Article

Characterization and Impact of Waste Plastic Oil in a Variable Compression Ratio Diesel Engine

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Abstract: The characterization of pyrolysis oil obtained from mixed waste plastics and its utilization in a compression ignition engine were investigated. The chemical compositions and physicochemical properties of distilled waste plastic oil (WPO) and crude waste plastic oil (CWPO) were analyzed. The experiment was conducted with a variable compression ratio diesel engine at various loads and compression ratios to evaluate combustion characteristics, exhaust emissions, and engine performance. The experimental results show that CWPO contains the highest percentage of carbon atoms in the C4–C11 group, while WPO contains the highest percentage of carbon atoms in the C12–C20 group, similar to the main compositions of diesel fuel. According to the preliminary study in chemical compositions and physicochemical properties, WPO and diesel fuel were selected for the engine test at different compression ratios of 16, 17, and 18 and different engine operating loads of 25%, 50%, and 75% of maximum engine torque at an engine speed of 1500 rpm. It was found that increasing the engine operating load and the compression ratio tends to increase the brake thermal efficiency. Increasing the compression ratio results in a significantly shorter delay time in a combustion state. A lower cetane index and a higher percentage of long chain carbon compounds (C12–C20) could be the main factors affecting higher NO_x, CO, and HC emissions with the combustion characteristics of WPO, compared to diesel fuel. The disadvantage of emissions by the use of WPO can be alleviated when the engine is running at maximum load and a high compression ratio.

Keywords: waste plastic oil; compression ratio; emission; diesel engine

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1. Introduction

Fuels for energy is very important to industry, transportation, and agriculture. Currently, the fluctuation of fuel price conditions affects the cost of production and the country's development in various fields. Therefore, the government has promoted the use of renewable energy as an alternative to incentivize people to use other fuels, to replace diesel fuel and to reduce the demand for oil. Thailand mainly relies on imported energy from abroad, because it is unable to increase the domestic production of petroleum to meet demand. The development of renewable energy will seriously reduce the dependence on and import of fuels [1]. Thailand has continued to increase the use of renewable energy as a result of alternative energy development policies with the goal of increasing the use of renewable energy in all sectors of society and reducing the consumption of energy from fossil fuels. This will also reduce the import of energy from abroad [2,3]. Moreover, Thailand is faced with a large amount of solid waste. Large, medium, and small cities all face unsanitary waste management issues that affect the environment. Data on the situation of waste in Thailand show that, in 2018, there were approximately 27.93 million

tons of waste, with a rate of solid waste of 1.15 kg per person per day. Approximately 39% of the total solid waste (10.85 million tons) and 35% of solid waste (about 9.76 million tons) generated has been properly disposed. Approximately 7.32 million tons of solid waste have been improperly handled [4]. Generated plastics are about 12% of the total waste and take a long time to decompose [5]. Therefore, engineering waste management is necessary because, at present, there is technology to effectively manage this waste. One technology that has received attention is oil production technology from plastic waste through the pyrolysis process, due to its potential to convert plastic waste to energy in petroleum-based fuel. This is in line with the National Energy Integration Framework of the Ministry of Energy, devised to develop energy strategic plans in the name of the TIEB (Thailand Integrated Energy Blueprint) 2015–2036, which pays attention to energy security, economic, and environmental aspects of society [3].

Pyrolysis is the process of chemically cycle-debasing long chain polymer particles into small chain hydrocarbons in the absence of air or oxygen at the relatively high temperature range of 300–500 °C [6]. The three significant products from those pyrolysis methodologies are liquid, gas, and char, while the quantity of each product largely depends on such parameters as the type of feedstock and on pyrolysis procedure parameters, such as temperature, the type of reactor, pressure, residence time, heating rate, and the type of catalyst [7]. With respect to the feedstock, plastic waste mainly consists of high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), polypropylene (PP), and polyvinyl chloride (PVC). Studies on the thermal degradation temperature of common plastic materials under thermogravimetric analysis have revealed that degradation begins at a temperature depending on the plastic type and the heating rate. The breakage of carbon chains was induced at a temperature above 325 °C for HDPE and was completed at about 470 °C. Additionally, the degradation process was accelerated at a higher heating rate. The lowest temperature of the starting degradation was obtained with PS. It has been suggested that all plastics initiate degradation at a temperature below 400 °C [8]. The liquid oil derived from the pyrolysis of various types of plastic waste contain physical and chemical properties similar to those of fossil fuel [9–12]. Therefore, waste plastic oil (WPO) is favorably appropriate to be developed as an alternative fuel in internal combustion engines [13].

