Investigation on the impact of papaya biodiesel-diesel blends on combustion of an agricultural CI engine

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Abstract. In this study, an overview of combustion characteristics of an agricultural diesel engine fuelled with papaya seed oil (PSO) biodiesel and diesel is presented. A naturally aspirated four-cylinder four-stroke tractor engine was used for all experiments. Various PSO blends (5%, 10%, and 20%) were tested and compared with diesel at speeds of 1400 rpm and 2400 rpm at full load condition. The combustion characteristics such as in-cylinder pressure, heat release rate, ignition delay, mass fraction burned, ignition duration and cylinder temperature were tested. The results show that PSO blends have some excellent attributes as fuel in regard to combustion characteristics. All PSO biodiesel blends have higher in-cylinder pressure; for example, PSO20 has 2.4% more than diesel. Heat release rate values of all PSO biodiesel blends were found to be lower than diesel due to the shorter ignition delay and lower calorific values of biodiesel. PSO20 biodiesel shows faster combustion than diesel by about 11.92% at 1400 rpm and 7.93% at 2400 rpm. The maximum cylinder temperature of all PSO biodiesel blends are also higher than that of diesel, such as PSO20 at 1400 rpm by 3.17% and at 2400 rpm by 3.73%.

Keywords: Biodiesel, Combustion, Papaya, Cylinder pressure, Heat release rate

1. Introduction

Recently many research studies have been conducted on biodiesels and their amazing environmental attributes over traditional fossil fuel, i.e., diesel. Numerous vegetable oils have been investigated as alternative fuel sources. Some researchers are concerned over the classical debate on “food vs. fuel” due to excessive usage of food/grain-based biodiesel as an energy source. However, animal fats and non-edible vegetable-based oils have been proved as renewable sources of energy and have largely solved this debate. Among more than 350 biodiesel feedstocks, waste seed-based fruits/crops are drawing attention these days. Some of the popular waste seed based non-edible feedstocks are beauty leaf, rubber seed, jatropha, rapeseed, cottonseed, moringa, neem, pongamia seed, stone fruit seed, and papaya seed. The debate about the best feedstocks for biodiesel in terms of their technical environmental, economic and social aspects continues. Researchers are working tirelessly to find alternative sources of fuel that are affordable, locally available and sustainable. This paper examines the potentiality of papaya seed oil (PSO) biodiesel from papaya seed waste.
Over the years, few researchers have investigated the opportunities of PSO biodiesel as a replacement of fossil fuel, i.e., diesel. Most of the researchers have worked on the papaya seed oil extraction techniques [1-3], optimisation of the PSO biodiesel conversion process [4], the effects of PSO biodiesel on diesel engine performance, and analysis of the emission parameters [5-7]. Anwar et al. [8] have optimised the biodiesel production process and obtained a 96.48% biodiesel yield. In another study, Anwar et al. [9] showed that PSO blends caused a slight reduction in brake power (2.88%-3.85%), torque (1.37%-3.85%), and brake thermal efficiency (3.1%-13.1%) and a slight increase in brake specific fuel consumption (3.35%-17.13%). A very few researchers have gone through the complete combustion process using PSO biodiesel over a fully instrumented multi-cylinder diesel engine. Instead, most have used a single cylinder diesel engine. For example, Prabhakaran et al. [10] investigated a single cylinder engine’s combustion characteristics using PSO biodiesel and reported that PSO has peak in-cylinder pressure due to the higher cetane number and oxygen contents of the biodiesel. Again, they found that the HRR of PSO blends were lower than that of diesel. Sundar Raj and Karthikayan [11] reported that PSO biodiesel blends ignited earlier and finished combustion earlier than diesel. However, the above studies and other literatures do not report on analysis of combustion characteristics of a fully instrumented four cylinder 4-stroke diesel engine fuelled with PSO biodiesel. The objective of this study is to investigate three blends of PSO biodiesel with diesel in an agricultural diesel engine to analyse the overall combustion characteristics.

2. Methodology

The experiment was conducted at the School of Engineering and Technology of Central Queensland University, Rockhampton, Australia. An agricultural tractor four-stroke diesel engine with four-cylinders (Kubota model V3300) was coupled with an eddy current dynamometer. The schematic of the experimental setup of the engine is shown in Figure 1. This tractor engine was used for testing both diesel and PSO biodiesel blends regarding engine performance, exhaust emissions, and combustion characteristics. A piezoelectric pressure transducer and crank angle encoder were used to monitor the combustion characteristics. Heat release rate (HRR) is an important combustion parameter that can be used for measuring ignition delay, start of injection, start of combustion, end of combustion and combustion duration [12]. HRR at different crank angles can be calculated using equation (1) derived from the first law of thermodynamics [13].

\[
\dot{Q} = \left\{ \frac{\gamma}{\gamma-1} \right\} \times P \times \frac{dV}{d\theta} + \frac{1}{(\gamma-1)} \times V \times \frac{dP}{d\theta}
\]

where \( \dot{Q} \) is HRR (J/° CA), \( P \) is the cylinder gas pressure (kPa), \( \gamma \) is the ratio of specific heat (air), hence \( \frac{C_p}{C_v} = 1.4 \), and \( V \) is the instantaneous volume of the cylinder (m³).

