical formulation involved in tabulation of heat balance analysis:

1. **Brake power (B.P)** = (2πNT*3600)/60000 kilojoules per hour
   Where T is torque produced = mg*r; m is load applied; g is acceleration due to gravity;
   r is Brake drum radius
2. **Mass of water (mw)** during 10cc consumption of fuel = 3600/t kilogram per liter
   Where t is time taken for 10cc consumption of fuel; t = 88 sec/l
3. **Head of air (H)** = {(h_2-h_1) * density of water}/density of air at RTP
   Units is meter; Density of water (ρw) = 1000 Kg/m3; Density of air (ρa) = 1.29 Kg/m3
4. **Mass of air (ma):** Va * Density of air at RTP * 3600
   Where Va = Cd*A $\sqrt{2gH}$;Cd is coefficient of discharge of 0.6;
   A is area of the orifice with a diameter of 15mm = $1.76*10^{-4}$ m^2
   Unit is kilogram per hour.
5. **Mass of the exhaust gases (meg)** = m_a + T.F.C
   Units is kilogram per hour; T.F.C is total fuel consumption = (specific gravity *3600*10)/ (1000*t);
   Specific gravity of Biodiesel is 0.86 kilogram per liter;
   Specific gravity of Diesel is 0.83 kilogram per liter; t is time taken for 10cc of fuel consumption.
6. **Heat supplied by the fuel Qs** = T.F.C * CV
   Unit is kilojoules per hour: CV for Biodiesel is 37.015 megajoules per kilogram and for
   Diesel is 44.8 megajoules per kilogram.
7. **Heat carried away by cooling water (Qcw):**
   Q_{cw} = M_{cw} * C_{pw} * temperature difference between outlet and inlet
   Where, C_{pw} is the specific heat of water is 4.18 kilojoules per kg-Kelvin
8. **Heat carried by the exhaust gases (Qeg):**
   Q_{eg} = M_{eg}*C_{peg} * temperature difference between outlet and inlet
   C_{peg} is the specific heat of gases is 1.005 kilojoules per kg-Kelvin

9. Heat loss unaccounted (Qun):
$Q_{un} = Q_s - \{Q_{cw} - Q_{eg} - Q_{bp}\}$

10. % of Heat supplied by the fuel, shared among all as:
% of Heat utilized for B.P = $(B.P/Q_s)$ *100
% of Heat lost due to coolant = (Q_{cw}/Q_s) *100
% of Heat lost due to exhaust gases = (Q_{eg}/Q_s) *100
% of Heat loss unaccounted = (Q_{un}/Q_s) *100

11. Temperature legends followed:
T1 = Room Temperature; T2 = Water Inlet Temperature; T3 = Water Outlet Temperature;
T4 = Exhaust Gas Temperature.

RESULTS AND DISCUSSION

Estimation of Fuel Properties

This study investigates the kinematic viscosity of various blends of soybean biodiesel at a temperature of 40 °C, Table 2. A stopwatch is employed to measure the duration needed to gather 60 CC of biodiesel and its various blends. The collection times recorded were 33 seconds for B25, 34 seconds for B50, 35 seconds for B75, and 36 seconds for B100.

The kinematic viscosity values recorded were 1.35 centistokes, 1.74 centistokes, 2.12 centistokes, and 2.50 centistokes for B25, B50, B75, and B100, respectively. The Saybolt viscometer and the Pensky-Martin apparatus are employed to assess the kinematic viscosity, flash, and fire points of various soybean biodiesel blends. The flash points recorded were 38 °C, 42 °C, 54 °C, and 74 °C for B25, B50, B75, and B100, respectively, Table 3. The corresponding calorific values were 42.19 MJ/kg, 40.34 MJ/kg, 38.49 MJ/kg, and 37.01 MJ/kg. The fire points identified for B25, B50, B75, and B100 were 58 °C, 62 °C, 80 °C, and 110 °C, respectively.

The observations reveal a correlation among the share of biodiesel inside the blends (starting from B25 to B100) and an increase in kinematic viscosity, representing the ratio of dynamic viscosity to the density of fluids. This located trend aligns with ASTM standards specifying that the kinematic viscosity of biodiesel must fall inside the variety of 1.90 to 6, a criterion met through the values observed from the experiments.