Several experiments have been conducted on the use of plastic waste derived as a fuel in compression ignition diesel engines. Previous investigations of using WPO in diesel engines compared with diesel fuel operation are summarized in Table 1. Most of the investigations show similar trends of increase in brake-specific fuel consumption and brake thermal efficiency, with increasing concentrations of WPO in blends of diesel and WPO. Moreover, oxides of nitrogen (NO_x), unburnt hydrocarbon (HC), and carbon monoxide (CO) tend to increase with the use of WPO. In a recent work, Kalargaris et al. [14] studied the effect of pyrolysis oil from polypropylene on the characteristics of combustion, exhaust emissions, and engine performance at different temperatures of the pyrolysis process in a diesel engine. The experiments showed that the pyrolysis oil promoted steady engine operation with a longer combustion duration, a lower engine performance, a higher NO_x and HC, and lower CO emissions when compared with the engine operating on diesel fuel. Venkatesan et al. [15] studied the combustion characteristics and the engine performance of a diesel engine fueled with WPO blends. The brake thermal efficiency (BTE) for the WPO blends was found to be slightly higher than that of the diesel fuel. The engine performance and combustion characteristics of the diesel engine were significantly affected by the physical and chemical properties of WPO. Furthermore, at the highest load conditions, WPO blends yield better results in comparison to diesel fuel with respect to peak pressure, the rate of pressure rise, in-cylinder pressure, and the rate of heat release. The use of WPO as an alternative fuel in diesel engines tends to result in an increase in BTE, NO_x, and smoke emissions, while BSFC, CO, and HC emissions decrease with an increasing engine load [16–22].

Table 1. Summary of previous investigations on using waste plastic oil (WPO) in diesel engines compared with diesel fuel operation.

Diesel Engine Specifications	Types of Fuel	Performance		Combustion		Emissions				Ref.
		BSFC	BTE	ICP	RoHR	NO _x	CO	HC	Smoke	
AKSA-A4CRX46TI, 4-cylinder, 4-stroke, 68 kW at 1500 rpm	WPO	-	↓	↑	↑	↑	↑	↑	-	[14]
Kirloskar AV1, DI, 1-cylinder, 4-stroke, 3.7 kW at 1500 rpm	WPO	↑	↑	↑	↑	↑	↑	↑	↑	[16]
AKSA1-A4CRX46TI, 4-cylinder, 4-stroke, 68 kW at 1500 rpm	WPO	↑	↓	↑	↑	↑	↑	↑	↑	[17]
4JA1, DI, 4-cylinder, 4-stroke, 68 kW at 1500 rpm	WPO	↑	↓	↓	↑	↑	↑	↑	↓	[18]
Kirloskar TAF1, DI, 1-cylinder, 4-stroke, 4.4 kW at 1500 rpm	WPO	↓	↑	-	-	↑	↑	↑	-	[19]
Eicher E483, DI, 4-cylinder, 4-stroke, Max. Power 70 kW	WPO	↓	↑	↑	↑	↑	↑	↑	↑	[20]
Kirloskar TV1, DI, 1-cylinder, 4-stroke, 5.2 kW at 1500 rpm	WPO	↓	↑	-	-	↑	↑	↑	↑	[21]
DI, Turbocharger, 4-cylinder in line T/C, 4-stroke, 70 kW	WPO	↓	↑	↑	↑	↑	↑	↑	-	[22]
DI, 1-cylinder, 4-stroke, 3.7 kW at 1500 rpm	WPO	-	↓	↑	↑	-	-	-	-	[23]
Lombardini-Kohler FOCS 1.4, IDI, 1-cylinder, 4-stroke,	WPO	↓	↑	↓	↓	-	-	-	↓	[24]
Kirloskar TAF1, DI, 1-cylinder, 4-stroke, 4.4 kW at 1500 rpm	WPO	-	↓	↑	↑	↑	-	↑	↑	[25]
AKSA-A4CRX46TI, 4-cylinder, 4-stroke, 68 kW at 1500 rpm	WPO	↑	↓	↑	↑	↑	↑	↑	-	[26]
DI, 1-cylinder, 4-stroke, 3.7 kW at 1500 rpm	WPO-RME	↑	↑	↓	↓	-	-	-	-	[27]
Kirloskar TV1, DI, 1-cylinder, 4-stroke, 3.5 kW at 1500 rpm	WPO-POME WPO-COME	↑	↑	↓	↓	↓	↑	↓	↑	[28]
Kirloskar TAF1, DI, 1-cylinder, 4-stroke, 4.4 kW at 1500 rpm	WPO-BU	↓	↑	-	-	↑	↑	↑	↓	[29]

