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Enhancing Biodiesel/Diesel blended Fuel Quality: A Comparative Study of Commercial Additives in Direct Injection Diesel Engine

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ABSTRACT: A lot of experimental research has been done to identify alternative, sustainable, renewable, and ecologically friendly fuels because of environmental pollution and the lack of energy security caused by engines using conventional fuels. An environmentally acceptable and alternative fuel for engines powered by compression ignition is biodiesel, which can replace diesel fuel entirely or in part. The purpose of this study is to develop the additives for use as a fuel mix with 45% Biodiesel as fuel, which will be used to feed the diesel engine of a single cylinder, four strokes. The engine will be tested experimentally with varying loads at fixed speed of 1500 rpm, using blends of [(5% PRETSONE additive + 50%Diesel + 45% Biodiesel fuel), (5% THERMOL-D additive + 50% diesel +45%Biodiesel fuel), (5% ECO diesel additive + 50% diesel + 45% Biodiesel fuel), (5% ABRO additive + 50% Diesel + 45%Biodiesel fuel)], respectively. The impact of varying blends of additives on engine performance and emissions has been studied and evaluated. The results of the experiment show that 45% biodiesel and additive blends can be used in the diesel engine under the same operating conditions with increasing brake thermal efficiency by 4 % in the case of THERMOL-D additive, decreasing exhaust temperature by 5% for ABRO additive than 45% Biodiesel, and decreasing brake specific fuel consumption by 4% for THERMOL-D additive. The results show that Carbon monoxide CO, Carbon dioxide CO2, Soot level emissions, and NOx emissions decreased by 32%,38%,11% and 36%, respectively for the THERMOL-D additive. In addition, the Oxygen O_2 concentration was increased by 11% for THERMOL-D additive. Finally, it is recommended to use additives with Biodiesel blends, which improve combustion properties, Engine efficiency and emission of the engine.

Keyword: Biodiesel fuel additives; engine emissions; biodiesel/diesel blends; NOx emissions; Soot opacity

I. INTRODUCTION

The increasing demand for renewable energy sources and the growing concerns about climate change have led to a surge in interest in biodiesel as an alternative to fossil fuels [1-5]. Biodiesel, a renewable fuel derived from vegetable oils or animal fats, offers several environmental benefits, including reduced greenhouse gas emissions and improved air quality. However, the use of biodiesel in diesel engines often presents challenges related to fuel properties, engine performance, and emissions [6-10].

To address these challenges and enhance the sustainability of biodiesel fuel, researchers have explored the use of various additives [11-14]. Additives can be added to biodiesel blends to improve their Cetane number, viscosity, cold flow properties, lubricity, and other characteristics. By optimizing these properties, additives can contribute to better engine performance, reduced emissions, and increased fuel efficiency [15-18]. The research on additives for biodiesel fuel aligns with several of the United Nations Sustainable Development Goals (SDGs)[19-22]:

- **SDG 7: Affordable and Clean Energy:** Biodiesel, when used with appropriate additives, can provide a cleaner and more sustainable alternative to fossil fuels [23-27].
- **SDG 9: Industry, Innovation, and Infrastructure:** The development and use of additives can contribute to technological advancements in the fuel industry and

support the development of sustainable transportation infrastructure [28-31].

- **SDG 13: Climate Action:** Biodiesel and its associated additives can help reduce greenhouse gas emissions and mitigate climate change [32-38].
- **SDG 15: Life on Land:** By promoting sustainable agriculture and land use practices for biodiesel production, additives can contribute to the protection of ecosystems and biodiversity [39-46].

However, this research aims to explore the potential of additives to enhance the sustainability of biodiesel fuel and contribute to a cleaner and more environmentally friendly transportation sector [47-51]. Depletion of fossil fuel reserves and environmental degradation are the two major problems the world is currently confronting[52]. By extracting these fossil fuels and using them extensively, the amount of carbon originating from the ground is decreased [53]. Consequently, given the current circumstances, research into alternative fuels is warranted as it promises to enhance sustainable energy supplies generally, improve the environment, and develop a sustainable fuel life cycle[54]. Alternative fuels, such as those derived from plant and animal fats, have the potential to address global petroleum-related issues[55]. The primary drawbacks of fossil fuels are that they are an exhaustible energy source that will eventually run out and that they negatively affect the environment and climate by raising the atmospheric concentration of nitrogen and carbon oxides, which exacerbates the greenhouse effect and raises temperatures [56-61]. Scientists have therefore looked to fossil fuel substitutes like renewable energy sources [62-65]. Wind energy, biomass energy, and biofuels are examples of common renewable energy sources[66]. For both environmental and economic reasons, the contribution of all these resources is significant, and biodiesel may be one of the answers [39, 67-69].

Among these sources is biodiesel[70], which is made from the seeds of some plants and leftover food [71]. Additionally, researchers have recently thought about removing it from food waste, sunflower, soybean, corn, and flaxseeds as well as palm oil [42, 72-75]. The advantages of biodiesel use[76]. Include the fact that it is a renewable fuel as opposed to diesel fuels derived from fossil fuels and that it emits fewer unburned hydrocarbons into the exhaust[77]. Additionally, biodiesel lowers wear on engines and extends their lifespan because it is a superior lubricant to diesel fuel. Because there is more oxygen present and less sulfur, the engine produces less waste and the combustion is more complete [46, 58, 59, 78, 79]. Moreover, the capacity of biodiesel to operate internal combustion engines without modifying engine design is one of its primary characteristics. However, owing to its high viscosity, low volatility, and cold flow properties, using biodiesel for an extended period might also create certain engine issues[69].