On the contrary, the flash and fire factors show off a decline from B100 to B25 because the diesel content material inside the blends increases. Precise readings for flash and fire points have been systematically recorded at 2 °C periods for the duration of engine performance tests carried out on the laboratory. Table 4 summarises the measured properties of biodiesel blends.

Table 2. Tabulation of kinematic viscosity for biodiesel and its blends

Biodiesel blend	Temperature (°C)	Time for collection of 60 CC of fuel (seconds)	Kinematic viscosity (centistokes)	Kinematic viscosity (m^2/s)
B25	40	33	1.35	1.35 X 10^{-6}
B50	40	34	1.74	1.74 X 10^{-6}
B75	40	35	2.12	2.12 X 10^{-6}
B100	40	36	2.50	2.50 X 10^{-6}

Table 3. Tabulation of kinematic viscosity for biodiesel and its blends

Biodiesel blend	Flash point (°C)	Fire point (°C)	Density (Kg/m^3)	Calorific value (MJ/Kg)
B25	38	58	838	42.19
B50	42	62	848	40.34
B75	54	80	858	38.49
B100	74	110	866	37.01

Table 4. Fuel properties of biodiesel blends

Biodiesel blend	Flash point (°C)	Fire point (°C)	Kinematic viscosity (centistokes)
B25	38	58	1.35
B50	42	62	1.74
B75	54	80	2.12
B100	74	110	2.50

Power Developed and Fuel Consumption

The experimentations were performed with a single-cylinder 4-stroke diesel engine that coupled with a Rope Brake dynometer. The engine was fueled by the mixture of petroleum diesel, B100, and various biodiesel fractions. The aim was to evaluate the operational traits of the engine using these fuels, with a focus on comparing parameters such as Brake Thermal Efficiency, Brake Power (B.P), Mechanical Efficiency, Specific Fuel Consumption (SFC), and Indicated Thermal Efficiency.

As Figure 3 shows, the BTE of B 100 blend is higher than that of petro-diesel and of some of the blends up to 2 KW but lower for higher KW. Petro-diesel and the B25 blend exhibit remarkably similar characteristics, with their curves aligning almost completely throughout the entire range of observation. The maximum load applied to the engine is 12kg, which correlates to a brake power of 3.05 KW. Specifically, B100 is more effective than B75 under the maximum load. The chart presented in Fig shows that the B100 blend has a similar brake thermal efficiency (BTE) to that of diesel. These results are in harmony with the previous work of Gupta et al. (2016), Hussain et al. (2020), Seraç et al. (2020), , and Gavhane et al. (2021) [46-49].

The analysis of Figure 4 indicates that the thermal efficiency for the B100 blend surpasses that of diesel and other biodiesel blends. Note that the indicated thermal efficiency shown is influenced by the engine B.P and F.P, as it represents the sum of these two components. The diesel performance curve tops with over the biodiesel blends with the only exception of B100 when the engine load is intensified. The diesel trend follows a smooth linear evolution. B100 displays a distinctive curve that rises initially up to 1.52 KW, followed by a decrease, and then a gradual increase towards the conclusion. B25 demonstrates a consistently uniform linear trajectory throughout. In the blends, B75 outperforms B50 and B25 at loads of up to half (2.50 H.P or 1.82KW). Consequently, B100 exhibits competent and sufficient performance characteristics, particularly when contrasted with petroleum-diesel and various biodiesel mixtures.

From Figure 5, the linear pattern of mechanical efficiency (Brake HP/Indicated HP) versus Brake Power is observed for both petro-diesel and biodiesel, wherein both lines are approximately line to each other at similar brake power levels. B50 demonstrates better performance compared to all other biodiesel blends for higher brake power, although the performance differences amongst each other have been observed to be less pronounced in this range. Hence, the contrast between B100 and petroleum diesel indicates that biodiesel consistently yields analogous outcomes in comparison to diesel.

Turning to Figure 6, which illustrates specific fuel consumption against Brake Power, it is evident that specific fuel consumption, representing the mass flow rate of fuel consumed per unit KW of brake power produced, declines with an increase in the applied load on the engine, corresponding to an elevation in brake power. According to the graph the per energy requirement of biodiesel is greater than that of diesel due to its lower calorific value by 20% as compared to diesel. As such, combustion of biodiesel results in less heat being released as compared to diesel, which requires 1.20–1.30 litres of biodiesel to deliver the same power as 1 litre of diesel. While biodiesel may have a higher fuel consumption than diesel, the heat produced by both fuels is nearly equivalent, a point further illustrated in the next section. These observations are also supported by previous work by Gupta et al. (2016), Hussain et al. (2020), Seraç et al. (2020), and Gavhane et al. (2021) [46-49].