↑—increases, ↓—decreases, WPO—waste plastic oil, RME—rice bran methyl ester, POME—palm methyl ester, COME—castor methyl ester, BU—Butanol, DI—Direct injection.

Currently, there is an increasing amount of research on alternative fuels for engines, and due to energy, environmental, and economic problems, it is necessary to encourage studies on alternative fuels to reduce the amount of primary fuel consumption. For the adoption of WPO gained from the pyrolysis process for compression ignition engines, it is necessary to study the effects of various factors. Therefore, this research aims to investigate the effects of changes in the compression ratio on the characteristics of combustion, exhaust emissions, and engine performance when using WPO as an alternative fuel in a variable compression ratio diesel engine. The outcome of this research can promote WPO as an alternative fuel for diesel engines and accords with alternative energy development plans in Thailand.

2. Materials and Methods

2.1. Fuels

In this work, crude waste plastic oil (CWPO) and distilled waste plastic oil (WPO) obtained by fractional distillation were studied. The mixed plastic waste used as feedstock in the pyrolysis process was collected from Nakhon Ratchasima, Thailand, and included bags, bottles, and other products made of plastic. The diesel fuel was commercial diesel fuel (B7), which is diesel fuel containing 7% biodiesel by volume, according to the Ministry of Energy. The master plant that processes mixed waste plastic into fuel by pyrolysis is located at Suranaree University of Technology.

Pyrolysis is the thermal decomposition of plastics in the absence of air or oxygen. Waste plastics are gently cracked by adding a catalyst, and the gases are condensed in a series of condensers to yield a low-sulphur distillate [28]. The pyrolysis reactor system is of a continuous vertical type. The plastic waste from the MBT system was used as a raw material for fuel production. The principle of operation is that the plastic scraps are conveyed to a screw feeder at a rate of approximately 250 kg/h, where the screws are preheated to allow the plastic to melt and be ready to evaporate as a vapor when heated up. After that, the liquid plastic flows into the reactor and then the continuous stirred tank reactor, where the reactor is temperature-controlled at 350–400 °C. When the plastic changes from liquid to vapor, it flows into the fractional distillation tower at a temperature of 340 °C, and at this distillation tower, it separates the heavy and light oil vapor molecules. After that, the oil vapor enters the condenser and flows into the oil/water separator, and the oil that is produced, i.e., CWPO, will flow into the storage tank. We used an oil distillation system to improve the quality of liquid fuels from plastic waste by using a vacuum separation tower to separate the mixtures into the form of individual elements (fractions). The middle fraction or diesel fuel, i.e., WPO, is taken from the center of the distillation tower, and the lighter part (the light fraction) or gasoline is released from the top of the distillation tower.

2.2. Gas Chromatography Analysis

Gas Chromatography–Mass Spectrometry (GC–MS) is extensively used as a method for the chemical characterization of the fuels. The presence of the compound identification of test fuels was used to determine the chemical compositions. One microliter was injected into a GC–MS system equipped with a DB-wax capillary column of a length of 60 m, an internal diameter of 0.25 mm, and a film thickness of 0.25 µm. The operating conditions were as follows: The helium gas flow rate of approximately 1.0 mL/min was utilized as a carrier gas. The temperature of the GC oven was performed in a temperature-programmed mode at 70 °C for 3 min, raised at 3 °C/min to 180 °C, and finally ramped to 250 °C (held for 25 min) at a heating rate of 10 °C/min. The inlet gas temperature was maintained at 250 °C with a separation ratio of 20:1. The mass spectra detector was operated in a mass range from 35 to 550 m/z with a 250 °C source [28]. GC–MS data are often demonstrated as total ion current (TIC) intensity. The data obtained from TIC can be used to identify the chemical composition of the test fuels.

