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Performance Characteristics of a Compression Ignition (CI) Engine Using an Environmentally Friendly Waste Plastic Fuel

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Abstract

Due to growing demands and depleting reserves of petroleum-based fuel, there is a necessity to find an alternative fuel for IC engines. Also, environmental concerns and globally faced problems like lots of garbage generated through plastics is a major issue in India. There is a significant disparity between plastic production and waste plastic generation. Therefore, the need for alternative fuels derived from municipal plastic waste has emerged to enhance the performance of IC engines, decrease emissions, and address other environmental concerns in line with the "Swachh Bharat Mission of India". In this study, the alternative fuel was produced from a municipal mix of plastic waste by pyrolysis process. The experiments were carried out with a constant speed of 1500 rpm at different load conditions and fueled with standard diesel, waste plastic fuel and other blends to investigate IC engine performance and combustion and emissions in terms of brake thermal efficiency, brake power, brake specific fuel consumption, cylinder pressure, net heat release, mean gas temperature, rate of pressure rise, andbrake specific CO2, NOx, CO and HC emissions parameters were investigated and it is compared with standard diesel. The overall result shows that WPO20D80 and WPO30D70 exhibit the peak performance (torque, BP, BTE and BSFC) and lowest emissions (HC, CO, NOx) at all load conditions. Moreover, according to all the performance results, the lowest BSFC with maximum brake thermal efficiency and variations was 24.01% and 0.346 Kg/kWh for the WPO30D70 blend at part load condition. The minimum brake-specific NOx produced by the diesel blend at peak load conditions (WPO20D80) is 138.66 ppm, which is higher than other blends. This phenomenon may be attributed to an elevated proportion of pre-combustion and an extended ignition duration, resulting in a high cylinder temperature and an enhanced rate of heat release. This analysis contributes to a deeper understanding of the environmental implications associated with different fuel blends and load conditions. Notably, the blends ranging from 10% to 50% showed good tendencies to be utilized with diesel engines and consistently exhibit favourable brake-specific emission profiles, suggesting its potential as an environmentally friendly alternative fuel.

Keywords: *Alternative Fuels, Combustion, Diesel Engine, Emissions, Performance, Waste Management, Waste Plastic Fuel*

1.0 Introduction

Fossil diesel use is steadily increasing in the transportation, manufacturing, and industrial sectors, rendering its existence obsolete soon. Numerous researchers have conducted extensive research to identify a viable substitute for diesel fuel. In this scenario, the abundance of plastic garbage and their incorrect disposal procedures have piqued the interest of researchers in converting them into alternative fuel for IC engines[1]. Yaqoob *et al.*, for their experimental research, over the past few decades, there has been a substantial increase in the usage of plastic, which is one of the main sources of solid waste generation in several countries. There are several ways to handle

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plastic waste, two of which are recycling and converting it into energy. Consequently, the procedure for turning waste plastic into energy and utilizing it in diesel engines without any modification. The findings demonstrated that blends of PPO into diesel fuel resulted in enhancements in cylinder pressure, BP, and BTE, while simultaneously reducing BSFC. It is recommended to utilize a 10% to 90% blend of PPO-diesel as a viable fuel[2]. Mani *et al.,* looking for alternate fuel sources is becoming even more important in the current economic crisis brought on by rising oil prices. Due to rapid population growth in the economy, energy consumption is expected to double by 2030, even though energy demand is continually increasing[3]. Kumar and Singh have considered that waste plastics are high in energy, so turning them into fuels is a promising solution. Kumar *et al.,* have used conventional processing techniques like pyrolysis, gasification, hydro cracking, catalytic cracking, and others can be used to do it. Pyrolysis is the most recommended and effective method for turning waste plastic into plastic oil[4,5]. The process of thermal decomposition known as pyrolysis takes place in the absence of oxygen. Waste plastics may be pyrolyzed into such products are liquid, solid and gas. The types of waste plastic used to feed the pyrolysis reactor and the process variables determine the quality of the pyrolysis products. Kalargaris *et al.,* in their experimental results, showed that BTE was found lower and NOx was found higher than diesel. Furthermore, as the blending ratio of PPO increased, all emissions including NOX, UHC, CO, and CO_2 also increased. It is important to highlight that at blending ratios ranging from low to moderate, the increase in Nitrogen oxide and levels of CO concentrations was quite insignificant. It should be noted that for low to moderate blending ratios, the rise in NOX and CO levels was relatively minimal[6]. Wallis and Bhatia discussed the types of plastic, the pyrolysis reactor, and process variables like catalyst, residence time, and temperature all influence how effectively a pyrolytic product turns out[7]. Wan Mahari *et al.*, the current research focuses on the co-pyrolysis technique used for recovering biofuel from municipal waste[8]. Kalargaris *et al.*, research studied the pyrolysis oils produced from polyethene. LDPE700 has lower peak values of rate of heat release compared to diesel under full load conditions. Found that a viscosity increase can cause poor atomization and sluggish heat release, contributing to these behaviours[9]. Lakshmana Kumar *et al.*, trials were carried out using waste plastic oil combined with diesel fuel and conducted an analysis of the physicochemical features of waste plastic and differentiated between the fuel injection characteristics of the pyrolysis oil and diesel[10]. Jha and Kannan research studied in thermal cracking. This technique is the most significant method for converting plastic waste collected from municipal solid waste such as HDPE, LDPE, PP, and PS into fuel. According to the findings, an optimized pyrolysis process reduces carbon emissions and environmental burdens[11]. Othman *et al.*, research focused conversation to biodiesel, the biodiesel was made from waste plastic oil, and its performance and emissions were studied. The results demonstrate that performance metrics improved, increased torque output and specific fuel consumption was reduced. Also found that HC reduces CO emissions while increasing NOx and CO_2 emissions[12]. Damodharan *et al.*, found that plastic garbage is a multifaceted problem that has both economic and ecological impacts. The several experiments were conducted on diesel engines and found higher NOx emissions produced and decreased HC and CO with WPO[13]. Kaimal and Vijayabalan studied their research based on statistical data, approximately 11% of the 19-23 million metric tons of plastic waste that was transported worldwide in 2016 ultimately found its way into marine habitats. Given the alarming concerns expressed by various nations, it is projected that the annual amount of plastic waste entering the oceans could potentially escalate to 53 million metric tons by the year 2030. The results showed that the performance and emissions were reduced while using plastic blends[14]. Kaimal and Vijayabalan conducted numerous experiments in a diesel engine with a single cylinder, in which various mixtures of PO 50 and PO 75 were prepared using plastic oil. The findings indicated that the thermal efficiency of both the blends and pure plastic oil consistently exhibited lower values compared to diesel under all loading circumstances. In addition, the fuel's combustion characteristics of the fuel are significantly influenced by its physical properties[15]. Pal *et al.*, their experimental results showed that when the load increased, BTE, HC, CO, CO_2, and level of smoke were increased, but BSFC levels decreased and NOx emission was also decreased[16].

