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Usability Assessment of Diesel Blends with Vegetable Oil and Ethanol in Diesel Engines

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Abstract

Vegetable oil is a type of biofuel that is renewable and capable of reducing emissions and harmful components in diesel engine exhaust. However, vegetable oil has several properties that differ from mineral diesel, such as high viscosity and large surface tension, making it unsuitable for direct use in conventional diesel engines. To overcome these drawbacks, several solutions have been proposed, such as pyrolysis, blending, esterification, and emulsification. Among these, the method of blending vegetable oil with low-viscosity fuels is considered simple and highly feasible. This paper presents some research results on the technical characteristics and emissions of a diesel engine using a diesel-ethanol-vegetable oil blended fuel.

Keywords: Vegetable oil, Ethanol, Emission reduction, Diesel engine, Diesel-ethanol-vegetable oil blend.

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1. Introduction

Currently, the depletion of global petroleum fuel reserves and concerns about environmental pollution have stimulated interest in alternative fuel sources. According to scientists' forecasts, with the current rate of extraction, the world's oil reserves will only last for about 50 more years. Additionally, the combustion of fossil fuels releases many pollutants such as COx, NOx, HC, particulate matter (PM), etc., causing numerous adverse effects on the environment, ecosystems, and significantly impacting the quality of life. Therefore, the research and application of biofuels, which are renewable and environmentally friendly, for internal combustion engines is an urgent issue. The two biofuels most widely used today are biodiesel, commonly used for diesel engines, and bioethanol, typically used for gasoline engines. Biodiesel is processed from various vegetable oils through an esterification process. Raw vegetable oil can also replace mineral diesel as fuel for diesel engines; however, due to its high viscosity, it may adversely affect engine performance [1, 2]. Conversely, ethanol has low viscosity and poor lubrication properties, so it is only blended in small proportions with diesel to be used as fuel for diesel engines. Simultaneously blending vegetable oil, ethanol, and mineral diesel can ensure that the viscosity of the mixture is comparable to mineral diesel, reducing its impact on engine performance while increasing the proportion of biofuel.

In this topic, many studies focus on non-food vegetable oils (such as jatropha oil, used cooking oil, etc.) to mitigate the impact on food security. In [3], the fuel properties, technical characteristics, and emissions of engines using diesel-jatropha-ethanol blended fuels have been studied. The results showed that mixtures with low ethanol content provided engine power, fuel consumption, and exhaust temperatures comparable to diesel, especially at low engine speeds with moderate load (50%). CO, CO_2 emissions, and smoke concentrations tended to be lower than diesel. In [4], Yerren-nagoudaru and colleagues studied the performance

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and emissions of diesel engines using diesel-ethanol and jatropha blends. The results indicated that biofuels compared to diesel fuel had equivalent performance, lower fuel consumption, and lower HC and CO emissions, suggesting that biofuels can be used as a replacement for mineral diesel. Rifat Bin Islam and colleagues researched the fuel properties and performance of diesel engines using biodiesel from waste cooking oil (WCO) collected in Dhaka city. The research results showed that the kinematic viscosity of waste cooking oil was much higher than diesel, making direct use in CI engines difficult. The cross-esterification and blending with diesel reduced the kinematic viscosity to levels comparable to diesel, allowing it to be used as diesel engine fuel. These results demonstrate that diesel, jatropha, and ethanol blends can be used as engine fuel to replace mineral diesel.

Vietnam is an agricultural country with significant potential for ethanol production from raw materials such as cassava, corn, straw, rice husk, coffee husk, sugarcane bagasse, and many other sources. According to current statistics, Vietnam has six ethanol production plants that have been constructed, with a total designed capacity of 500,000 m³ per year. Meanwhile, ethanol is currently only blended at a 5% ratio with mineral gasoline (known as E5 biofuel) for use in gasoline engines. In 2018, the highest consumption was approximately 3.56 million m³ of E5 gasoline, accounting for 41%, but this gradually decreased, with consumption reaching around 1.5 million m³ by 2022 and just over 544,000 m³ in the first five months of 2023. It is evident that E5 gasoline consumption remains low and is declining, leading to an increasing surplus of ethanol production [5-6]. Research into blending diesel with ethanol will enhance ethanol usage, leverage the advantages of biodiesel, and capitalize on Vietnam's ethanol production strengths. From the above analysis, it can be seen that researching the use of diesel-ethanol-vegetable oil blends as fuel for existing diesel engines is necessary and aligns with the practical conditions in Vietnam.

2. Evaluation of the potential use of diesel-ethanol-vegetable oil blended fuel

2.1. Effects of ethanol-blend fuels on diesel engine performance and emissions

Firstly, research in [7] conducted a study on the effects of ethanol-jatropha and ethanol-pongamia fuel blends on the performance and emissions of a single-cylinder diesel engine operating at a fixed speed of 1500 RPM. In this study, the fuel blends included jatropha-ethanol and ethanol-pongamia in ratios of 40-60, 45-55, 50-50, and 55-45. The results showed that the jatropha-ethanol (50-50) blend achieved an efficiency of approximately 29.39%, while the pongamia-ethanol (50-50) blend reached an efficiency of about 30.3%, slightly lower than diesel at 31.46% (Figure. 1, Figure. 2). Notably, NO_x emissions from the ethanol-jatropha (40-60) and ethanol-pongamia (40-60) blends were around 120 ppm, significantly lower than diesel at 553 ppm (Figure. 3). Furthermore, HC emissions from the jatropha-ethanol (55-45) and ethanol-pongamia (55-45) blends were also lower compared to diesel, indicating the superior emission performance of these blends.

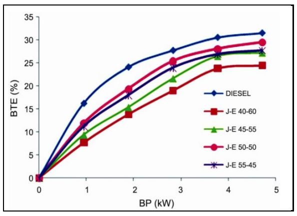

Figure 1. Brake Thermal Efficiency with respect to Brake Power

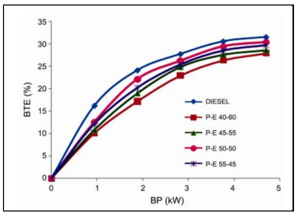

Figure 2. Brake Thermal Efficiency with respect to Brake Power

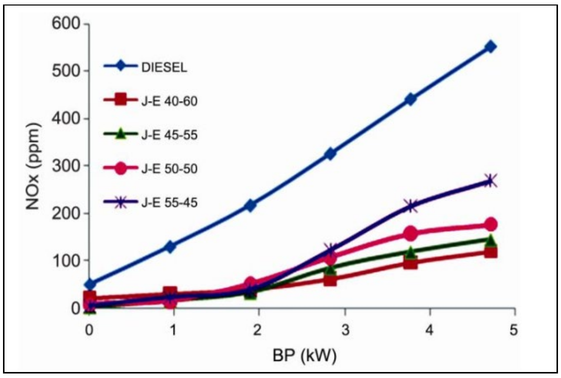

Figure 3. NO_x Emission with respect to Brake Power

Subsequently, developers in [8] steered another study on the emissions of a diesel engine using ethanol-palm oil-diesel fuel blends at 1200 RPM under two different load conditions. In this experiment, the fuel blends included diesel-palm oil (at a 1:1 volumetric ratio) combined with ethanol, methyl oleate, and three co-surfactants (1-butanol, 1-octanol, or 1-decanol) in various proportions. These results indicated that the kinematic viscosity and fuel properties were comparable to diesel (Table 1), but the fuel consumption of the blends was higher under all engine operating conditions due to the lower combustion temperature. Moreover, According to Figure 5, Figure 6, NO_x and CO_2 emissions, as well as exhaust gas temperature, were significantly lower than diesel, while CO emissions were higher under load conditions (Figure. 7). Particularly, the effect of surfactants on biofuels did not significantly alter NO_x, CO emissions, or exhaust temperature under any load condition. However, biofuels using octanol as a surfactant tended to produce lower CO and NO_x emissions compared to butanol and decanoyl.

Table 1. Composition (% vol.) for Palm Oil-diesel Blends, Biodiesel-diesel Blends, and Microemulsion Fuels Where the Ratio of Cosurfactant and Palm Oil-diesel Blends Was Varied. Methyl Oleate to Ethanol Ratio Was Fixed at 1:1.25

Sample	Formulation						Fuel properties				
	Diesel	Palm oil	Surfactant	Cosurfactant	Ethanol	B100	Viscosity @ 40°C (cSt)	Density @25°C (g/mL)	Heat of Combustion[b] (MJ/kg)	Water Content[c] (%vol.)	A/F_{st} ratio[d]
Diesel	100.0	-	-	-	-	-	4.1	0.83	45.8	0.01	14.86
Palm oil-Diesel (PD)	50.0	50.0	-	-	-	-	11.7	0.88	42.5	0.06	13.49
Biodiesel-Diesel (BD)	50.0	-	-	-	-	50.0	4.5	0.87	39.2	0.09	13.5
Microemulsion fuel											
1-butanol (MO+But)	32.5	32.5	6.0	9.0	20.0	-	4.3[a]	0.85	39.2	0.16	12.39
1-octanol (MO+Oct)	29.0	29.0	6.0	16.0	20.0	-	4.3[a]	0.87	39.2	0.16	12.47
1-decanol (MO+Dec)	27.5	27.5	6.0	19.0	20.0	-	4.6[a]	0.88	39.5	0.18	12.50

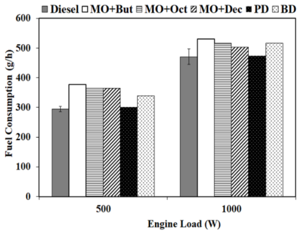

Figure. 4. Fuel consumptions of diesel, microemulsion fuels, palm oil-diesel blends, and biodiesel-diesel blends.