2.3. Experimental Setup and Procedure

The study on combustion and emissions characteristics was conducted using a variable compression ratio (VCR) diesel engine, a single-cylinder and four-stroke engine with a direct fuel injection system. The air was naturally induced to the combustion chamber, while water and a water-cooling system were used to control the temperature of the engine. The engine was coupled with an eddy current dynamometer to provide the engine load. The technical specifications of the engine used for the investigations are described in [28]. A schematic diagram of the experimental installation is shown in Figure 1. The engine operated at 1500 rpm with three different engine loads (25%, 50%, and 75% of the maximum engine torque) under compression ratios of 16, 17, and 18. The fuel consumption of the engine was calculated by the fuel volume and testing time, which were recorded by a burette and stopwatch, respectively.

Figure 1. A schematic diagram of the experimental installation.

EngineSoft software was used to analyze the combustion characteristics. A data acquisition card (DAQ) placed between the engine and computer converted the analog signal to a digital value. The PCB Piezotronics pressure transducer was mounted on the cylinder head for the measurement of the in-cylinder pressure. A Kubler crank angle sensor was used to detect the engine crank angle. The in-cylinder pressure data were averaged for 100 cycles in succession at each crank angle. A Testo 308 smoke tester was used to determine smoke emissions, and a Testo 350 flue gas analyzer was applied to determine carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbon (HC). The technical specifications of the exhaust gas analyzer are shown in Table 2.

Table 2. Specifications of the engine exhaust gas analyzer.

Parameter	Measuring Techniques	Measuring Range	Resolution	Accuracy
<i>TESTO 350</i>				
NO	Chemiluminescence	0–4000 ppm	1 ppm	±5 <100 ppm
NO ₂	Chemiluminescence	0–500 ppm	0.1 ppm	±5 <100 ppm
CO	Nondispersive Infrared	0–10,000 ppm	1 ppm	±10 <200 ppm
HC	Flame Ionization Detector	0–40,000 ppm	10 ppm	±400 ppm
<i>TESTO 308</i>				
Smoke index	Photodiode (filter paper)	0–6	0.1	±0.2

The measurements of the various parameters were recorded only after the engine attained the steady state. To assure the reproducibility of the experimental data, each test was duplicated three times, and the average value of the reported parameters was then evaluated. The statistical significance of the experimental data was provided using the confidence interval with a 95% confidence level to consider the trends of the results.

3. Results and Discussion

3.1. Test Fuels

The physicochemical properties of distilled WPO and CWPO obtained by fractional distillation were studied. Analysis of fuel properties is essential, as it can ensure the suitability of a fuel for use with a compression ignition engine. Standard grade diesel fuel with 7% biodiesel (B7) was used for our baseline study. This percentage of biodiesel present in the diesel fuel was prescribed by the Thailand Energy Business Department in January 2019.

3.1.1. Chemical Compositions

The distillation characteristics of hydrocarbon fuel have an important effect on their safety, combustion characteristics, exhaust emissions, and engine performance, especially in the case of waste fuels. The WPO from pyrolysis and the diesel fuel were tested by performing a simple batch fractional distillation on a laboratory scale. The distillation curves of the test fuels were tested according to the standard ASTM distillation apparatus. The distillation curves of the test fuels obtained under standardized conditions of temperature with a percentage of recovered volume and distillation curves of standard gasoline by Lobato et al. [30] are compared in Figure 2. The distillation curves of CWPO were closer to those of gasoline, with a distillation temperature between 76 and 252 °C. On the contrary, the distillation temperature of distilled WPO was much closer to that of diesel fuel as the recovered volume increased, with a distillation temperature between 188 and 324 °C. Lines in Figure 2 also confirm that WPO can be used as an alternative fuel in diesel engines. This is due to the distillation temperature that is desired to produce motor engines. This can be done with hydrocarbon fuel with boiling point ranges between 35 and 185 °C for gasoline, between 180 and 350 °C for diesel fuel, and between 180 and 350 °C for vacuum gas oil [31].

