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Analysis of Compression Ignition Engine Performance of a Produced B20 Flaxseed Biodiesel

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ABSTRACT

This research focuses on producing flaxseed oil methyl ester from raw flaxseed oil and evaluating its characteristics and performance on compression ignition (CI) diesel engine using diesel-biodiesel blends. Four samples of biodiesel blends (B20) have been prepared with a mixture of 20% flaxseed biodiesel and 80% pure diesel. The maximum yield of flaxseed oil has been found 84.67% for methanol-oil molar ratio of 6:1 using catalyst of 2 wt. % concentrations at reaction temperature of 65°C stirred at 720 rpm for 80 minutes. The calorific value of the blend biodiesel B20 is 41.9 MJ/Kg and kinematic viscosity is 5.87 mm^2/s. The calorific value of flaxseed oil is 36.17 MJ/Kg which is substantially lower than that of the diesel and biodiesel B20 having 43.05 MJ/Kg and 41.9 MJ/Kg respectively. The engine used for this research is a Four-Stroke Diesel Engine with IB30-2 Fuel type having maximum output power of 4.5 kW manufactured by Hatz. It is found that brake power, torque and brake specific fuel consumption of diesel with respect to engine speed is relatively higher than that of biodiesel B20. The brake thermal efficiency of the biodiesel blend B20 has been always higher than diesel at various engine speeds.

Keywords: Flaxseed Biodiesel, B20, CI Engine, BP, Engine Performance, BTE, and BSFC.

INTRODUCTION:

Protecting the environment and preserving non-renewable natural resources are becoming more and more important issues on a global scale. There has been significant interest in developing alternative energy sources over the past few decades as a means of replacing traditional fossil fuels. In recent years, biodiesel has gained popularity because of growing public awareness of environmental problems and limited fossil fuel resources. To replace or reduce fossil fuel use, biodiesel was created by extracted glycerin from vegetable oil or fat during trans-esterification process. However, beyond replacing diesel, biodiesel offers many advantages over fossil fuels - the biggest benefit is reducing CO_2, CO and SO_2 emissions (Silva *et al.,* n.d.). Many different feedstock oils, such as grapeseed, soybean, sun-flower, safflower and others are used to make biodiesel all around the world since they are edible in their natural state. Bangladesh is still a growing economy, commercially producing biodiesel from edible oil is not feasible in this country, considering food security (Umaru, 2012). Moreover, the exorbitant price of these oils may boost the total expenditure of biodiesel production (Abdullahi *et al.,* 2023; M *et al.,* 2019). An efficient approach for reducing the cost of biodiesel production involves utilizing readily accessible, inexpensive non-edible oils, algae, waste cooking oil, and animal fats (Arunachalam Sivagurulingam *et al.,* 2019; Ashokkumar *et al.,* 2017; Lawan *et al.,* 2020; Sharif *et al.,* 2019; Prasad *et al.,* n.d.).

Non-edible oils including karanja, neem, jatropha, pumpkin and flaxseed oil have been used to produce biodiesel, particularly in India. Flax, which is one among the world's major oilseed crops produced 1.956 million tons each year, is a multipurpose and economical (Ahmad *et al.,* 2019). The oil content of flaxseed (Linseed) varies depending on genotype and environmental factors; however, it is normally around 46%. The oil from seed is evenly distributed throughout the seed with 74% cotyledons, 4.4% embryo and 21.6 % combined testa and endosperm. Although flaxseed oil has various medical applications, it is mostly used in the manufacturing of industrial items including linoleum, paints, and varnishes (Mandal & Kundu, 2021). Using non-edible vegetable oils like flaxseed and jatropha, emerging countries like India and Bangladesh may assure their energy future as Flaxseed (*Linum usitassimum*) may be grown in these regions because of the favorable climate and soil conditions (Dixit *et al.,* 2012). Nabi *et al.* obtained the maximum biodiesel production yield of around 88% by using a 20% methanol concentration, 0.5% NaOH catalyst, and a reaction temperature of 550°C from linseed oil (Nabi & Hoque, n.d.). Ullah *et al.* achieved a biodiesel yield (97±1.045% w/w) from linseed oil by using a catalyst concentration of 0.5%, a temperature of 65°C, a reaction duration of 180 minutes, and methanol to oil molar ratio of 6:1 (Ullah *et al.,* 2013).