Figure 1. Schematic of the experimental setup of the engine.
The Kubota V3300 used in this experiment is an indirect injection tractor engine with a spherical combustion chamber, i.e., three vortex type combustion system. A detailed engine specification is presented in Table 1. A detailed engine performance analysis was performed in a separate experiment using the same engine and has been well documented in Anwar et al. [9].

Table 1. Specification of the diesel engine.

| Items                        | Unit | Specifications                                      |
|------------------------------|------|-----------------------------------------------------|
| Model                        |      | Kubota V3300, Indirect injection                     |
| Type                         |      | Vertical, 4 cycle liquid cooled diesel                |
| No. of cylinders             |      | 4                                                   |
| Total displacement           | L    | 3.318                                               |
| Bore × Stroke                | mm   | 98 × 110                                            |
| Combustion type              |      | Spherical type [E-TVCS (Three vortex combustion system)] |
| Intake system                |      | Naturally aspirated                                  |
| Rated power output           | kW/rpm | 53.9/2600                                          |
| Rated torque                 | Nm/rpm | 230/1400                                            |
| Compression ratio            |      | 22.6:1                                              |
| Fuel injection timing        |      | 16° before TDC                                       |
| Injection pressure           | MPa  | 13.73                                               |
| Emissions certification      |      | Tier 2                                               |

PSO Biodiesel blends of 5% biodiesel with 95% diesel (denoted as PSO5), 10% biodiesel with 90% diesel (PSO10), and 20% biodiesel with 80% diesel (PSO20) along with pure diesel (B0) were tested in the engine. Before these fuels were tested, a thorough fuel properties characterisation has been conducted, and Table 2 presents the relevant information. Various PSO blends and diesel were tested at full load conditions for an engine speed of 1400 rpm (max. rated torque) and 2400 rpm (near max. rated power output).

Table 2. Basic fuel properties of B0, refined papaya seed oil (PSO), pure PSO biodiesel (PSO100), PSO5, PSO10, and PSO20.

| Fuel          | Density (kg/m³) | Viscosity at 40°C, mm²/s | Acid Value, mg KOH/g | Cetane number (CN) | Calorific value, MJ/kg | Flash Point, °C | Iodine Value (IV) mg.I²/100g | Oxidation stability (OS), h |
|---------------|-----------------|--------------------------|----------------------|--------------------|------------------------|-----------------|-------------------------------|----------------------------|
| B0            | 827.2           | 3.23                     | 0.05                 | 48.00              | 45.30                  | 68.5            | 38.3                          | 39.0                        |
| Refined PSO   | 885.0           | 27.3                     | 0.98                 | 40.23              |                        |                 | 79.95                         | 77.97                       |
| PSO100        | 840.0           | 3.53                     | 0.42                 | 48.29              | 38.49                  | 112             | 115.89                        | 5.61                        |
| PSO20         | 829.76          | 3.29                     | 0.12                 | 48.06              | 43.94                  | 77.20           | 53.82                         | 32.32                       |
| PSO10         | 828.48          | 3.26                     | 0.09                 | 48.03              | 44.62                  | 72.85           | 46.06                         | 35.66                       |
| PSO5          | 827.84          | 3.25                     | 0.07                 | 48.01              | 44.96                  | 70.68           | 42.18                         | 37.33                       |
| ASTM          | 870-353         | 1.9-6.0                  | max                  | min. 47            | -                      | min.            | -                             | min. 3                      |
| D6751-2       | 890.0           | 0.5                      | 93                   |                     |                        |                 |                               |                             |