Figure 2. Distillation curves of test fuels obtained by fractional distillation.

GC–MS (compare with Section 2.2) for the test fuels was done to its chemical composition and is shown in Figure 3. The area percentage (%Area) is presented in Table 3. The test fuels consist of different amounts of hydrocarbons, which were separated by their carbon atomic weight from the minimum carbon atom (C4) to the maximum carbon atom

(>C20) and can be categorized as C4–C11, C12–C20, or higher than C20. The C4–C12 group represents light hydrocarbons (gasoline fuel), which generally contain hydrocarbons between C5 and C9. The C12–C20 group represents middle hydrocarbons (diesel fuel), which generally contain hydrocarbons between C16 and C20. Table 4 compares the test fuels and shows that there was a similar trend between WPO and the standard-grade diesel fuel. Both WPO and diesel fuel have carbon atoms in the C12–C20 group [13,28]. However, CWPO has a high percentage of carbon atoms in the C4–C11 group. Based on the results of the chemical composition tests, CWPO was estimated to have a similar chemical composition to fuel in the category of the gasoline group, and the WPO has a chemical composition similar to diesel fuel. The chemical compositions obtained by GC–MS are consistent with the distillation curves, and the distillation curves of WPO and diesel fuel are similar. As a result of this finding, WPO was used on a VCR diesel engine to evaluate combustion characteristics, exhaust emissions, and engine performance in comparison to diesel fuel. Different plastic sources used in the pyrolysis process to produce oil resulted in different chemical compositions of CWPO, which may have affected the result of the engine tests in different ways. This can be supported by the chemical compositions (by GC–MS analysis) of WPO derived from the mixtures of plastic waste used in our current study and in previous studies [28]. In addition, different GC–MS results of liquid oil from pyrolysis of different types of plastic waste were reported in [32]. Therefore, the distillation process may be needed to control the chemical compositions of fuels derived from plastic oil.

Figure 3. GC–MS chromatogram for (a) Diesel, (b) CWPO, and (c) WPO.

Table 3. Components of diesel and WPO by GC–MS analysis.

Carbon Content	Diesel	CWPO	WPO
C4	ND	2.77	ND
C5	ND	0.84	ND
C6	ND	3.76	ND
C7	ND	5.38	ND
C8	2.54	34.02	1.03
C9	5.61	19.94	0.73
C10	5.23	28.49	2.28
C11	4.18	0.53	5.71
C12	7.08	0.75	9.78
C13	6.39	ND	10.08
C14	8.09	ND	11.03
C15	5.66	0.67	10.48
C16	5.95	0.19	8.71
C17	15.80	0.26	7.90
C18	4.30	0.32	8.88
C19	16.11	0.36	7.86
C20	3.90	0.24	8.10
C21	3.19	0.36	3.63
C22	ND	0.27	2.29
C23	2.36	0.20	1.08
C24	ND	0.19	0.43
C25	1.19	0.20	ND
C26	1.13	0.18	ND
C27	0.62	ND	ND
C28	0.34	0.08	ND
C29	0.33	0.08	ND

ND—Not detected.

Table 4. Carbon content of the test fuel compared with diesel fuel by GC–MS analysis.

Carbon Content	Area Percentage		
	Diesel	CWPO	WPO
C4–C11	13.38	95.72	9.74
C12–C20	75.00	2.79	82.83
>C20	11.62	1.49	7.43

3.1.2. Chemical and Physical Properties of the Test Fuels

The physicochemical properties of CWPO, WPO, and diesel were tested according to the American Standard of Testing Methods (ASTM). The characteristic properties of the test fuels are shown in Table 5. The kinematic viscosity, flash point, calorific value, cetane index, and distillation temperature of CWPO and WPO were lower than they were in diesel fuel. In addition, the kinematic viscosity, surface tension, flash point, and distillation temperature of WPO were higher than those of CWPO. Thus, the characteristic properties of CWPO were more similar to those of gasoline. However, the kinematic viscosity, specific gravity, density, gross calorific value, and distillation temperature of WPO were closer to those of diesel fuel.

