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Article

Evaluating the Performance and Emissions of a Diesel Engine Blended with Cottonseed

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Abstract:

Considering the importance of Biodiesel, its use in various blends with other seeds available in Iraq may be enhanced. This study's main goal is to determine the potential of cottonseed to produce biodiesel as an efficient, low-emission, and low-cost alternative. Investigations were conducted on the engine performance and emissions at different cottonseed-diesel (CSB) blend ratios. Transesterification was used to produce cotton biodiesel, which was then blended with D100 petro-diesel fuel in volumetric ratios of 10% (CSB10), 20% (CSB20), and 30% (CSB30). Using petro-diesel as a benchmark, the properties of cotton biodiesel and its blends were investigated in accordance with ASTM standards. The produced biodiesel's fuel properties were found to be within ASTM-acceptable limits. Engine tests revealed that the CSB10 blend has a slightly higher specific fuel consumption (SFC) than the D100; however, it is lower than that of the CSB20 and CSB30 blends, i.e., 0.6 kg/kWh. Among the other diesel blend samples investigated, the CSB10 had the highest brake thermal efficiency (BTE), i.e., 13.08%. All cottonseed blends have been found to have a reduced heat dissipation rate than D100. Emissions of carbon monoxide (CO) and carbon dioxide (CO_2) from cotton blends were generally lower than those from D100. This study also revealed that all mixes had lower nitrogen oxide (NOx) emissions than biodiesel. Emissions from the CB10 blend were significantly lower than those from the CSB20 and CSB30 blends. Out of all the blends, CSB10 was the best alternative fuel for diesel engines. Engine changes are not necessary when combining it with petroleum-based diesel.

Keywords:
Cottonseed; Diesel engines; Emissions; Performance; Transesterification process.

Highlights:

- Cottonseed oil biodiesel produced via alkaline transesterification.
- Physicochemical properties evaluated according to ASTM standards.
- Diesel engine tested with different biodiesel–diesel blends.
- Combustion, performance, and brake thermal efficiency analyzed.
- CO and CO2 emissions decreased, while NOx showed slight variation.