As a part of the "Swachh Bharat Mission of India", this research work aims to use an alternative fuel that is

produced from municipal mix waste plastics to improve the IC engine performance, and combustion and correspondingly reduce emissions without modification of the engine.

2.0 Conversation of Waste Plastic into Useful Alternative Fuel

The fixed pyrolysis system plant is available at Petlad Nagar Palika, Anand, Gujarat, and with the help of this process municipality mix plastic waste is converted into useful products like oil, gas, wax, and char by using the catalytic thermo chemical decomposition process. Pyrolysis is a thermo chemical process that involves the degradation of organic material at high temperatures without the presence of oxygen. Plastic pyrolysis is a very efficient procedure in which plastic is subjected to elevated temperatures of around 430°C in an atmosphere devoid of oxygen. The plastic pyrolysis process consists of five key steps: Waste plastic, pretreatment process, shredder, pyrolysis process after condensation, and purifying processes. The initial step involves subjecting the waste plastics to a pretreatment procedure, which effectively eliminates any extraneous substances. Subsequently, the plastics are directed to a specialized machine designed to shred them into smaller pieces. Make use of this apparatus to break down the plastic into smaller pieces. The smaller pieces of plastic are next placed into a densifier, which compresses them into a dense substance for more convenient storage or handling. They are then directed into a reactor chamber where the pyrolysis process takes place. The plastic is heated up to temperatures ranging from 450 to 500°C in the presence of catalysts such as zeolites except for oxygen. The plastic begins to undergo stages of melting and conversion into a gaseous state. The gases produced are subsequently transferred into a condenser, where they undergo condensation. Once the condensed liquid is introduced into an oil refinery chamber, the plastic waste undergoes a refining process that results in the production of around 75 to 80% oil, 10 to 15% gas, and 5 to 7% carbon black or ash. This procedure is friendly to the environment as the water-deducting procedure may prevent the emission of black smoke. The exhaust gas will be reused in the heating reactor, ensuring that no gas emission occurs. The pyrolysis technique is being used to transform waste plastic into a viable resource.

3.0 Materials and Methodology

In the exploration of fuel performance under controlled conditions, a series of experiments were conducted, maintaining consistent parameters: A constant 1500 rpm, a compression ratio of 18, and varying loads from 0% to 100% intervals. This systematic approach was designed to elucidate the influence of various loads on distinct fuel blends, examining their performance parameters, combustion and Brake-Specific Emission (BSE) characteristics through the experimental analysis.

4.0 The Arrangement and Process Used for the Experiment

4.1 Fuel Preparation

Numerous experiments were conducted using different proportions of Waste Plastic Fuel (WPO) to Standard

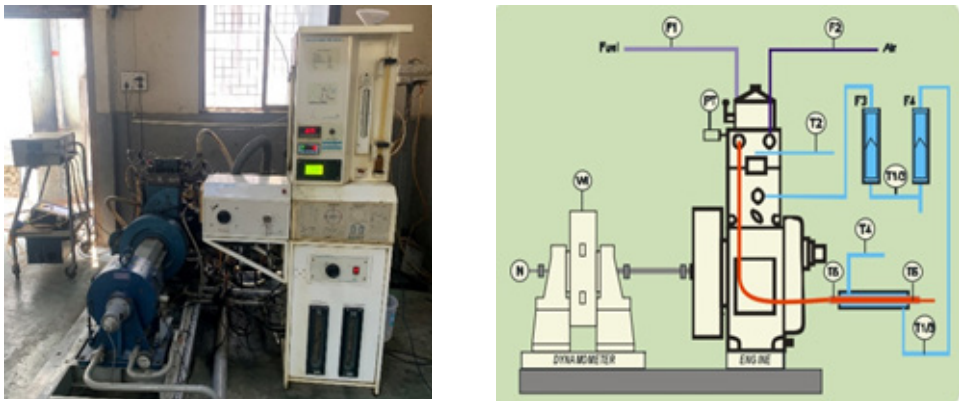


Figure 1. Schematic diagram of the test engine.

Table 1. Specifications of tested fuels

Property	Method	D100	WPO10D90	WPO20D80	WPO30D70	WPO50D50	WPO100
Density at 25°C (kg/m^3)	ASTM D287	821	817	814	811	804	796
LCV Calorific Value (Cal/gm)	ASTM D4809	10131	9948	9872	9771	9644	9586
HCV Calorific Value (Cal/gm)	ASTM D4809	10717	10534	10458	10337	10230	10172
Flash Point (°C)	ASTM D93-58T	51	44	40	38	37	36
Fire Point (°C)	ASTM D93-58T	57	49	45	44	43	42
Kinematic Viscosity at 40°C (CST)	ASTM-D445	2.95	3.02	3.14	3.17	3.20	3.27
Cetane Number	ASTM D603	55.4	-	-	-	-	50.2

Diesel (SD). The mechanical stirrer was operated for 20-30 minutes at a speed of 400-500 revolutions per minute to ensure thorough blending of WPO with standard diesel. The fuels subjected to testing comprised a range of compositions, including 100% SD (D100), 100% WPO (WPO100), and the different blends of WPO with standard diesel are WPO 10% (WPO10D90), WPO 20% (WPO20D80), WPO 30% (WPO30D70), and WPO 50% (WPO50D50). The experimental fuels were characterized based on their key properties and their specifications were determined according to ASTM standards. The fuel properties as shown in Table 1.