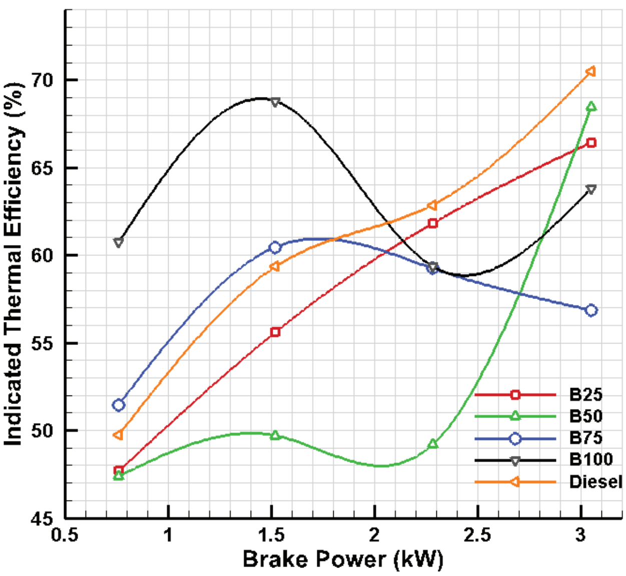

Figure 3. Estimation of Brake Thermal Efficiency with variation in Brake Power.

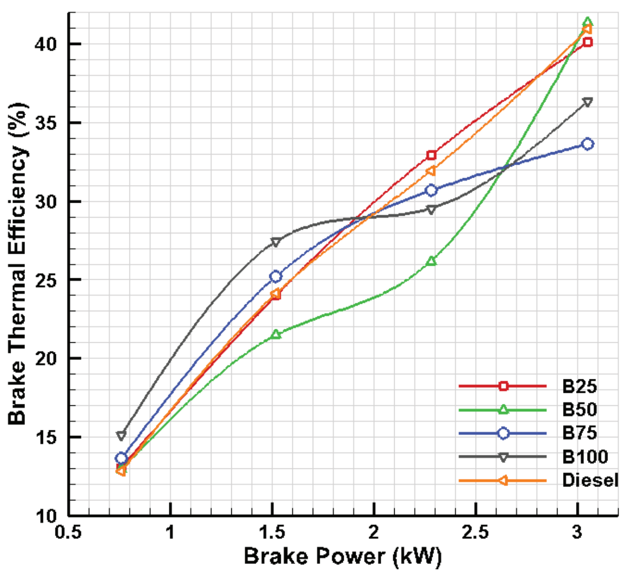

Figure 4. Estimation of Indicated Thermal Efficiency with variation in Brake Power.

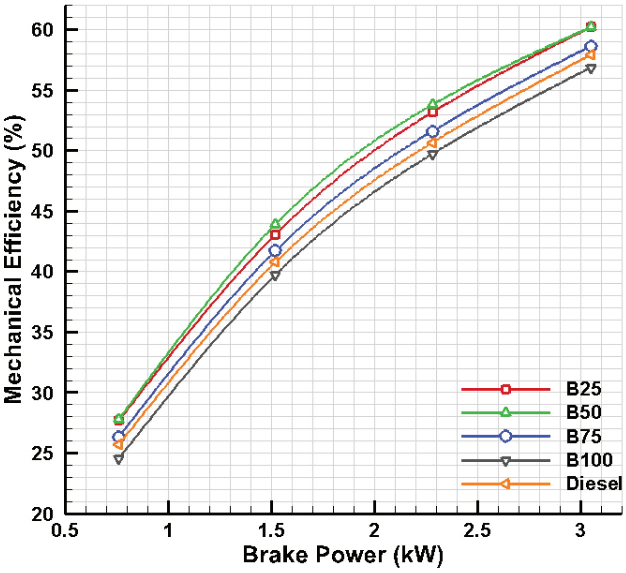

Figure 5. Estimation of Mechanical Efficiency with variation in Brake Power.