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1.INTRODUCTION

Oil reserves may soon run out due to the world's rapidly growing consumption of liquid fossil fuels, and shortages could occur by 2020–2030 [1]. Maintaining global economic and technological advances without damaging resources for future generations is one of the two challenges humanity faces [2]. Fuel emissions provide a serious health concern; in 2010, they caused 600,000 premature deaths in EU nations and $1.575 trillion in associated morbidity [3,4]. In 2010, the World Trade Organization estimated that the fuel market accounted for approximately 15.8% of total primary product and merchandise trade. Diesel fuel, which is widely used in heavy-duty engines and transportation, has been identified as a major contributor to this issue [5]. The main gas responsible for global warming, carbon dioxide, is primarily emitted by burning fossil fuels. Based on available evidence, controlling global warming will soon become more expensive and challenging as carbon dioxide emissions rise [6]. According to 2018 measurements by Hawaii's Mauna Loa Observatory, the concentration of carbon dioxide is 409 ppm; however, the suggested maximum safety level is 350ppm [7]. Air pollutants, including sulfur dioxide (SO_2) and nitrogen oxides (NO_x), are generated alongside carbon dioxide emissions, harming the environment and public health. Fossil fuel extraction, transportation, and processing all contribute to air and water pollution [8,9]. Renewable energy is energy generated primarily from natural sources, such as hydropower, geothermal energy, biomass, wind, solar, and tidal energy. About 24 percent of the world's electricity is currently generated by renewable resources. Among these renewable energy sources, biomass shows promise as a biofuel that may replace fossil fuels in several industries, particularly transportation, where the majority of renewable energy sources are used to supply all or part of the electricity and heating requirements. It will be mostly reliant on renewable energy sources by 2040, primarily biomass, which is estimated to be equivalent to about 3271 million tons of oil. Biomass refers to all biological resources derived from living or recently living plants, e.g., algae and crops, and their associated wastes [10]. Biodiesel, bio-oil, biogas, bioethanol, and biomethane are all examples of biomass that can be converted into biofuels via biological, chemical, or thermochemical processes. One possible alternative fuel that could help mitigate global warming. The most promising energy source for the transportation sector in the future [11]. Reduced smoke, carbon dioxide, sulfur oxides, nitrogen oxides, and carbon monoxide. Total unburned hydrocarbons (HCs) and aromatic hydrocarbons (PAHs) significantly decreased when Cottonseed diesel biodiesel is burned. Particulates are also significantly reduced. Diesel engine performance and emissions can be evaluated and improved depending on the engine and subsequent test processes [12–14]. Locally produced, renewable oilseed crops can be used to produce biodiesel. Compared with mineral diesel, biodiesel is less hazardous to transport and store. Unlike mineral diesel fuel, it is safe to handle and transport due to its high flash point and biodegradability. It can be used either exclusively or in combination with mineral diesel fuel at specific ratios [15]. Aparna Singh et al. investigated the performance and exhaust emissions of a diesel engine operating on blends of Jatropha biodiesel and conventional diesel fuel. The results showed that using B30 Biodiesel blend reduced CO emissions by approximately 24% and HC emissions by 16.7%. However, compared with conventional diesel, CO2 and NOx emissions increased by 13.3% and 2.12%, respectively [16]. In another study, Gad et al. examined the performance and emissions of a diesel engine fueled with Jatropha biodiesel. Tests were performed at 75% engine load and at different engine speeds. The maximum decreases in thermal efficiency and volumetric efficiency for B100 were 33 and 9%, respectively. The highest increase in NOX emission for B100 was 47% compared to diesel oil—tests conducted in a diesel engine [17]. Prabhu et al. used palm biodiesel and diesel fuel and found that their properties were similar. Due to its low heat content, palm biodiesel has a similar output power to diesel fuel; however, it has a higher brake-specific fuel consumption. According to the study, using palm biodiesel in place of unmodified diesel fuel in a diesel engine greatly reduces hazardous emissions [18]. Since Cottonseed is a plant that produces oilseeds, it is recognized as one of the best non-edible feedstocks for biodiesel production [19,20]. Cotton oil is being tested as a fuel alternative for compression-ignition engines. This annual herbaceous plant is used for fiber in 59 countries. It is oxygenated, non-aromatic, non-toxic, and contains no sulfur. Cotton is rich in unsaturated chemicals, with 35-45% oil by weight [21]. Previous studies have shown that cottonseed biodiesel blends can improve combustion characteristics and reduce harmful emissions in compression ignition engines. Aydin and Bayindir found that cottonseed oil methyl ester blends produced lower exhaust emissions while maintaining engine performance comparable to that of diesel fuel [22]. Recent studies have also explored the use of additives and nanoparticles to enhance the performance of cottonseed biodiesel. Debas Dessie and Eyob Sisay Yeshanew concluded that adding Al_2O_3 and CeO_2 nanoparticles to cottonseed biodiesel blends improved brake power and reduced emissions of CO, CO2, and hydrocarbons, due to more complete combustion [23]. Despite these studies, there is still a need to optimize cottonseed-based biodiesel production further and to evaluate its detailed effects on engine performance and emissions under different operating conditions. Therefore, the novelty of this study lies in the use of locally sourced cotton oil produced and processed under specific local production conditions, and looked at exhaust emission rates and the performance of diesel engines utilizing various blends with petroleum diesel, which may impart physicochemical properties different from those of commercially available oils used in previous studies, such as density, calorific value, cetane number, pour point, flash point, and kinematic viscosity, are included in the study. Variations in extraction and processing methods directly influence fuel properties and combustion behavior, thereby affecting engine performance and emission characteristics. Performance parameters, including fuel consumption, coolant heat transfer, and brake thermal efficiency (BTE), were examined under different load conditions. Nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO2) were also examined in exhaust gas emissions. As a result, cottonseeds are used to produce biodiesel, which is considered an improved alternative to petroleum-based diesel [24].

2.MATERIALS AND METHODS

The present research used processed cottonseed oil as the raw material for producing biodiesel. Also, it examined the performance and emission characteristics of cottonseed methyl ester compared to petroleum diesel under different combinations. Cottonseed oil can be extracted using a variety of processes, including enzymatic extraction, solvent extraction, and screw press. Since the screw press method produces higher yields, it is preferred and has been used [25,26]. The cottonseed oil was extracted by the biofuel's screw press mechanical expeller. The seeds were first cleaned to remove impurities, foreign objects, and any agrochemical sprays that might have remained on the seed's surfaces. After sterilization, double-distilled water washing, and oven drying, the extracted oil was collected in airtight glass bottles. Single esterification was utilized to reduce the amount of free fatty acids in the oil.

