Benha Journal of Applied Sciences (BJAS) **print: ISSN 2356–9751**
Vol. (10) Issue (7) (2025), (97- 105) **online: ISSN 2356–976x**
https://bjas.journals.ekb.eg/
engineering sciences

Biodiesel production from Castor oil via transesterification and its combustion features blended with diesel in a diesel engine

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Abstract

Population growth and lifestyle changes have increased energy demand, while the availability of fossil fuels has decreased. This has led to the development of alternative energy sources, such as biodiesel fuel. Castor biodiesel is capable of being decomposed by biological processes, harmless, beneficial, and replenishable. The transesterification process can be utilized to generate biodiesel from castor oil, yield of production was 92% for the Transesterification. Mixing biodiesel castor with diesel positively affects its physical and chemical properties and also the running, exhaust pollutants, and combustion features, for performance BTE (Brake thermal efficiency) and BSFC (Brake specific fuel consumption). The biodiesel blend has higher BTE and lower BSFC than D100(pure diesel); it is D80TR20(80 vol% pure diesel + 20 vol% transesterification biodiesel), which gives an enhancement of 14.69% and 10%, respectively. Emissions like (CO, NOx, and soot) of biodiesel are better than those of D100; the D80TR20 emits lower emissions than the D100 by factors of 57%, 25%, and 28%, respectively. Also, the EGT(Exhaust gas temperature) of biodiesel is lower than D100, EGT of D80TR20 is lower than D100 than with a percentage equal to 9.76%, all of these values are with respect to D100 and at a load of 100%. It is recommended that the biodiesel blend is better than diesel and may be increasing of its ratio slightly, improving performance and emissions features more and more.

Keywords: *Biodiesel castor; Biodiesel production; Transesterification, Engine performance; Emissions Aspects.*

1. Introduction

Traditional petroleum fuel refers to finite resources, specifically fossil fuels. By the year 2050, the transportation field will continue to predominate fuel requirements [1]. The predominant utilization of diesel surpassed that of others, as demonstrated in Fig. 1 [2]. Identifying substitute energy is crucial, given the annual decline in the availability of fossil fuels [1].

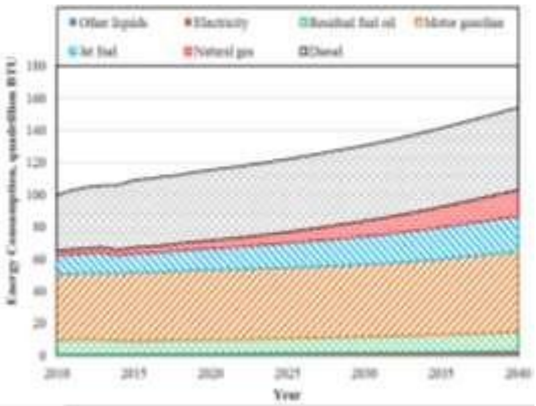


Fig. 1. Global energy utilization within the transport domain [2].

Biodiesel, an alternative energy source for diesel engines, can be extracted from plant and animal lipids. Organic oils can be classified as usable or non-palatable and may be utilized for the production of biodiesel. the growth of people and their demand increases the requirement for palatable oil; so non-palatable oils represent the optimal choice for the production of biodiesel [3].

Castor oil is a non-palatable oil suitable for biodiesel production. The comparative advantage of castor lies in its significantly shorter growing period compared to other non-palatable oils; its seeds have a range of 50% oil, predominantly consisting of triglycerides, chiefly ricinolein [4]. The FA(Fatty acids) of the castor oil gives an unusual chemical feature; it is a triglyceride containing an 18-carbon hydroxylated FA with one double bond [5]. Castor oil has properties that make it a suitable fuel for the production of biodiesel. It is a nonvolatile oil with an unpleasant flavor, making it unsuitable for eating but good for the industrial field. Its fatty acid composition is particularly beneficial, boasting high solubility in alcohols due to the hydroxyl group, and it delivers a comparatively high calorific value of over 40 MJ/kg. Additionally, it features a high cetane number, low phosphorus content, and reduced carbon residue, all of which increase its combustion performance. However, castor oil also has severe constraints that prohibit its direct utilization in diesel engines. Its high viscosity impacts fuel injection, while the increased water content might add to corrosion and filtering difficulties. Furthermore, its considerable compressibility poses further technological difficulties during engine operation [6] .