Additionally, several alcoholic and nanometric additives are added to biodiesel to enhance its performance in engines[80]. These nano-additives include iron oxide, copper oxide, graphene oxide, and titanium oxide, while these alcoholic additives include heptane, methanol, and other substances[81]. The fuel source and production efficiency have an impact on the yield of biodiesel made chemically [82-85]. The differences in physical and chemical characteristics affect how efficient biodiesel engines are[86]. Viscosity, density, and temperature value in contrast to diesel. This review looks at how biodiesel made from used cooking oil and hydrodynamic cavitation affect compression ignition engine performance measures in both theoretical and practical ways[87]. Due to serious worries about energy security and the shortcomings of fossil fuels, biodiesel is becoming more and more popular worldwide [88-90]. Many countries have put forth different methods, incentives, and subsidies to encourage the use of biodiesel[91].

II. EXPERIMENTAL METHODOLOGY AND PROCEDURE:

The engine is mounted on a test rig designed to allow the operator to modify, measure, and adjust numerous parameters while the engine is running. The direct injection engine (model ZS1125NM) is connected to a hydraulic dynamometer (model ATE-160 LC), which enables load adjustments during operation [63, 89, 92-95].

The test rig is equipped to facilitate fuel type changes while the engine is running, utilizing flow control valves to open, close, or switch the fuel supply. Fuel consumption is measured using a fueling system bench with calibrated markings for precise fuel volume measurement. Exhaust emissions are analyzed using a gas analyzer (model GASBOARD-5020), while soot levels in the exhaust are determined with a soot analyzer (model GASBOARD-6010), which provides printed readings of soot content. Additionally, the test rig includes an RPM indicator to monitor engine speed. Inlet and exhaust temperatures are recorded using thermocouples for accurate temperature measurements. Figures 1 and 2 provide a detailed schematic and an actual representation of the test rig setup [69, 72, 96, 97]. The direct injection engine has the following characteristics in the Table 1.

Table 1. Specifications of direct injection engine.

Parameters	Specifications
Type of engine	Engine model "ZS1125NM" Single cylinder, four strokes, horizontal, water cooling
Bore* stroke* displacement	125 mm * 120 mm* 1.473 L
Power of the engine	30 HP /2200 rpm
Cooling system	condenser
Lubrication system	Pressure /splash

The dynamometer attached to the engine has the following characteristics in **Table 2.**