2.1.Transesterification Process

The process of transesterification (or alcoholysis) entails exchanging the alcohol component of an ester, specifically called methanolysis when methanol is used. When KOH is used as a catalyst, cottonseed oil reacts to produce biodiesel (fatty acid esters) and glycerin. Figure 1 demonstrates this mechanism, showing the transition of triglycerides from a solid form into their respective esters and glycerol. Biodiesel made from cottonseed was produced. To remove moisture, 400ml crude cottonseed oil was heated to 100°C for 15 min. Next, 4.25 gm of potassium hydroxide (NaOH) and 100 ml of ethanol were mixed to prepare potassium methylate. The reactor vessel was then filled with 400 ml of heated cottonseed oil. The potassium methylate mixture was then injected through the charging hole, and the reaction was allowed to run for 50 min while maintaining a reaction temperature of 50°C and a stirrer speed of 600 rpm. Crude cottonseed biodiesel was transferred to a separating funnel after transesterification to separate crude glycerin. To eliminate the catalyst and unreacted reagents, water washing was performed with hot water at a rate of 150 ml/L. Figure 2 illustrates the transesterification setup. The prepared sample was washed five times until the desired pH value was reached.

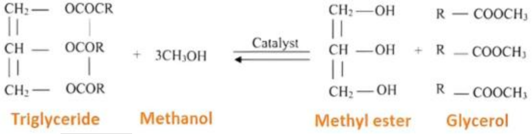

Fig. 1 Transesterification Reaction.

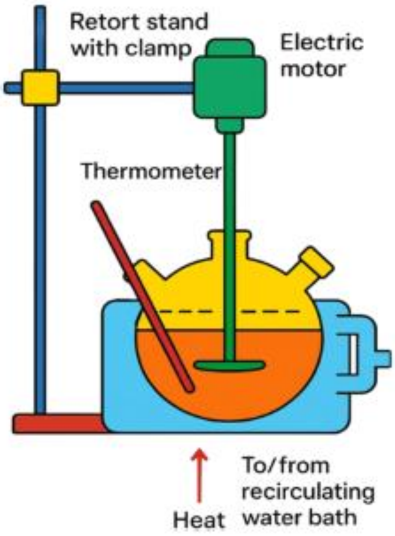

Fig. 2 Transesterification Setup.

2.2.Preparing the Blends, the Performance of the Engine, and Exhaust Emissions

At room temperature, the Biofuel Laboratory prepared blends with various concentrations of petro-diesel and cottonseed biodiesel. Cottonseed biodiesel was blended with petroleum diesel in volumetric ratios of 10% (CSB10), 20% (CSB20), and 30% (CSB30). A slow-speed diesel engine (Kirloskar, Model TAF 1) was used to evaluate various cottonseed biodiesel blends. Table 1 shows the diesel engine specification [6].

Table 1 Diesel Engine Specifications.

Parameter	Specifications
Engine Type	Four-stroke cylinder vertical air-cooled diesel engine
Producer and Model	Kirloskar TAF 1
Bore and stroke	87.5 and 110 mm
NO of cylinders	Single cylinder
Compression ratio	17.5:1
Rated power	4.4 Kw
Injection timing	23°
Injection pressure	200 bar
Rated speed	1500 rpm
Rotameter	Calorimeter 25–250 LPH, engine cooling 100–1000 LPH

The engines consist of a variety of systems, including the water-cooling system, fuel supply system, lubrication system, and various sensors connected to a measurement instrument [25]. The engine's load was gradually increased from zero to a maximum of one kilowatt. As the engine's load increases, the engine's rpm decreases. An eddy-current electric dynamometer was utilized to measure the power output (torque). A volumetric approach was used to measure fuel usage [7,27]. The indicators evaluated included torque, lubricating oil temperature, inlet and outlet temperatures, suction and exhaust pressures, exhaust gas temperature, brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). Furthermore, several types of flue gas emissions, including carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NOx), were assessed using the exhaust gas analysis unit.