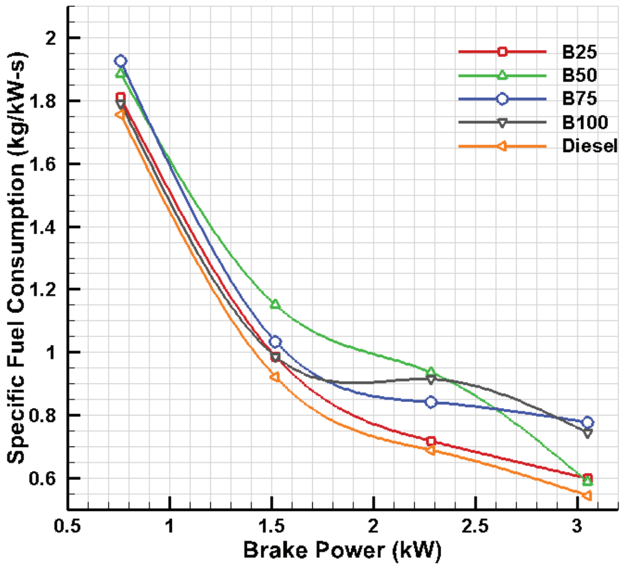

Figure 6. Estimation of specific fuel consumption with variation in Brake Power.

Heat Balance Analysis

The evaluation of engine performance is typically expressed through a heat balance sheet. Various quantities, including the total heat generated during fuel combustion to produce brake power and the heat dissipated through the use of coolant and into the surroundings, have been calculated. These results are then compared to illustrate their overall efficiency. The core principle underlying this sheet is that not all the heat generated during fuel combustion is transformed into useful work at the engine's crankshaft; a portion is lost as previously described. The findings are visually represented through the pie charts, and the outcomes are explored herein.

Figure 7 clearly demonstrates that B100 utilizes the heat generated from fuel combustion within the engine more efficiently, leading to a greater production of brake power in comparison to diesel. B100 is recognized as the most effective biodiesel blend for delivering output power. The heat losses that are not accounted for, resulting from conductive, convective, and radiation processes, are significantly greater in the engine fueled by B100 in comparison to diesel. The heat from the exhaust gas can be effectively harnessed using techniques for recirculating exhaust gases, thereby improving both the volumetric and thermal efficiency of the engine. B25 demonstrates superior performance compared to B50 and B75 in the biodiesel blends category, providing a more efficient overall heat utilization. The heat balance performed by B100 has a higher level of efficiency than diesel. Table 5 summarizes heat utilization and heat losses for the different blends of biodiesel.

Table 5. Heat balance observation

Biodiesel blend	Heat Utilization (%)	Heat losses (%)
B25	24.10	75.90
B50	22.76	77.24
B75	23.08	76.92
B100	24.16	75.84

Analysis of diesel engine exhaust gas with diesel and different blends of biodiesel

Emission levels from the exhaust were assessed using the AVL Di Gas 444 exhaust gas analyzer, connected to the exhaust pipe of the diesel engine. Figure 8 illustrates a clear trend in which CO emissions from B100 gradually decrease with increasing applied load. B100 exhibits a 40% reduction in CO emissions compared to diesel, with 5-15% lower emissions in comparison to biodiesel blends. CO emissions on first rising are also higher as rich mixture is initially employed. B100 exhibits good burning behaviour at higher loads with lower CO in the exhaust.

The HC emissions yield a 10-15% increase for B100 compared to diesel; this may be due to the fuller composition of the B100 blend and longer hydrocarbon molecules formed. B25, among biodiesel blends, demonstrates reduced emission levels.

B100 shows a 16% increase in CO_2 emissions relative to diesel. B25 exhibits reduced CO_2 levels, while B75 demonstrates elevated CO_2 levels. Oxygen gas emissions from B100 are the lowest among all blends, demonstrating the effective use of oxygen for optimal combustion in biodiesel. The plots demonstrate that biodiesel blends B75, B25, and B50 show enhanced oxygen availability in comparison to diesel.