S. Jindal *et al.* found that the calorific value of linseed biodiesel was 41.820 MJ/Kg, density was 830 Kg/m^3, kinematic viscosity was 3.33 cst at room temperature, free fatty acid was 0.72% and flash point was 180^{0}C (Jindal & Salvi, 2012). J. M. Encinar *et al.* attempted to make biodiesel from beef tallow that has a lot of free fatty acids. Trans-esterification of animal fats was performed using acid and basic catalysts, as well as pre-esterification or not. By using acid-transesterification (9 wt. % H_2SO_4, six times methanol fat molar ratio, 60^{0}C, for 48 hours), biodiesel with an ester content of 89.0 wt. % was produced. The transesterification of esterified lipids with alkali produced a final product that contained 97.3 percent ester (Encinar *et al.,* 2011). A. S. Ramadhas *et al.* analyzed how to produce high-quality biodiesel using a low-cost feedstock that contains a lot of FFA. They discovered that an alkaline-catalyzed esterification process could be completed in 30 minutes with a molar ratio of 6:1 They observed that the flash point (approximately 130°C) was higher and the viscosity was comparatively similar to that of diesel (Ramadhas *et al.,* 2005). G. Vicente *et al.* focused on employing different catalysts to synthesize biodiesel from sunflower oil. The findings indicated that NaOH was the most effective catalyst. It was optimized using a factorial design and a response surface approach (Vicente *et al.,* 1998). G. T. Jeong and D. H. Park *et al.* tried multiple responses surface methodology (RSM) experiments to find the optimal reaction conditions for producing biodiesel from castor oil. The following values were determined to be optimal for the response factors: 40 minutes reaction time, 35.5 °C reaction temperature, 1:8.24 molar ratio of oil to methanol, 1.45% weight percent catalyst (KOH), and 35.5°C reaction temperature. The percentage of fatty acid esters in the castor oil biodiesel was close to 92% (Jeong & Park, 2009). I. A. Musa *et al.* found that many biodiesel factories use methanol because of being cheap and it has a short chain of molecules. It was found that adding co-solvents like n-hexane and ethyl alcohol, sodium thiosulfate, and tetrahydrofuran to solid catalysts could reduce problems with diffusion, make it easier for oil but also alcohol to mix, and help accelerate the reaction rate (Musa, 2016).

S. N. Gebremariam *et al*. observed that the cost of feedstock had the greatest impact on the economic viability of biodiesel manufacturing procedures. For fuel-grade biodiesel, the acid-catalyzed synthesis process found to be the most economical option to use feedstock with a higher FFA concentration at a lower cost (Gebremariam & Marchetti, 2018). O. J. Alamu *et al.* found coconut oil's high viscosity (43.3mm^2/s). Transesterification produced 10.4 grams of coconut biodiesel and 67.4 grams of glycerol, however, 22.20 grams of reactive mass was lost. Due to coconut biodiesel's low production, B10 was mixed. Physical qualities of coconut oil, B10 mix, and diesel were compared. It was also noticed that pure coconut oil had a substantially higher viscosity than B10 (Oguntola *et al.,* 2010). According to the investigation, there are either very few or no studies that investigate how well CI engines run with biodiesel-diesel blends when making biodiesel from flaxseed seed oil. In an effort to increase the usage of renewable energy, specifically the performance of biodiesel, this research will examine the impact of diesel-biodiesel mixes in CI engines. According to research, flaxseed oil with a moisture level of 4% may provide a maximum biodiesel production of 93% (Dixit *et al.,* 2012). However, there is a noticeable gap in research in biodiesel synthesis from flaxseed oil, especially regarding the improvement of fundamental preparation parameters such as trans-esterification process, reaction time, temperature, methanol to oil molar ratio and catalyst concentration. The aim of this research is to create biodiesel from non-edible flaxseed oil utilizing two-stage esterification procedures and analyze the performance of the four-stroke diesel engine by using diesel and biodiesel blends in Bangladesh as flaxseed properties and its yield varies from country to country.