4.2 Engine Testing

The schematic diagram of the set up is shown in Figure 1 and test engine specifications are given in Table 2. The

Table 2. Engine test setup

Brand	Kirloskar
Model or product	Computerized CRDI VCR Engine
Number of cylinders	01
Compression ratio range	12:1 to 18:1
Displacement	661 cc
Stroke length	110 mm
Connecting rod length	234 mm
Bore (cylinder diameter)	87.5 mm
Rated power	3.5 kW
Rated speed	1500 rpm
Injection pressure	Bar
Dynamometer arm length	185 mm
Orifice diameter	20 mm

experiments were conducted at the rated engine speed of constant 1500 rpm, 18:1 compression ratio and six different loads, namely 0%, 20%, 40%, 60%, 80% and 100%. Six blending ratios of WPO and SD were tested at each load. Each sample was tested for 30 cycles. During the test, the engine was started firstly on SD and switched to WPO after 30-45 minutes when all the conditions such as coolant and oil temperatures were stabilized.

4.3 Uncertainty Analysis

Significant errors and uncertainties in experiments may occur from factors such as the selection, condition, calibration, and environment of the instruments used, as well as the observation, reading, and planning of the tests. Conducting uncertainty analysis is crucial for verifying the accuracy of the experimental findings. The difference between the true value (known) and the result (best experimentally obtained value) is the error. Uncertainty is the best estimate of the magnitude of the known error. The error limits for the measured variables or parameters and the error limits for the calculated result are represented as R ± ΔR. To determine the accurate error boundaries for the calculated outcome, Holman adopted the root-mean-square method to find out the error[17].

R = f (x1, x2, ..., xn)

x1 ± n1, x2 ± n2, ..., xa ± Δxa

Where, `R' is the computed result function of the independently measured variables x1, x2, x3, ... xn, as per the relation.

An uncertainly analysis was performed using Equation 1.

$$\Delta R = \sqrt{\left\{\left(\frac{\delta R}{\delta x1} * \Delta x1\right)^2 + \left(\frac{\delta R}{\delta x2} * \Delta x2\right)^2 + \cdots \ldots \ldots \ldots \ldots \ldots + \left(\frac{\delta R}{\delta xn} * \Delta xn\right)^2\right\}} \quad 1$$

Using the above equation, the uncertainty in the computed values such as BP, BTE and fuel flow measurements were estimated. The % uncertainties of parameters such as load, BTE, and BSFC were determined by utilizing the percentage uncertainties of several instruments. Given in Table 3.

The observed data, including voltage, current, fuel duration, and speed were calculated using their respective uncertainties according to the Gaussian distribution equation[17]. The errors in the observed parameters, RPM (N) and load (Kg) found using the Gaussian technique, are ± 2 RPM and ± 0.05 torque respectively. Fuel consumption, the uncertainties are taken as ± 0.1 Kg/h (ΔFC).

5.0 Results and Discussion

5.1 Engine Performance

Figure 2 illustrates the variation in the Brake Thermal Efficiency (BTE) for D100 and WPO combinations at varying engine loads. The BTE of the standard diesel is 19.83% at full engine load 100%. However, the WPO mixtures such as WPO10D90, WPO20D80, WPO30D70, WPO50D50, and WPO100 produce higher thermal

Table 3. Evaluation of experimental apparatus uncertainties

Instruments	Measurement	Accuracy	Uncertainty (%)
Gas Analyzer	CO: 0-15 % Vol. HC: 0-20000 ppm Vol. CO_2: 0-20% Vol. O_2: 0-25% Vol. NO: 0–5000 ppmVol.	±0.001%Vol. ±0-2000 ppm ±0.1 %Vol. ±0.01% Vol. ±1 ppm Vol.	±0.2 ±0.2 ±0.15 ±0.20 ±0.2
BP	-	-	±0.08
BTE	-	-	±2.38
BSFC	-	-	±0.05

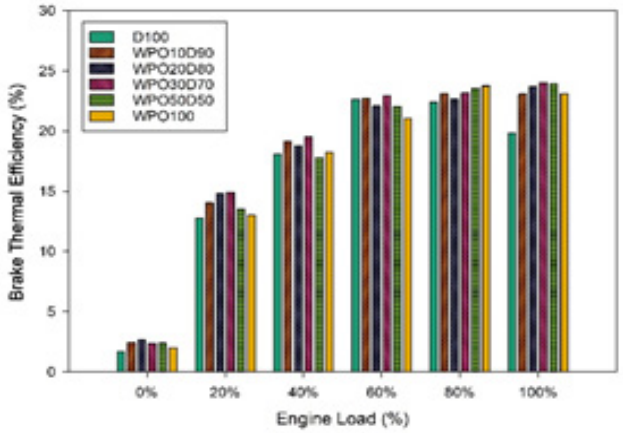


Figure 2. BTE *vs* load.