Castor biodiesel is composed of monoalkyl esters derived from the interaction of organic fatty acid (FA) esters with alcohols, such as ethanol or methanol, under specific conditions. The type and the factor ratio of FA in the source of oil that is used in the extraction of biodiesel are more important, and also the type of organic oil as raw oil, as it displays the grade of the produced fuel derived from biodiesel. There are many types of processes used to produce biodiesel; the most common way is the transesterification, which is used in this work to produce biodiesel from castor.

The transesterification method is the predominant technique for biodiesel production, which involves the transformation of esters into other esters through interchange of alkoxide moieties, wherein the oil undergoes esterification with lower alcohols. (such as methanol or ethanol) at the existence of catalysts (acidic, essential catalysts, and enzymes), with alkalis (NaOH or KOH) employed as catalysts. That extraction method involves heating the source oil to the boiling temperature of water for a few minutes to extract the water from the oil. Subsequently, the oil is combined with a mixture of alcohol and alkali, and the reaction proceeds for a specified duration and temperature, yielding glycerin and FA esters as the primary products. Glycerin is then separated from the output mixture, and the FA esters are washed to obtain the needed output (biodiesel) [7].

There are different studies for the manufacturing of castor biodiesel via transesterification, and also studies regarding the effect of adding the biodiesel to diesel with different ratios, besides utilizing more additives to boost the performance and the combustion characteristics, like the following. **Attia et al,** utilized Castor biodiesel with a viscosity (usually surpassing 150 cSt at 40 °C) that is several times superior to the viscosity of most oils used for biodiesel synthesis (ranging from 15 to 20 cSt). The materials used in the process of biodiesel production from Egyptian castor oil are raw Castor oil, components used to generate the biodiesel in this article, methanol, and KOH as a catalyst. The instruments used in the process include glasses serving, a heater, a Sensitive scale, Glass beakers, a Magnetic stirrer, a Rotor stator, Progressive cylinders, and bottles for storing prepared solutions. Ratio of alcohol was 6:1, KOH 2% wt./wt, stirring for 45 minutes [5].

Silva et al. stated the Conditions for manufacture process: temperature of reaction in range of (30 to 80 C); catalyst was in ratio between 0.5%wt to 1.5%wt; ethanol: raw oil molar ratio was in ratio range of 6:1 to 20:1 and process period was 30 min. the optimum condition was, the yaild of biodiesel was of 99%wt acquired at 30 C, 1 %wt of NaOH, with stirrer mechanical, alcohol: raw oil molar ratio of 16:1 and at a time of reaction equal 30 min [8].

Attia et al. studied the castor biodiesel produced through the transesterification process, using diesel as the base fuel. The biodiesel was blended with diesel at ratios of 10, 20, and 30%, representing the percentage of biodiesel castor in the blend. By burning this blend in a diesel single-cylinder engine, it was found that B10 gave optimal mechanical operation and unremarkable efficiency. CO and HC were at the lowest level for B10, B30 emitted the lowest level of opacity, and B20 was recommended to replace D100 [9].

Attia et al. examined castor biodiesel derived from the transesterification process, utilizing diesel as the primary fuel. The biodiesel was mixed with diesel in proportions of 10%, 20%, 30%, and 40%, representing the percentage of castor biodiesel in the mixture. By combusting this mixture in a diesel single-cylinder engine, examining that maximum increase in BSFC(Brake specific fuel consumption) was 8% for B30, only 1% increase in BTE(Brake thermal efficiency) for B20, HC, CO and NOx reducing by 40, 17 and 0.05% for B10, CO2 reducing by 7.5% for B20, B20 was the recommended ratio [5].