MATERIALS AND METHODS:

Materials

The materials used in this research were - Flaxseed oil (Principal feedstock), methanol (CH_3OH, 99.9%, Merck KGaA, 64271 Darmstadt, Germany), potassium hydroxide pellets (KOH, 84%, Merck Specialities Private Ltd., Mumbai, India) and sulfuric acid (H_2SO_4, 98%, BDH Chemicals Ltd., England) - collected locally in Bangladesh. The chemical and physical properties of raw flaxseed oil utilized in this work are shown in **Table 1**.

Table 1: Physiochemical properties of Flaxseed Oil.

Properties	Characteristics
Dynamic viscosity	30.7 CP (Spindle L1) 38.5 CP (Spindle L2)
Color	Golden Yellow
Physical state (NTP)	Liquid
Solubility	Slightly soluble in alcohol
Molecular weight	554 g/mole
Density	0.859 g/mL
Specific gravity	0.876
Acid Value	1.5±0.2

Dynamic viscosity was measured by the Fungilab digital viscometer at a speed of 100 rpm using 2 different spindles at room temperature. Density and specific gravity were calculated by using the equation 1 and 2 respectively. Acid value was determined by using 1N NaOH and few drops of phenolphthalein by titration. For evaluating the acid value of flaxseed oil, equation 3 was used.

$$\text{Density, } \rho = \frac{mass\ of\ biodiesel}{volume\ of\ biodiesel} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

$$\text{Specific gravity, S}= \frac{specific\ weight\ of\ biodiesel}{specific\ weight\ of\ water} \quad \ldots\ldots\ldots\ldots\ldots\ldots..\ (2)$$

$$\text{Acid value, A/V} = \frac{volume\ of\ titrant\ in\ ml \times 0.1 \times 40}{mass\ of\ sample\ oil} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

Preparation of Biodiesel

Biodiesel production from flaxseed oil involved the fundamental processes of raw oil filtration, heating and esterification reaction. In this experiment, four samples were made by varying the weight of the raw oil (120 g, 190 g, 100 g and 242 g). Firstly, filter paper was used to remove insoluble impurities from the flaxseed oil. Then, the raw oil was preheated at 65^0C for 8 minutes to remove all the moisture. After warming up raw oil, it went through a two-step esterification reaction. In the first step of the esterification process, the molar ratio of methanol to crude flaxseed oil of 6:1 and 2% (w/w %) of sulfuric acid was both required as additions. The oil and methanol were then heated individually to 45^0C before being combined with the aid of a magnetic stirrer and a stirring bit and the reactor was appropriately sealed in a 250 ml three-neck flask. Sulfuric acid was added to the heated oil mixture after it reached the predetermined temperature of 60^0-70^0 C and heated for 90 minutes at a speed of 700 rpm. Both the fatty acid and alcohol content of the treated oil were lowered due to the triglyceride breakdown. After that, the mixture was transferred in a separating funnel and kept overnight to settle down the sulfuric acid and contaminants by creating two layers. After removing the bottom layer, the sample went under titration to ensure that it was suitable for further processing and its acid value was determined to be 1.5 (<2) mg KOH/g oil, which proved that the esterification had finished. After that, under specific reaction conditions, esterified flaxseed oil was subjected to base catalyzed transesterification for biodiesel production. Trans-esterification reactions were performed for 60 minutes at 60°–70°C with a methanol to oil molar ratio of 6:1 and 2% (w/w oil) potassium hydroxide at a stirring speed of 700 rpm. Afterwards, the final product was again moved to a separatory funnel and allowed to settle overnight which created two visible layers. Separator funnel was used to remove the bottom layer and store the clean top layer for further washing. Raw flaxseed biodiesel was found to include excessive amounts of methanol, sodium hydroxide and other impurities. These extra materials were washed with hot distilled water. After the biodiesel separated, a spray of warmed distilled water at 50ºC (oil to water ratio of 50%) was used to wash away any remaining impurities in the ester. Finally, the obtained biodiesel was heated to 70ºC for removing moisture content and filtered for further purification. The experimental procedure of this research is shown schematically in **Fig. 1**.