2.3. Uncertainty Analysis

Evaluating error propagation is a fundamental step in assessing the accuracy of engine-related experimental data. Uncertainties—originating from calibration offsets or equipment tolerances—must be considered when combining various measurements. By utilizing specific propagation formulas based on the mathematical functions involved. For a function:

$$Y = f(x_1, x_2, x_3, \ldots, x_n)$$

the combined uncertainty u(Y) is:

$$\boldsymbol{u(Y) = \sqrt{\left(\frac{\partial Y}{\partial X_1} u(X_1)\right)^2 + \left(\frac{\partial Y}{\partial X_2} u(X_2)\right)^2 + \ldots + \left(\frac{\partial Y}{\partial X_n} (X)_n\right)^2}} \qquad \textbf{(1)}$$

where u(Y) represents the uncertainty of the calculated parameter, and u(X) represents the uncertainty of the measured variable.

$$\boldsymbol{\sigma_{BP} = \sqrt{\sigma_N^2 + \sigma_T^2}} \qquad \textbf{(2)}$$

$$\sigma_{BP} = \sqrt{1^2 + 1^2}$$

$$\sigma_{BP} = 1.41$$

where N represents speed, and T represents torque.

The following error-propagation model is applied to determine the cumulative uncertainty for performance metrics that depend on Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC). This formula integrates the individual variances of each independent variable to quantify the total experimental error:

$$\boldsymbol{\sigma_Z = \sqrt{\left(\frac{\partial Z}{\partial \mathrm{BTE}} \sigma_{BTE}\right)^2 + \left(\frac{\partial Z}{\partial \mathrm{BSFC}} \sigma_{BSFC}\right)^2}} \qquad \textbf{(3)}$$

$$\boldsymbol{\sigma_Z = \sqrt{\sigma_{BTE}^2 + \sigma_{BSFC}^2}} \qquad \textbf{(4)}$$

$$\sigma_Z = \sqrt{1{,}73^2 + 1.73^2}$$

$$\sigma_Z = 2.44$$

The resultant uncertainty for emission-related parameters, defined by the relationship, is derived by propagating errors through the relationship. This calculation accounts for the individual variances of each measured gas species using the following expression:

$$\boldsymbol{\sigma_z = \sqrt{\sigma_{CO}^2 + \sigma_{CO2}^2 + \sigma_{NOx}^2}} \qquad \textbf{(5)}$$

$$\sigma_z = \sqrt{(0.02)^2 + (0.03)^2 + (0.7)^2}$$

$$\sigma_z = 0.701$$

$$\boldsymbol{\sigma_{(overall)} = \sqrt{\sigma_{BSFC}^2 + \sigma_{BTE}^2 + \sigma_{CO}^2 + \sigma_{CO2}^2 + \sigma_{NOx}^2} = 2.2} \qquad \textbf{(6)}$$

With an error percentage below the 5% limit, the measurements were deemed statistically significant. Therefore, no further adjustments to the experimental variables were required during data collection.

3. RESULTS AND DISCUSSION

3.1. Engine Performance and Fuel Properties

The diesel used in the present study is locally sourced commercial diesel, and its high sulfur content underscores the importance of blending it with biodiesel, which acts as an effective sulfur-free oxidizing agent, thereby reducing the overall sulfur content in the fuel blends and mitigating sulfur oxide emissions. This diesel is intended for heavy trucks or marine applications, which permit a higher sulfur content. The results in Table 2 illustrate the properties of the various cottonseed biodiesel blends produced. It was found that the generated biodiesel had a higher cetane number and flash point, and lower density and viscosity. The maximum cetane number in blend CSB10 was 46.5, whereas in blend CSB20 it was 45.4, achieving the ASTM standard [28]. It was found that CSB20 and CSB30 had flash points higher than diesel. All mixes contained less sulfur than diesel in 100%. The calorific values remained within the acceptable range. In all, the CSB10 blend's fuel properties were found to be enhanced, with a higher cetane number, lower kinematic viscosity, and higher calorific value. Compared with CSB20 and CSB30, CSB10 is a more feasible combination. Every blend sample outperformed petro diesel. Results were similar to those reported in [29].

Table 2 Characteristics of Fuel Blends with Cottonseed Biodiesel.