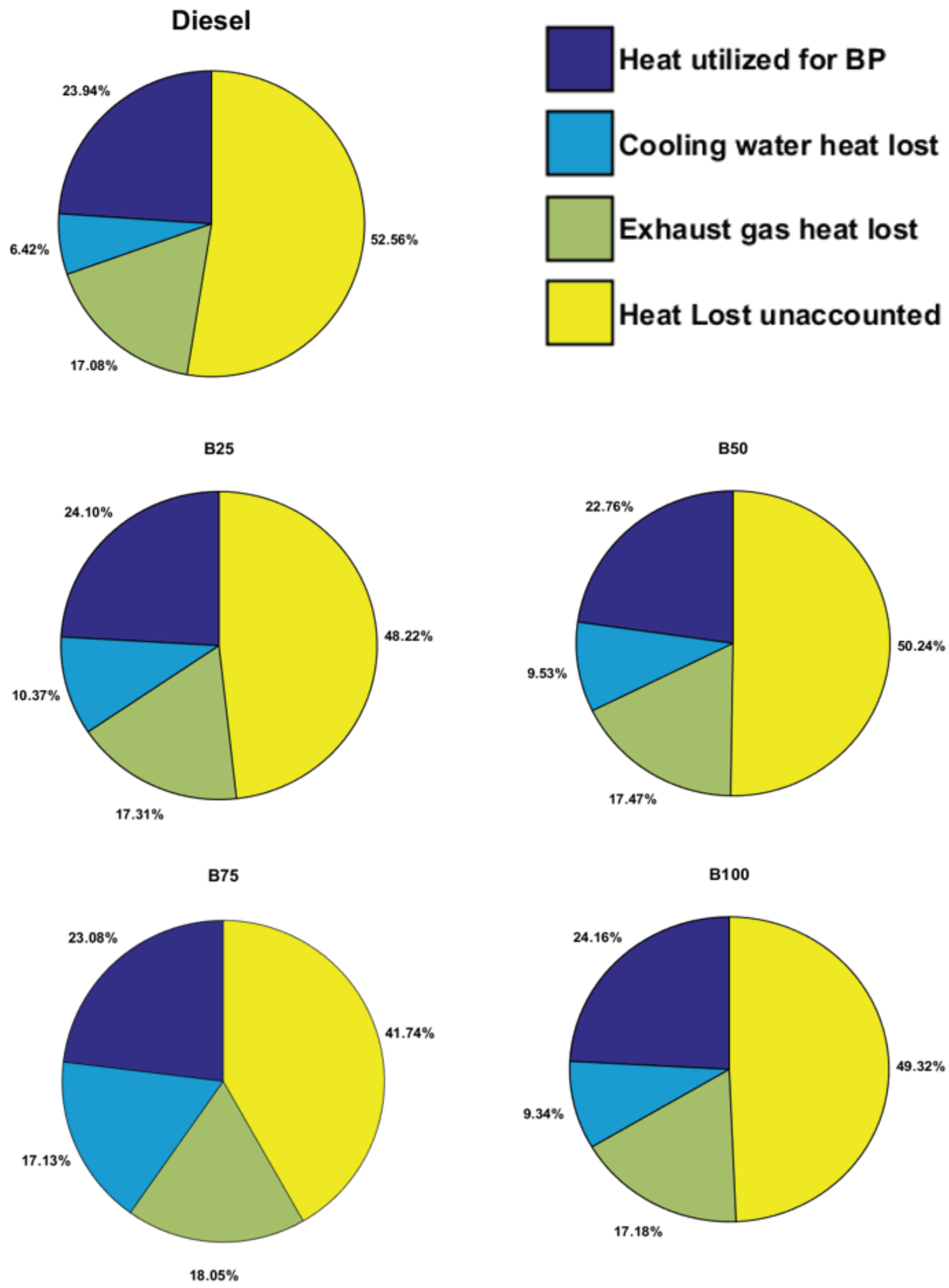

Figure 7. Utilization of Heat in an Engine Fueled with Biodiesel, Diesel, and their Blends.

Emissions of NO_x from B100 exceed those from diesel as a result of elevated combustion temperatures, which enhance the production of NO_x. Additives such as ethanol can be utilized to effectively manage charge temperature. Biodiesel blends have NO_x emissions which move in the upward direction with an increase in the load until the maximum level is reached when B100 is used due to its the presence of more oxygen. The B25 and B50 blends, on the other hand, showed lower NO_x emissions, which means replacing diesel with biodiesel to some extent can decrease NO_x emissions. However, at low loads, NO_x emissions do not vary with fuels used but at high loads, there is a marked increase in emissions for B100. The mitigating approaches for NO_x emissions includes but not limited to the exhaust gas recirculation, NO_x-reducing additives, blended optimization, advanced combustion techniques, after-treatment systems, and optimization of injection timing.