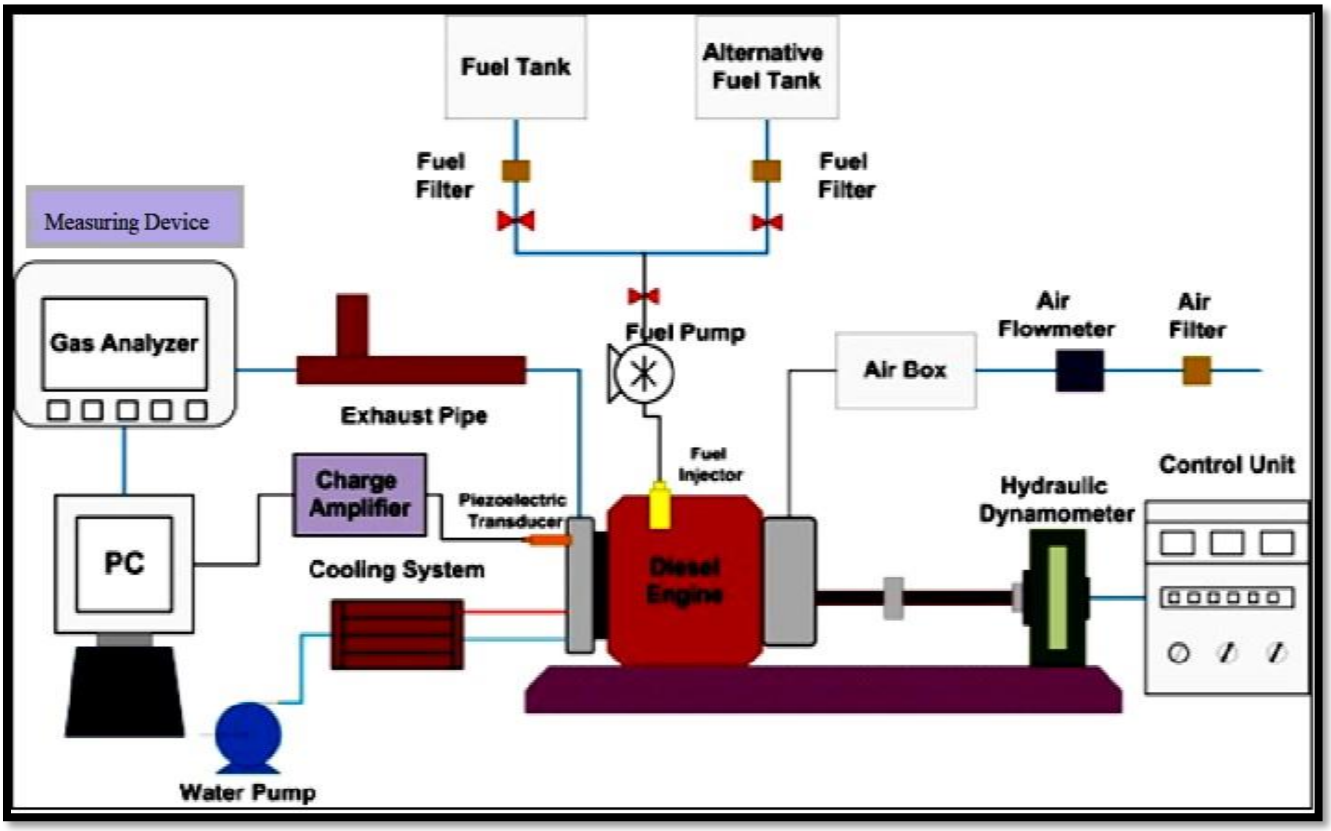

Fig. 1Schematic diagram of the test rig

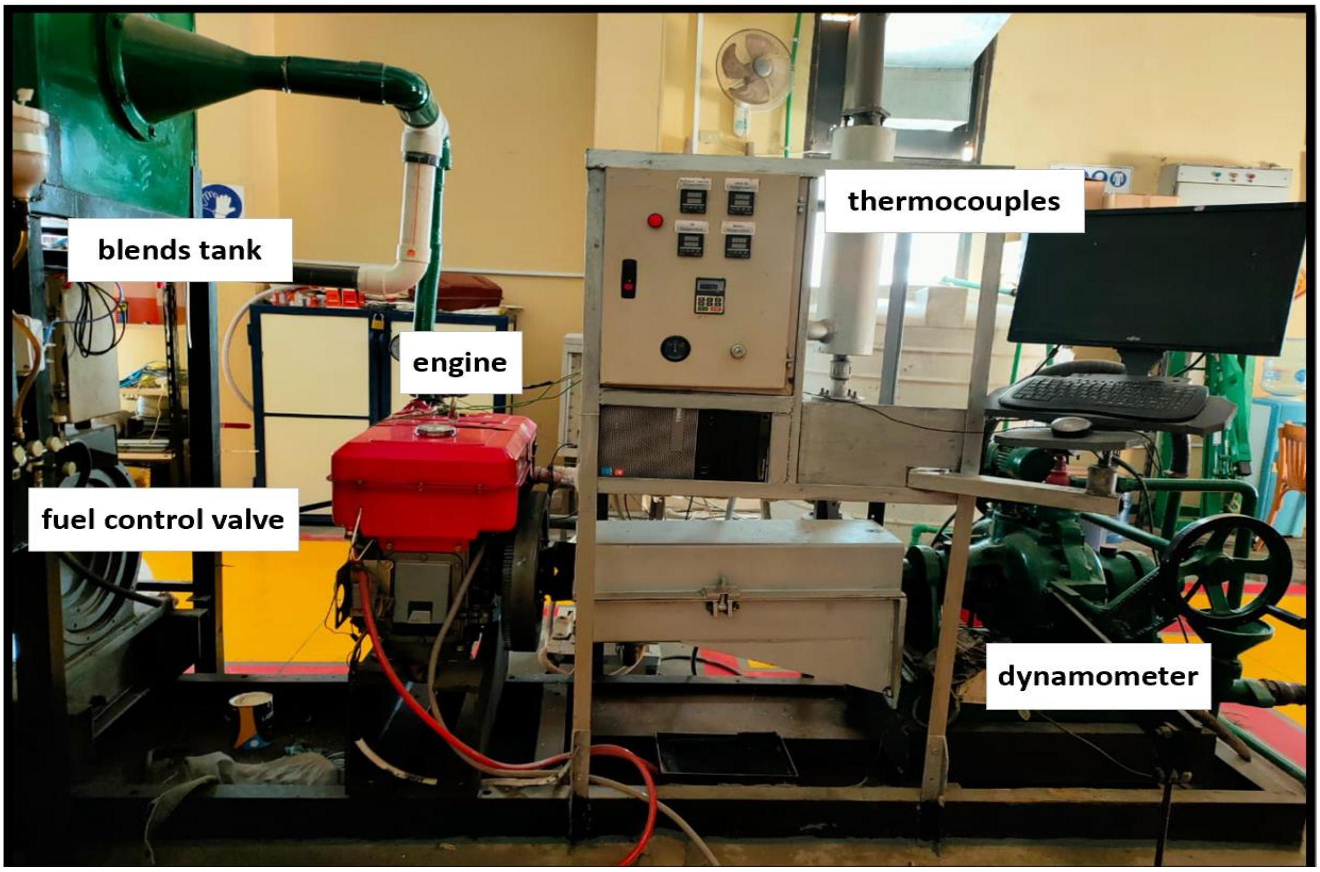

Fig. 2 Actual photo of the test rig.

Table 2. Characteristics of Dynamometer.

Parameters	Specifications
Model	ATE-160LC
Type of Weighing Mechanism	Digital Torque indicator Load Cell
Load Cell Capacity	0 - 350 Kg. (0 - 1050 N-m)
Calibration Lever Arm Length	0.7645 m
Speed Sensing	60 Teeth Wheel with Sensor
Drive Attachment	Shaft Attached to Half Coupling
Absorption Type	Water/Hydraulic

During the production stage, a catalytic transesterification reaction is employed to convert waste cooking oil (WCO) into biodiesel. The key reactants in this process are waste cooking oil, methanol, and potassium hydroxide (KOH) as a catalyst. Biodiesel was successfully produced with a high yield of **96%** under optimal conditions: a methanol-to-oil ratio of **1:4 V/V%**, **0.01 mass percent** KOH, a stirring speed of **550 rpm**, a reaction time of **60 minutes**, and a reaction temperature of **65 °C**. The production process utilized a specialized test rig designed to produce large quantities of biodiesel with superior quality from various feedstocks [98-103].

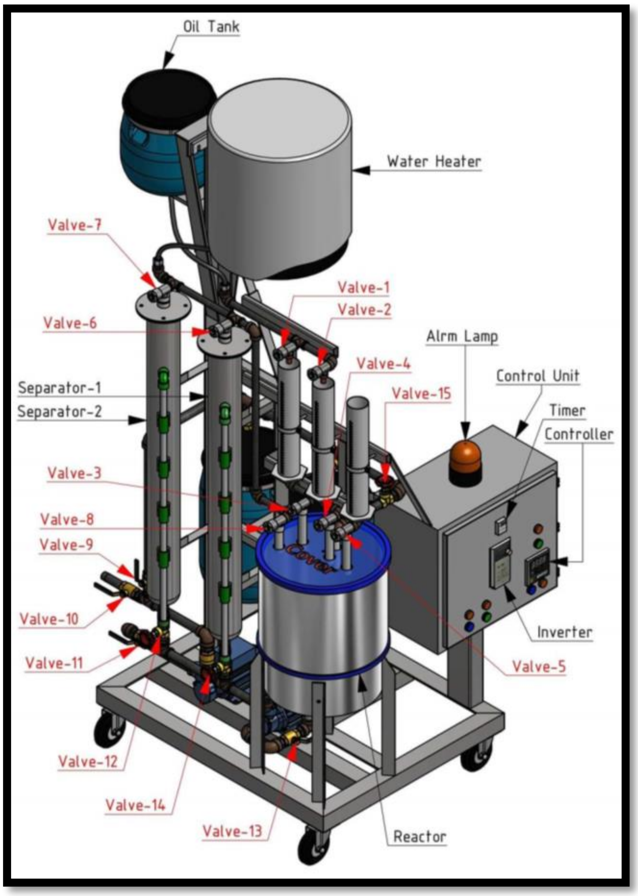

Figure 3. Schematic diagram of production rig.