Pinzi et al. reviewed castor biodiesel produced by the transesterification process, employing diesel as the principal fuel. The biodiesel was blended with diesel in quantities of 10%, 20%, 30%, and 40%, indicating the percentage of castor biodiesel in the mixture. By igniting this combination in a diesel single-cylinder engine, it was found that B30 was the best for energy utilization, fuel consumption, and BTE was the best for B20. HC, CO, NOx, and PM were the lowest for B10. The minimum opacity was observed for B30, and B20 was the recommended ratio [10].

In this study, production techniques for castor biodiesel were utilized rather than a single one to leverage the advantages of each. A previous study indicates that the optimal environment for combustion was centered around a ratio of 20%. In this study, castor biodiesel was combusted alongside diesel to demonstrate the differences.

2. Castor biodiesel preparation using transesterification.

This chapter describes the test fuel preparation and covers the preparation procedures for castor biodiesel production, including the transesterification reaction. The sample of produced biodiesel is then evaluated by determining its physical and chemical characteristics according to standard test methods and compared. The optimum sample is selected.

2.1 Raw oil characteristics.

Biodiesel may be produced from castor oil, and its properties are listed in Table 1.

Table 1 Properties of the raw castor oil [2].

Fuel Property	Value
Density at 20°C, kg/m^3	964
Viscosity at 40°C, cSt	246
Flash Point °C	220
Pour Point °C	-78
Cloud Point °C	-75
Molecular weight, kg/kmol	298
Higher heating value, MJ/kg	41.3

According to the concentration of FFA, the first step in biodiesel production is to choose between a single-step and a two-step preparation method. As FFA <3%, one-step transesterification is sufficient for our raw oil to be transformed into biodiesel.

2.2 Transesterification procedures.

Castor oil is refined by removing impurities and solids, then heated to 110 °C for 10 minutes to remove moisture that could cause saponification [11]. Now that the oil has been refined, it can be trans-esterified by a single-step process. The alcohol used in our study is methanol (99.9 %), and KOH serves as a catalyst [12], Methanol is utilized as an alcohol. Based on reviewing previous studies and trying and failing, it took a long time to separate the glycerin. At the right time, a new step was added through experimentation. This step involves heating the mixture after stirring it to 85 degrees Celsius, then leaving it to separate, which actually occurred. The conditions of the transesterification reaction are presented in the current work and are listed in Table 2.

Table 2 Variables of the transesterification process.

Alcohol	Molar ratio	Catalyst	Mixing technique	Reaction temperature and time
Methanol	10:1	KOH 1% wt.	Mechanical mixer	63℃, 3 hours

The following steps of generating castor biodiesel were :

1. A digital scale was used to assess the weight of one liter of castor oil, the typical weight was 964 grams.
2. The oil was dried by heating it to 110°C for 10 minutes, then allowing it to cool to 63°C.
3. The KOH (KOH + methanol) solution is prepared by adding 9.64 grams of KOH (1% wt. of raw oil) to 285 mL of methanol (methanol-to-oil molar ratio is 10:1), and subsequently homogenizing them thoroughly with a magnetic stirrer for 5 minutes.
4. The methoxide solution is added to a beaker containing oil, and the mixture is maintained at 63℃ while the mechanical stirrer is set to 12,000 r.p.m. for 3 hours.
5. The biodiesel and glycerol do not separate until the mixture is heated to 85℃.
6. The mixture is poured into the separating funnel and left to sit for 1 day. The lower layer is the glycerol that is removed, while the upper layer is the wanted biodiesel. Washing the upper layer with warm water numerous times to eliminate any remaining glycerin and soap until clear water is observable.
7. The biodiesel is heated to about 110℃ for 10 minutes to eliminate any remaining water and acquire the ultimate castor biodiesel product.

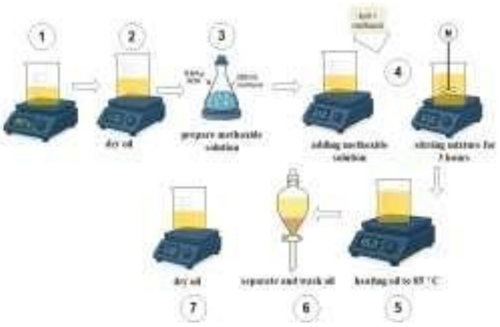


Fig. 2. Procedures for producing castor biodiesel through transesterification.