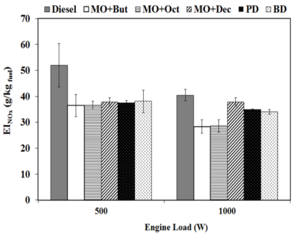

Figure. 5. NOx emissions for diesel, microemulsion fuels, PD, and BD

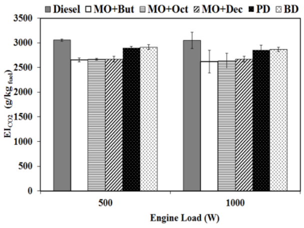

Figure. 6. CO2 emissions for diesel, microemulsion fuels, PD, and BD

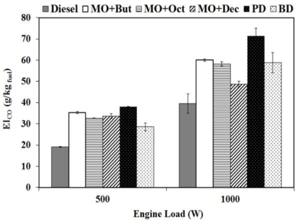

Figure. 7. CO emissions for diesel, microemulsion fuels, PD, and BD

Continuing on this topic, another work in [9] presented the technical characteristics and emissions of a single-cylinder diesel engine using PB10E5D85 (10% palm oil biodiesel, 5% ethanol, 85% diesel), PB10E10D80 (10% palm oil biodiesel, 10% ethanol, 80% diesel), PB20E5D75 (20% palm oil biodiesel, 5% ethanol, 75% diesel), PB20E10D70 (20% palm oil biodiesel, 10% ethanol, 70% diesel), PB30E5D65 (30% palm oil biodiesel, 5% ethanol, 65% diesel), and PB30E10D60 (30% palm oil biodiesel, 10% ethanol, 60% diesel) fuel blends. The research results mentioned that compared to biodiesel-diesel blends, the addition of ethanol improved thermal efficiency by approximately 8.3% (Figure. 8).

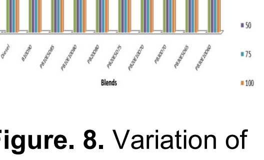

Figure. 8. Variation of Brake Specific Energy Consumption with respect to load

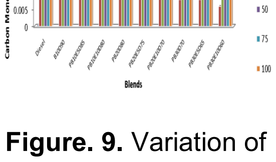

Figure. 9. Variation of Carbon Monoxide emission with respect to load

However, fuel consumption also increased. Especially, CO emissions decreased with the addition of ethanol to the blends (Figure. 9), while CO_2 and NO_x emissions increased (Figure. 10), and HC emissions remained relatively unchanged compared to biodiesel-diesel blends (Figure. 11).

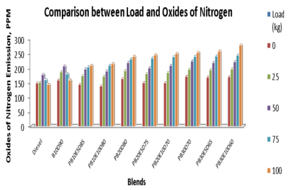

Figure. 10. Variation of Oxides of Nitrogen emission with respect to load

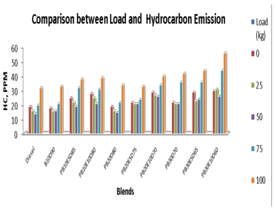

Figure. 11. Variation of Hydrocarbon emission with Respect to Load

In the same approach, investigators in [1] studied the effects of ethanol-vegetable oil-diesel fuel blends on the technical characteristics, emissions, and combustion process of a diesel engine. In this study, the fuel blends included rapeseed oil-diesel (at a 1:1 ratio) and ethanol with varying proportions from 0% to 30% by volume (denoted as BE0, BE10, BE20, and BE30). Specifically, oleic acid was used as a surfactant, and 1-butanol was chosen as a co-surfactant. As a result, it implied that high ratios of rapeseed oil blended with diesel could be directly used in diesel engines, but due to the high viscosity of rapeseed oil, the fuel consumption, smoke, CO, and HC emissions of the engine using these blends were higher compared to diesel. Though, the addition of ethanol to the rapeseed oil-diesel blend using emulsification techniques could further reduce the viscosity and density of the blend while improving engine performance (Table 3). As the ethanol ratio increased, the combustion process was delayed, with higher cylinder peak pressure and heat release rate, resulting in a corresponding delay in the crank angle, especially for blends with a high ethanol ratio (Figure. 12, Figure. 13). Figure 14 shows BE0 and BE10 produced the highest smoke emissions, while BE30 reduced and even performed better than diesel under certain operating conditions. Additionally, BE30 exhibited the lowest NO_x emissions under all operating conditions, indicating that a high ethanol ratio can simultaneously reduce both smoke and NO_x (Figure. 15). Nevertheless, CO and HC emissions increased with higher ethanol content (Figure. 16, Figure. 17).

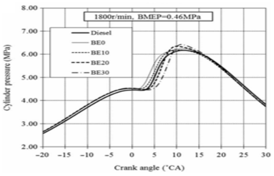

Figure 12. Variation in cylinder pressure with respect to crank angle at high engine load

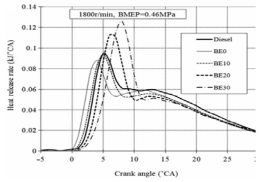

Figure 13. Variation in heat release rate with respect to crank angle at high engine load

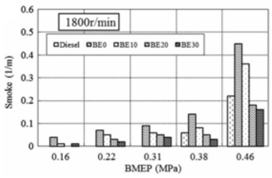

Figure 14. Variation in smoke emission with respect to engine loads at 1800 r/min

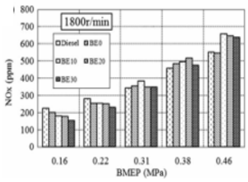

Figure 15. Variation in NOx emission with respect to engine loads at 1800 r/min

Table 2. Main properties of blending compositions.

Properties	Diesel	Rapeseed oil	Ethanol	Oleic acid	1-butanol
Density at 25°C (g mL^{-1})	0.829	0.912	0.789	0.89	0.81
Latent heat of evaporation (kJ kg^{-1})	250	-	840	200	585
Lower calorific value (kJ kg^{-1})	42.636	36.995	26.778	38.650	33.070
Cetane number	46	41.6	5-8	-	25
Kinematic viscosity at 40°C (mm^2 s^{-1})	2.68	23.91	1.2	19.69	3.6^a
Stoichiometric air–fuel ratio (kg kg^{-1})	14.45	12.56	9.05	-	11.2
Flash point (°C)	78	244	13.5	>110	29
Boiling point (°C)	180-330	335	78	286	117.7
Self-ignition temperature (°C)	250	320	420	362.8	562
Oxygen content (wt%)	0	10.8	34.8	11.3	21.6
Molecular weight	170	885	46.07	282.46	74.1

Table 3. Composition of the test fuels and main properties

Fuels	Diesel	BE0	BE10	BE20	BE30
Diesel, %(v/v)	100	50	44.2	37.3	31.25
Rapeseed oil, %(v/v)	0	50	44.2	37.3	31.25
Ethanol, %(v/v)	0	0	9.8	18.7	26.8
Oleic acid/1-butanol, %(v/v)	0	0	1.8	6.7	10.7
Density at 25°C (g mL^{-1})	0.829	0.873	0.865	0.856	0.848
Kinematic viscosity at 40°C (mm^2 s^{-1})	2.68	9.64	6.81	5.29	3.78
Lower calorific value (MJ kg^{-1})	42.64	39.68	38.5	37.3	36.08
Stoichiometric air–fuel ratio (kg kg^{-1})	14.45	13.46	13.06	12.65	12.23

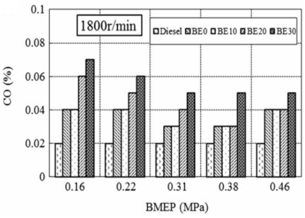

Figure 16. Variation in CO emission with respect to engine loads at 1800 r/min

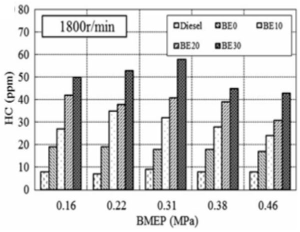

Figure 17. Variation in HC emission with respect to engine loads at 1800 r/min

2.2. Performance and Emissions Analysis of Diesel Engines Using Alternative Fuel Blends

In this domain, the performance and emissions of a turbocharged diesel engine using a fuel blend of vegetable oil, and ethanol were studied [10]. According to their developments, the vegetable oils used included apricot oil, Pongamia oil, and cottonseed oil. The results of this research disclosed that the turbocharged engine exhibited better performance and emission characteristics compared to a conventional engine.