Table 5. Basic physicochemical properties of CWPO, WPO, and diesel fuel.

Properties	Test Method	Diesel	CWPO	WPO
Kinematic viscosity at 40 °C (cSt)	ASTM D445	3.44	1.66	3.11
Surface tension (mN/m)	ASTM D971	-	27.77	27.85
Specific gravity at 15.6 °C	ASTM D1298	0.835	0.900	0.824
Density at 15.6 °C (kg/m ³)	ASTM D1298	834	899	823
Flash point (°C)	ASTM D93	66	35	54
Gross calorific value (MJ/kg)	ASTM D240	45.56	37.72	45.24
Cetane index	ASTM D976	56.57	-	46.7
Distillation temperature (°C)	ASTM D86			
10% Recovered (°C)	ASTM D86	228	112	232
50% Recovered (°C)	ASTM D86	290	164	276
90% Recovered (°C)	ASTM D86	348	252	324

3.2. Engine Tests

We investigated the use of WPO in a VCR diesel engine. WPO was compared with diesel fuel. The present study focuses on engine performance, the characteristics of combustion, and engine exhaust emissions.

3.2.1. Engine Performance

The variation in brake-specific fuel consumption (BSFC) with engine loads at different compression ratios is shown in Figure 4. BSFC is the fuel flow rate needed by the engine to produce unit power. The BSFC decreases with any increase in engine operating loads or compression ratio. This may be due to the efficiency increase caused by the cylinder temperature increase, the reduced ignition delay period, or the total timing increases, which bring about the better combustion at higher engine loads and higher compression ratios [33,34]. Moreover, the BSFC of WPO was higher than that of diesel at all compression ratios due to its lower gross calorific value, as can be seen in Table 5, showing that more fuel is needed in the combustion process to obtain the same power output as diesel fuel [16,29,35].

Figure 4. Variation in brake specific fuel consumption (BSFC) with engine loads.

The variation of brake thermal efficiency (BTE) with engine loads at different compression ratios is shown in Figure 5. BTE indicates the conversion of the energy in the fuel to brake power output. Increasing the engine operating loads tends to result in more BTE.

The BTE of WPO was found to be lower than that of diesel fuel at all engine loads and all compression ratios. More energy is needed to break down the heavy hydrocarbon chains (C13 to C22) in WPO, which might explain the lower BTE of WPO [29]. BTE also increased with the increase in compression ratio for all test fuels, since the increase in compression ratio also increases the in-cylinder temperatures, which improves combustion and thermal efficiency [36,37]. This improvement in BTE could also be attributed to the reduction in ignition delay as the compression ratio increases [38].

Figure 5. Variation of the brake thermal efficiency (BTE) with engine loads.

3.2.2. Combustion Characteristics

The variation in heat release rate and in-cylinder pressure is summarized as follows.

The variation in the rate of heat release (RoHR) and in-cylinder pressure (ICP) with the crank angle for WPO and diesel fuel at different engine loads is presented in Figure 6. ICP measurements play a key role in combustion analysis of the thermal energy produced during the fuel combustion process in each engine cycle. The RoHR was calculated using the in-cylinder pressure, which is measured according to the first law of thermodynamics and isentropic relations [39]. ICP and RoHR were found to increase as the engine load increased in all tests due to the higher charge of the mixture that was carried to the cylinder [40]. Compared with diesel fuel, a lower in-cylinder pressure was obtained with WPO at medium and high engine loads for CR18. In addition, the start of the combustion of WPO, compared to that of the diesel fuel, was more delayed. This may be due to the lower density of WPO, which can result in a lower bulk modulus. In addition, the lower cetane index of WPO could explain the delay time in combustion with WPO [18,41]. A higher engine load leads to a shorter ignition delay period and longer combustion periods. This is due to the increase in temperature inside the combustion chamber, which tends to improve the quality of the air–fuel mixture, leading to a decrease in the ignition delay [42].

Figure 6. Variation in heat release rate and in-cylinder pressure with the crank angle.