Hence to reduce the NO_x emissions, the following approaches can be used, for instance:

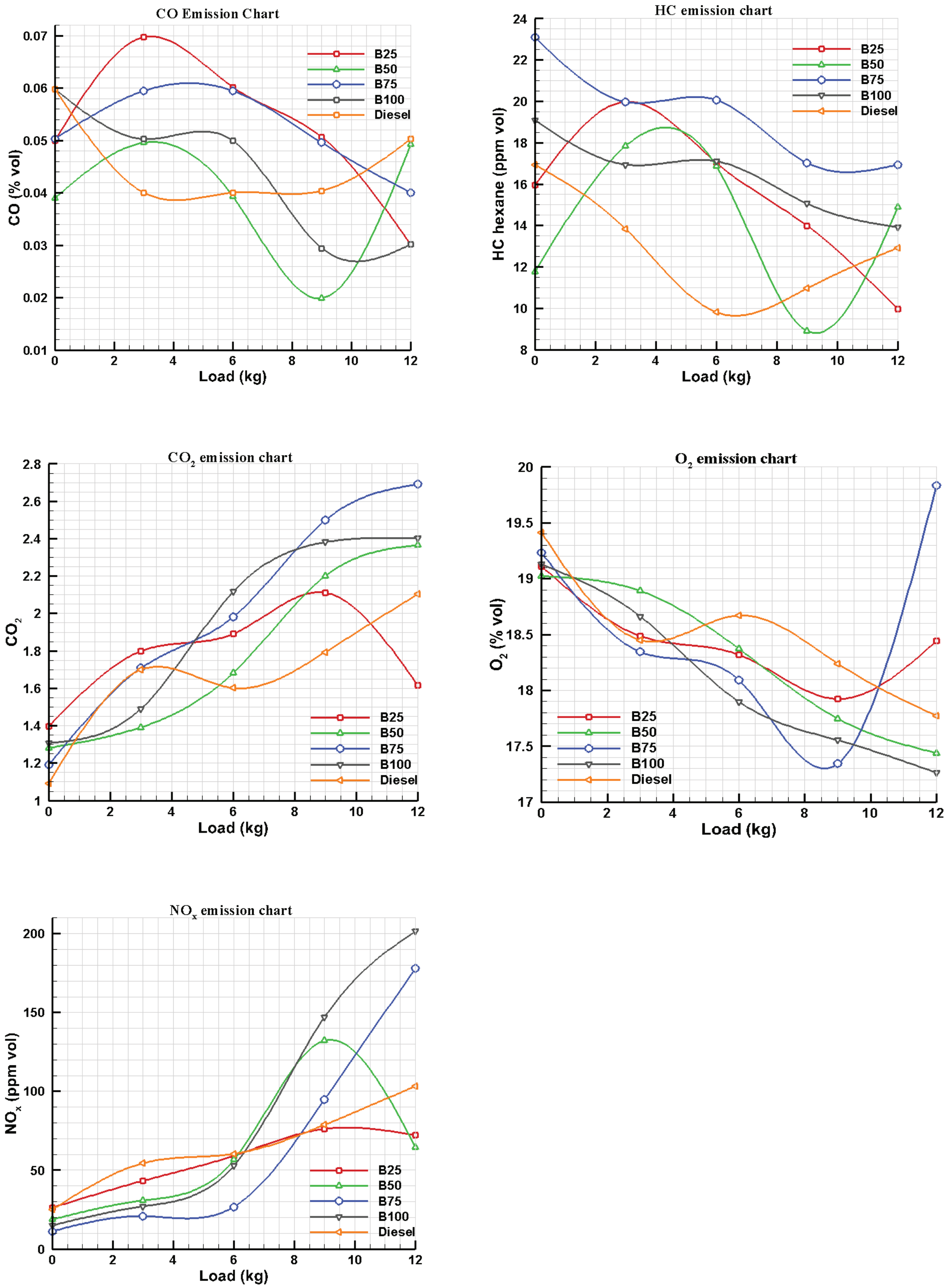

Figure 8. Analysis of Exhaust Gas Emissions from Biodiesel (B100), its Blends and Conventional Diesel

Exhaust Gas Recirculation (EGR): It involves the reintroduction of some of the burnt gases into the combustion chamber which reduces the oxygen levels available in the chamber.