3. Results and discussion

3.1. In-cylinder pressure
The variation of in-cylinder pressure (CP) with the crank angle (CA) for diesel and PSO blends at 1400, and 2400 rpm at full engine load conditions are presented in Figure 2(a) and 2(b). At 1400 rpm speed, PSO20 has a peak CP of 66.15 bar at 3° CA, followed by 64.5 bar at 3° CA for PSO10, 64.29 bar at 3° CA for PSO5 and 64.07 bar at 3° CA for diesel. At the higher speed and load, the temperature increases with the increase of pressure that resulted in a higher evaporation rate and better combustion. At 2400
rpm, peak CP was recorded at 0° CA for diesel and all PSO blends. PSO20 was found to be 67.33 bar while PSO10, PSO5, and diesel were 66.29 bar, 65.93 bar, and 65.75 bar respectively. CP of biodiesel blends were found to be higher than diesel due to the higher density of biodiesel being injected for the same injection duration compared with diesel [14, 15]. At full load and 2400 rpm speed, the maximum CPs of PSO5, PSO10, and PSO20 were found to be 0.27%, 0.82%, and 2.4% higher than diesel. All graphs trends are similar and in line with previous researcher Prabhakaran et al.[10].

![Graph showing cylinder pressure vs. crank angle for different blends and diesel at 1400 rpm and 2400 rpm](a) 1400 rpm  (b) 2400 rpm

**Figure 2.** The differences of in-cylinder pressure for PSO blends and diesel under full load at speeds of: (a) 1400 rpm, and (b) 2400 rpm.

### 3.2. Heat release rate

Heat release rate (HRR) of PSO biodiesel blends and diesel are shown in Figure 3(a) and (b). At 1400 rpm with full load condition, the maximum HRR was recorded as 201.78 J/°CA at 16° CA with diesel, 192.42 J/°CA at 16° CA with PSO20, 186.78 J/°CA at 16° CA with PSO10, and 176.22 J/°CA at 16° CA with PSO5. Several fuel characteristics such as calorific value, cetane number, fuel-air mixing rates, cetane number, ignition number and ignition timings can affect HRR [12, 16]. At 2400 rpm and full load condition, the maximum HRR was found to be 250.59 J/°CA at 15° CA with diesel, 237.15 J/°CA at 15° CA with PSO20, 240.34 J/°CA at 15° CA with PSO10, and 244.56 J/°CA at 15° CA with PSO5. The maximum HRRs at 2400 rpm of PSO20, PSO10, and PSO5 were found to be 5.36%, 4.1%, and 2.40% lower than diesel. PSO biodiesel blends have lower calorific values and lower ignition delay that resulted in lower HRR values than diesel. Again, diesel has longer ignition delay that retarded the start of combustion led to higher HRR [17]. Some researchers also mentioned that diesel has higher HRR values due to its higher calorific value [12, 14, 18].

![Graph showing heat release rate vs. crank angle for different blends and diesel at 1400 rpm and 2400 rpm](a) 1400 rpm  (b) 2400 rpm

**Figure 3.** The differences of heat release rate for PSO blends and diesel under full load at speeds of: (a) 1400 rpm, and (b) 2400 rpm.
3.3. Ignition delay

The time difference between the start of injection and combustion of a diesel engine is the Ignition delay (ID). Fuel quality, engine speed, load, air temperature, and fuel-air mixing ratio affect ID [12]. ID also represents the fuel quality as well as being a measure of the ignition quality (cetane number) and knocking tendency of the fuel [19]. The PSO biodiesel blends have higher cetane numbers than diesel, and Figure 4 shows that all blends have a lower ID period compared with diesel. The ID (MS) decreases with the increase of engine speed. Higher oxygen content, i.e., the higher level of biodiesel blends, PSO20, resulted in lower ID (8.5 °CA at 1400 rpm and 9.5 °CA at 2400 rpm) at full load condition compared with that of diesel (11 °CA at 1400 rpm and 13 °CA at 2400 rpm).

![Figure 4. Ignition delay of diesel and PSO biodiesel blends at full load condition.](image)

3.4. Mass fraction burned

The variation of the mass fraction burned (MFB) with the crank angle for PSO biodiesel blends and diesel at 1400 rpm and 2400 rpm engine speed at full loading condition are compared in Figure 5(a) and (b). Biodiesel blends and diesel showed similar trend and the MFB for biodiesel blends were found earlier than that of diesel at full load condition. From Figure 5(a) at 1400 rpm, 90% of the PSO20 biodiesel blend was burnt at 41.5 °CA after TDC, and the same amount of diesel was burnt at 47.2° CA. Again, from Figure 5(b) at 2400 rpm, the same amounts (90%) of PSO20 biodiesel blend and diesel were burnt at 40° CA, and 43° CA respectively.