- **Investigation of the produced biodiesel**

The prepared biodiesel is evaluated based on its physical and chemical characteristics. Additionally, the product yield is calculated as the ratio of the mass of biodiesel produced to the mass of the raw oil, using the following equation [13] :

$$\eta_{conv} = \frac{weight\ of\ biodiesel\ produced\ (g)}{weight\ of\ oil\ used\ (g)} \quad (1)$$

The yield of the biodiesel from transesterification was about 92%.

Table 3 Diesel and castor oil biodiesel properties.

Property	**Test Method**	**Diesel**	**Castor biodiesel (trans.)**	**Required specs. At ASTM D6751 (No. 2-B)**
Density at 20°C, kg/m3	ASTM D-1298	827.7	919.4	860□ 900
Viscosity at 40°C, cSt	ASTM D-445	2.72	10.32	1.9□ 6
Flash Point °C	ASTM D-93	56	146	130
Lower heating value, MJ/kg	ASTM D-240	42.49	37.5	-
Molecular weight,	-	191	271	-
Cetane number	ASTM D613	52	60.2	47
Elemental analysis, % by mass:				
Carbon	EUROVECTOR EA3000 Element Analyzer	86.21	73.35	-
Hydrogen		13.47	12.027	-
Sulfur		Nil	Nil	-
Oxygen		Nil	14.296	-
Nitrogen		0.113	0.127	-

Castor biodiesel has a high viscosity, especially for transesterification biodiesel, also high density in comparison to diesel, and a lower heating value. These values were evaluated by specialists as shown in Table 4, to git good performance and combustion, it must be taken into consider the fuel atomization and spray formation. Viscosity, surface tension, and density directly affect the spray generation process after fuel injection. The high viscosity mitigates the aerodynamic disturbances on the liquid jet's surface when it is fed through the nozzle, so postponing its breakup. An elevated surface tension coefficient affects the cohesive force, lowering the viscosity and density more effectively than achieving good combustion, according to the improved spray characteristics and fuel atomization.

Table 4 Properties of castor biodiesel.

Properties	Transesterification biodiesel
Lower heating value, MJ/kg	37.466
viscosity at 40°C, cSt	10.320
Density at 20°C, kg/m^3	919.4

3. Test rig and procedures

This section delineates the experimental setup and testing methodologies. The initial subsection depicts the elements of the test rig. The second subsection discusses the preparation of the tested fuels and their physical and chemical properties. The third and fourth subsections outline the testing methodologies and measurement techniques.

3.1. Experimental setup

The present setup uses an engine that has the following specifications, as shown in Table 5:

Table 5. Specifications of the engine used in the experiment.

Model	DEUTZ F1L511
Quantity of cylinders	One cylinder
System of cooling	Cooled with air
Power rated	5.7 KW
Tested speed	25 RPS

Its power is measured by a (MEZ-BURNO, 10.5 kW) DC generator connected to the engine by a flexible connection. As it transfers the mechanical power to electrical power, consuming this electrical power by water electric heaters placed in a tank, measuring the current and the voltage, and estimating the power. A variac regulates the alternating current voltage from the power supply. A rectifier circuit transforms the incoming voltage into a direct current excitation voltage. The fluctuation of the generator excitation field signifies a changing engine load at a specific engine speed, as the generator is directly connected to the engine shaft. To estimate the operation features of the engine and the exhaust gases that come out of its exhaust, some accessories will be linked to this system, such as :

Table 6 Measuring instruments specifications.