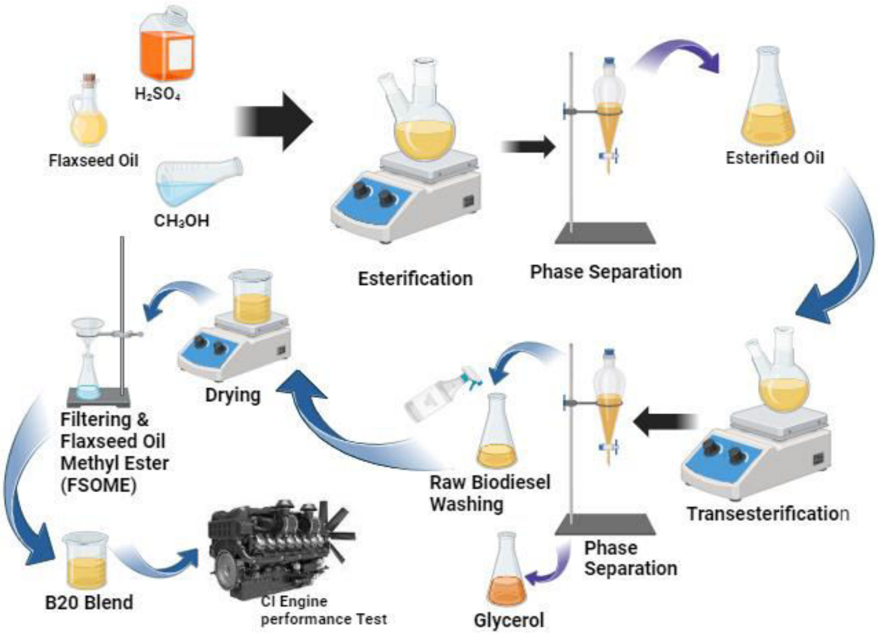

Fig. 1: Schematic diagram of the experiment.

Preparation of blends

As a transportation fuel, pure biodiesel known as B100 is not commonly used as a blend stock in the production of lesser blends. In this experiment standard B20 samples are produced with a mix of 20% flaxseed biodiesel and 80% conventional diesel. B20 is a popular blend because it is a good mix between price, emissions, cold-weather efficiency, compatibility with materials and solvent properties. However, engines that operate on B20 have the same fuel economy, brake power and torque as those that run on petroleum diesel.

Specification of the Engine

Torque, fuel consumption mass flow rate, speed, output power and temperature were measured by the "Four-Stroke (Bio) Diesel Engine CT 110" and specification of the engines is as follows: Engine Name Air-cooled single cylinder four stroke diesel engine, Company - Hatz, Type - IB30-2 Fuel, Fuel CT100.22 Diesel, Compression ratio-22.1 and Oil capacity -1.1 L.

Brake power (BP)

The power which is measured at the crankshaft is calculated using equation 4.

$$\text{Brake Power} = T \times \frac{2\pi N}{60} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, T = Torque at the crankshaft (Nm) and N = Speed of the Engine (rpm)

Brake specific fuel consumption (BSFC)

The crankshaft braking power divided by the mass flow rate of fuel fed to the engine is brake specific fuel consumption and the mathematical expression is shown in equation 5.

$$BSFC = \frac{Fuel\ mass\ flow\ rate(mf)}{Brake\ Power\ (BP)} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where, m_f = mass flow rate (Kg/s)

Brake Thermal efficiency (BTE)