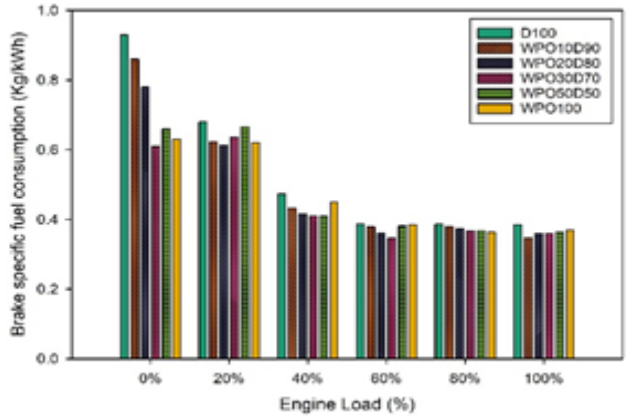


Figure 3. BSFC *vs* load.

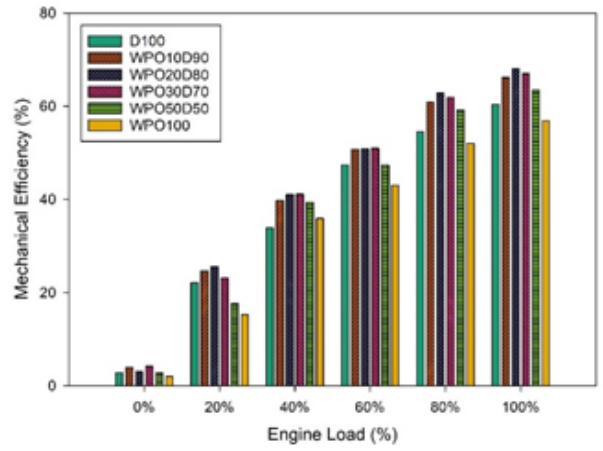


Figure 4. ME vs load.

efficiency of 23.07%, 23.69%, 24.00%, 23.92%, and 23.10% than D100 at 100% engine load. Kaewbuddee *et al.,* found that the increase in BTE can be attributed to the effective

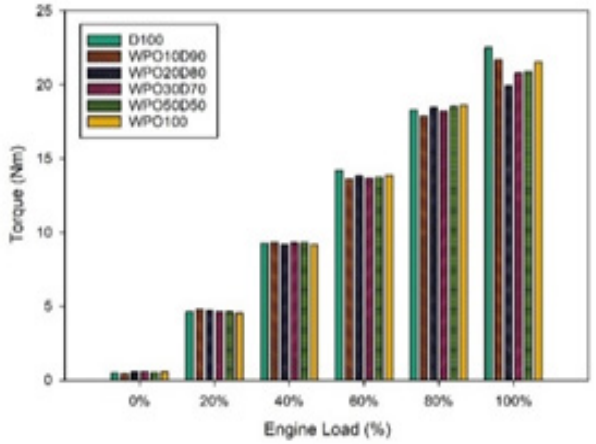


Figure 5. Torque *vs* load

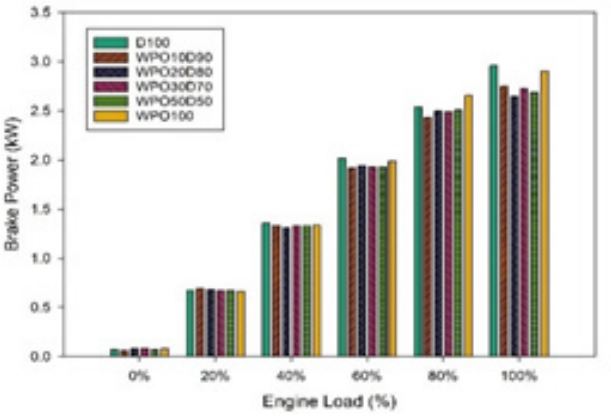


Figure 6. BP *vs* load.

use of WPO blends. This may be due to an increase in the oxygen content caused by the oxygen molecules present in the additives, which would lead to more efficient combustion due to the oxygen molecules present[18]. Several studies from Rajak and Verma have investigated the BTE of engines running on waste plastic-diesel blends, providing valuable insights into their performance. The marginal decrease in Brake Thermal Efficiency (BTE) is observed while using different Waste Plastic Oil (WPO) blends at different engine loads. Higher engine loads result in increased heat generation in the cylinder, which leads to an increase in BTE[19].

Figure 3 shows the Brake Specific Fuel Consumption (BSFC) for D100 changes ranges from 0.930 kg/kWh at 0% engine load to 0.385 kg/kWh at 100% engine load. Furthermore, it varies for WPO blends such as WPO10D90, WPO20D80, WPO30D70, WPO50D50, and WPO100 from 0.860 kg/kWh to 0.347 kg/kWh,

0.780 kg/kWh to 0.360 kg/kWh, 0.610 kg/kWh to 0.360 kg/ kWh and 0.660 kg/kWh to 0.363 kg/kWh and 0.630 kg/kWh to 0.370 kg/kWh respectively. It has been noted that Brake Specific Fuel Consumption (BSFC) decreases as engine load increases from low to full load conditions. With the rise in engine loads, the combustion process experiences an acceleration attributed to enhanced fuel atomization, more effective mixing, and elevated in-cylinder temperatures. Devaraj *et al.,* explained that the manifestation of this phenomenon under such conditions[20]. It also observed that the incorporation of WPO in the SD and WPO blends results in a slightly lower BSFC. Murugan *et al.,* suggested that the high calorific value of WPO allows for reduced consumption when blended[21]. Moreover, Panda *et al.,* studied that the higher calorific value of WPO compared to diesel results in lower consumption of blended fuels in comparison to SD[22].

Figure 4 shows the variation of Mechanical Efficiency (ME) for SD and WPO blends at 0% to 100% of engine load conditions. The ME refers to the quantification of productive output achieved by a system through the utilization of fuel and energy input. The accompanying figure illustrates the range of ME across all fuel blends, from minimum to maximum loads. The plot demonstrates a consistent rise in ME as the load increases from 0% to 100% for D100, WPO, and blends. WPO20D80 and WPO30D70 showed 68.07% and 67.01% better efficiency at part loads compared with D100, likely due to its longer ignition delay which enables a longer premixed combustion period. Venkatesan *et al.,* explained, at high loads, there was poorer atomization of the fuel[23]. The ME of WPO20D80 was found to be maximum at 68.06 %.