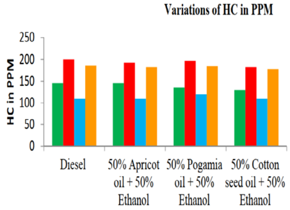

Figure 18. Shows the variations of unburnt hydro carbonfor diesel and different vegetable oils blends with ethanol

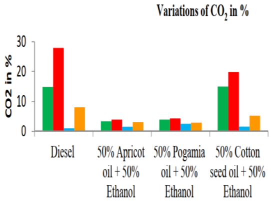

Figure 19. Shows the variations of corbon dioxidefor diesel and different vegetable oils blends with ethanol

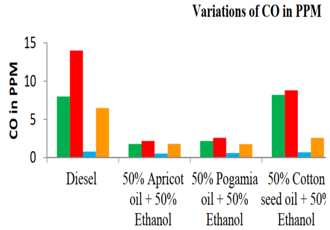

Figure 20. Shows the variations of corbon monoxidefor diesel and different vegetable oils blends with ethanol

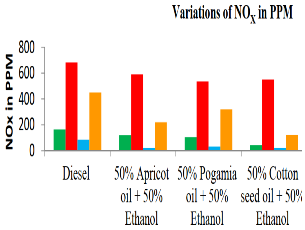

Figure 21. Shows the variations ofnitrogen dioxidefor diesel and different vegetable oils blends with ethanol

In addition, Figure 18, Figure 19, Figure 20, Figure 21 Shows the variations of emissions of HC, CO_2, CO, NO_x, and smoke concentration were significantly reduced.

Following, the use of vegetable oil and animal fat as fuel for diesel engines were steered [11]. Due to their findings, vegetable oil can be used as a fuel for diesel engines (Table 4), but its prices due to their use in food production. Meanwhile, beef tallow and yellow grease, which are low-cost feedstocks often discarded by some industries, can be effectively utilized in the production of biodiesel. Besides, biodiesel derived from used cooking oil is considered a promising option due to its relatively low production cost. Nonetheless, the widespread use of vegetable oil could lead to significant issues, such as hunger in developing countries.

Table 4. Comparisons of some fuel properties of vegetable oils with No. 2 diesel fuel

Fuel type	Heating value (MJ/kg)	Density (kg/m^3)	Viscosity at 300 K (mm^2/s)	Cetane number[a]
No. 2 diesel fuel	43.4	815	4.3	47.0
Sunflower oil	39.5	918	58.5	37.1
Cottonseed oil	39.6	912	50.1	48.1
Soybean oil	39.6	914	65.4	38.0
Corn oil	37.8	915	46.3	37.6
Opium poppy oil	38.9	921	56.1	-
Rapeseed oil	37.6	914	39.2	37.6

Table 5. The fuel properties for the fuels used

Fuel	Density kg/L@15 C	Viscosity (mm^2/s) @15 C	Calorific Value kJ/kg	Chemical Formula	Molecular Weight g/mole	H/C Ratio
Microalgae oil	0.908±0.015	56.3	35,800	$C_{16.94}H_{32.86}O_2$	268.57	1.94
Ethanol	0.785±0.015	1.94	29,700	C_2H_5OH	46	2.5
Diesel	0.821±0.015 -	3.34	44,800	$C_{12}H_{23}$ [15–17] *	167	1.92
MOE50-50			-	$C_{9.4}H_{19.43}O_{1.5}$	156.5	2.06
MOE20%	8.22±0.015	3.5	42,390	$C_{11.48}H_{22.29}O_{0.3}$	164.85	1.94

In the other efforts, several colleagues investigated diesel engines using fuel blends consisting of diesel, ethanol (99.5% and 95%), and biodiesel or vegetable oil [12]. The tested blends included 90% diesel - 10% ethanol, 80% diesel - 15% ethanol - 5% soybean biodiesel, 80% diesel - 15% ethanol - 5% castor biodiesel, 80% diesel - 15% ethanol - 5% residual biodiesel, 90% diesel - 7% ethanol - 3% soybean oil, and 90% diesel - 7% ethanol - 3% castor oil. They stated that the emission of carbonyl compounds from these blends was higher than that of diesel (On the other hand, among the blends, the one containing castor biodiesel had the lowest emission of carbonyl compounds. As well, the diesel-ethanol blend had the lowest NOx emissions (Figure. 22), while the CO emissions of the blends did not change significantly compared to diesel, and CO2 emissions were observed to decrease at an engine speed of 2000 RPM (Figure. 23).

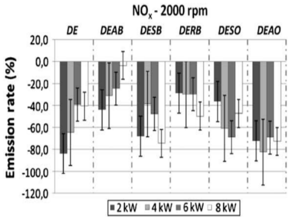

Figure 22. Decreases in the NOx emission rate (%) at 2000 rpm constant speeds using DE, DEAB, DESB, DERB, DESO, and DEAO fuel blends in relation to pure diesel

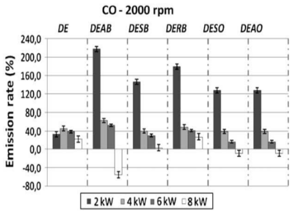

Figure 23. Increases in the CO emission rate (%) for 2000 rpm constant speeds using DE, DEAB, DESB, DERB, DESO, and DEAO fuel blends in relation to pure diesel

Likewise, Al-lwayzy Saddam H conducted a study on a microalgae oil-ethanol-diesel blend in a diesel engine [13]. The experiment was conducted at engine speeds of 2900 RPM, then reduced to 2600 RPM, 2300 RPM, 2000 RPM, and 1700 RPM. The fuel blend used consisted of 10% microalgae oil, 10% ethanol, and 80% diesel. Those results exposed that using ethanol as an additive could improve diesel engine emissions, although engine power decreased, and the viscosity and cetane number were lower according to Table 5. Yet, the blend had fuel properties similar to diesel, making it suitable for use without engine modification. Compared to diesel, the results indicated that NOx and HC emissions were reduced at most engine speeds, while CO and CO2 emissions were lower at lower engine speeds.

To our best knowledge, scholars in [14] considered the use of diesel, palm oil, and ethanol blends in a diesel engine, with tested ratios of 85% diesel - 10% palm oil - 5% ethanol, 80% diesel - 10% palm oil - 10% ethanol, and 70% diesel - 25% palm oil - 5% ethanol (% v/v). From their results, it was shown that the engine's performance using the fuel blends did not change significantly compared to diesel. But engine power decreased by 7.4% (Figure. 24), and fuel consumption increased by 10.9% the 70:25:5 blend (Figure. 25). Remarkably, HC emissions were significantly reduced (Figure 26).

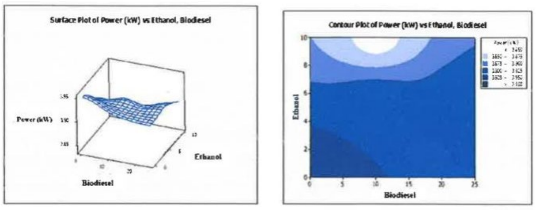

Figure 24. Surface and contour plot of power against ethanol and biodiesel

2.3. Research on performance and emissions of diesel engines using alternative fuel blends.

In most of recent works, a study on the technical characteristics and emissions of a diesel engine using a blend of ethanol with waste cooking palm oil based biodiesel was deployed in [15]. It causes some significant improvements in fuel properties at low temperatures, with reductions in CO and CO_2 emissions compared to diesel (Figure. 29, Figure. 30). Figure. 27 and Figure. 28 shows the B90E10 blend (90% biodiesel, 10% ethanol) improvement in brake thermal performanceand lower NO emissions than diesel. Still, the ignition delay for ethanol-waste cooking oil blends was longer than that of diesel. However, the B90E10 blend is considered suitable for use in diesel engines without requiring engine modifications.

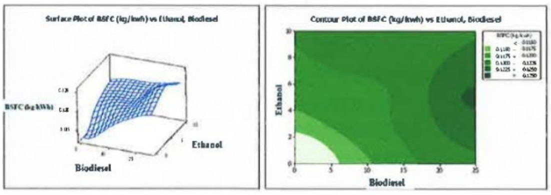

Figure 25. Surface and contour plot of BSFC against ethanol and biodiesel

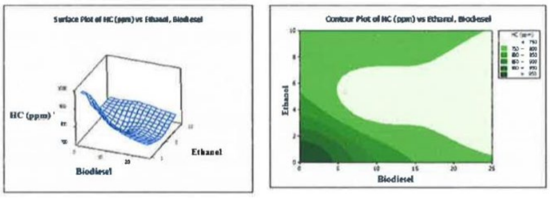

Figure 26. Surface and contour plot of HC emission against ethanol and biodiesel

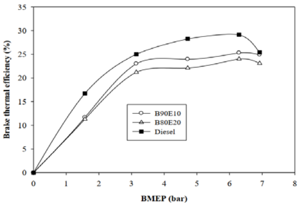

Figure 27. Variation of brake thermal efficiency of biodiesel-ethanol blends with BMEP

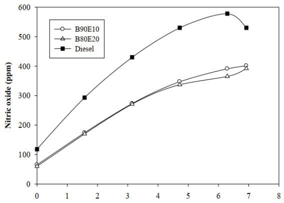

Figure 28. Variation of NO emission of biodieselethanol blends with BMEP

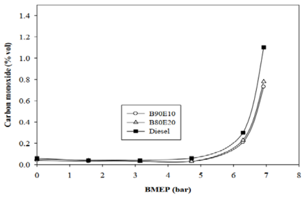

Figure 29. Variation of CO emission of biodieselethanol blends with BMEP

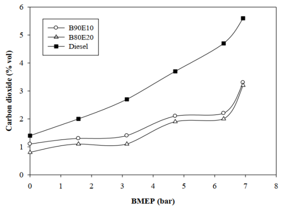

Figure 30. Variation of CO2 emission of biodieselethanol blends with BMEP

In [16], the technical characteristics and emissions of a single-cylinder diesel engine using a diesel-waste cooking oil (WCO)-ethanol blend was examined. These findings indicated that, at an injection pressure of 220 bar, the B20 blend (80% diesel, 20% biodiesel derived from waste cooking oil) achieved maximum thermal efficiency (33.7%), which was 8.3% higher, and a 9.09% reduction in specific fuel consumption compared to diesel. Emissions of HC, CO, and CO2 were also lower than those of diesel. The blends containing ethanol, such as B20E10 (80% diesel, 20% biodiesel from waste cooking oil, 10% ethanol), exhibited 9.7% higher thermal efficiency (Figure 31), 18.18% lower specific fuel consumption (Figure 32), lower HC, and CO2 emissions (Figure 33, Figure 34), but higher NOx emissions compared to diesel.