Quality parameters	Allowable limits	Diesel 100%	CSB 100%	CSB 10 %	CSB 20%	CSB 30%
Density at 15°C kg/L	0.880	0.829	0.920	0.833	0.848	0.882
Kinematic Viscosity at 40°C (mm^2 / SEC)	1.9–6.0	2.8	4.00	3.23	3.41	3.62
Sulfur %wt	0.05 max	0.719	0.001	0.661	0.542	0.462
Flash point °C	130 min	71	233	77	83	89
Total Acid Number mgKOH/gm	0.80 max	0.066	0.336	0.083	0.135	0.184
Pour point °C	-15 to +5	-18	10 -	-14.5	-13	-11
Cetane number	47 mini	47	42	46.5	45.4	42.3
Calorific value MJ/kg	37.5 - 42.80	43	40	42.6	41.3	40.8

By varying the load, the engine's performance and brake power output were examined. Figure 3 illustrates how brake-specific fuel consumption (BSFC) varies with brake power for various fuel blends. The average BSFC for CSB10, CSB20, and CSB30 was 0.6 kg/kW.h, 0.64 kg/kW.h, and 0.76 kg/kW.h, respectively, which were higher than D100 (0.62 kg/kW.h, except for CSB10, which was lower. Ultimately, it is determined to be cost-effective because it produces the best results from mixed oil while using less than diesel oil. It is evident that, in the majority of the studied situations, both CSB20 and CSB30 blends significantly increased BSFC compared to D100. The variation in BSFC values is mainly attributed to differences in calorific value, viscosity, oxygen content, and cetane number of the fuel blends. This behavior is explained by the fact that fuel blends with a higher residual oil content have lower combustion efficiency because their cetane numbers are reduced, requiring more fuel to produce the same amount of power. However, under medium and low loading conditions, the BSFC increments generated by the CSB10 blend vary. Nevertheless, at maximum load, the BSFC significantly drops to 0.6 kg/kW.h. This improvement is due to a more efficient combustion process [30, 31].

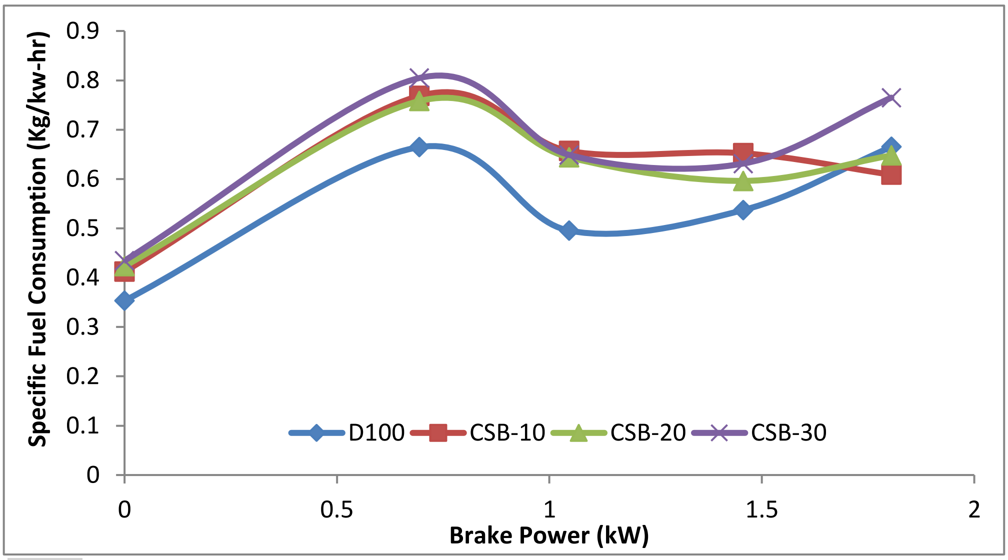

Fig. 3 Brake Power Versus Engine Brake Specific Fuel Consumption for Cottonseed.