Figure 5 illustrates the engine torque levels to changes in engine load. The torque values exhibit a positive correlation with the load, as a result of the enhanced power output. Furthermore, the values of torque for D100 exceed the values of WPO blends across load conditions ranging from 20% to 100%. Gautam and Kumar described that the shaft undergoes rotation to extract the necessary torque on a load at a certain rpm, hence generating the power supplied by the engine[24]. The maximum torque for standard diesel is 22.53 Nm at high load 100% whereas the torque values for WPO blends at full load conditions and blends WPO10D90, WPO20D80, WPO30D70, and WPO50D50 are 21.70 Nm, 19.93 Nm, 20.78 Nm, 20.87 Nm respectively. From the graph, the lowest torque WPO20D80 blend was 19.93 compared to the maximum torque for D100 at 22.53 Nm. The findings emphasize the impact of both fuel composition and engine load on torque, with WPO50D50 fuel generating the least torque and WPO30D70 fuel producing the highest.

Figure 6 shows the experimental results indicating that the engine Brake Power (BP) values for WPO blends were consistently lower when compared to D100 in all loading circumstances. Furthermore, the difference in BP values between WPO blends and D100 decreased as the blending ratios increased[24]. The brake power output of the D100 is 3.21 kilowatts when operating at full engine load under 100% condition. However, different blends of WPO such as WPO10D90, WPO20D80, WPO30D70, and WPO50D50 produce lower brake power is 2.75 kW, 2.65 kW, 2.73 kW, and 2.69 kW than D100 at higher engine load 100%. The WPO produces 2.90 kW compared to D100 lowest value was observed. It is also observed that the minimum was observed for the WPO10D90 blend at 0% of engine load, measuring 0.063 kW, while D100 fuel displayed the maximum brake power at 100% load, registering 3.217 kW. This indicates that brake power is influenced by both fuel type and load, with D100 fuel yielding the highest BP and WPO10D90 fuel resulting in the lowest.

5.2 Combustion Characteristics

Figure 7 shows the variation of cylinder pressure concerning crank angle for blends of SD and WPO. The rate at which fuel is consumed in the premixed stage plays a crucial role in determining the pressure produced by combustion within the cylinder of the engine. Pal *et al.*, described in the research that the rate of fuel consumption during the premixed stage has a considerable effect on the pressure produced by combustion within the engine cylinder[25]. The several studies from Rajak and Verma's experimental results showed that the WPO30D70 cylinder pressure is notably higher compared to that of D100 and WPO blends. The pressure within the cylinder has a direct impact on the temperature of the exhaust gases produced by the engine[19]. Furthermore, the maximum pressure achieved by pure diesel fuel was certainly lower when compared to the pressure achieved by the blends of waste plastic and Waste Plastic Oil (WPO) under both no-load and maximum-load

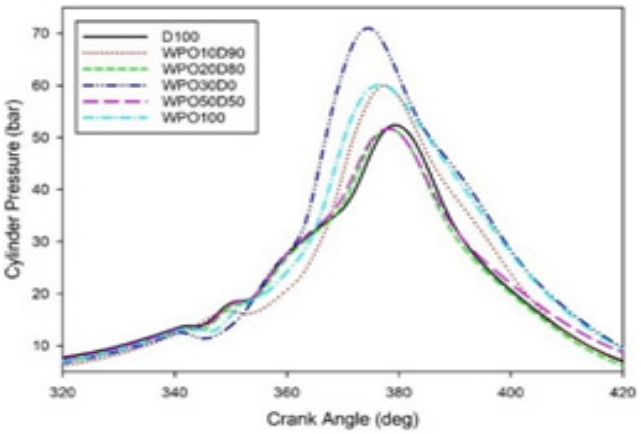


Figure 7. Cylinder pressure vs CA.

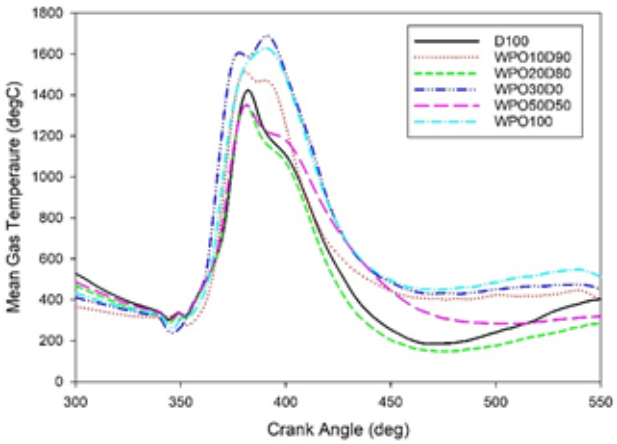


Figure 10. Mean gas temperature vs CA.

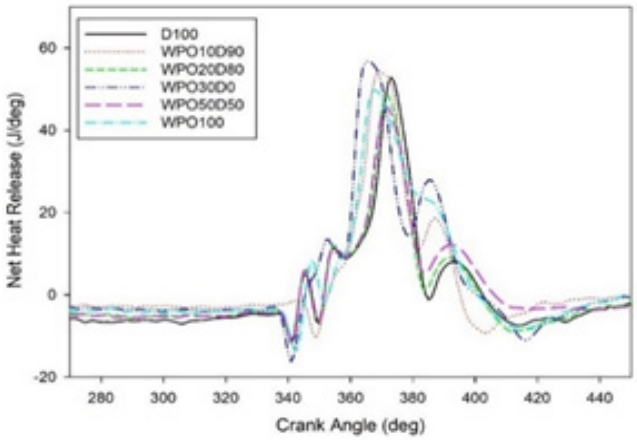


Figure 8. Net heat release vs CA.