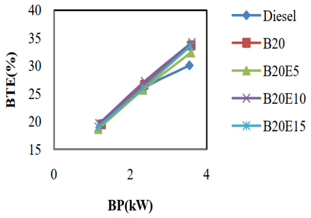

Figure 31. Variation of brake thermal efficiency with brakepower for diesel, WCO and ethanol blends at 220 bar IOP

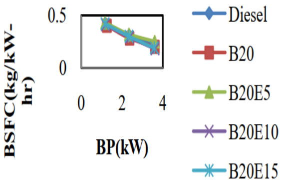

Figure 32. Variation of brake specific fuel consumption with Brake Power for diesel, WCO and ethanol blends at 220 bar IOP

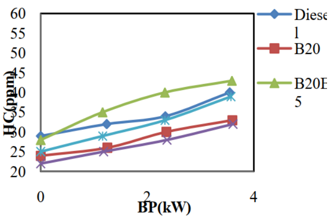

Figure 33. Variation of HC emission with brake power for diesel, WCO and ethanol blends at 220 bar IOP

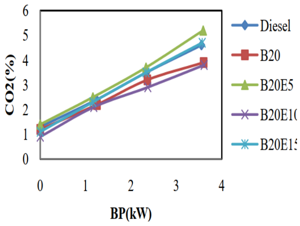

Figure 34. Variation of CO_2 emission with brake power for diesel, WCO and ethanol blends at 220 bar IOP

Similarly, researchers in [17] studied the use of a diesel-waste cooking oil blend as fuel in a four-cylinder, four-stroke diesel engine. The experiments were conducted at engine speeds ranging from 1000 to 4000 RPM, with technical characteristics evaluated at 50% load and emissions measured at 20%, 40%, 60%, 80%, and 100% load. The test fuels included diesel-WCO blends, with fuel properties detailed in Table 6. It is clearly seen that when blending 30% WCO with 70% diesel, the viscosity, calorific value, density, and flash point were comparable to those of diesel. The engine power output and specific fuel consumption were also similar to diesel. Compared to diesel, CO_2 and NO_x emissions were lower (Figure. 35, Figure. 36), while CO emissions were higher (Figure. 37).

Table 6. Properties of blended fuel.

Property	Fuel				
	A	B	C	D	E
Gross HV [kJ/kg]	45609	44712	44126	43485	42949
Viscosity [mPa.s]	3.743	5.042	6.121	6.733	7.628
Specific gravity	0.838	0.844	0.857	0.864	0.870
Pour point [^oC]	8	8	8	9	9
Cloud point [^oC]	15	16	18	18	19

Flash point [ºC]	84.8	89.1	91.4	93.4	98.8

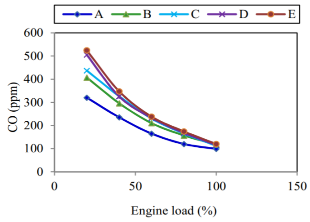

Figure 35. CO$_2$ emission vs engine load for the test fuels

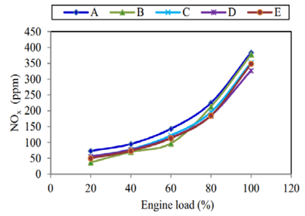

Figure 36. NO$_x$ emission vs engine load for the test fuels

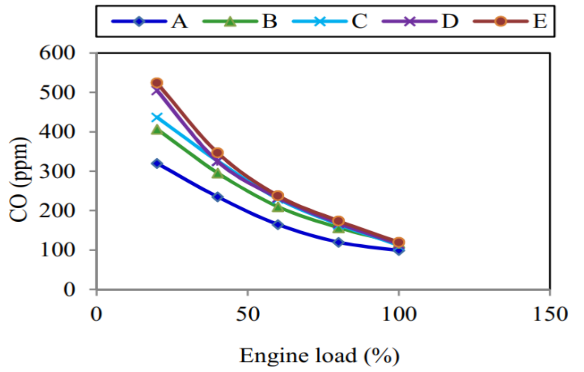

Figure 37. CO emission vs engine load for the test fuels

Furthermore, their efforts investigated the technical characteristics and emissions of a CI engine using Waste Cooking Oil Methyl Ester-Ethanol-Diesel Oil blend [18]. The practical validations were examined on a diesel engine with fuel blends such as B20 (20% biodiesel, 80% diesel), B20E10 (20% biodiesel, 70% diesel, 10% ethanol), and B15E5 (15% biodiesel, 80% diesel, 5% ethanol). It was acknowledged that thermal efficiency increased with engine load, with the B20E10 blend outperforming diesel and other blends (Figure. 38). Specific fuel consumption for B20 decreased with increasing engine load, while blends containing ethanol, such as B20E10 and B15E5, showed an increase in specific fuel consumption (Figure. 39). Compared to other sources, NO$_x$ and CO emissions were reduced in blends containing ethanol (Figure. 40, Figure. 41), while HC emissions increased (Figure. 42).

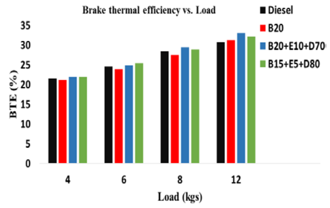

Figure 38. Variation of brake thermal efficiency with load of various fuel blends

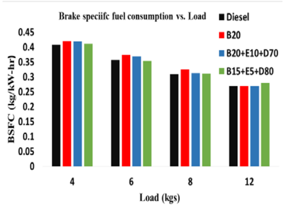

Figure 39. Variation of brake specific fuel consumption with load of various fuel blends

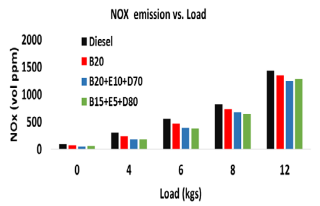

Figure 40. Variation of NO$_x$ with load of various fuel blends

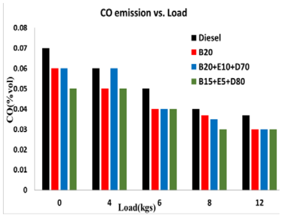

Figure 41. Variation of Carbon monoxide with load of various fuel blends

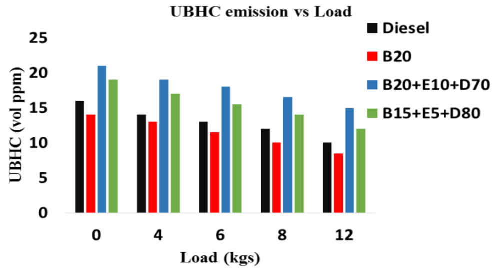

Figure 42. Variation of unburnt hydrocarbons with load of various fuel blends

In [19], the combustion characteristics of a waste oil cooking-butanol/diesel/gasoline blend become target research. The fuel blends used in the study included 90% WCO-10% butanol (90WCO10BL), 80% WCO-20% butanol (80WCO20BL), 70% WCO-30% butanol (70WCO30BL), 90% WCO-10% diesel (90WCO10FD), 80% WCO-20% diesel (80WCO20FD), 70% WCO-30% diesel (70WCO30FD), 90% WCO-10% gasoline (90WCO10G), 80% WCO-20% gasoline (80WCO20G), and 70% WCO-

30% gasoline (70WCO30G). This study found that the viscosity and combustion temperature of waste oil cooking decreased with the addition of additives (Figure 43, Figure 44). The specific fuel consumption of the blends increased, and thermal efficiency decreased by 0.3–8% compared to diesel. Figure 45 shows CO_2 emissions decreased with the increasing ratio of additives, with the 90WCO10BL fuel at 100% load showing CO_2 emissions 3.5% and 4.3% lower than 100FD and 100WCO fuels, respectively. CO and NO_x emissions decreased, with the 90WCO10BL blend showing a 25% greater reduction in NO_x compared to diesel (Figure. 46). Smoke density also decreased significantly, with the 80WCO20BL blend showing a 71% reduction compared to FD (Figure. 47). The peak cylinder pressure was highest for diesel, with the lowest observed in the 90WCO10BL blend (Figure. 48). Heat release rates were highest for diesel and lowest for the 90WCO10BL blend. The combustion duration compared to diesel was reduced by approximately 13% for the 80WCO20BL and WCO blends at 100% load, and by about 8.4% for the 80WCO20BL, 80WCO20FD, and WCO blends at 70% load.