The chemical reaction was conducted at 65 °C under well-controlled mixing for one hour. To prevent overheating, which could burn the oil, the electric heater was programmed to turn off once the temperature reached 65 °C and resume heating if the temperature dropped below this level. The reaction produced biodiesel along with by-products such as fat, dirt, and glycerol. After the reaction, a separation phase is required to isolate glycerol from the biodiesel, which typically takes around 12 hours to ensure complete separation. Figures 3 and 4 illustrate the schematic diagram and the actual setup of the biodiesel production rig [104-108].

Figure 4. Production test rig.

The next stage of the production process is the washing stage, which aims to purify the produced biodiesel by removing dirt, unresolved fats, and other impurities using water under controlled temperature and mixing conditions. In this stage, hot water at 100 °C is mixed with biodiesel in a 1:1 volumetric ratio for one minute [109-113]. To prevent foam formation during mixing, the electric mixer operates in short cycles—turned on for 8 seconds and off for 3 seconds. The process allows sufficient time for water and impurities

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to separate from the biodiesel. This washing cycle is repeated **3 to 5 times** until the water appears clean, ensuring the biodiesel is thoroughly purified. It is critical to maintain proper timing and the water-to-oil ratio during this stage, as deviations can lead to soap formation instead of biodiesel. Throughout the washing process, some physical properties of biodiesel change. For example, its colour becomes lighter and cleaner, and its density decreases from **885.6 kg/m³ to 851.6 kg/m³**. This reduction in density is particularly advantageous as it narrows the density difference between diesel and biodiesel, making the biodiesel more compatible with fuel systems originally designed for diesel. The final biodiesel product complies with **ASTM D6751 standards**, boasting high oxygen content, a golden-yellow colour, and a flash point of **160 °C**. However, due to its oxygen content, biodiesel has a lower heat and calorific value compared to conventional diesel. The production test rig, schematic diagram, washing stage, and purified biodiesel are illustrated in **Figures 5, 6, 7, and 8**.

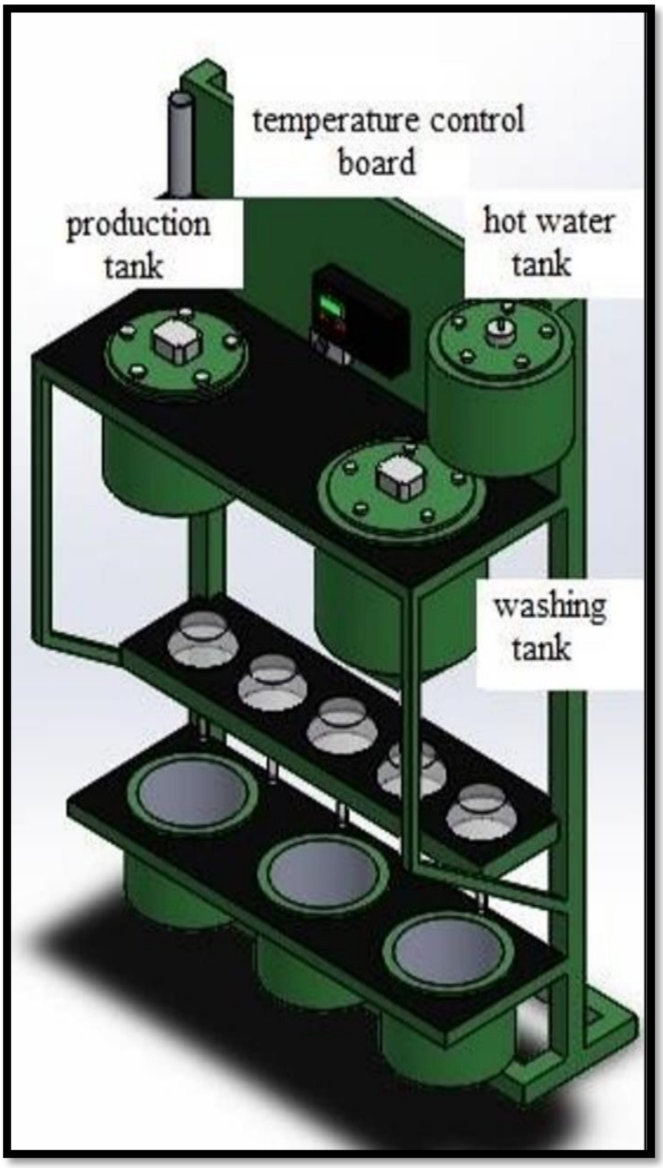

Figure 5. Schematic diagram of washing rig.

Figure 6. Washing test rig.

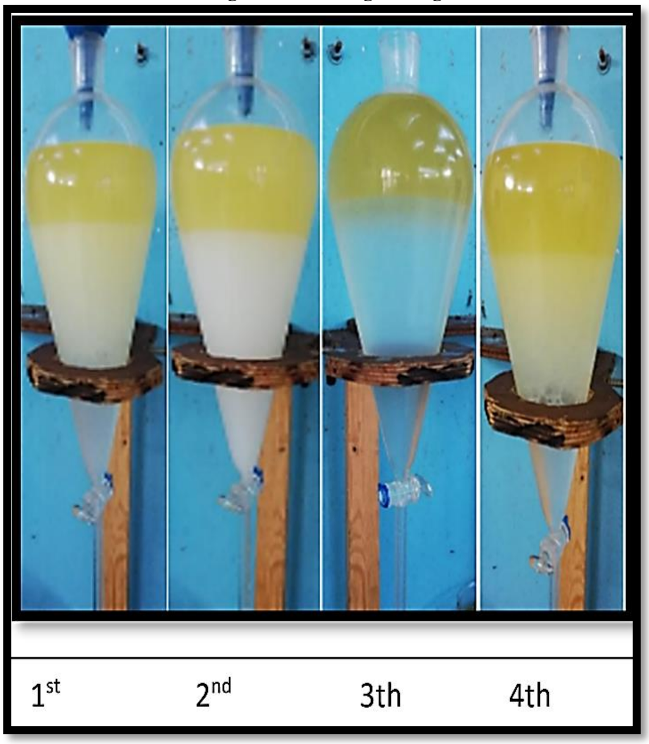

Figure 7. Stage of washing biodiesel.