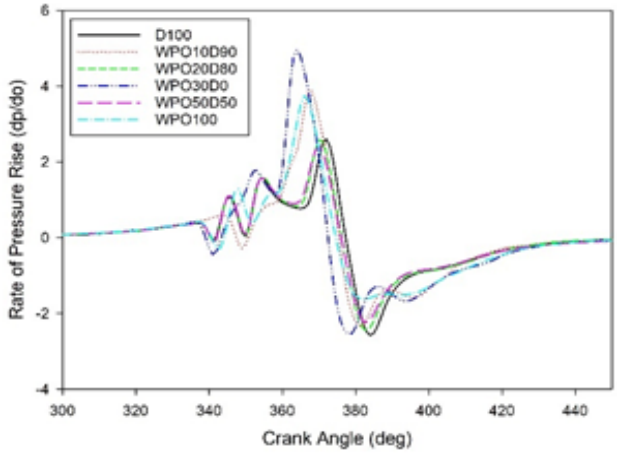


Figure 11. Rate of pressure rise vs CA.

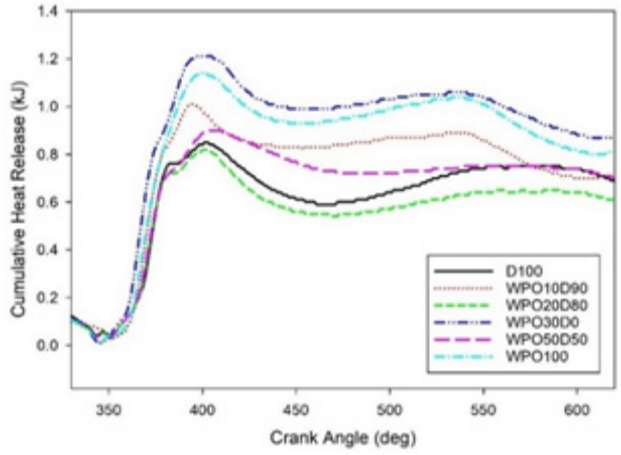


Figure 9. Cumulative heat release vs CA.

situations. The pressure inside the cylinder consistently increased as the concentration of WPO was elevated, reaching its extreme level of 30%. Additionally, the higher density of the WPO30D70 blends likely contributed to this rapid increase in pressure. The usage of PO20D80 plastic fuel does not have a substantial impact on the maximum pressure, irrespective of the circumstances of the engine. Nevertheless, a higher blending ratio does result in a rise in peak pressure, except in low engine load conditions. Karishma *et al.*, enlightened that this can lead to a decrease in the calorific value and viscosity in comparison to diesel, hence enhancing spray atomization and evaporation. As a result, there is a greater amount of premixed combustion occurring[26]. Rajak *et al.*, showed in their results, that higher premixed combustion % led

to a more vigorous and powerful combustion process, resulting in elevated peak pressures under high engine loads[27].

Figure 8 shows the net heat release rate *vs* crank angle. It is visible that the ignition of D100 occurs earlier than that of WPO mixes. The D100 fuel has a maximum heat release of 52.89 J/deg, but the heat release for WPO blends varies. The heat release increases from 51.54 J/deg for WPO10D90, to 47.13 J/deg for WPO20D80, to 34.67 J/deg for WPO30D70, to 44.28 J/deg for WPO50D50, and ultimately to 41.76 J/deg for WPO100 blends. The maximal heat release of WPO10D90 and WPO30D70 blends is greatly enhanced due to the higher calorific value and larger oxygen content in waste plastic oil[23]. The Heat Release Rate (HRR) of the waste fuel mixes exhibits a constant structure, with the highest amount of heat being released at the same crank angle. The only one that differs from this is the WPO30D70 blend, as its elevated viscosity necessitates an extended duration for the production of the fuel-air combination. The early negative area observed in the graph can be ascribed to the vaporization of the injected fuel, which is succeeded by premixed combustion. In this phase, a considerable fraction of the air-fuel mixture experiences swift combustion, leading to a significant emission of heat. The previous investigation revealed a notable difference in the net heat release rate between plastic oil and diesel fuel, with plastic oil exhibiting a 3.2% higher value. The prior analysis revealed a notable difference in the net heat release rate when comparing diesel fuel to plastic oil, with plastic oil exhibiting a 3.2% greater value. Fiore *et al.*, showed in their results, that an increased heat release rate, as the higher adiabatically released flame temperature is reached. Also, found that the presence of oxygen enhances the efficiency of the combustion process by reducing the cylinder's equivalency ratio[28].

Figure 9 shows the Cumulative Heat Release (CHR) *vs* crank angle. The CHR is higher for WPO30D70 compared to D100 and WPO blends. This is due to the higher heating value of the WPO mixes. Emiroglu *et al.,* found in the reduction in heat release observed in blended fuels during the secondary stage of combustion is attributed to two factors, one is inadequate blending and another one is lower cetane number[29]. The data depicted in the graph indicates a delayed ignition of the WPO20D80 mixture in comparison to D100 and other WPO blends. Throughout the combustion process, the WPO blends outperform the WPO10D90 blend. The rapid combustion of diesel is attributed to the superior ignition characteristics of WPO and D100. Hosamani and Katti research studies showed that CHR for diesel blends made from plastic is lower during the initial stages of combustion. This could be attributed to delayed combustion compared to blends[30].

Figure 10 illustrates the relationship between Mean Gas Temperature (MGT) and crank angle. The gas temperature for D100 is 1416.41°C and WPO blends such as WPO10D90, WPO20D80, WPO30D70, WPO50D50, and WPO100 produce gas temperature limits are 1511.99°C, 1343.35°C, 1685.28°C, 1342.80°C, and 1627.48°C respectively. EL-Seesy *et al.,* suggested that the air temperature at the end of compression is high enough for the fuel droplets to vaporize and ignite upon entering the cylinder. In comparison, the gas temperature in diesel engines is higher during combustion, leading to increased pressure during this stage. This decrease in heat release and subsequent drop in mean gas temperature can be ascribed to the lower heating value of the mixture[31].