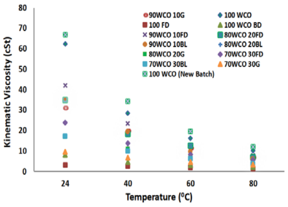

Figure 43. Viscosity values of fuel samples as a function of temperatures

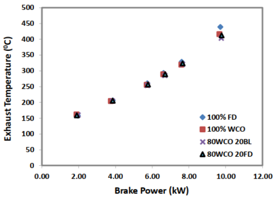

Figure 44. Exhaust gas temperature as a function of additives concentration

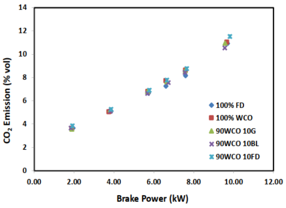

Figure 45. CO_2 gas emission of various fuels

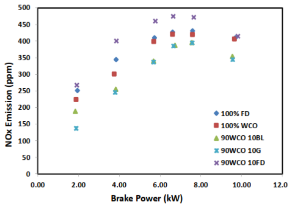

Figure 46. NO_x gas emission of various fuels as a function of additives concentration

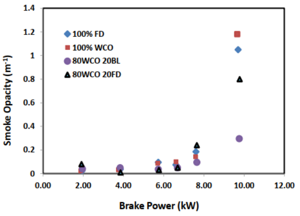

Figure 47. Smoke opacity (m^{-1}) of various fuels as a function of additives concentration

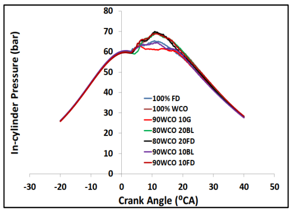

Figure 48. In-cylinder pressure (bar) at 100% load

In the same context, the impact of diesel-ethanol-waste oil cooking and plastics blends on a single-cylinder diesel engine was evaluated [20]. The test blends included BF0 (100% diesel), E20 (20% ethanol, 80% diesel), W20 (20% waste oil cooking, 80% diesel), and P20 (20% waste plastics, 80% diesel). The results of this approach specified that BF0 had higher peak cylinder pressure and greater thermal efficiency compared to E20, P20, and W20, with lower specific fuel consumption than the other blends in the Figure 49 and Figure. 50. NO_x emissions in W20 and P20 at 23.5°C TDC under 100% load were lower by 17.6% and 39.7%, respectively, compared to BF0 (Figure 51). Peak cylinder pressures for E20 (119.6 bar), P20 (86.3 bar), and W20 (106.8 bar) were lower by 2.3%, 41.9%, and 12.8%, respectively, compared to BF0 (122.5 bar). Figure 52 shows smoke density for P20 and W20 was significantly higher than BF0, while E20 showed much lower results.

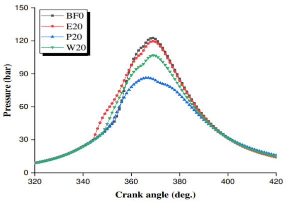

Figure 49 Cylinder pressure with crank angle

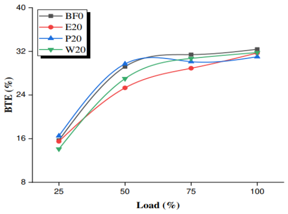

Figure 50. BTE with load

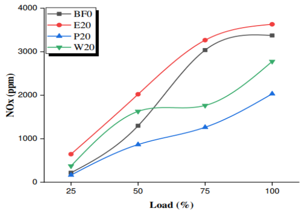

Figure 51. Engine NO$_x$ emission with loads

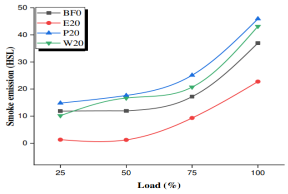

Figure 52. HSL emission with load

Lastly, the technical characteristics and emissions of a single-cylinder diesel engine running at 1300 RPM using a diesel-waste oil cooking blend was explored in [21]. The blends tested comprised D95WCO5 (95% diesel, 5% waste oil cooking), D65WCO20Pe15 (65% diesel, 20% waste oil cooking, 15% n-pentanol), and D60WCO20Pe20 (60% diesel, 20% waste oil cooking, 20% n-pentanol). Those results confirmed that the physical and chemical properties of D95WCO5, DF65WCO20Pe15, and DF60WCO20Pe20 were suitable for use as diesel engine fuels (Table 7). Specific fuel consumption improved by 0.32% for DF95WCO5 and increased by 0.49% and 0.68% for DF65WCO20Pe15 and DF60WCO20Pe20, respectively, compared to diesel (Figure. 53). The thermal efficiency of DF95WCO5, DF65WCO20Pe15, and DF60WCO20Pe20 was 38.7%, 39.2%, and 39.6%, respectively (Figure. 54). Figure 55 shows CO emissions in DF65WCO20Pe15 (0.15%) and DF60WCO20Pe20 (0.14%) decreased, while DF95WCO5 (0.18%) showed an increase compared to diesel. CO$_2$ emissions improved for DF95WCO5, DF65WCO20Pe15, and DF60WCO20Pe20, with values of 0.48%, 0.511%, and 0.518%, respectively (Figure 56). PM emissions tended to decrease when using blends containing WCO.

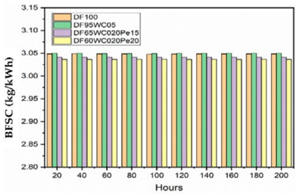

Figure 53. Comparison of BSFC for all test fuels

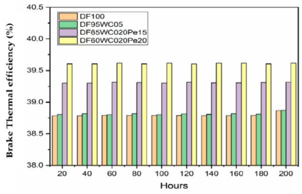

Figure 54. Comparison of BTE for all test fuels.

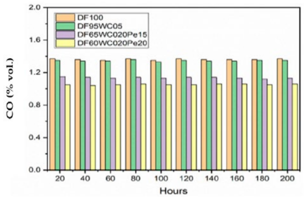

Figure 55. Carbon monoxide emissions versus engine running hours.

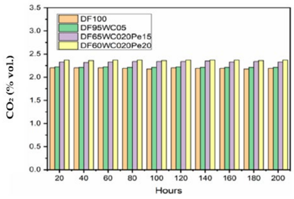

Figure 56. Carbon dioxide emissions versus engine running hours.

2.4. Application and Performance of Biofuel-Diesel Blends on Diesel Engines

In previous section, research [3] investigated the use of Jatropha-diesel-ethanol blends on a two-cylinder diesel engine. The blends studied included MF(E5) with a ratio of 20:75:5 (without surfactant), MF(E5)-LS1 with a ratio of 20:75:5 (low concentration surfactant), and MF(E10)-LS1 with a ratio of 20:70:10 (high concentration surfactant) [3]. The study found that the kinematic viscosity, water content, and higher heating value (HHV) of these blends met biodiesel standards and were close to the properties of diesel (Table 8). Blends with a lower ethanol ratio, such as MF(E5) and MF(E5)-LS1, exhibited engine power, fuel consumption, and exhaust gas temperature similar to diesel, particularly at low engine speeds and moderate engine loads (50%) (Figure 57, Figure 58, Figure 59). Figure 60 and Figure 61 shows CO and CO$_2$ emissions were generally lower, with smoke concentrations significantly reduced compared to diesel, especially for the higher ethanol blend, MF(E10)-LS1 (Figure 62).

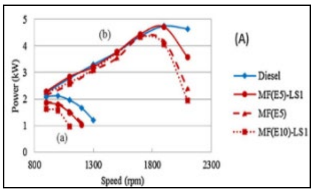

Figure 57. The engine power at a low and medium load with each type of fuel

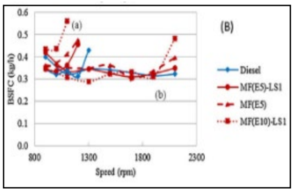

Figure 58. The BSFC of all fuels at a low and medium engine load

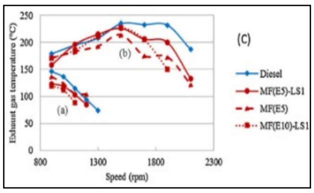

Figure 59. The exhaust gas temperature

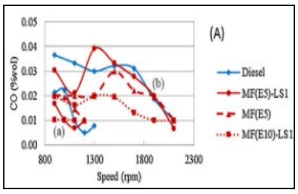

Figure 60. The CO emission

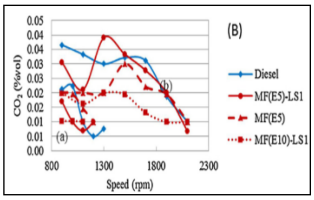

Figure 61. The CO$_2$ emission

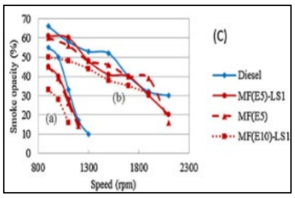

Figure 62. The smoke emission

Table 7. Fuel characterization

Properties	D100	D95-WCO5	D65-WCO15-Pe15	D60-WCO20-Pe20	Test Method
Calorific valve MJ/Kg	42.5	39	40	41.5	ASTM D-240
Viscosity 40 °C Cst	2.28	2.34	1.95	1.14	ASTM D-88
Density g/mL	0.85	0.89	0.84	0.83	ASTM D-854
Flash point °C	78	85	94	98	ASTM D-92
Cetane number	50	53	55.5	56	ASTM D-4737

Table 8. Properties of the original components and MFs.

