EXPERIMENTAL EVALUATION OF DIESEL ENGINE OPERATING WITH A TERNARY BLEND (BIODIESEL-DIESEL-ETHANOL)

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3Abstract: The present investigation aims to study the future potential fuel of a non-edible tamanu oil (calophyllum inophyllum). The raw oil of tamanu oil was converted into biodiesel in two-step esterification process and different test fuel blends with biodiesel were prepared with conventional diesel and ethanol as an additive to evaluate its effect on engine characteristics such as BP, BTE, and BSFC, EGT and smoke density on a 4.4 kW rated power, single-cylinder four-stroke of constant rpm C.I. engineat different loads (25%, 50%, 75%, and 100% of rated power). The fuel blends were prepared with biodiesel in the ratio of 40%,100% coded as B40 and B100 respectively along with diesel fuel and ethanol as an additive in the fixed ratio of 10%, 15%, and 20%. It was found that B40E20D40 showed a reduction in smoke density and BSFC of 14.28% and 5.9% respectively, 18.3% increase in BTE and 3.73% reduction in exhaust gas temperature at full load whereas B100 showed a maximum reduction in smoke density of 15.97% with 4.53% increase in BSFC and a marginal increase in EGT of 0.53%. B40E20D40 gave a better performance in a diesel engine from the perspective of minimum BSFC, lower exhaust gas temperature and higher BTE among all other blends

Keywords: Biodiesel, Exhaust emissions, Ethanol, Engine performance

1. INTRODUCTION

The Energy utilization per capita is 33% of the worldwide average, with the growing development in Indian's economy will drive interest for energy throughout many sectors. Thus, access to sufficient and solid wellsprings of energy ends up noticeably imperative; especially when one-fourth of the population doesn’t have access to electricity and reliance on sources of energy of non-renewable either imported or produced locally keeps on increasing. The latter meets around three-quarters of India's energy demand [1].

The energy consumption on an average total of India out of which 44 % originates from coal. Energy-rich sources, for example, petroleum and biomass constitute 22 % each. The transport and industry sectors are the biggest consumer of energy in India. The petroleum product usage will keep on growing due to development in the transport area, especially road transport, which represents a significant share of automobiles. The road transport share as a percent of freight and passenger traffic is assessed above 60 % and 90 %, expecting 10 % vehicle growth every year. As of now, 46 % of demand for transportation fuel is alone fulfilled by diesel whereas 24 % is fulfilled by gasoline. It is anticipated that in further next ten
years, the demand on average for transport fuels will go up from an expected 134000 million liters in the year 2015 to 225000 million liters in the year 2026 [1].

The above data suggest that consumption of fossil fuels at the present rate would cause irreversible energy crisis along with a sharp increase in carbon footprints and other emissions which would not only cause environmental hazards but also deteriorate human health. The growth in transportation and continuous increase in demand on crude oil has led to life-threatening pollution level leading to stricter emission norms that have forced the engine manufacturers to comply with the norms which cost company money and time.

Biofuels are considered to provide energy security which is eco-friendly, recyclable, and biodegradable. Biodiesel and alcohol are considered to be potential renewable energy sources [2,3]. Based on many types of research on biodiesel it has been found that diesel fuel can be replaced to a greater extent but diesel engine running on biodiesel produces higher Nox emission as compared to diesel fuel. But the addition of alcohols with biodiesel reduces the Nox emission to some extent found by several authors. Renewable energy sources or oxygenated sources that are widely being researched nowadays provides similar physio-chemical fuel properties when compared to fossil fuels. There exists about more than 350 vegetable oil-bearing crops which have been studied by numerous authors, are considered among the most suitable vegetable oils. The most widely used vegetable oil such as jatropha curcas, tamanu oil, mustard oil, rapeseed oil, palm oil soybean oil sunflower oil, etc are considered future potential fuel for diesel engines [3].