The ICP and RoHR variation with the crank angle for WPO and diesel fuel at different compression ratios are illustrated in Figure 7. The maximum ICP was found at CR18. Maximum ICP mainly depends on the quality of the fuel oil, injection timing, ignition timing, and the atomization of fuel [26]. From Figure 7, it can be seen that, as compression ratio increases, ICP also increases. This increase in ICP may be attributed to the better mixing of air and fuel during the initial stage of combustion [42]. On the other hand, as the compression ratio increases, the peak of the RoHR decreases. In general, a higher accumulation of injected fuel over a longer delay period can result in a higher RoHR in the premixed combustion [43]. A higher compression ratio leads to an advance at the start of combustion because of the higher in-cylinder temperature and pressure, which results in better atomization with a higher fuel vaporization rate, leading to an earlier ignition or a shorter ignition delay [44].

Figure 7. Variation in the rate of heat release (RoHR) and in-cylinder pressure (ICP) with the crank angle at different compression ratios at a 75% maximum engine torque: (a) diesel; (b) WPO.

3.2.3. Emission Characteristics

The engine-out emissions comprised carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbon (HC), and smoke, which were produced by the combustion of distilled WPO and diesel fuel, were investigated under different engine operating loads and compression ratios. The specific emissions that relate to the mass flow rate of emissions per unit power output were calculated for carbon monoxide, nitrogen oxides, and unburned hydrocarbon.

The variation in specific nitrogen oxide (NO_x) emissions with engine loads at different compression ratios is shown in Figure 8. Nitrogen oxide (NO_x) is nitric oxide (NO) and nitrogen dioxide (NO₂) in the exhaust of internal combustion engines [45]. The experiment showed that the NO_x emissions decreased as the engine operating load increased for all test fuels. In general, specific quantities can decrease as power output increases. A lower oxygen availability can be taken into account for a reduction in NO_x when an engine is run at a high engine load. As compared with diesel fuel, the NO_x emissions of WPO were higher than those of diesel fuel. This was due to the longer ignition delay owing to the long chain carbon compounds in the WPO [46]. In addition, the increase in the compression ratio increased the NO_x emissions of WPO and diesel fuel. Increasing the cylinder pressure at a higher combustion temperature tends to be conducive to NO_x formation. Furthermore, the advance in the combustion state due to a higher compression ratio can increase the combustion duration, leading to improvements in the combustion process that result in higher NO_x emissions. Evidence of the advance at the start of combustion and the higher in-cylinder pressure as the compression ratio increases is shown in Figure 7.

Figure 8. Variation in the nitrogen oxide (NO_x) emissions with engine loads.

The variation in carbon monoxide (CO) emissions with engine loads at different compression ratios is shown in Figure 9. CO emission is an intermediate product in the combustion of hydrocarbon fuels that contain no oxygen in their molecular structure [47]. It is formed mainly due to incomplete combustion, which is exacerbated by a lack of oxygen, the in-cylinder temperature, and the residence time of combustion [45]. We observed that increasing the engine operating loads resulted in a decrease in CO emissions for all test fuels. The reason behind these decreased CO emissions may be due to the increase in combustion efficiency as engine operating load increases [34,48]. Comparing the test fuels, higher CO emissions were found due to the combustion of WPO. The lower cetane index of WPO, which tended to delay the combustion state, resulting in a reduction in the residence time of combustion, can explain the higher CO emissions from the use of WPO. This can

be more effective in increasing CO emissions when the engine is run at a low engine load condition, where the ICT is not high enough to convert the injected fuel to vapor. In addition, a higher amount of long chain carbon compounds (C12–C20) in WPO tended to cause more difficulty in combustion, leading to an increase in CO emissions [48]. The CO emissions increased as the compression ratio changed from CR16 to CR17. However, the CO emissions were considerably reduced when the engine operated at CR18, especially at a low engine load. The CO emissions of WPO tended to decrease as the compression ratio increased and the engine was run at a maximum load. A higher combustion efficiency was found at a higher compression ratio due to a higher charged air temperature, leading to improved air–fuel mixtures and faster fuel vaporization, resulting in more complete combustion (Figure 5).

Figure 9. Variation in the carbon monoxide (CO) emissions with engine loads.