Device Model	Accuracy	Measuring Range	Output Signal	Power Supply
Kistler 6061B Piezoelectric Sensor	≤±0.5% FSO	0–250 bar	Charge Output	N/A
Kistler 5018A Charge Amplifier	<±2% (for FS <10 pC)	±2 to ±2,200,000 pC	Voltage	30 V
LM12-3004NA Proximity Sensor	Not specified	0–4 mm	NPN/NO	10–30 VDC
NI PCI-6251 DAQ Card	±0.02% to ±0.2% (typical)	±0.1 V to ±10 V	Digital	PCI Bus
Type K Thermocouple	±2.2°C or ±0.75% (Class 2)	–200°C to +1260°C	Millivolt	N/A
Setra 239 Pressure Transducer	±0.14% FS	0 to 70 kPa	1–5 V / 4–20 mA	24 VDC
DS-303 Digital Stroboscope	Not specified	60–30,000 FPM	Digital	AC Powered
Cylinder Burette	±0.05 mL (typical)	Up to 50 mL	Manual	N/A

The TDC's location in relation to the proximity was ascertained utilizing a (Sony-Magnescale LY-1115) as a digital linear displacement sensor (it exhibited a sensitivity of 5 µm). In this work, the injector was detached; The displacement linear detector was attached to the piston head. The flywheel was incrementally rotated higher until the device's readout was altered. This position was identified as the TDC, and the proximity sensor was adjusted to be responsive only to this place. This technique was conducted three times to verify the proximity measurement at the TDC. Table 6 presents the specifications of the measuring equipment and further information regarding the test setup [14]. Two devices of gas analyzers were employed to assess the exhaust gases of the diesel engine exhaust gases, as demonstrated in Fig 2. Firstly, ECOM gas analyzer (type J2KNpro), utilized for the analysis of CO, NOx, and UHC concentrations. The smoke opacity is measured by an AVL DiSmoke 4000 in a smoke chamber. The location of the smoke sampling probe within the exhaust line determines opacity, quantified as percentages ranging from 0 to 100%. Subsequently, Emissions samples were collected from the exhaust line through each exhaust probe. Subsequently, each equipment evaluates the exhaust gases and provides the data

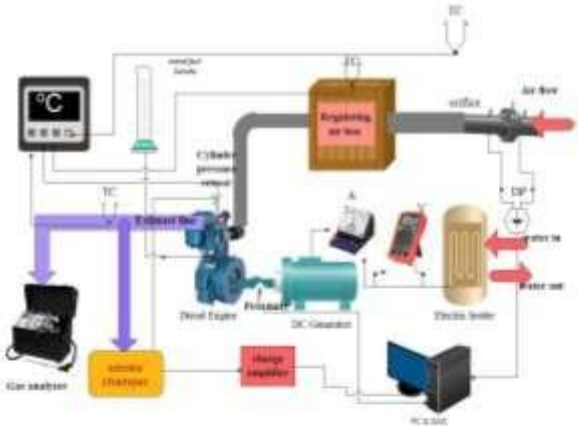


Fig. 3. Schematic diagram of the test rig.

- Investigation of calculating the brake thermal efficiency (BTE) and the brake specific fuel consumption(BSFC).

Firstly, for the BTE, voltage and current can be measured for the load (heaters), from which the power was estimated, the volumetric fuel flow was measured, and by having the density of the fuel that was measured in the lab, the mass flow rate of fuel is calculated.

$$\text{BTE} = \frac{V * A}{\text{mf}' * \text{HV}} \qquad (2)$$

A is the current, V is the voltage, mf ‘ is the mass flow rate of the fuel, and HV is the heating value. Secondly, for the BSFC, it is the ratio between the mass flow rate of the fuel and the brake power.

$$\text{BSFC} = \frac{\text{mf}'}{A * V} \qquad (3)$$

4. Results and analysis.

The combustion and emission characteristics of the evaluated fuels are examined in the subsequent subsections.