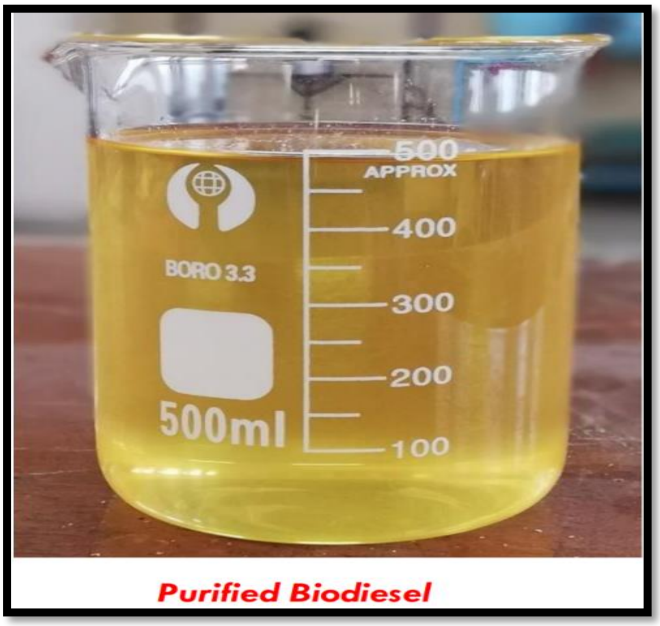

Figure 8. purified biodiesel.

The additives were blended with Biodiesel 45% with volumetric proportions. The mixtures were thoroughly mixed with a manual stirring device for five consecutive minutes at a mixing speed of nearly 100 rpm at room temperature before being placed within the fuel tank. Four blends were created by combining diesel and in the following portions: [(5% PRETSONE additive + 50%Diesel + 45% Biodiesel fuel), (5% THERMOL-D additive + 50% diesel +45%Biodiesel fuel), (5% ECO diesel additive + 50% diesel + 45% Biodiesel fuel), (5% ABRO additive + 50% Diesel + 45%Biodiesel fuel)]. to ensure that the fuel does not separate for one hour for each mixture, figure 9 show Blends of biodiesel 45% with additives.

Figure 9. Blends of biodiesel 45% with additives.

The Following Table shows the Emission Analyzer and Sensors Used in the test Table 3. In Figure 10 we find actual pictures of the measuring devices used to measure polluting emissions and soot resulting from the engine.

Table 3. Devices and sensors utilization

Device/sensor	Utilization
1st thermocouple	To measure air temperature
2nd thermocouple	To measure exhaust temperature
Speed sensor	To measure engine speed, attach to the engine's crankshaft.
DASHBOARD-	Measure the values of [CO, O2, and CO2] in (% vol) and [HC, NOx] in (ppm).
Orifice system	Measure the volume of air flowing into the engine
GASBOARD-6010 opacity meter	Used to measure soot opacity

Figure 10. Emission gas and opacity analyzers.

Because of the use of many devices, equipment, and optical measurement methods, each of them has an error rate that makes the results of the studied research need to be

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reviewed. Therefore, the total error rate resulting from the research must be studied by using.

$$\frac{\Delta w}{w}=\sqrt{\sum_{x=1}^{\infty}\left(\frac{\Delta x_n}{x_n}\right)^2}--------eq.1$$

Where; $\frac{\Delta w}{w}$ is a total uncertainty rate of the experimental results, Δx_n is an error of the equipment, $\frac{\Delta x_n}{x_n}$ is an Equation 1[103-105]. Uncertainty of each device used. Measuring fuel consumption is one of the methods used to measure specific fuel consumption (SFC) [84, 106, 107], in which the measurement is done using a stopwatch and looking to determine the scale on the burette for its range. Where 10 cubic milliliters are measured during the time measured on the stopwatch, and we find the percentage of error in the measured volumeΔ x = ± 0.1cm, x =10 cm the uncertainty value (accuracy) will be Δ x/x= ±0.01=±1%. Table 4 shows the devices used, their range, and the measurement accuracy of each device.

Table 4. Device characteristics and accuracy.

Instrument	Parameters	Range	Accuracy
GASBOARD-6010 opacity meters	Soot opacity	0-100%	+2%, -2%
Shaft encoder	Speed	0-7200CA	+0.2%, -0.2%
Thermocouple	Exhaust gas temp.	0-800 0C	+1%, -1%
GASBOARD-5020 emission gas analyzers	CO	0-20%	+0.06%, -0.06%
	HC	0-9999ppm	+0.12%, -0.12%
	CO2	0-20%	+0.4%, -0.4%
	NO	0-5000ppm	+0.5%, -0.5%
	O2	0-25%	+0.1%, -0.1%
Graduated cylinder/stopwatch	Fuel flow meter	1-30 cm3	+1%, -1%

From the above, the total uncertainty includes many factors in the experiment, as appeared in the accuracy of the devices used and the accuracy of the methods used [108, 109]. Thus, by applying Equation 1 to the coefficients, it becomes clear that the accuracy of the results in the experiment is as follows:

$$\frac{\Delta w}{w}=\sqrt{(1)^2+(2)^2+(0.2)^2+(1)^2+(0.06)^2+(0.12)^2+(0.4)^2+(0.5)^2+(0.1)^2+(1)^2}*\%$$

Δ w / w =2.735 %

The total error value will be Δ w = ± 0.02735

In this study, the experiment was conducted on a single-cylinder, four-stroke diesel engine operating at a constant speed of 1500 rpm under different load conditions. The experiments begin at no load and partial load and reach full load. The experiments were carried out using a mixture of diesel with additives. The effect of the combustion of the mixture on the combustion characteristics, engine performance, and the value of the resulting emissions was studied. This mixture includes a volume percentage of additives and diesel .05% - 99.5%, respectively, and compares it with its values for pure diesel.