Selective Catalytic Reduction (SCR): It is the process that employs the use of a catalyst and a reducing agent for certain nitrogen oxides for example moccasin which is used to transform NO_x into benign nitrogen and water.

Fuel Additives: The addition of cetane improvers and other combustion modifiers targeting lowered peak temperatures for suppression of NO_x generation.

By this, the negative effects of centered biodiesel coupled with soybeans as raw material can be reduced thus providing enhanced benefits environmental impacts of biofuels.

The adoption of biodiesel results in lower CO emissions which is an environmental advantage but then its effect on NO_x emissions is a problem. More research and optimization on the blends and combustion technologies will sort these trade-offs out. The use of appropriate catalytic converters can also efficiently manage these emissions. As a result, the emission patterns have been plotted and compared and they are resulting from fuels having different compositions. Other research carried out by Hussain et al. (2020), Seraç et al. (2020), Gupta et al. (2016), and Gavhane et al. (2021) also corroborate these tendencies [46-49].

Performance vs. Emissions Trade-offs

The performance/emission balance is readily observable from the results with the soybean biodiesel blends. The benefits and limitations brought about by biodiesel blends over conventional dieels can thus be documented:

Performance Benefits: Using B100 biodiesel blends at all load conditions results in higher Brake thermal efficiency (BTE). This is because biodiesels have higher oxygen content hence better combustion. Unfortunately, this efficiency leads to an increase in SFC at higher concentrations of biodiesel. This is brought about by the fact that biodiesels have a lower calorific value compared to diesel.

Emission Trade-offs: However, biodiesel blends lead to an increase in Nitrogen Oxide (NO_x) emissions despite demonstrating lower Carbon Monoxide (CO) emission (the reduction can be as high as 40 when using B100), which is about the same HC emission volume. This trend is consistent with the previous studies, for instance, the investigation done by Canakci et al. [10], where it was established that the best performance attained with biodiesel usage was coupled with an increase of NO_x emissions for B100 this is the result of better combustion capabilities of biofuels in general because of increased combustion temperatures.

Balancing Performance and Emissions: Employing Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR) technologies can maintain the NO_x emission level at a low concentration while leveraging the vigorous combustion efficiency offered by biodiesel, a mixture with a less concentration of biofuels. Similarly, SFC and NO_x emissions would be less than what they would be if the ratio of the biofuel was lower while still giving good performance gains, approaches could include B50 or B75 optimum ratio blending.

Potential Limitations and Environmental Considerations

Impact of Environmental Conditions: There are some factors fuel characteristics which can shift the performance and emissions characteristics of soybean biodiesel blends they include temperature, humidity and altitude.

Cold Weather Performance: Biodiesel's fuel characteristics results in high cloud and pour points which means biodiesel tends to gel in colder climates. This is preventable by using winterization enablers or blending.

Effects of High Altitude: A lack of oxygen reduces the efficiency of combustion and results in higher emissions.

Opportunity for Variation in Engine Specificity: The results from the single-cylinder engine that we used in this study may not be fully representative of multi-cylinder or heavy-duty engines.

Fuel Stability: The fuel could deteriorate and become oxidised if kept too long, and hence strong storage is required.

COMPARISON WITH PREVIOUS STUDIES

The present study is contrasted with that of Gupta et al. (2016) and the work of Kumar et al. (2020), as shown in Figure 9.

One set of experimental work is compared for the validation purpose, which is a variation of brake thermal efficiency with brake power. Gupta et al. (2016) work focused on the soybean biodiesel with maximum blends of 20%, i.e.,

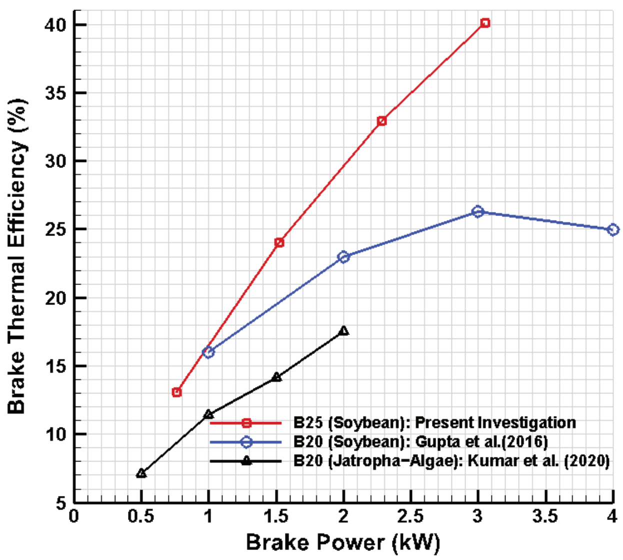

Figure 9. Validation of the experimental work [46,50]. [It was drawn by the author].