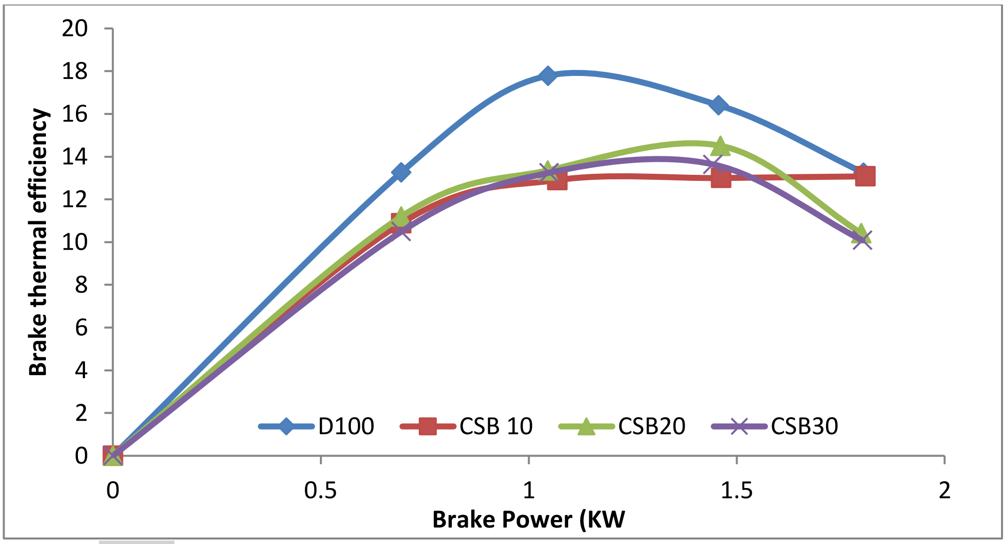

Fig. 4 Brake Power Versus Brake Thermal Efficiency for Cottonseed.

Figure 4 shows the variation between brake thermal efficiency (BTE) and brake power output for the various cottonseed biodiesel blends. It was found that brake thermal efficiency increased with increasing brake power. The highest brake thermal efficiency of CSB10, CSB20, and CSB30 was 13.08%, 10.42%, and 10.08%, respectively. At maximum brake power, the CSB10's IC. The thermal efficiency was 13.08% higher than that of diesel. Due to their improved thermal efficiency, these blends could be used realistically in internal combustion (IC) engines. Blends with higher percentages of used CSB20 and CSB30 exhibit reduced efficiency due to their higher viscosity and impurity levels, leading to incomplete combustion [24,31,32]. The (CSB10) blend significantly improved by (13.08%) in BTE at a maximum load because diesel fuel has advantageous combustion properties [33]. The low (BTE) is attributed to low-load operating situations, where heat and frictional losses exceed power output. Additionally, the engine used is small and single-cylinder, and the higher viscosity of biodiesel results in weak atomization and decreased combustion efficiency at these places.

3.2.Emissions of Exhaust

In addition to emission trends, carbon monoxide (CO) emissions from the exhaust by load are shown in Fig. 5. The present study compared exhaust emissions from diesel and biodiesel blends. The CO emissions exhibit a distinct downward trend as the load increases. With a sudden decrease of 170 and 190 ppm at no load, and 25% of the 10% CSB blend. Compared to D100. The CSB30 mixture's emissions were higher than the 10% CSB blend and CSB20 at 100 loads; however, they increased noticeably. The Carbon monoxide (CO) emissions increased with the molecular percent of fuel decomposition at full loading; however, they remained lower than those observed for pure diesel fuel (D100) [21,25]. All blends exhibit this decrease, indicative of more complete combustion at higher load percentages. The results have shown that biodiesel and waste oil blends can similarly reduce CO emissions because waste oils contain higher levels of oxidation and oxygen [34]. Biodiesel generates slightly more particulate matter, which is made up of carbonaceous material, than other vehicular fuels [15]. Therefore, environmental impacts can be reduced by using alternative biofuels. Temperature and unburned flue gases combine to generate carbon monoxide (CO), which regulates the rates of fuel oxidation and decomposition [29]. Figure 6 shows that the minimum CO_2 was observed in the 10% CSB blend at no load, 25% load, and 50% load conditions with 1.32%, 1.98%, and 2.4% ppm, respectively, compared to CSB20 and CSB30 under the same blend condition. However, at a load of 75%, the CO_2 emission of CSB10 was 2.53%, which was lower than that of all biodiesel blends. At various load conditions, it was found that all 10% biodiesel mixes were less than 100% diesel. This result is likely because, although the fuel blend has a lower overall calorific value, it burns more efficiently at higher CSB levels. Variable CO_2 trends have been observed in research on the combustion of biodiesel and waste oil, often linked to fuel content and engine load [35].