Tamanu oil is a non-edible oil tree found among the Clusiaceae family. Tamanu oil tree are found in Africa, Asia, and Pacific areas. These plants are also called by the name as Alexandrian Laurel, Tamanu, Pannay Tree, Sweet Scented Calophyllum, Punmai, etc. Usually, these trees are available in seashore areas, which are planted to neutralize soil breaking. They grow around 2-3 m in length with a thick trunk having broken barks. The leaves are strong and round perfectly which transmits sweet lime-like smell. They bloom twice a year and yield different round seed found in clusters. Each seed has a smooth epidermis layer and is covered by a hard layer and has a diameter of about 50 mm, encasing a light-yellow piece of around 25 mm in length weighing generally 7g [5,6]. The word "Calophyllum" means "Beauty leaf" from Greek word.

This seed has numerous physio-chemical properties that might be utilized as an alternate future renewable energy source for automotive vehicles running on diesel engines that are not only searched for transportation services but also industrial and power sectors as well [6].

Tamanu oil has been studied by several researchers for alternative fuel on diesel engine by analyzing engine characteristics curve such as performance and emissions out of which few of them are discussed below [7-10].

Ong et al. [7] conducted a comparison on biodiesel production among palm oil, jatropha seed oil, and tamanu oil and showed that tamanu oil has the similar properties to conventional diesel fuel and could be the potential future fuel to replace depleting fossil fuel.

Deepan [8] investigated on tamanu oil biodiesel on performance and emission characteristics of CI engine and analyzed that biodiesel mixed with diesel fuel coded as B15, B25, B50, and B100 respectively, performed from on diesel engine no load to full load resulted in higher BTE of 30% for B15, compared with diesel and lowest BSFC at all loads. With 100 % biodiesel, mechanical efficiency was higher at all loads and B100 produced higher smoke at all loads along with higher NOx emission from the engine. Krishnan et. al. [9] performed the experiment on tamanu oil biodiesel and studied the effect on engine performance and emission characteristics on a single-cylinder multi-fuel engine. Blends of biodiesel i.e., 10%, 20%, 40%, and 60% with diesel showed the brake power reduced when compared with diesel fuel. NOx emission from the blend B40 resulted in a lower amount, while at full load NOx emission increased as compared to reference diesel fuel. The CO emission was also found to be higher for
B40 fuel blend. Arun [10] studied performance of CI engine running on tamanu oil-diesel blends with the conclusions that BSFC consumption was lower for B10 and B20 than the diesel fuel. Blends with 30% biodiesel reduced CO2 emissions along with decrement in HC and NOx emissions. BTE (brake thermal efficiency) slightly increased when load was increased when compared to diesel fuel and recommended that up to 30% biodiesel could be used in an unmodified CI engine.

Pugazhvadivu[11] experimented on the performance and emission characteristics of a diesel engine with ethanol in the Pongamia oil biodiesel-diesel blend. The ethanol addition in B100 (pure biodiesel) and B50 (50% biodiesel + 50% diesel) showed a reduction in BTE and NOx emission reduced at full load. B100 and B50 fuel blends showed reduction in the smoke opacity. The ethanol blend with B100 and B50 showed better results when compared to the engine running on diesel fuel. Mofijur [13] studied the comparison of performance and emission characteristics between biodiesel–diesel and ethanol–biodiesel–diesel blends showed a reduction in CO emissions due to presence of oxygen in biodiesel and concluded that the exhaust gas emission with 5–10% of ethanol with 20–25% biodiesel could be added to diesel fuel and further investigation on biodiesel from second generation plants are required. The work on tamanu oil discussed above showed that further investigations are required by esterification process and addition of ethanol as an additive.

Thus, in this investigation, the engine performance parameters such as BSFC, BTE, and emission parameters on 4.4 kW rated power, single-cylinder four-stroke CI engine of constant rpm on Tamanu oil biodiesel and diesel with ethanol addition was studied. The other engine parameters such as compression ratio, injection timing, inlet temperature, and pressure were kept constant.