B20. The results show similar trends, but the trends also suggest an increase in breakdown thermal efficiency with increasing the blends. B20 blends will obviously not be the feasible alternative of the diesel; hence, the comparison supports going with a higher amount of blends in order to achieve a complete alternative of the diesel with soybean biodiesel. The result is also compared with the other biodiesel, Kumar et al. (2020), and the performance of soybean biodiesel is found to be better than previously used jatropha and algae biodiesel.

CONCLUSION

Using data obtained from performance tests on a single-cylinder 4-stroke 5 H.P diesel engine, employing petroleum-diesel, Biodiesel (B100), and their blends, satisfactory results have been observed. Many reports have shown that B100 and its blends with other fuels pass ASTM standards for fuels and fuel blends. In addition, the operational engins parameters of biodiesel are very similar to those of diesel fuel, providing a more environmentally friendly alternative. However, the specific fuel consumptions for biodiesel and its blends are higher than that of diesel due to the lower heating value of the biodiesel and its blends.

For the operational parameters of biodiesel and diesel fuels concerning brake power, brake thermal efficiency, fuel consumption, and mechanical efficiency, the fuel consumption and other parameters seems to have the same pattern. There is a cross in the B100 biodiesel and other fuels, and B100 biodiesel is the only fuel that has the highest brake thermal and indicated free thermal efficiency which indicates the best performing fuel.

The heat balance graphs for blends with biodiesel indicate better performance than petroleum-diesel in the more effective use of the heat provided by combustion of the fuel to produce brake power. This is very important in determining the thermal efficiency of a cycle of an engine. In addition, for the engine cycle exhaust emissions with diesel, biodiesel, and other blends, it is observed that biodiesel has more HC and CO2 emissions. This is owing to the longer length of the hydrocarbon chains in biodiesel, which results in a higher concentration of combustibles

NO_x emissions result from higher combustion temperatures, but effective control can be achieved through the addition of appropriate additives (such as ethanol) and the use of catalytic converters.

The paper demonstrates how biodiesel can be obtained from soybeans while running multipurpose engines that use biodiesel on model based conditions. The findings also indicate that there can be multi usage of soybean biodiesel as sustainable fuel in agriculture, transportation, and power generation while putting low pollution strategies in place.

In conclusion data shows that biodiesel has better performance and makes efficient use of heat than diesel petrol. From the observed date, biodiesel is a possible alternative fuel for present-day diesel engines without any modification. It is characterized as a clean, green, economically feasible, eco-friendly, renewable, and biodegradable option in contrast to petroleum-diesel.

Future Scope

In the case of soybean biodiesel, the process of optimization of the blends will increase fuel performance and cold weather characteristics and minimize NO_x emissions, and there is scope of introducing more feeds to achieve sustainability. The study can be aimed at creation of blends with more advanced additives and formulations to reduce emissions and enhance combustion efficiency. Co-processing of soybean oil along with non-food feed providers like algae or used cooking oil can resolve the "fuel versus food" dilemma and help in fuelling diversification. The improvement can come from the advancement in purification, catalysis, and genetic improvement for higher-yield soybean varieties. Moreover, supportive policies and international cooperation can facilitate and make financially feasible, the large-scale application, hence, increasing the competitiveness of soybean biodiesel in the transition to energy.

NOMENCLATURE

ARR	After-tax rate of return
ASTM	American Society of Testing Materials
B100	Biodiesel with 5% ethanol
B75	75% biodiesel + 20% petro-diesel + 5% ethanol
B50	50% biodiesel + 45% petro-diesel + 5% ethanol
B25	25% biodiesel + 70% petro-diesel + 5% ethanol)
BBP	Biodiesel break-even price
BP	Brake Power
CO_2	Carbon dioxide
CO	Carbon monoxide
FP	Frictional Power
HC	Hydrocarbon
IP	Indicated Power
NNP	Net annual profit after taxes
NO_x	Nitrogen oxides
O_2	Oxygen
SFC	Specific Fuel Consumption

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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