Figure 11 shows the relationship between the Rate of Pressure Rise (RPR) *vs* crank angle. The peak pressure increase for the D100 is 2.49dp/do and WPO blends such as WPO10D90, WPO20D80, WPO30D70, WPO50D50, and WPO100 pressure rise values are, 3.84 dp/do, 2.61 dp/do, 4.97 dp/do, 2.58 dp/do and 3.84 dp/do respectively at engine load. From the study, during the combustion process, diesel fuel experiences a higher peak pressure due to the effect of ignition delay. Murugesan *et al.,* their results showed in combustion starting before the top dead centre, causing a rapid release of heat during premixed burning[32].

5.3 Brake Specific Emissions

Figure 12 demonstrates that brake-specific Carbon monoxide (CO) emissions vary with engine load. The findings show that higher CO emissions are a result of higher engine load. The BSE CO varies from 0.083% at minimum engine load to 0.630% at higher engine load for D100. The BSE of CO is considered toxic and therefore requires regulatory measures[33]. Venkatesan *et al.,* findings indicate that blends of WPO20D80 and WPO30D70 significantly reduce CO emissions, making

them a more environmentally friendly option at engine load conditions ranging from 20% to 80%. The emissions showed higher at high loads due to lean air-fuel mixtures and insufficient oxygen, resulting in poor combustion[22]. According to a study incomplete combustion, poor air-fuel mixing, and oxygen deficiency, the higher CO emissionemits[28].

Figure 13 shows the brake specific Hydrocarbons (HC) emission. Extreme HC produces at 80% and 100% of engine load. They were shown to rise in proportion when the blend's WPO % increased. At 0% engine load, brake specific HC emissions were found to be significantly lower for pure HC at 14.89 ppm, as compared to WPO100 at 21.33 ppm. Nagarajan *et al.,* suggested that the increased emission of HC in the blend, as opposed to diesel, can be attributed to two factors. Firstly, it is possible that the fuel spray does not penetrate deeply into the combustion chamber, causing gaseous hydrocarbons to accumulate along the cylinder wall and in the crevice volume, resulting in incomplete combustion[34]. Kidoguchi *et al.*, objective was the existence of unsaturated hydrocarbons in the WPO, which remain intact throughout the combustion process[35]. Sambandam *et al.,* research suggests that the increased amount of plastic oil, which causes incomplete combustion and oxygen deprivation, may be the cause of the rise in hydrocarbon emissions[36].

Figure 14 shows the variation in brake specific Carbon dioxide (CO_2) emissions with engine load. It is

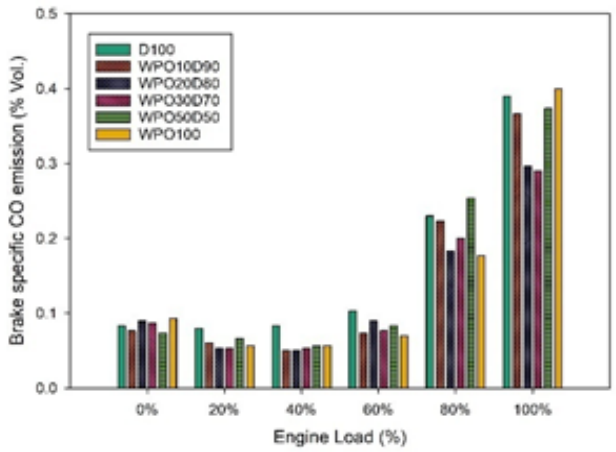


Figure 12. Brake specific CO emission.

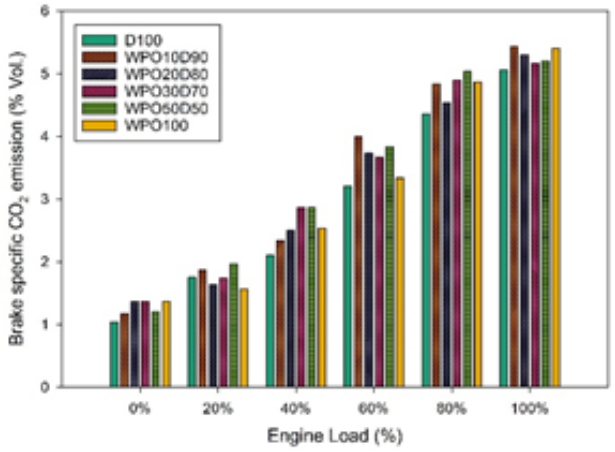


Figure 14. Brake specific CO_2 emission.

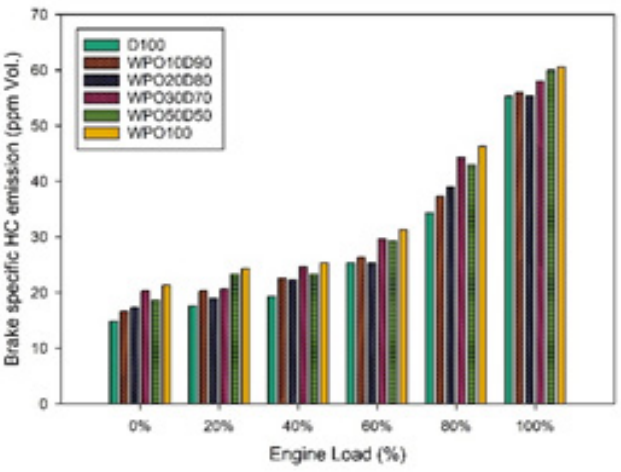


Figure 13. Brake specific HC emission.