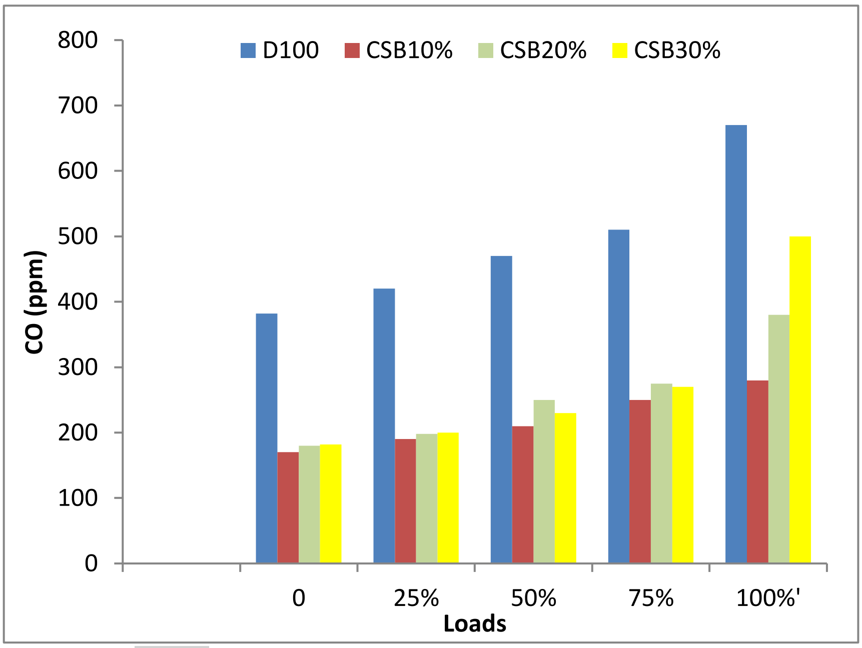

Fig. 5 CO Exhaust (ppm) Comparison with Loads.

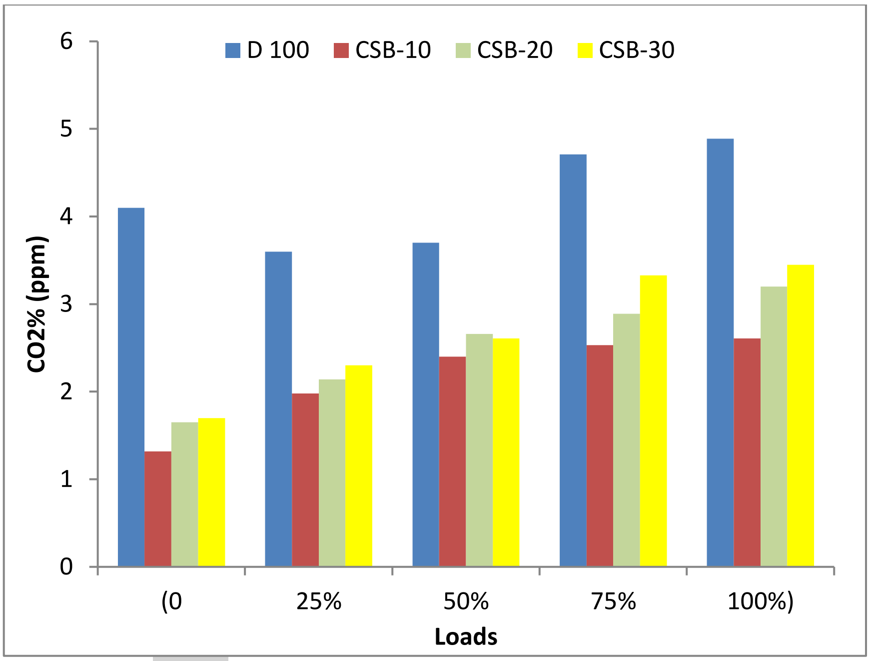

Fig. 6 Comparison of Land Exhaust CO_2 (ppm).

Figure 7 shows that one exhaust emission from diesel engines is nitrogen oxides (NOx). When it is inhaled, it may pose health risks [27]. The NOx emissions showed a non-linear trend; all mixes had lower nitrogen oxide (NOx) emissions than petrodiesel. Emissions from the CB10 blend were significantly reduced (33%, 48%) at no load, and 25% less than those from the CSB20 and CSB30 blends. Biodiesel blends reduce NOx due to their modified combustion properties and lower flame temperatures [36]. However, under load, cottonseed biodiesel is feasible when used in various blends to reduce nitrogen oxides (NOx). However, D100's NOx emission reduced significantly at [75% load (60 ppm) and much more at 100% load (27 ppm)]. In contrast, at [75% and 100% load (42 ppm and 18 ppm], respectively), CSB30's nitrogen oxide (NOx) emissions decreased significantly. Also, Nitrogen oxide (NOx) emissions decreased as the load increased. Similarly, all biodiesel blends were higher than O2 levels. The various combustion properties of the blends are responsible for this decrease. Higher cetane numbers and chemically bonded oxygen enhance ignition quality and reduce ignition latency, preventing the formation of high-temperature zones inside the combustion chamber. A decrease in peak flame temperature immediately results in lower NOx emissions, since NOx formation is largely dependent on peak combustion temperature and the residence time of gases at elevated temperatures.