2. MATERIALS AND METHODS

The raw tamanu oil was purchased from Tamil Traders, Suramangalam Salem, Tamilnadu. The raw tamanu oil possesses higher viscosity and has a free fatty acid (FFA) value found to be more than 3% [5]. The FFA content in vegetable oils, if found in higher amount require whether the oil could be utilized in pure form or it requires an esterification process depending on the FFA content. If FFA is found to be more than 3% in vegetable oil, a two-step esterification process is required, for a single step esterification process would convert into soap rather than biodiesel when reacted with alkali catalysts having FFA content more than 3%. The first step known as the pre-esterification process requires the raw vegetable oil to get reacted with an acid catalyst such as sulphuric acid (H2SO4), thereby reducing FFA content to some extent which is again processed in the second step known as transesterification process where this low FFA oil obtained in the first step, is get reacted with base catalysts such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) [5]. The chemical process of soap formation if the percentage of FFA is higher (> 3%) and the pre-esterification process is shown in Fig. 1 and Fig. 2

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\begin{align*}
\text{CH}_3 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{OOH} + \text{CH}_3 \cdot \text{OH} & \rightarrow \text{CH}_3 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{OO} - \text{Na}^+ \text{ or } \text{K}^+ + \text{H}_2\text{O} \\
\text{CH}_3 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{OOH} + \text{H}_2\text{SO}_4 & \rightarrow \text{CH}_3 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{CH}_2 \cdot \text{OOCH}_3 + \text{H}_2\text{O}
\end{align*}
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Fig. 1 Soap formation in high FFA oils [5]

Fig. 2 Acid pre-esterification [5]

All the parameters for esterification were set according to the investigation of Jahirul et al.[5,6]. The temperature in the pre-esterification process was set at 75°C, acid catalyst sulphuric acid (H2SO4) with
10% by weight of oil and methanol to oil ratio of 30:1 of the mixture was prepared and the mixture was continuously stirred for 2 hours. After the pre-esterification chemical process was completed in the reactor, the mixture was transferred into separating funnel from where two layers were found after settling: methanol and low FFA Tamanu oil as shown in **Fig. 4(a)**. The upper layer (methanol) was removed and low free fatty acid tamanu oil was again put on the reactor for base-catalyst transesterification process for the second step or transesterification process in which the temperature set was at 55°C in reactor setup, 7.5:1 methanol to oil ratio and 1% by weight NaOH as base catalyst was prepared and the mixture was stirred continuously for 1 hour. Once it was completed and again poured into separating funnel where after settling, two layers were visible: biodiesel (upper layer), glycerol (bottom layer) as shown in **Fig. 4(b)**. Glycerol was removed from the bottom layer and the upper layer of crude biodiesel was processed for water wash to remove the excess methanol and impurities remained during the esterification process. The water wash was done in successive steps with hot water to avoid trapping of air bubbles for at least 4 times to have completely clean water visibility in successive steps and due to higher density, it was collected at the bottom part as shown in **Fig. 4(c)**. The conversion efficiency was obtained by approximately 89%. Eventually, the finished biodiesel was heated at about 50°C in an oven for 15 minutes to remove moisture trapped into it during a water wash.

Further, the fuel blends were prepared with final processed biodiesel with the reference fuel i.e. diesel and with ethanol as an additive that was purchased from the local market of the technical grade of 99.9% purity. The tamanu oil biodiesel was mixed with diesel fuel by 40% and 100% coded as B40, and B100 respectively. Afterward, ethanol was mixed in the ratio of 10%, 15%, and 20%. The composition and nomenclature of each blend fuel are shown in **Table 2**.

The important fuel properties of different fuel blends were carried out as per the ASTM standards. The important fuel properties - Density, cloud and pour point, flash and fire point kinematic viscosity, and calorific value for all the blends were determined and are tabulated in **Table 3**. The test was carried out on a 4.4 kW/6HP, single-cylinder four-stroke diesel engine at various load (25%, 50%, 75%, and 100% load of rated torque) at a constant speed of 1500 rpm. The engine specification is shown in **Table 1** and the schematic diagram of an engine test rig is shown in **Fig. 3**. The investigations were studied on engine characteristics and emission characteristics of these different blends.