III. RESULTS AND DISCUSSION:

The use of additives with Biodiesel 45%will improve the combustion characteristics and thermal efficiency of the engine.

A. BRAKE THERMAL EFFICIENCY-BTE:

The Brake thermal efficiency is defined as the percentage of chemical energy produced by the fuel that is converted into usable work. We can evaluate its value from Equation 2,3.

$$BTE=\frac{power}{m^{\bullet}*Cv}*100\%------(eq.2) \qquad [122].$$

$$m^{\bullet}=\rho*V^{\bullet}_{ol}----(eq.3)$$

where; $m^{\bullet}$ is defined as mass flow rate, Cv is defined as the calorific value of each fuel, ρ is defined as the density of each fuel, $V^{\bullet}_{ol}$ is defined as volume flow rate.

Figure 11 shows the difference in BTE for Biodiesel45% and a mixture (Biodiesel45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It is clear from the figure that thermal efficiency increases with increasing load under all operating conditions due to decreased heat loss. The results show that adding THERMOL-D additive to Biodiesel 45%fuel increases the average thermal efficiency by 4% and for PRETSONE additive and ECO diesel additive there is no significant difference in average thermal efficiency but for ABRO additive it decreases by 2%.

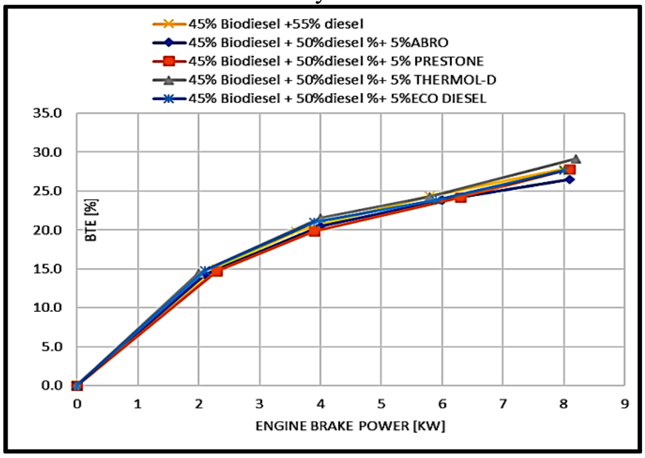

Figure 11. Brake Thermal Efficiency- BTE under Various Loads Conditions.

B. **BRAKE-SPECIFIC FUEL CONSUMPTION-BSFC**:

Brake-specific fuel consumption, or BSFC, is the amount of fuel required to produce one unit of braking power and is determined by the calorific value of the fuel. Brake-specific energy consumption (BSEC) should be utilized as the benchmark when using a variety of fuels with different calorific values. By dividing the overall energy used by the braking force produced, the BSEC is determined. To get the BSEC value in MJ/kWh, use equation 4. [123]

$$BSEC = \frac{[(m^{\circ} * LHV)_{diesel} + (m^{\circ} * LHV)_{NH4OH} + (m^{\circ} * LHV)_{WCO}] * 3600}{power} --- eq.4$$

Where, BSEC in (MJ/kW.hr), m˚ in (kg/sec), LHV in (MJ/kg), and Power in (kW).

Figure 12 shows the difference in BSEC for Biodiesel 45%and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It is clear from the figure that adding THERMOL-D additive to Biodiesel 45%fuel decreases the average BSEC by 4 % and for PRETSONE additive and ECO diesel additive there is no significant difference in average BSEC but for ABRO additive it increases by 2 %.

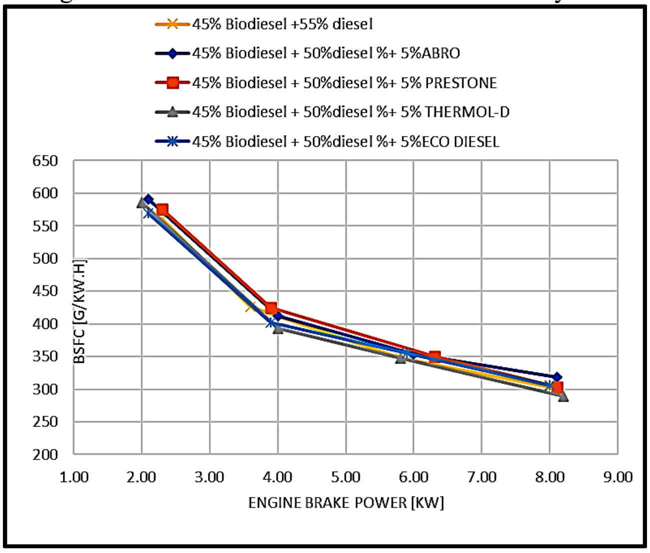

Figure 12. Brake-Specific Fuel Consumption Under Variation of Load Conditions.

C. **EXHAUST GAS TEMPERATURE**:

Since the temperature of the exhaust gases and the heat loss from them are directly related to the thermal efficiency of the engine, measuring the temperature of the exhaust gases is essential. Figure 13 shows an example of how exhaust temperatures fluctuate under different loads. The results show the difference in exhaust gas temperatures for Biodiesel 45%and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It is clear from the figure that adding additives to Biodiesel 45% fuel decreases the average exhaust gas temperatures by 4%, 3%,2%, and 5% for PRETSONE additive, THERMOL-D additive, ECO diesel additive and ABRO additive respectively.