4.1. *Fuel Blending and its characterization.*

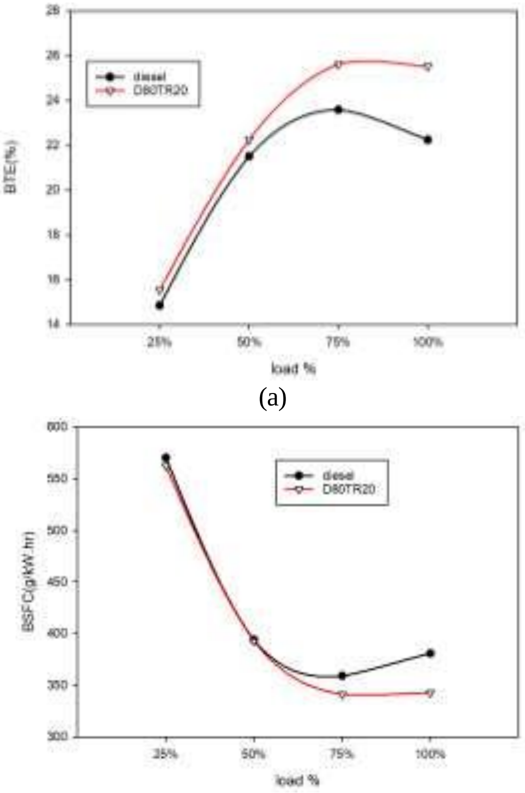
In this section, the program gives us the optimum ratios and the blends that give me the best performance. The properties of these mixtures are almost close to those of diesel, as we can see in Table 7.

Table 7 Properties of Diesel and Its Blends.

Property	Diesel	D80TR20
Lower heating value, MJ/kg	42.49	41.40
Viscosity at 40°C, cSt	2.72	3.60
Density at 20°C, kg/m3	827.7	846
Cetane number	52	50
Flash point, °C	56	64.95
Surface tension, N/m	0.0275	0.0284

4.2. *Performance characteristics.*

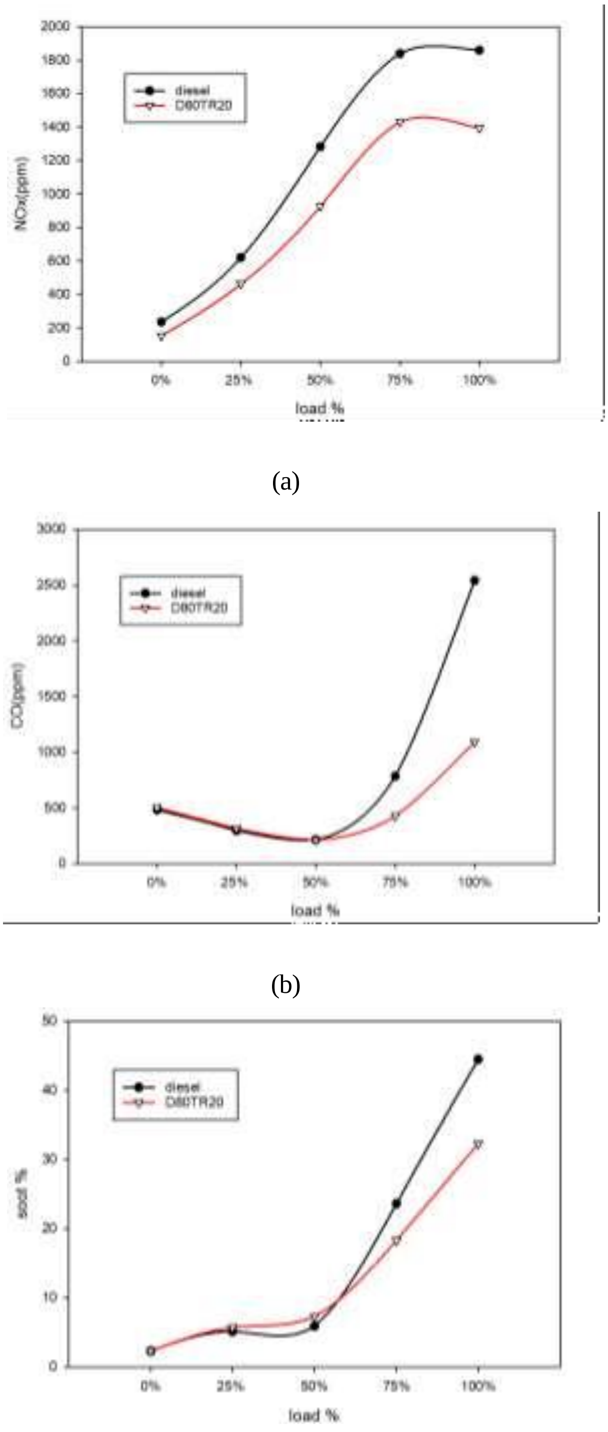
Fig. 4 demonstrates the fluctuations in BTE and BSFC for the fuels at varying engine loads. BSFC is mainly affected by the efficiency of fuel combustion, exhibiting advantageous combustion properties resulting in reduced BSFC values [15]. In comparison to the D100, the D80TR20 has a lower BSFC and a higher BTE. This is due to the higher oxygen content in biodiesel, which accelerates the oxidation rate and optimizes fuel–air mixing. Additionally, it has a lower cetane number, which slows the ignition of the fuel and facilitates good combustion, resulting in a decrease in the brake-specific fuel consumption (BSFC) and an increase in the brake thermal efficiency (BTE).