BTE is calculated by comparing engine heat energy to braking power (measured at the crankshaft) and mathematically it is expressed as equation 6.

$$BTE = \frac{Brake\ power}{Heat\ energy\ supplied} = \frac{BP}{\frac{mf}{3600} \times Cv} \ldots\ldots\ldots (6)$$

$$m_f = 0.0288 \times \frac{\rho}{t}$$

Where, C_v = calorific value of fuel (KJ/Kg), m_f = mass flow rate (Kg/s), ρ = Density of fuel (Kg/m^3) and t = Time required for 8 ml fuel consumption

RESULTS AND DISCUSSION:

The impact of varying oil weights at a catalyst concentration of 2% and a methanol to oil molar ratio of 6:1 on the reaction yield was investigated and illustrated in **Fig. 2**. Four samples were prepared under different conditions for chemical reactions. Esterification was carried out at a stirring speed of 650 rpm and a temperature range of 60ºC to 70ºC for 30 minutes. Transesterification was conducted at a stirring speed of 720 rpm and a temperature of 65ºC for 80 minutes.

Table 2: Characteristics of Flaxseed biodiesel.

Fuel Property	Diesel*	Diesel	Biodiesel*	Flaxseed Biodiesel	Biodiesel (B20)
Fuel standard	ASTM D975		ASTM D 6751		
Kinematic viscosity mm^2/s (at 40 °C)	1.3 – 4.1	4.72	1.9 – 6.0	7.86	5.87
Specific gravity	0.85	0.60	0.88	0.90	0.579
Calorific Value (MJ/Kg)	43	43.057	39.3-39.8	36.17	41.9
Flashpoint, °C	60 – 80	55	100 –170	>100	
Fire point, °C	125.6	65	-	>100	

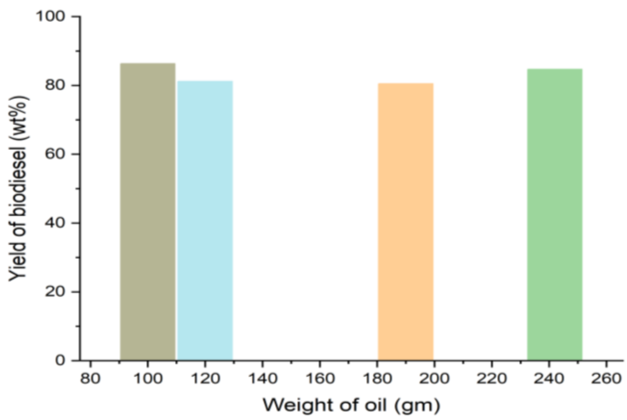

Fig. 2: Yield percentage of biodiesel.

Table 2 shows that kinematic viscosity of Flaxseed Biodiesel is 7.86mm²/s, while that of a Diesel-Biodiesel blend (B20) is 5.87 mm²/s at 40°C. The international standard kinematic viscosity values for Diesel ASTM D975 range from 1.3 to 4.1mm^2/s, diesel is 4.72 mm^2/s and biodiesel ASTM D6751 is 1.9 to 6.0 mm²/s, all measured at the room temperature. Compared to diesel and biodiesel, flaxseed biodiesel and the B20 blend have higher viscosity. **Table 2** demonstrates B20 have a specific gravity of 0.579 which is lower than the specific gravity of Biodiesel ASTM D6751. In this comparison, flaxseed biodiesel and the B20 blend have higher specific gravity than diesel ASTM D975 and diesel, but less than biodiesel ASTM D6751. The flaxseed biodiesel has a calorific value of 36.17 MJ/kg, whereas a diesel-biodiesel blend (B20) has a slightly higher calorific value of 41.9 MJ/kg. In comparison, the calorific value of diesel according to ASTM D975 is 43 MJ/kg, while the ASTM D6751 standard specifies a range of 39.3 to 39.8 MJ/kg for biodiesel. This indicates that both flaxseed biodiesel and the B20 blend have lower calorific values compared to pure diesel fuel, with the blend being closer in value to diesel. However, all biodiesel properties remain within the range specified by ASTM D6751, ensuring compliance with international standards for biodiesel quality. Flash and fire points of flaxseed biodiesel exceed 100^0C suggesting significant ignition and combustion resistance relative to traditional fuels. Diesel fuel has a flash point of 60–80 ^{0}C and a fire point of 125.6 ^{0}C, according to ASTM D975.