![Figure 5. The differences of mass fraction burned (%) for PSO blends and diesel under full load at speeds of: (a) 1400 rpm, and (b) 2400 rpm.](image)
Combustion duration is affected by several factors such as engine speed, load, ignition delay, and fuel characteristics. The higher the engine speed, the lower the combustion duration. Table 3 presents the MFB data for both speeds of 1400 and 2400 rpm at full load condition. PSO20 biodiesel shows faster combustion of about 11.92% at 1400 rpm and 7.93% at 2400 rpm compared to diesel. The fact that biodiesel has a higher content of oxygen than diesel is the primary cause for the shorter combustion duration.

Table 3. Mass fraction burned at full load condition for 1400 rpm and 2400 rpm.

| Fuel   | Speed | 10% Crank angle (°ATDC) | 50% Crank angle (°ATDC) | 90% Crank angle (°ATDC) | Combustion duration (°CA) |
|--------|-------|-------------------------|-------------------------|-------------------------|---------------------------|
| Diesel | 1400  | 8.6°                    | 21.7°                   | 47.2°                   | 38.6°                     |
| PSO5   | 1400  | 8.6°                    | 21.2°                   | 47.1°                   | 38.5°                     |
| PSO10  | 1400  | 8°                      | 20°                     | 42.5°                   | 34.5°                     |
| PSO20  | 1400  | 7.5°                    | 19.5°                   | 41.5°                   | 34°                       |
| Diesel | 2400  | 11.5°                   | 23.1°                   | 43°                     | 31.5°                     |
| PSO5   | 2400  | 11.5°                   | 22.5°                   | 42.8°                   | 31.3°                     |
| PSO10  | 2400  | 11.5°                   | 22.5°                   | 42.5°                   | 31°                       |
| PSO20  | 2400  | 11°                     | 22.5°                   | 40°                     | 29°                       |

3.5. In-cylinder temperature

In-cylinder temperature can be derived from HRR, in-cylinder pressure and fuel injection. The variation of in-cylinder temperature with crank angle for PSO biodiesel blends and diesel are shown in Figure 6(a) and (b). At both engine speeds of 1400 rpm and 2400 rpm, PSO biodiesel blends have higher cylinder temperature compared with diesel. It can be seen that, at full load conditions, all cylinder temperature trends of biodiesel blends and diesel are similar. At the start of combustion, the cylinder temperature increases to the maximum temperature corresponding to the peak cylinder pressure during the diffusion combustion phase. As the combustion finished, the cylinder temperature slowly decreased. At 1400 rpm, PSO20 gives the maximum cylinder temperature of 1642 °C at 30 °CA. However, at 2400 rpm, PSO20 gives the maximum cylinder temperature of 1880 °C at 30 °CA. The maximum cylinder temperature of PSO20, PSO10, and PSO5 blends are higher than that of diesel by 3.17%, 2.75% and 0.31% at 1400 rpm; and 3.73%, 1.86% and 0.39% at 2400 rpm. Biodiesel has a higher oxygen content that increases cylinder pressure as well as cylinder temperature during the transition from compression phase to the combustion phase.

Figure 6. The differences of in-cylinder temperature for PSO blends and diesel under full load at speeds of: (a) 1400 rpm, and (b) 2400 rpm.
4. Conclusion
This study investigated the combustion characteristics of papaya seed oil (PSO) biodiesel in an agricultural diesel engine. Various PSO biodiesel blends and their effects on cylinder pressure, heat release rate, ignition delay, mass fraction burned, combustion duration and cylinder temperature at full load condition at 1400 rpm and 2400 rpm has analysed as well. The results of this investigation can be summarised, as follows:

- In-cylinder peak pressure for PSO biodiesels is higher than that of diesel irrespective of engine speed. At 2400 rpm and full load conditions, the peak cylinder pressure for PSO5, PSO10, and PSO20 were found to be 0.27%, 0.82%, and 2.4% higher than diesel.
- HRR values of PSO biodiesel blends, PSO5, PSO10, and PSO20, were found to be 2.40%, 4.1% and 5.36% lower than diesel due to the lower ignition delay and lower calorific values of biodiesel.
- PSO biodiesel blends have a shorter ignition delay period compared with diesel.
- The mass fraction burned for PSO biodiesel blends is slightly faster than diesel. PSO20 biodiesel shows faster combustion by about 11.92% at 1400 rpm and 7.93% at 2400 rpm than diesel.
- The maximum cylinder temperatures of PSO5, PSO10, and PSO20 blends are higher than that of diesel by 0.31%, 2.75% and 3.17% at 1400 rpm, and by 0.39%, 1.86% and 3.73% at 2400 rpm.

Therefore, it is evident that all PSO biodiesel blends have excellent fuel attributes to be considered as an alternative fuel for agricultural diesel engines. However, a tribology test should be conducted in the future to identify the lubricity behavior of PSO biodiesel blends.

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