(a)

(b)

Fig. 4 (a) BTE and (b) BSFC of fuels via loads.



(a)

(b)

(c)

Fig. 5 Effects of the analyzed fuels on NOx, CO, smoke opacity, and UHC at various loads.

4.3. *Smoke opacity, NOx, CO, and UHC.*

Fig. 5(a) illustrates the variation in NOx emissions with different loads. The NOx levels for the assessed fuels escalate with rising engine load. This could be because reduced combustion velocities in lean mixtures necessitate an extended assessment duration, and the combustion velocity significantly influences NOx emissions [16]. Additionally, at higher loads, the fuel injected has a higher pressure and temperature, resulting in increased NOx levels. The production of NOx is primarily influenced by temperature, O_2 concentration, and combustion duration [17]. Two primary tactics for reducing NOx emissions are to lower combustion temperatures and shorten the duration of combustion [17].

Temperature plays a key role in the formation of NOx emissions, and castor biodiesel helps mitigate this due to its cooling effect in the combustion chamber. This effect is primarily attributed to several factors.

First, castor biodiesel has a higher latent heat of vaporization (300 kJ/kg) compared to diesel (270 kJ/kg). Although the difference may seem minor, the larger molecular size and higher boiling point of castor biodiesel require more energy for vaporization, which cools the combustion chamber and lowers its temperature. Second, the oxygen content in transesterified castor biodiesel (FAMEs) is around 10–12% by weight, while conventional diesel contains no oxygen. This inherent oxygen affects combustion timing by slowing the rate of heat release, thereby reducing the peak temperature. Additionally, because biodiesel has a lower energy content—approximately 10–15% less than diesel—more fuel is injected to maintain engine power output. This increased fuel mass results in more evaporation, which absorbs additional heat and contributes to the cooling effect. Lastly, the higher boiling point of castor biodiesel leads to slower evaporation and delayed combustion, further lowering the peak cylinder temperatures. Consequently, all biodiesel blends exhibit reduced NOx emissions compared to pure diesel.

Figure 5(b) illustrates the fluctuation in carbon monoxide emissions for the test fuels with the loads. CO gases typically diminish with rising engine load, unless at elevated loads. This is due to the elevated rate of CO oxidation at higher combustion temperatures. Under elevated engine loads, an increase in fuel in the combustion chamber may result in an oxygen deficit. This oxygen limitation hinders the complete oxidation of fuel, resulting in incomplete combustion [18].

In comparison with D100, the CO concentration for D80TR20 decreases, which can be attributed to the primary parameters influencing CO emissions, including low gas temperatures, low cetane numbers, elevated oxygen levels within the combustion zone, and adequate residence time for the complete oxidation of CO to CO2. The reasons mentioned above, applicable to the D80TR20, contribute to reducing CO2 emissions.

Figure 5(c) demonstrates a rise in smoke opacity corresponding to heightened engine load. This can be ascribed to the augmented role of diffusion combustion under elevated loads. Smoke generation primarily transpires in the fuel-rich zones of the diffusion flame. During the decomposition of heavy hydrocarbons into lighter ones, soot nuclei are generated, expand, and are emitted in areas with elevated soot concentrations, reduced local temperatures, and limited oxygen supply.