Properties	Biodiesel standard	JCO	Ethanol	Diesel	MF(E5)	MF(E5)-LS1	MF(E10)-LS1
Optical	Clear	Clear	Clear	Clear	Clear	Clear	Clear
HHV (MJ/kg)	–	39.35±0.07	28.95±0.35	45.60±0.14	43.35±0.07	43.40±0.00	42.45±0.21
Kinematic viscosity at 40°C (cSt)	3.5–5.0	34.62±0.31	1.05±0.01	2.96±0.01	4.55±0.05	4.43±0.04	4.31±0.00
Water content (ppm)	500	929.00±6.08	1873.75±148.00	67.25±4.03	425.43±3.18	430.55±3.89	500.55±0.92

Besides, another studies, i.e. [22] examined the technical characteristics and soot emissions of a diesel engine using diesel-jatropha-butanol fuel blends, including DJ10E5, DJ10E10, DJ10E15, DJ20E5, DJ20E10, DJ20E15, DJ30E5, DJ30E10, and DJ30E15 by volume. Measurements were taken at 2500 rpm and across load conditions from 0% to 100%. The results showed that the DJ10B15 blend had performance comparable to diesel fuel, with increased power and thermal efficiency and reduced fuel consumption. Furthermore (Figure 63, Figure 64, Figure 65), DJ10B15 produced lower soot emissions compared to diesel, while DJ30 had the lowest performance and the highest soot emissions (Figure 66).

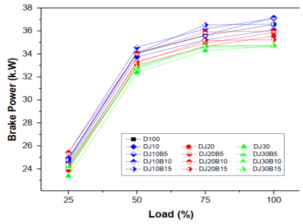

Figure 63. Brake power of diesel engine diesel-jatropha-butanol fuel

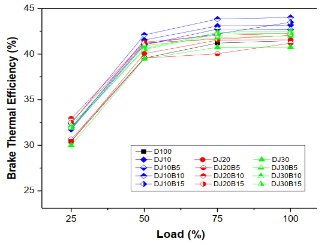

Figure 64. Brake Thermal Efficiency (BTE) of diesel engine diesel-jatropha-butanol fuel

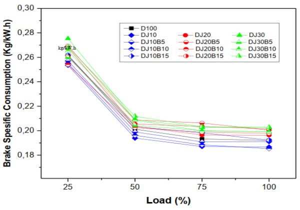

Figure 65. Brake specific fuel consumption (BSFC) of diesel engine diesel-jatropha-butanol fuel

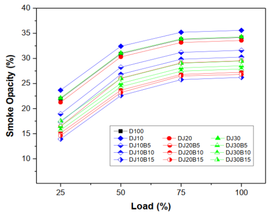

Figure 66. Smoke opacity of diesel engine diesel-jatropha-butanol fuel

In [2], the emission characteristics and combustion process of a diesel engine using diesel-jatropha Curcas fuel blends, including V05, V10, V20, and V50, at an engine speed of 2000 rpm was invented. This study revealed that THC and CO emissions were lower at low loads, but increased to levels comparable to diesel as the engine load increased (Figure 67, Figure 68). Figure 69 and Fugure 70 shows CO_2 emissions and smoke opacity and were higher than diesel, and NO_x levels increased with the higher concentration of vegetable oil in the blend (Figure 71). Under all operating conditions, vegetable oil blends had lower heat release rates and occurred earlier compared to diesel. The peak cylinder pressure of the blends was higher than that of diesel, and the engine operated more smoothly and steadily.

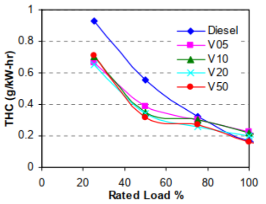

Figure 67. THC emissions from different jatropha oil blends

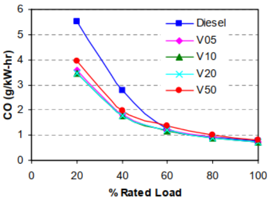

Figure 68. Carbon monoxide emissions from different Jatropha oil blends

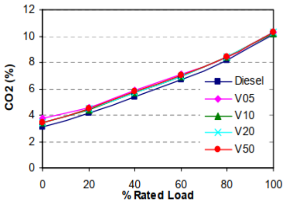

Figure 69. CO_2 emissions from different Jatropha oil blends

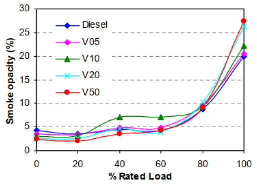

Figure 70. Smoke opacity from different Jatropha oil blends

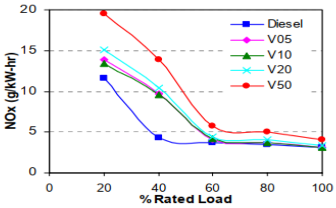

Figure 71. NO_x emission from different Jatropha oil blends

Also, scholars in [23] focused on the production of jatropha oil and its application as a fuel for diesel engines. The jatropha-diesel blends studied included J5 (5% jatropha, 95% diesel), J10 (10% jatropha, 90% diesel), J20 (20% jatropha, 80% diesel), J50 (50% jatropha, 50% diesel), and J80 (80% jatropha, 20% diesel) by volume. The results indicated that blending jatropha up to 20% did not significantly reduce thermal efficiency. J5 provided better thermal efficiency and fuel consumption compared to diesel (Figure. 72, Figure. 73). CO_2 emissions of the blends were lower than diesel at loads below 50%, but at high loads above 50%, the J50 blend emitted 20% more CO_2 than diesel (Figure. 74). CO emissions from the blends were significantly higher than those from diesel across all load conditions (Figure. 75).

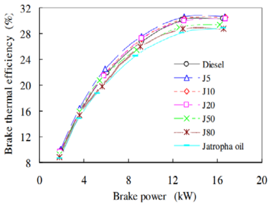

Figure 72. Brake thermal efficiency of the engine with various fuels

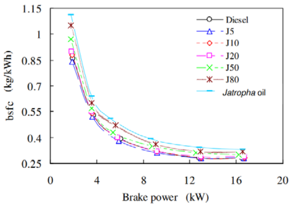

Figure 73. Brake specific fuel consumption of the engine with various fuels

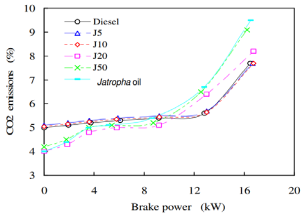

Figure 74. CO_2 emissions with various fuels

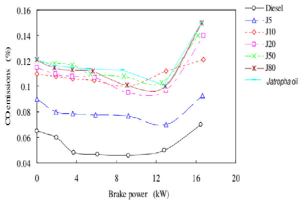

Figure 75. CO emissions with various fuels

A fuel blend consisting of 90% jatropha oil and 10% ethanol on a diesel engine was noticed in [4]. The study showed that this blend had better thermal efficiency and lower fuel consumption compared to diesel (Figure 76, Figure 77). Additionally, particulate emissions, HC, and CO levels were lower than those of diesel (Figure. 78, Figure. 79). In [24], the technical characteristics and emissions of a single-cylinder diesel engine using biodiesel-diesel-ethanol blends (with biodiesel sourced from jatropha) has been validated. The blends included B0D95E5, B0D90E10, B15D70E15, and B20D60E20, with fuel properties listed in Table 9. The engine operated at 1500 rpm with varying loads. The study found that blends with lower ethanol ratios (5%-10%) showed stability after adding emulsifiers (0.7% and 1%), while blends with higher ethanol ratios (15%-20%) tended to phase-separate quickly and required biodiesel as a surfactant to prevent phase separation. Figure 80 and Figure 81 shows thermal efficiency of the ethanol-biodiesel-diesel blends was significantly lower than that of diesel, with fuel consumption increasing with higher oxygen content in the blend. Emissions of B0D90E10 and B0D95E5 were reduced by 20% to 40%, HC increased compared to diesel, and CO decreased significantly, especially for the B0D90E10 blend, which showed up to a 40% reduction in CO at low and medium loads (Figure. 82). NOx emissions were higher for diesel compared to the B0D90E10 blend at low, medium, and high loads by 50%, 84%, and 34%, respectively (Figure. 83).