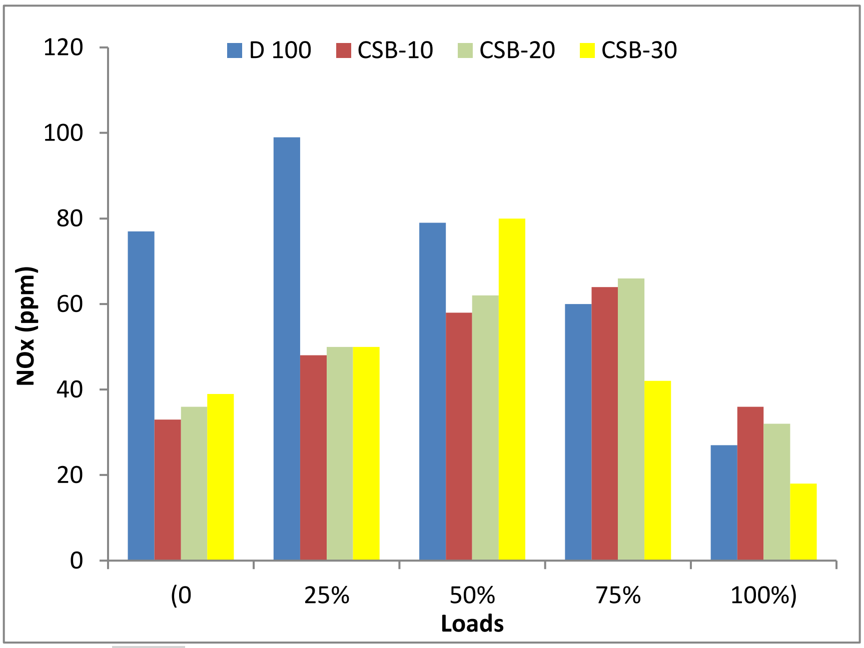

Fig. 7 Comparison of Loads with Exhaust NOx (ppm).

4.CONCLUSION

Native cottonseeds have been used in the esterification process to generate cottonseed biodiesel. Petroleum diesel fuel (D100) was blended with the produced biodiesel at 10% (CSB10), 20% (CSB20), and 30% (CSB30) volume ratios. It was discovered that the biodiesel's fuel properties remained within ASTM's allowable limits. It was found that the CSB10 blend consumed less specific fuel than the CSB20 and CSB30 blends. The performance of the blend (CSB10) was comparable to that of D100 and, in many instances, even better. At a load of 6 kg and 1500 rpm, it outperformed diesel, with BSFC and BTE of up to 0.6 kg/kWh and 13.08 percent, respectively. In all operating settings, it resulted in a notable decrease in CO emissions of 190 ppm at 25% load. On the other hand, because of its higher nitrogen content and lower cetane number, the CSB30 blend had the highest (NOx) emissions, the percent reached 3.45%. All carbon-separation chemistries contain a lower percentage of carbon monoxide than petroleum diesel. Cottonseed blends were shown to release less carbon monoxide (CO) and nitrogen oxides (NOx) than petroleum diesel fuels. It has been observed that all three blends, i.e., CSB10, CSB20, and CSB30, are better alternatives to diesel for engines and can be blended with petroleum diesel without requiring engine modifications. According to the emissions findings from the addition of CSB10, there is a clear decrease in greenhouse gas emissions, which significantly benefits the environment and generates substantial economic returns. Additionally, cottonseed production worldwide shows great promise.

NOMENCLATURE

Abbreviations	Description
ASTM	American Society for Testing and Materials
B100	Biodiesel 100 %
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CSB	Cottonseed Biodiesel
CSB10	10% Cottonseed Biodiesel
CSB20	20% Cottonseed Biodiesel
CSB30	30% Cottonseed Biodiesel
CH_3OH	Methanol
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CP	Cloud Point
D100	Diesel 100%
FP	Flash Point
PM	Particulate Matter
PP	Pour Point

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