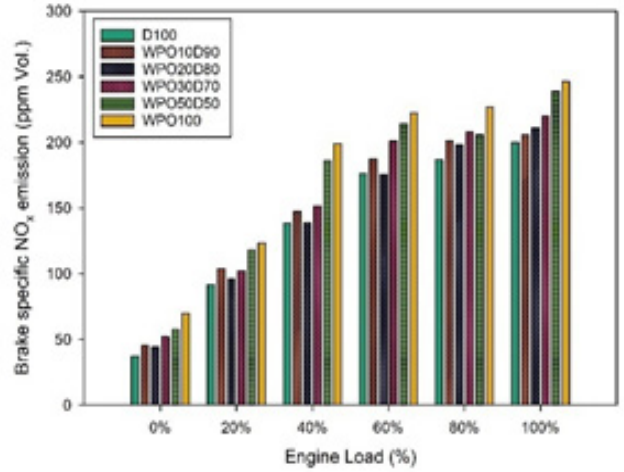


Figure 15. Brake specific NO_x emission.

indicated that there is a slight increase in brake specific CO_2 emissions as the load increases from 0% to 100%. Moreover, the findings demonstrate that increasing the concentration of WPO in diesel results in either equal or higher CO_2 emissions compared to SD across all loads, potentially attributed to the elevated exhaust temperatures of the blended fuels enhancing combustion efficiency. Mariappan *et al*., research studies on the combustion of fuel in a proper manner results in the production of CO_2 emissions. This phenomenon may arise from the total oxidation of the carbon atoms included in the fuel. Although CO_2 is not usually subject to strict emission laws and is not considered dangerous, it plays a vital role in contributing to the release of greenhouse gases and the occurrence of climate change. Therefore, it is crucial to implement steps to limit carbon dioxide emissions. However, as previously stated, the disposal of plastics in landfills and through incineration emits much greater quantities of CO_2, posing considerable threats to human health[37]. The CO_2 emissions of blends WPO10D90, WPO20D80, and WPO30D70 are inferior compared to pure diesel fuel D100. This is probably because the heating value of diesel is comparable to that of plastic oil, which allows for more thorough combustion in the engine[16]. The study shows how plastic garbage may be used as a substitute fuel to generate electricity with less carbon dioxide emissions[5].

Figure 15 demonstrates how brake-specific oxides of nitrogen (NOx) emissions for D100, WPO, and blends grow with engine load. Nitrogen Oxides (NOx) are readily formed during fuel combustion in air at high temperatures, as described by three mechanisms in combustion theory: Fuel NOx, thermal NOx, and prompt NOx[13]. Sindhu *et al*., research studies on the higher cylinder temperature and fuel oxygen concentration from the thermal process led to increased NOx emissions[38]. Also, Y. Ren *et al*., despite always running lean and emitting high amounts of NOx, IC engines produce even higher levels of NOx at high load and temperature conditions, as well as in larger regions of near-stoichiometric burned gas[39]. The higher levels of Nitrogen Oxides (NOx) in the Waste Plastic Oil (WPO) blend, as opposed to diesel fuel, can be attributed to the extended period it takes for ignition to occur. This delay is caused by the presence of long-chain carbon molecules in the plastic fuel. Furthermore, the presence of nitrogen in the plastic oil might lead to the production of nitrogen oxides through the development of fuel NOx. Studies have shown that when the amount of plastic oil in diesel is raised at higher engine loads, it results in elevated NOx emissions from CI engines. The greater peak of premixed combustion and the presence of nitrogen in the plastic oil may contribute to increased emissions of NOx from the fuel mechanism[6].

6.0 Conclusion

An experimental study was conducted for an alternative fuel produced from municipal mixed waste plastics. The investigation indicates that there was an enhancement in engine performance with an increase in the ratio of WPO and SD blends. WPO20D80 and WPO30D70 demonstrate superior performance in terms of BTE (Brake Thermal Efficiency), BSFC (Brake Specific Fuel Consumption), BP (Brake Power), and torque across all load circumstances. Additionally, they also display the lowest brake-specific emissions of HC (Hydrocarbon), CO (Carbon Monoxide), and NOx (Nitrogen Oxides). In addition, the highest variation in Brake Thermal Efficiency (BTE) was 24.01% for the WPO30D70 engine operating at 1500 rpm. Conversely, the lowest variation in Brake Specific Fuel Consumption (BSFC) was 0.346 Kg/kWh for the WPO30D70 engine operating at 1500 rpm and 60% load. The thermal efficiency of WPO and blends was found to be larger, along with improved mixing preparation of air and fuel, resulting in enhanced combustion. Consequently, it is recommended that WPO be added to blends to minimize the quantity of diesel fuel consumed in diesel engines.

The blends ranging from 10% to 30% blends showed good tendencies to be utilized with diesel engines through the experimental results in this work. However, brake-specific CO, HC, CO_2 and NOx emissions are found to be insignificant to the SD. The CO and HC of WPO blends were found lower at peak load compared with SD. Maximum CO and HC were produced at a higher load with WPO100. The minimum brake-specific NOx produced by the diesel blend at peak load conditions (WPO20D80) is 138.66 ppm, which is higher than other blends. This might be attributed to a larger proportion of pre-combustion and a longer ignition time, which raises the heat release rate and cylinder temperature. The study revealed that WPO blends, specifically

WPO10D90, WPO20D80, and WPO30D70, have lower brake-specificCO_2 emissions when compared to standard diesel.

In conclusion, the compression ignition engine is appropriate for WPO at all engine loads. The PO20D80 and PO30D70 blends and some extent PO50D50 outperform other waste plastic blends by a significant margin. When compared to D100, the PO20D80 blend exhibits higher BTE, lower BSFC, and emits less pollution. Consequently, PO20D80 has the potential to replace diesel in the compression ignition engine without requiring any additional modifications. Through the studies, the waste plastic physicochemical properties like density, viscosity, and cetane number may be improved by using nano additives to improve diesel engine performance, combustion, and emission characteristics. These results confirm that WPO may be utilized as a fuel without requiring any changes to the engine, making it a viable and eco-friendly option.

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8.0 Author Designation

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