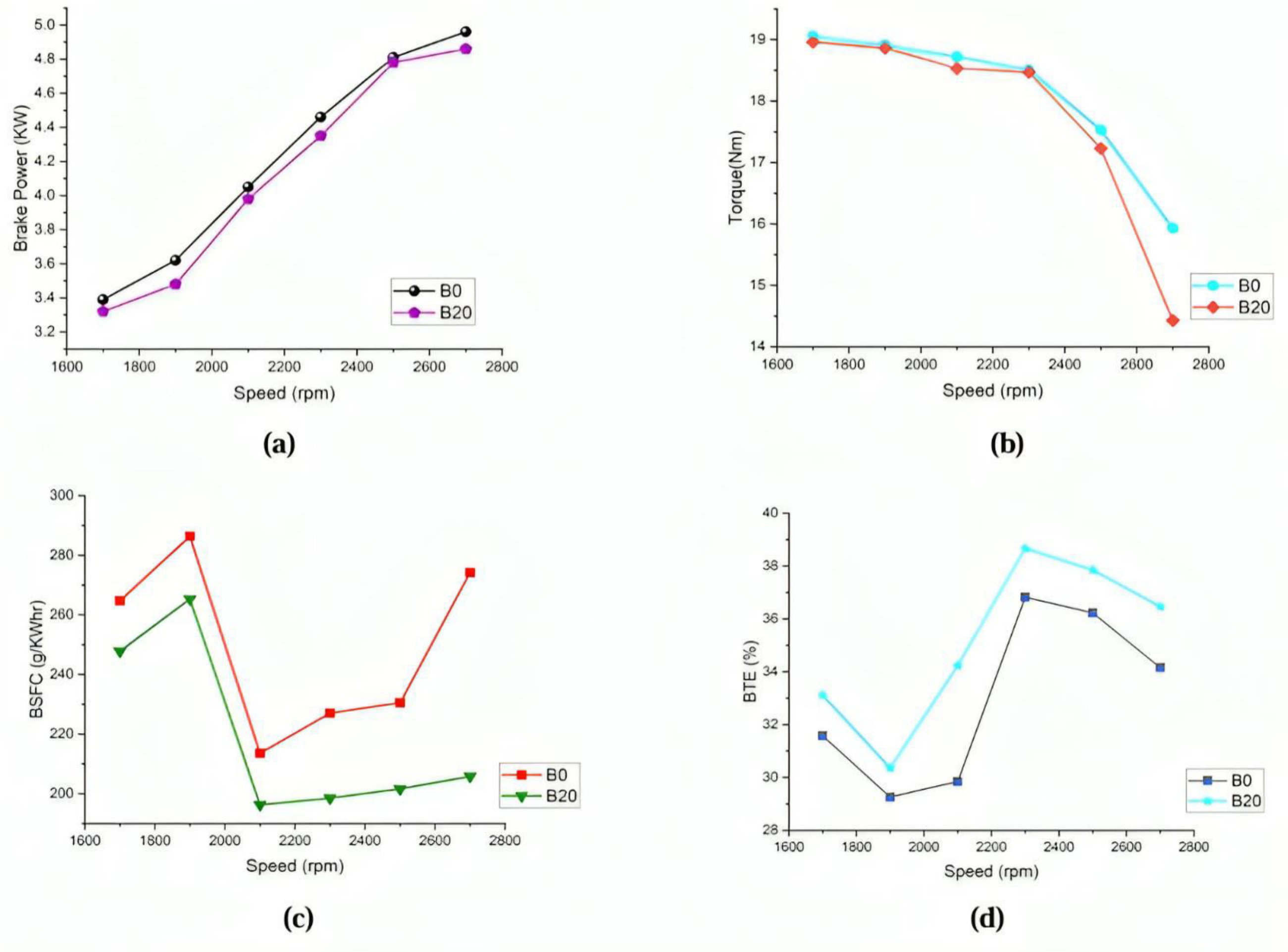

Fig. 3: (a) Brake power (BP) VS engine speed, (b) Torque VS engine speed, (c) Brake specific fuel consumption (BSFC) VS engine speed, (d) Brake thermal efficiency (BTE) VS engine speed.

The BP produced by B0 and B20 by varying the engine speeds is illustrated in **Fig. 3(a)** - indicates that B0 or conventional diesel has greater brake power yield than flaxseed biodiesel blend or B20. The reason behind this behavior can be described by analyzing the energy content, i.e., the calorific value of these two samples. As the high calorific value of a fuel ensures a higher gain of brake power, the BP achieved from B0 was greater than B20. However, **Fig. 3(b)** shows that torque reduces at a similar rate for both B0 and B20 samples - after the speed of 2300 rpm the torque noticeably separates due to diesel's high calorific value. However, biodiesel has a higher viscosity than diesel fuel, which has an impact on the injection characteristics. Furthermore, one factor reducing engine torque is the lower heating value of biodiesel. The BSFC for diesel engines initially drops from 1700 rpm to 2100 rpm at full load which is shown in **Fig. 3(c)**. The BSFC decreased because of the enriched chemical and physical qualities of fuel, which increased the combustion even at very low engine speeds. It is noticed that the BSFC suddenly increased with engine speed within the range of 2100 rpm to 2700 rpm. The combustion process is degraded and the BSFC is increased at high speeds due to frictional heat losses. The BSFC produced by B20 biodiesel was lesser compared to conventional diesel due to the higher density and lower calorific value of B20. **Fig. 3(d)** shows that diesel has a higher BTE than regular B20 which is being burned unevenly owing to a lack of air - BTE has increased due to increased heat production and decreased fuel use. More specifically, this can be ascribed to the enhanced air-fuel mixing and more efficient combustion that results from the decreased viscosity and higher volatility of fuel.