On the other hand, soot particles undergo oxidation in the presence of adequate oxygen, resulting in a decrease in their concentration in the exhaust. The degree of smoke production is strongly associated with the equivalency ratio. This suggests that even at elevated cylinder temperatures, there may be insufficient oxygen to fully oxidize the soot produced within the reaction zone as the equivalence ratio approaches stoichiometric values.

In comparison with D100, smoke opacity is reduced for D80TR20 at higher engine load. This is due to the elevated oxygen level in the blend, which facilitates the oxidation process and diminishes soot production. A trade-off arises between smoke opacity and NOx emissions [19].

The D80TR20 exhibited reduced soot generation. This phenomenon can be attributed to the elevated oxygen enrichment associated with higher biodiesel ratios in the mixture, which enhances the oxidation rate and subsequently leads to a decrease in soot content. Daniel et al [20], Veinblat et al [21], and Uyumaz [18], It was noted that augmenting biodiesel in the blend led to a substantial decrease in soot concentrations.

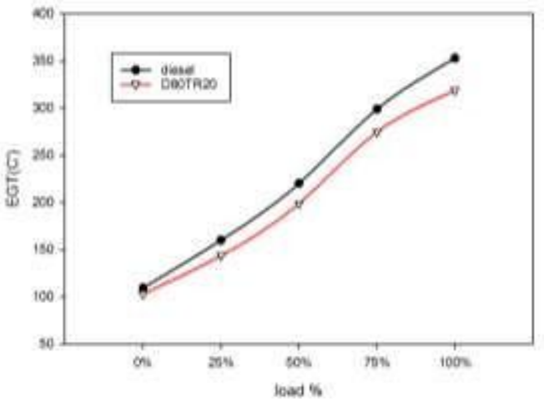


Fig. 6 Exhaust gas temperatures (EGT) increased with load levels ranging from 0% to 100%.

As the engine load and speed increased, the injected fuel mass also escalated. Moreover, the exhaust gas temperatures of the biodiesel/diesel blend were lower than those of D100. This is due to the cooling effect that biodiesel produces in the combustion chamber, and the reasons for this have been elucidated, including the elevated heat of vaporization, increased droplet size, and a higher boiling point.

5. Conclusion.

Castor biodiesel was selected as an alternative fuel to ordinary fuels, such as fossil fuels. It can be generated through various processes, as discussed in this paper, including methods for producing it via transesterification.

The transesterification method has commendable attributes that make it advisable for utilization, although it also has a detrimental aspect that discourages its recommendation. For example, transesterification is lower in terms of operational and production costs, and the production yield is higher, reaching 92%. On the other hand, it has inferior properties for producing biodiesel. It has a higher viscosity compared to biodiesel.

The utilization of castor biodiesel improves combustion results, whether enhancing performance or reducing emissions. As seen, the performance of the representative in BTE and BSFC is better for biodiesel, particularly concerning D100, especially at 100% load. The percentage of enhancing these features with a load higher than other loads is 14.69% and 10% for BTE and BSFC, respectively, for the same blend, D80TR20.

For emissions, the D80TR20 emits lower exhaust gases than the D100, with a notable percentage. Firstly, CO emissions are slightly higher than those of D100 at low loads (0% and 25%), and almost equal to those of D100 at a load of 50%. At high loads, 75% and 100%, the CO of biodiesel is lower than that of D100, especially at 100% load, where it reaches 57% for D80TR20. Secondly, Nox of D80TR20 is lower than that of D100 at all loads, by percentage of 29.9% at 100% load. Finally, the soot emission is higher than that of D100 at low loads until the load reaches 50%. At high loads, the soot value of biodiesel is lower than that of D100, with a value of 28% at a load of 100% for D80TR20.

The EGT of D80TR20 is lower than that of D100 for all loads; the lowest value of D80TR20 is 9.67% at D100; all percentages are referenced to the base fuel (D100).

It is recommended to use a fuel percentage within the range of 20% and add some additives to enhance the properties further. Since biodiesel's properties are slightly inferior, this approach helps increase the biodiesel percentage in the blends while minimizing the adverse effects and enhancing the properties over time.

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