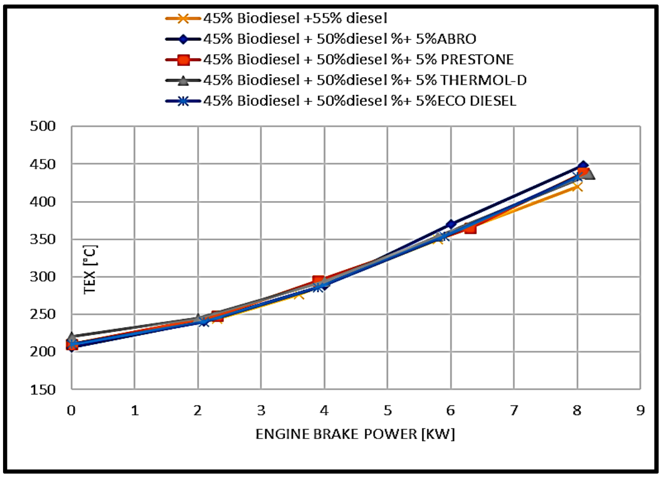

Figure 13. Exhaust gas temperature under variation of load conditions.

D. **OXIDES OF NITROGEN –NOX:**

The primary variables affecting NOx emission are oxygen supply, increased combustion period, and combustion chamber temperature. Figure 14 shows the difference between Biodiesel 45% and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. Figure 14 shows that NOx emissions rise with the load. This is due to an increase in the temperature of the combustion chamber, it is clear from the figure that adding additives to Biodiesel 45% fuel decreases the average NOx emission by 32%,36%,31%, and 34% for PRETSONE additive, THERMOL-D additive, ECO diesel additive and ABRO additive respectively.

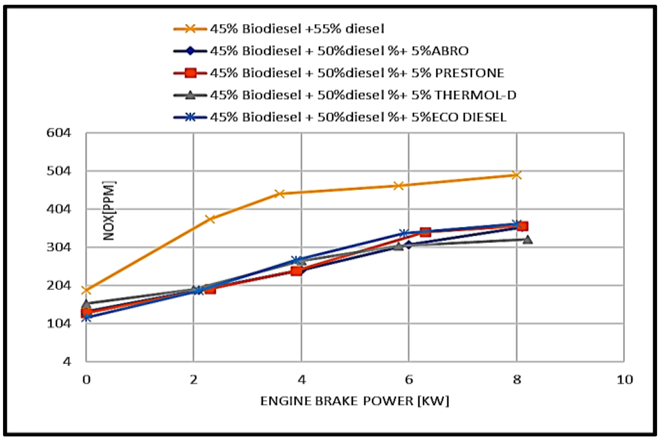

Figure 14. Oxides of Nitrogen under Variation of Loads Conditions

E. **CARBON MONOXIDE-CO**:

Carbon monoxide is one of the most dangerous engine emissions because it is a toxic and flammable gas. It is the product of incomplete combustion of carbon dioxide, and due to the low combustion temperature and low oxygen content, partial oxidation of carbon is generated, forming carbon monoxide. In Figure 15 the variation in carbon monoxide results for Biodiesel 45%and a mixture (Biodiesel 45%& additives) for different loads of engine and constant

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revolution per minute (RPM) 1500 rpm. It was shown that adding additives to Biodiesel 45% fuel decreased the average carbon monoxide CO by 14%,32%,23%, and 9% for PRETSONE additive, THERMOL-D additive, ECO diesel additive and ABRO additive respectively.

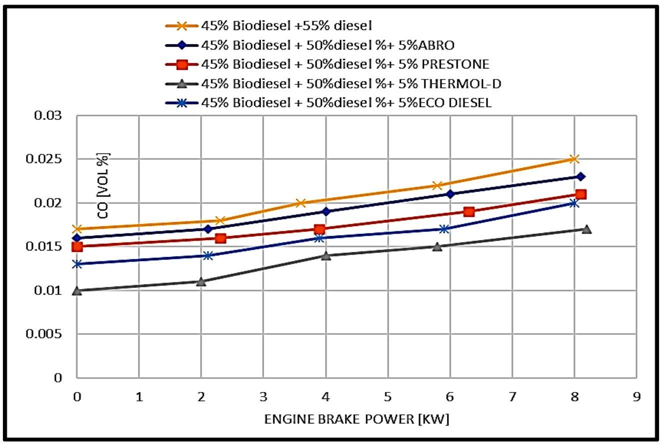

Figure 15. The variation of the Carbon monoxide under various load conditions.

F. CARBON DIOXIDE-CO2:

In Figure 16 the variation in carbon dioxide results for Biodiesel 45%and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It was shown that adding additives to Biodiesel 45% fuel decreased the average carbon dioxide CO2 by 25%,38%,35%, and 32% for PRETSONE additive, THERMOL-D additive, ECO diesel additive and ABRO additive respectively.

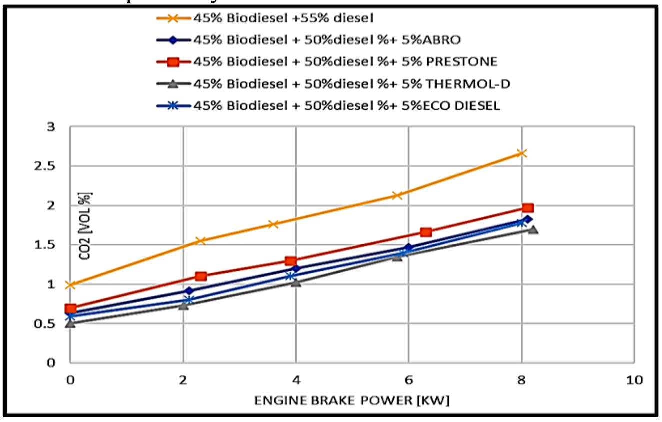

Figure 16. The variation of the Carbon dioxide under various load conditions.