**Table 1** Specification of engine test rig

| Engine Characteristic   | Specifications          |
|-------------------------|-------------------------|
| Make/Model              | Kirloskar TAFI          |
| Maximum Power           | 4.4 kW @1500 RPM        |
| Injection type          | Direct Injection        |
| Number of cylinders     | Single                  |
| Cylinder bore/Stroke    | 87.5/110 mm             |
| Compression ratio       | 17.5:1                  |
| Fuel Injection timing   | -24 CAD a TDC          |
| Fuel Injection pressure | 170 to 250 bar          |

**Fig. 3** Engine test rig
Table 2 Proportions and nomenclature of fuel blends

| Sl.No | Biodiesel (%) | Diesel (%) | Ethanol (%) | Nomenclature     |
|-------|---------------|------------|-------------|------------------|
| 1.    | 0             | 100        | 0           | Diesel           |
| 2.    | 40            | 60         | 0           | B40D60           |
| 3.    | 40            | 50         | 10          | B40E10D50        |
| 4.    | 40            | 45         | 15          | B40E15D45        |
| 5.    | 40            | 40         | 20          | B40E20D40        |
| 6.    | 100           | 0          | 0           | B100             |

Fig. 4. A photographic view of esterification product (a) pre-esterification acid catalyst product (b) transesterification base-catalysts product (c) Water wash

Table 3 Fuel Properties of all the Blends

| Fuels samples | Density (gm/cc) @15°C  | Cloud Point (°C) | Pour Point(°C) | Kinematic viscosity (mm²/s) @ 40°C | Flash Point(°C) | Fire Point(°C) | Calorific Value (MJ/Kg) |
|---------------|------------------------|------------------|----------------|------------------------------------|-----------------|----------------|------------------------|
| ASTM          | 0.860-0.900            | -3 to 12         | -15 to 10      | 1.9-6.0                            | -               | -              | -                      |
| Diesel        | 0.823                  | -2               | -10            | 2.51                               | 60              | 63             | 45.86                  |
| B40D60        | 0.842                  | 2                | -2             | 3.62                               | 78              | 84             | 43.82                  |
| B40E10D50     | 0.84                    | 1                | -2             | 3.37                               | 40              | 51             | 42.37                  |
| B40E15D45     | 0.837                  | 3                | -1             | 3.20                               | 30              | 40             | 41.68                  |
| B40E20D40     | 0.834                  | 1                | -1             | 2.82                               | 28              | 32             | 41.20                  |
| B100          | 0.88                   | 10               | 5              | 5.28                               | 180             | 193            | 40.09                  |
| Ethanol       | 0.794                  | -15*             | -              | 1.66                               | 17              | 36             | 27.42                  |

* = reference
3. RESULTS AND DISCUSSION

3.1 Brake Specific fuel Consumption

Fig. 5 shows the variation of brake specific fuel consumption versus load (%) for various blends. The brake specific fuel consumption (BSFC) decreases as the percentage of load increases for all the test fuels due to better combustion and lower heat losses. The brake specific fuel consumption for diesel were obtained as 0.544, 0.386, 0.330, and 0.322 kg/kWh. The observation with B40D60 the BSFC at 25, 50, 75, and 100% load were 0.554, 0.384, 0.344, and 0.326 kg/kWh respectively which indicated increase at all loads except 50% load by 4.22%. While the addition of ethanol with B40D60 the BSFC was increased for all the blends, with the highest percentage reported as 6.16% at 50% load for B40E15D45 as shown in Fig. 5. The BSFC with tamanu oil methyl ester (B100) at all loads were 0.565, 0.397, 0.351, and 0.337 kg/kWh increased by 3.75%, 2.93%, 6.36% and 4.4% respectively. This may be due to lower calorific value, higher viscosity and poor atomization of B100 and addition of ethanol further increase BSFC due to reduction in calorific value of the blend, lower heat release rate, and more energy consumption.