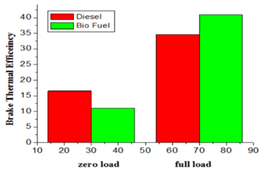

Figure 76. Brake Thermal Efficiency

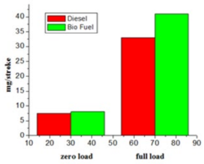

Figure 77. Specific Fuel Consumption

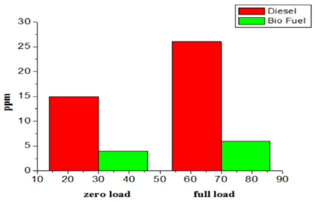

Figure 78. CO Comparison

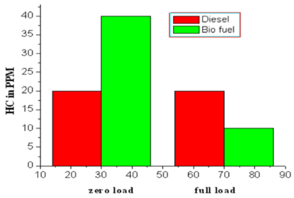

Figure 79. Unburnt Hydro Carbon

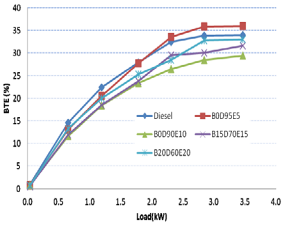

Figure 80. Variation of brake thermal efficiency with load

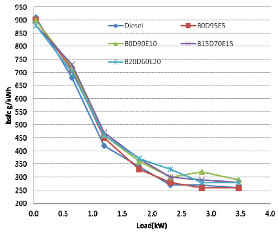

Figure 81. Variation of bsfc with load

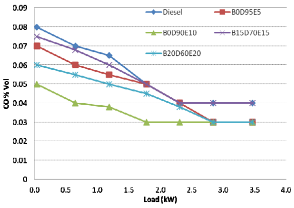

Figure 82. Variation of CO emission with load

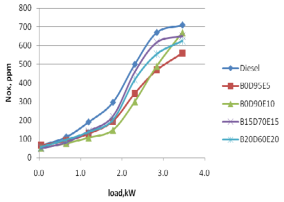

Figure 83. Variation of NOx emissions with load

Dahab Mohamed Hassan and colleagues explored the impact of diesel with biofuel (jatropha oil and ethanol) blends in a certain percentage on the technical characteristics of an agricultural diesel engine [25]. The blends studied included T1 (Pure diesel) T2 (10% Bio-diesel Jatropha oil with 90% pure diesel), T3 (14% bio-fuel Jatropha oil with 84% pure diesel), T4 (10%bio-ethanol with 90% pure diesel), T5 (14% bio-ethanol with pure diesel), T6 (10% bio diesel, 10% bio-ethanol with 80% of pure diesel), and T7 (14% bio diesel, 14% bio-ethanol with 72% of pure diesel). The results showed that diesel (T1) provided the highest engine power at 6.81 kW, while T3 had the lowest power output at 5.32 kW (Figure. 84). Ethanol blends provided 19.7% higher power compared to jatropha blends, and ethanol-containing blends had the highest fuel consumption values. CO and NO_2 emissions were lowest for T3, and T2, T5, and T6 had the lowest SO_2 emissions at 0 ppm (Table 10).

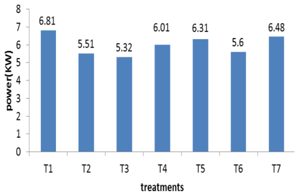

Figure 84. Effect of fuel type on power (KW)

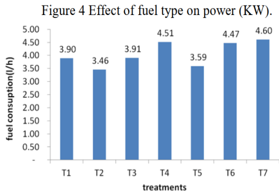

Figure 85. Effect of fuel types on fuel consumption (l/h)

In the other exertions, investigators studied the performance and emissions of a diesel engine fueled with Jatropha biodiesel oil and its blends [26]. Experiments were conducted at no load, 20%, 40%, 60%, 80%, and 100% load conditions. The different properties of Jatropha oil after transestrification were within acceptable limits of standards as set by many countries. The brake thermal efficiency of Jatropha methyl ester and its blends with diesel were lower than diesel and brake specific energy consumption was found to be higher (Figure. 86 and Figure. 87). However, Figure. 88, Figure. 89 and Figure. 90 shows HC, CO and CO_2 and smoke were found to be lower with Jatropha biodiesel fuel. NO_x emissions on Jatropha biodiesel and its blend were higher than Diesel (Figure. 91).

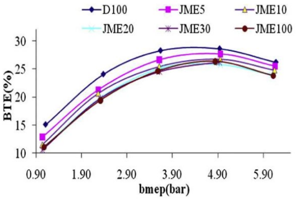

Figure 86. Variation of brake thermal efficiency with brake mean effective pressure

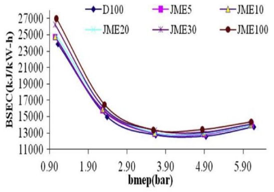

Figure 87. Variation of brake specific energy consumption with brake mean effective pressure

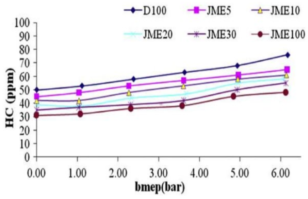

Figure 88. Variation of hydrocarbon with brake mean effective pressure

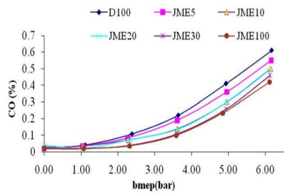

Figure 89. Variation of carbon mono oxide with brake mean effective pressure

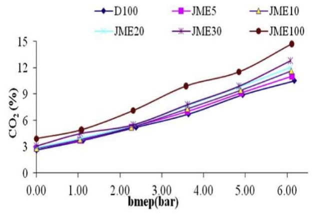

Figure 90. Variation of carbondioxide with brake mean effective pressure

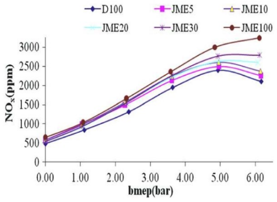

Figure 91. Variation of NO_x with brake mean effective pressure

Table 9. Physico-chemical analysis of fuels

Properties	Diesel	Biodiesel	Ethanol	B0D95E5	B0D90E10	B15D70E15	B20D60E20
Diesel Conten (%vol)	100	0	0	95	90	70	60
Biodiesel Content (%vol)	0	100	0	0	0	15	20
Ethanol Content(%vol)	0	0	100	5	10	15	20
Density at 15^0 C (Kg/m^3)	843	890	794.85	836	833	838	838
Viscosity at 40^0C (cP)	2.48	4.45	1.86	2.24	2.47	2.57	2.81
Flash Point (^{0}C)	50	145	13.8	17.3	16.5	15.0	14.2
Calorific Value (kJ/kg)	45000	35400	26400	43580	43053	41263	38840

Table 10. Effect of treatments on gases measured (ppm)

Fuel type	T1	T2	T3	T4	T5	T6	T7
CO	243	274	200	239	249	271	255
NO_2	6	7	0	3	4	4	3
SO_2	1	0	3	1	0	0	3
NO	71	96	97	97	109	96	92

Table 11. Property of the fuel blends.

Property	Diesel	J20	J15B5	J10B10	J15D5	J10D10	ASTM D7467
Kinematic viscosity at 40ºC	3.46	3.6	3.29	3.24	3.22	3.25	1.9-4.1
Density at 40ºC	833	837	834	831	840	823	n.s.
Lower heating value Mj/kg	44.66	43.69	43.40	43.15	43.39	43.10	n.s.
Flash point ºC	69.5	96.5	87.5	79.5	83.5	71.5	52 (min)

In the other exertions, investigators studied the performance and emissions of a diesel engine fueled with Jatropha biodiesel oil and its blends [26]. Experiments were conducted at no load, 20%, 40%, 60%, 80%, and 100% load conditions. The different properties of Jatropha oil after transestrification were within acceptable limits of standards as set by many countries. The brake thermal efficiency of Jatropha methyl ester and its blends with diesel were lower than diesel and brake specific energy consumption was found to be higher (Figure. 86 and Figure. 87). However, Figure. 88, Figure. 89 and Figure. 90 shows HC, CO and CO_2 and smoke were found to be lower with Jatropha biodiesel fuel. NO_x emissions on Jatropha biodiesel and its blend were higher than Diesel (Figure. 91).

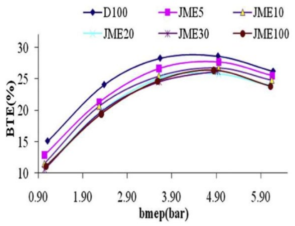

Figure 86. Variation of brake thermal efficiency with brake mean effective pressure

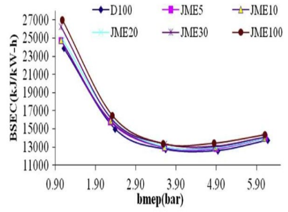

Figure 87. Variation of brake specific energy consumption with brake mean effective pressure

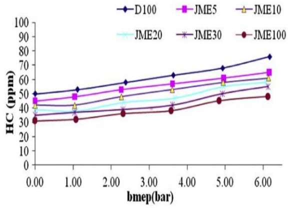

Figure 88. Variation of hydrocarbon with brake mean effective pressure

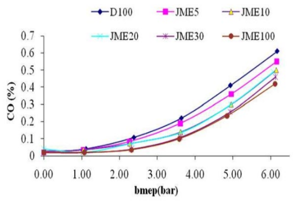

Figure 89. Variation of carbon mono oxide with brake mean effective pressure

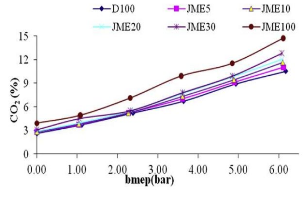

Figure 90. Variation of carbondioxide with brake mean effective pressure

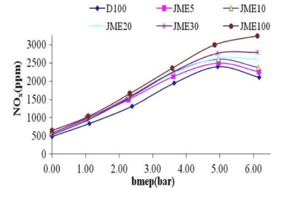

Figure 91. Variation of NO_x with brake mean effective pressure

To test various fuel blends, including diesel, J10 (20% jatropha biodiesel, 80% diesel), J15B5 (15% jatropha biodiesel, 5% n-butanol, 80% diesel), J10B10 (10% jatropha biodiesel, 10% n-butanol, 80% diesel), J15D5 (15% jatropha biodiesel, 5% DEE, 80% diesel), and J10D10 (10% jatropha biodiesel, 10% DEE, 80% diesel) by volume, engine tests were conducted at speeds ranging from 1000 rpm to 3000 rpm with a torque of 80 Nm [27]. The results showed that the addition of n-butanol and DEE reduced the density and viscosity of the jatropha-diesel blend (Table 11). J20 had higher peak cylinder pressure due to its higher cetane number, but the addition of n-butanol and DEE reduced peak pressure and latent heat of vaporization (Figure 92, Figure 93). Fuel consumption for J20 was 5.4% higher than diesel, while J10B10 and J10D10 showed reductions of 3.9% and 6.8%, respectively (Figure 94). Figure 95 shows NO emissions for J20 were approximately 8.2% higher than diesel, with J15B5, J15D5, and J10D10 showing higher NO levels compared to J20. CO emissions for J20 were reduced by approximately 27.5% compared to diesel, with J15B5 and J10B10 achieving even better results with CO reductions of 23% and 30.7%, respectively (Figure 96). Smoke opacity for J20 was approximately 6.2% lower than diesel, and the addition of 10% n-butanol and DEE reduced smoke opacity by an average of 27% and 38.5% compared to J20 (Figure 97). HC emissions for J20 were reduced by an average of 28% compared to diesel (Figure 98).