G. OXYGEN- O2:

In Figure 17, the variation in Oxygen results for Biodiesel 45%and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It was shown that adding additives to Biodiesel 45% fuel increases the average oxygen level O2 by 6%,11%,10%, and 8% for PRETSONE additive, THERMOL-D additive, ECO diesel additive and ABRO additive respectively.

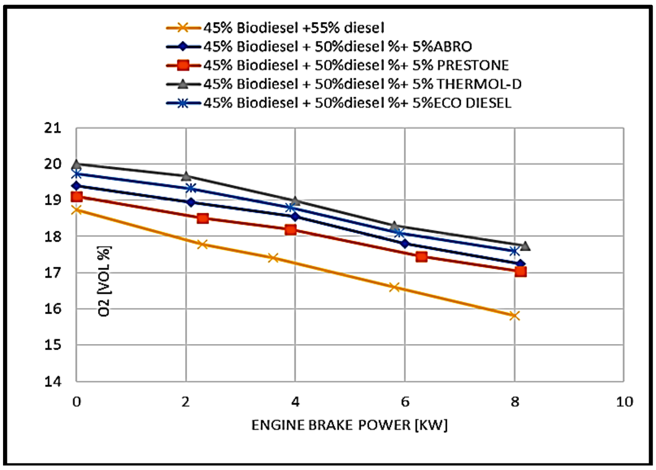

Figure 17. The variation of the oxygen under various load conditions.

H. SOOT LEVEL:

In Figure 18, the variation in Soot level results for Biodiesel 45% and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It was shown that adding additives to Biodiesel 45% fuel increased the average soot level by 34%,5%, and 30% for PRETSONE additive, ECO diesel additive and ABRO additive respectively, but for THERMOL-D additive it decreased by 11 %.

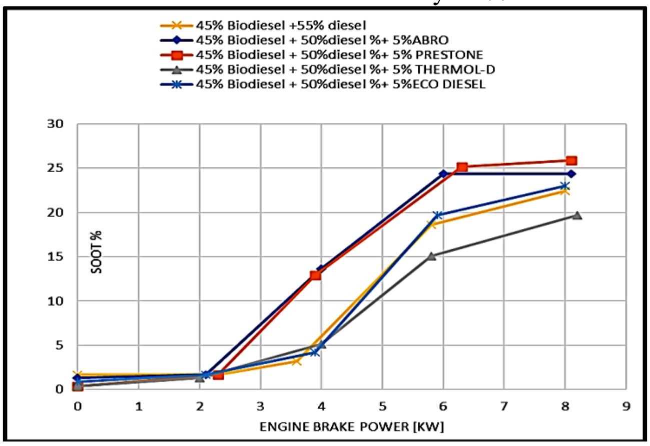

Figure 18. The variation of the soot level under various load conditions.

I. UNBURNED HYDROCARBONS-HC:

Un hydrocarbons are produced due to liquid wall wetting, abnormally lean or rich mixtures, and incomplete combustion of fuel confined in crack volumes, In Figure 19, the variation in engine unburned hydrocarbons emission for Biodiesel 45%and a mixture (Biodiesel 45%& additives) for different loads of engine and constant revolution per minute (RPM) 1500 rpm. It was shown that adding additives to Biodiesel 45% fuel decreased the average unburned hydrocarbon emission by 16%,25%,4%, and 9% for PRETSONE additive, THERMOL-D additive, ECO diesel additive and ABRO additive respectively.

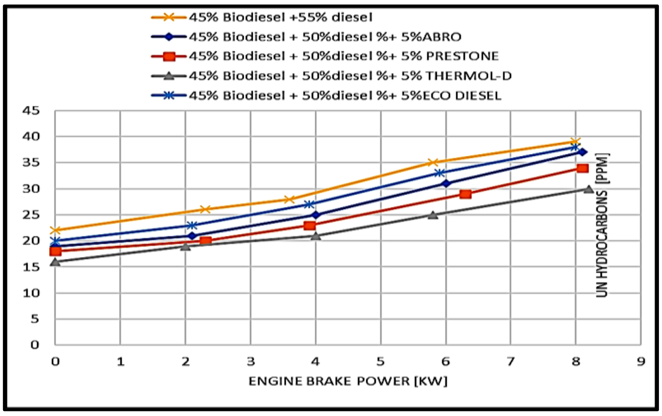

Figure 19. The variation of the Un hydrocarbons level under various load conditions.

IV. CONCLUSIONS:

Thermal efficiency, specific fuel consumption rate, and environmental pollutant emissions were studied in the case of using Biodiesel 45%fuel, and in the case of additives (PRETSONE, THERMOL-D, ECO, and ABRO). The results showed that adding additives with diesel as a mixture improves the performance of fire properties, emissions and thermal efficiency. The following results from the experiments will be summarized:

- In the case of the THERMOL-D additive, the average BTE value increases by about 4%, and the average fuel consumption (BSFC) decreases by about 4% compared to Biodiesel by 45%.
- NOx emissions values decrease for all additives and decrease for THERMOL-D additive by about 36% compared to Biodiesel 45% due to the lower exhaust temperature.
- Carbon monoxide CO values decrease for all additives and decrease for THERMOL-D additive by about 32% compared to Biodiesel 45%.
- Carbon dioxide CO_2 values decrease for all additives and decrease by 38% for THERMOL-D diesel additive compared to Biodiesel by 45%.
- Oxygen O_2 values increase for all additives and increase by 11% for THERMOL-D additive compared to Biodiesel by 45%.
- Soot level values decreased by 11% for THERMOL-D additive compared to Biodiesel by 45%.

Finally, it is recommended to use additives with Biodiesel 45%, which improves combustion properties, Engine efficiency and emission of engine.

V. FUTURE RESEARCH DIRECTION

Because the effect of additives with diesel on engine emission characteristics, performance and combustion characteristics has been discussed previously, future research on some interesting topics is recommended. The most important recommended topics are:

- Looking for other fuel sources that can be blended with Biodiesel and additives to create a homogenous mixture and assessing the impact of these additions on engine output, combustion characteristics, and fuel emissions.

Conflicts of Interest:

The authors have no conflict of interest.

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