AUTHOR CONTRIBUTIONS:

M.R.H.: Conducted the experiments, collection and analysis of data. M.A.I.: conceptualization, initial-final manuscript preparation, supervision, analysis, editing and reviewing. M.N.A.S.: final manuscript preparation, editing and reviewing.

CONCLUSION:

Creating alternate energy having sustainable and environmentally friendly properties has become a major challenge in the 21st century. Among alternative biofuels, flaxseed biodiesel blend up to 20% may be a good replacement for conventional diesel as pure flaxseed biofuel cannot be used as engine fuel. The results of the experiment conducted for the biodiesel blends are summarized as follows:

- The calorific value conventional diesel and B20 biodiesel is significantly higher than flaxseed biodiesel
- The kinematic viscosity of B20 biodiesel is 5.87 mm^2/s which is lower than flaxseed biodiesel
- The maximum BP of B20 is 4.84 KW at a speed of 2700 rpm
- The maximum torque for both fuels have been found at1900 rpm
- The BSFC of B20 is 247.82 gm/kW-hr which is near to the typical consumption of diesel fuel
- The maximum BTE is found for B20 biodiesel is approximately 39% at 2300 rpm

However, there are various drawbacks to utilizing biodiesel as an alternative to fossil fuel due to a lower energy density compared to gasoline, necessitating the construction of more fueling stations to keep vehicles fueled. To transform Flaxseed oil into biodiesel, many catalysts are required, which adds complexity to the manufacturing process as well. Finally, fuel modification of diesel with the inclusion of biofuel is a better proposition for biodiesel in terms of performance and combustion which will require further research for successful implementation in CI engines.

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CONFLICTS OF INTEREST:

The authors declare that they have no conflict of interests.

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