The variation in unburned hydrocarbon (HC) emissions with engine loads at different compression ratios is shown in Figure 10. In general, HC emissions indicate a very similar qualitative behavior to CO emissions. Both HC and CO emissions are useful for evaluating combustion efficiency. It was found that, as the engine operating load increased, the HC emission increased for all test fuels, at low and medium engine loads. However, at a high engine load, the HC emissions tended to decrease due to a more complete combustion. Comparing the test fuels, more HC emissions were obtained with the combustion of WPO compared to diesel fuel. The presence of 7% biodiesel present in standard diesel fuel enhanced the combustion process due to the oxygen content of the fatty acid methyl ester. Moreover, a lower cetane index and a higher amount of long chain carbon compounds (C12–C20) led to a longer ignition period and more difficulty in combustion, which can explain the higher CO emissions of WPO [18,27]. As compression ratio increased, in-cylinder pressure and temperature increased (Figure 7). This improved the air–fuel mixture, leading to a more complete combustion. In addition, a shorter delay at the start of combustion with an increasing compression ratio led to a longer combustion process, where lower CO emissions were found at higher compression ratios.

Figure 10. Variation in the unburned hydrocarbon (HC) emissions with engine loads.

The variation in smoke emissions with engine loads at different compression ratios is shown in Figure 11. Smoke emission is an indication of poor combustion caused by an over rich air-fuel mixture [45]. Smoke emissions increase with increases in engine operating loads when a rich mixture is burnt in the cylinder [33]. Compared with diesel fuel, a lower smoke emission was found with the combustion of WPO. It is noted that the diesel fuel used in this study is standard grade and contains 7% biodiesel. In general, the presence of oxygen in biodiesel is evidently associated with an improvement of smoke emissions. It was expected that the smoke emissions from standard diesel fuel would be lower than those of WPO. These lower smoke emissions could be explained by the lower viscosity and lower distillation temperature of WPO (Figure 2), which can improve fuel atomization, resulting in an enhancement in the combustion process. These two factors were more likely to contribute to the reduction in smoke emissions with WPO when the engine was run at low and medium loads, together with a high compression ratio. As the compression ratio increased, smoke emissions tended to decrease for all test fuels. The higher combustion temperature and shorter delay time of combustion could explain the lower smoke emissions at higher compression ratios. However, the combustion of WPO with an overly rich air-fuel ratio, when the engine was run at the highest load, tended to increase smoke emissions as the compression ratio increased. This implies that the effect of lower viscosity and distillation temperature cannot reduce emissions at the highest engine load and compression ratio.

Figure 11. Variation in smoke emissions with engine loads.

4. Conclusions

The effects of compression ratio on combustion characteristics, exhaust emissions, and engine performance using WPO obtained from the pyrolysis process as an alternative fuel for compression ignition engines were studied. The results of GC–MS show that CWPO in this study contains the highest percentage of carbon atoms in the C4–C11 group and cannot be directly used as fuel in a compression ignition engine. WPO was prepared by distillation to improve the quality of the pyrolysis oil, and its properties were very close to those of diesel fuel. It is notable that different plastic sources used in the pyrolysis process can result in different chemical compositions of CWPO. Thus, the distillation process may be needed to control the chemical compositions of fuels derived from plastic waste.

The WPO was tested in the variable compression ignition diesel engine to evaluate combustion characteristics, exhaust emissions, and engine performance. Diesel fuel was also tested in the engine as a baseline fuel. The findings from the engine test can be summarized as follows.

- A lower cetane index and a higher percentage of long chain carbon compounds (C12–C20) resulted in higher NO_x, CO, and HC emissions caused by the combustion of WPO.
- The disadvantage of emissions by the use of WPO can be alleviated when the engine operates at a high engine operating load and a high compression ratio.

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Nomenclature

BSFC	brake-specific fuel consumption
BTE	brake thermal efficiency
CO	carbon monoxide
CWPO	crude waste plastic oil
CR	compression ratio
GC–MS	gas chromatography–mass spectrometry
HC	hydrocarbon
ICP	in-cylinder pressure
NO	nitric oxide
NO ₂	nitrogen dioxide
NO _x	nitrogen oxides
RoHR	rate of heat release
TDC	top dead center
VCR	variable compression ratio
WPO	distilled waste plastic oil

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