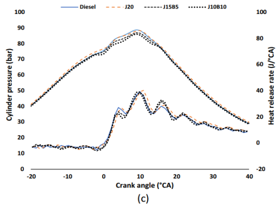

Figure 92. Cylinder pressure and heat release rate vs crank angle diagram for n-butanol blends at 3000 rpm

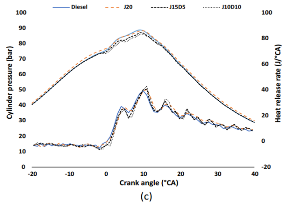

Figure 93. Cylinder pressure and heat release rate vs crank angle diagram for DEE blends at 3000 rpm.

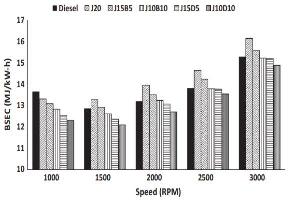

Figure 94. BSEC vs speed diagram for jatropha biodiesel and its modified blends at 80 Nm torque.

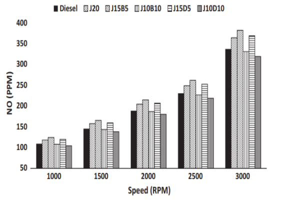

Figure 95. NO emission vs speed diagram for jatropha biodiesel and its modified blends at 80 Nm torque.

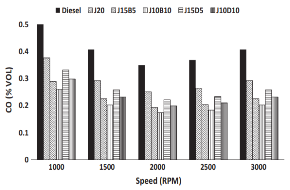

Figure 96. CO emission vs speed diagram for jatropha biodiesel and its modified blends at 80 Nm torque.

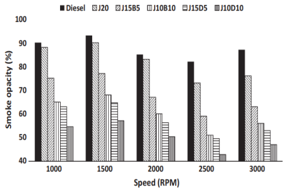

Figure 97. Smoke opacity vs speed diagram for jatropha biodiesel and its modified blends at 80 Nm torque.

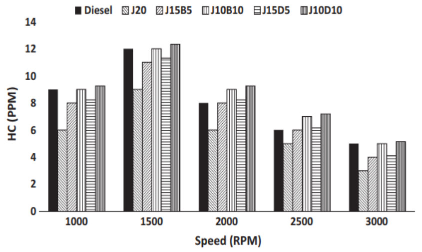

Figure 98. HC emission vs speed diagram for jatropha biodiesel and its modified blends at 80 Nm torque

For more advanced specifications, some tested fuel blends D90J7.5E2.5 (90% diesel, 7.5% jatropha biodiesel, and 2.5% ethanol), D95J3.75E1.25 (95% diesel, 3.75% jatropha biodiesel, and 1.25% ethanol), and D98J1.5E0.5 (98% diesel, 1.5% jatropha biodiesel, and 0.5% ethanol) on a single-cylinder diesel engine with electronic fuel injection was completed [28]. The experimental output showed a significant improvement in performance with three blends and when the percentage of blend increases, performance also slightly increases. On the other hand, when the engine is running with biodiesel and its blend, emission such as HC, CO_2, and NO_x emissions were reduced with increasing of biodiesel blend (Figure. 99, Figure. 100, Figure. 101) whereas the CO emission was reduced with decreasing of the biodiesel blend (Figure. 102).

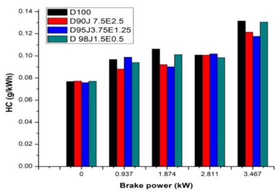

Figure 99. HC emission

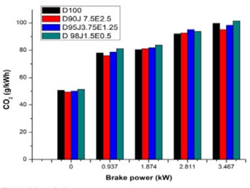

Figure 100. CO_2 emission

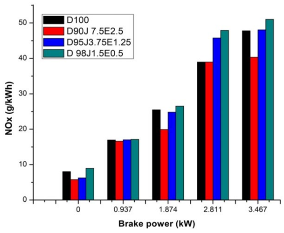

Figure 101. NO_x emission

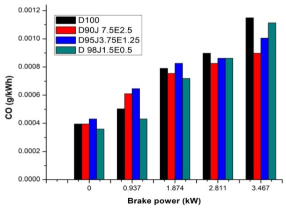

Figure 102. CO emission

Finally, biodiesel-diesel blends including B20 (20% jatropha, 80% diesel), B40 (40% jatropha, 60% diesel), and B60 (60% jatropha, 40% diesel) on a single-cylinder diesel engine was announced in [29]. The results Figure 103, Figure 104 and Figure 105 showed that CO, NO_x, and CO_2 emissions were significantly lower than those of diesel across the entire load range (0 to 75%). The reduction in emissions was attributed to the higher oxygen content in the blends, which improved combustion efficiency. Engine performance increased by 5.49% and 3.84% for B20 and B40, respectively, while fuel consumption and thermal efficiency increased slightly by 3.8% and 5.5% compared to diesel.

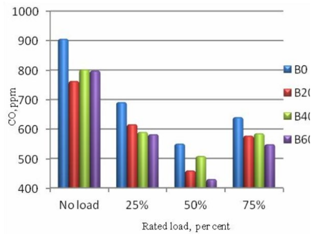

Figure 103. Effect of load on CO emission for HSD and different blends of biodiesel

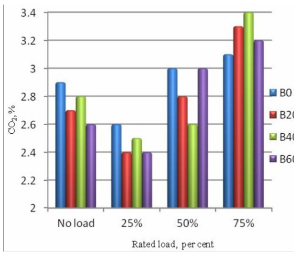

Figure 104. Effect of load on CO_2 for HSD and different blends of biodiesel

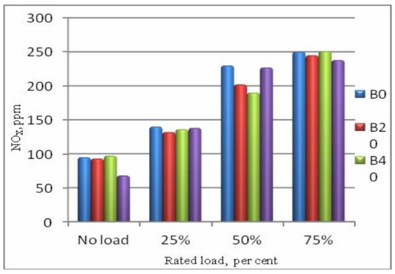

Figure 105. Effect of load on NO_x for HSD and different blends of biodiesel

Finally, biodiesel-diesel blends including B20 (20% jatropha, 80% diesel), B40 (40% jatropha, 60% diesel), and B60 (60% jatropha, 40% diesel) on a single-cylinder diesel engine was announced in [29]. The results Figure 103, Figure 104 and Figure 105 showed that CO, NO_x, and CO_2 emissions were significantly lower than those of diesel across the entire load range (0 to 75%). The reduction in

emissions was attributed to the higher oxygen content in the blends, which improved combustion efficiency. Engine performance increased by 5.49% and 3.84% for B20 and B40, respectively, while fuel consumption and thermal efficiency increased slightly by 3.8% and 5.5% compared to diesel.

3. Conclusions

In this paper, the impact of various alternative fuels used in blends on the performance of diesel engines is discussed:

- The significance of using alternative biofuels to meet the demand for energy sustainability by enhancing the use of renewable fuels, thereby reducing concerns about the depletion of fossil fuel resources.
- Analysis indicates that vegetable oils and ethanol are high-potential biofuels for replacing traditional diesel. However, due to the high viscosity and high flash point of vegetable oils, and the low cetane number, viscosity, and calorific value of ethanol—which reduces lubricating ability and increases fuel leakage—these two fuels cannot be used independently as diesel engine fuels. The proposed solution to improve the limitations of the fuel properties of vegetable oils and ethanol is to blend diesel-ethanol-vegetable oil.
- The analysis includes the potential use of vegetable oils as diesel engine fuels, particularly used cooking oil and jatropha oil. These oils are cost-effective to produce and are not used for food, meeting the fuel property requirements when blended with diesel-ethanol for use as an alternative diesel engine fuel.
- Using a diesel-ethanol-vegetable oil blend in diesel engines improves engine performance and has the potential to reduce emissions of NOx, HC, CO, etc. Additionally, the blend has similar properties such as viscosity, density, and flash point to diesel, allowing it to be used in diesel engines without the need for modifications to the engine structure.

The research on the application of diesel-ethanol-vegetable oil blended fuel in diesel engines has the potential to reduce the negative environmental impacts of emissions and plays an important role in finding alternative fuel sources to mineral diesel in the future.

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