![Fig. 5 Variation of brake specific fuel consumption of Diesel, B40D60 and its ethanol blends](image)

3.2 Brake thermal efficiency

Fig. 6 shows the comparison of brake thermal efficiency (BTE) versus load (%) for all different test fuels. For all the test fuels, the brake thermal efficiency was increased as the load was increased due to lower heat losses at higher loads. It was observed that the brake thermal efficiency (BTE) for, B40D60, B100, and Diesel was about 25.17%, 26.67%, and 24.35% respectively at full load and the percentage increase was 4.2%, 1.79%, and 9.56% with respect to diesel. The addition of ethanol to tamanu oil biodiesel reduces the viscosity of the fuel, increases volatility and the inherent oxygen (i.e. 32%) in ethanol improves the combustion phenomenon. The percentage of ethanol in blend reduces the calorific value of fuel which intakes more amount of fuel to develop the same power, and the highest BTE observed was 28.82% at 100% load for B40E20D40 increased by 18.41% with respect to diesel. The BTE with B100 was found to be 15.90%, 22.60%, 25.61%, and 26.67% at 25, 50, 75, and 100% load respectively with a percentage increase of 10.25%, 11.12%, 7.55%, and 9.56% with respect to diesel.

![Fig. 6 Variation of brake thermal efficiency of Diesel, B40D60 and its ethanol blends](image)

3.3 Exhaust gas temperature

Fig. 7 shows the variation in exhaust gas temperature for various test fuels versus load (%). The exhaust gas temperature (EGT) increases as the percentage of load increases for all the tested fuels. This increase in EGT was because, at higher load, an extra amount of fuel is required to be injected to develop
more power. The exhaust gas temperature for Diesel, B40D60, and B100 was 375°C, 361°C, and 377°C at full load. With B40D60 there is a decrement in the exhaust temperature while it was further reduced with various ethanol blends with the highest percentage reduction of 3.94% for B40E15D45 at 75% load as compared to diesel. The reason for higher EGT might be due to poor atomization of vegetable oil because of higher viscosity which causes slow combustion thus producing higher temperatures at the exhaust. But the addition of ethanol caused lower exhaust gas temperature because of inherent oxygen content present in the ethanol which causes complete combustion with blends and due to heat of vaporization and lower heat losses in exhaust gases. The exhaust gas temperature with B100 was found to be marginally increased as compared to diesel fuel with the highest increase of 1.71% at 75% load.

3.4 Smoke density

Fig. 8 represents the variation of smoke emission with respect to load. The smoke emission increased as the percentage of the load was increased due to more requirement of fuel at higher load to develop the power. The smoke density (HSU %) with Diesel, B40D60 and B100 at full load was found to be 39.9% and 33.52% respectively that indicated an increase in smoke as the percentage of biodiesel was increased which might be because of higher viscosity and higher volatility thereby leading to poor combustion due to improper atomization of fuels. The smoke density was lowered as the percentage of ethanol blending with biodiesel-diesel was increased to diesel due to the complete combustion process with oxygenated ethanol, lower viscosity, and reduced fuel-rich regions in the combustion chamber.

4. Conclusion

The performance evaluation of diesel engine on selected fuel blends was found acceptable based on brake power, brake specific fuel consumption, and brake thermal efficiency. The engine was able to develop similarly and accepted close results of brake power for all fuel blends as compared to diesel. It shows that the engine running on Tamanu oil biodiesel with ethanol as an additive was found to be potential fuel. Even 10 to 20% addition of ethanol, improves the properties, performance as well as emission characteristics of the. But in the present investigation where ethanol was added in diesel-biodiesel blends, it was observed that at 20% ethanol blend showed influential results with 40% of tamanu biodiesel by its smoke density reduction of the fuel at selected load condition and reduction in the exhaust gas temperature which is considered to be the main cause of NOx formation.
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