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Conversion of Waste Plastics into Hydrocarbon Fuel - Analysis of Combustion Behaviour and Emission Characteristics of Waste Plastics Derived Fuel Blended with Diesel in an IC Engine: A Sustainable Approach for Waste Plastic Recycling

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Abstract

Plastic waste has become a severe environmental challenge worldwide. Currently, practices like open dumping, land filling, and incineration for plastic waste recycling are haphazard and causing significant negative impacts on the environment and human health. Waste plastics can be converted into hydrocarbon fuel by the thermal pyrolysis technique, which was investigated in this study. The thermal pyrolysis technique is employed in a semi-batch type reactor to extract hydrocarbon fuels from the segregated waste plastics from the municipal waste. A maximum conversion rate of 99% is achieved at the operating temperature of 450°C and near atmospheric pressure. The properties of the liquid fuel extracted are close to commercial diesel. The combustion behaviour and emission characteristics of the extracted fuel blended with diesel percentage by volume 10% - 60% used in a compression ignition (CI) internal combustion (IC) engine are investigated. The brake specified fuel consumption (BSFC), brake power (BP), and brake thermal efficiency (BTE) of the engine were obtained for different fuel blends at various engine loads. The BSFC shows enhancement at all loads. Brake power and brake thermal efficiency were observed to be similar to those obtained with diesel. CO emission is higher than that of diesel, and CO_2, NO, and NOx emissions were found to be similar to those of diesel. The net energy returned from the waste plastic to fuel conversion process was found to be 16,521 kJ/kg of the waste plastics, and the developed reactor system represents a sustainable approach for waste plastic recycling.

Keywords: Pyrolysis, Waste plastics derived fuel, Engine performance, Emission characteristics, Sustainable approach, Solid Waste Recycling

1. Introduction

Economic growth and changing consumption and production patterns are resulting into rapid increase in generation of waste plastics in the world. Due to the increase in generation, waste plastics have become a major stream in solid waste. Even the cities with low economic growth have started producing more plastic waste due to plastic packaging, plastic shopping bags, PET bottles and other goods/appliances which uses plastic as the major component. This increase has turned into a major challenge for local authorities, responsible for solid waste management and sanitation. Due to the lack of integrated solid waste management, most of the plastic waste is neither collected properly nor disposed of in appropriate manner to avoid its negative impacts on environment and public health. Hence, Municipal Solid Waste (MSW) management has become a severe problem in many countries. Currently practicing techniques like open dumping, land filling, incineration are haphazard, and causing significant negative impacts on the environment and human health.

On the other hand, waste plastic recycling can provide an opportunity to collect and dispose of plastic waste in the most environmentally friendly way. Waste plastic recycling also has a great potential for resource conservation, such as producing hydrocarbon fuel from plastic waste. This resource conservation goal is very important for the national and local governments, where rapid industrialization and economic development is putting a lot of pressure on natural resources.

Waste plastic is one of the most promising resources for fuel production because of its high heat of combustion and increasing availability in local communities [1-3]. The technique for the conversion of waste plastics into liquid fuel is based on the thermal pyrolysis of the plastics and the condensation of the resulting hydrocarbons. The major product of the pyrolysis is the oil, which is a mixture of liquid hydrocarbons such as diesel, kerosene, and gasoline [1], [4]. In addition, gaseous hydrocarbons such as methane, ethane, propylene, and butanes are produced in the thermal pyrolysis process [2, 5-6].

In this study, waste plastics were converted into a liquid and gaseous hydrocarbon fuel by a thermal pyrolysis technique in a reactor system that consists of a semi batch reactor, a condenser and a liquid-gas separator. Properties, composition, combustion performance and emission characteristics of the generated fuel were analyzed focusing on determining its suitability in combustion applications. Net energy return of the waste plastics to fuel conversion process was also analyzed to assess the viability of the process in the context of commercialization.

2 Literature Review

Waste plastics to fuel conversion technique which is being used in this study is pyrolysis. This is one of the advanced techniques for waste plastics to fuel conversion process since this technique offers numerous advantages over other techniques.

Pyrolysis involves heating of plastic waste at temperatures between 220 and 900 ºC, in oxygen-free conditions and various residence times. Three different cracking processes such as hydro cracking, thermal cracking and thermal catalytic cracking are reported as different pyrolysis processes. Thermal and thermal catalytic cracking of waste plastic have been investigated by many researches in the past. The liquid yield obtained is in the range of 69% to 90%, and the solid residue left in the reaction zone is around 2% [1-2, 4-10].

Hoseini and Dastanian investigated the pyrolysis behaviour of low-density polyethylene (LDPE), polypropylene (PP), and polyethylene terephthalate (PET) using both experimental analysis and thermodynamic modelling. Pyrolysis experiments were carried out at 500 °C with heating rates of 6-14 °C/min, and the resulting products were classified into liquid (oil), solid (char), and gas phases. Results demonstrated that PP produced the highest liquid yield, reaching 82% at the lowest heating rate (6 °C/min), followed closely by LDPE (80%), while PET generated significantly less liquid (39%) and produced more char and gas. Further, the results showed nearly complete conversion of plastics into useful fuel fractions, with only a minimal amount of solid char remaining. Polypropylene and LDPE achieved the highest overall fuel conversion, producing more than 95% combined liquid and gas yields, while PET yielded lower overall fuel recovery (90%) due to its higher char formation. The distribution between liquid and gas depended strongly on heating rate: lower heating rates favoured liquid oil production, while higher rates enhanced gas generation through secondary cracking. The Non-Random Two-Liquid (NRTL) activity coefficient model was employed to predict product distributions, with binary interaction parameters optimized using experimental data. The model achieved a low RMSD (root mean square deviation) value of 0.0157, confirming good predictive capability. Excess Gibbs energy and activity coefficient analyses supported the thermodynamic consistency of the model. Overall, the results highlight PP and LDPE as the most suitable feedstocks for maximizing liquid fuel production from pyrolysis, while validating the NRTL approach as a reliable tool for predicting equilibrium product distributions in plastic pyrolysis processes [7].

Ahmad et al. examined the pyrolysis of polypropylene (PP) and high-density polyethylene (HDPE) with the objective of converting waste plastics into premium oil products. Experiments were conducted under an inert nitrogen atmosphere at temperatures ranging from 250 to 400 °C, and product yields were quantified as liquid oil, gaseous hydrocarbons, and solid residues. Results revealed high total conversion efficiencies, exceeding 98% for both plastics. PP achieved maximum conversion at 300 °C, yielding 69.82% liquid oil, 28.84% gas, and only 1.34% residue, while HDPE showed optimum conversion at 350 °C, producing 80.88% liquid oil, 17.24% gas, and 1.88% residue. Analysis of the liquid fraction using FTIR and GC-MS confirmed a hydrocarbon distribution dominated by paraffins, followed by olefins and naphthenes, with carbon chain lengths primarily in the C_6-C_{16} range. The physicochemical properties of the derived oils, including density, viscosity, and heating value, were found to be comparable to commercial fuels. These findings demonstrate that pyrolysis of PP and HDPE offers a highly efficient route for the production of fuel-grade hydrocarbons from waste plastics [8].

Avila et al. found that that the highest liquid yield of 69% was achieved at a temperature of 410 °C with a heating rate of 10 °C/min during the pyrolysis of mixed waste plastics composed of PP, LDPE, and HDPE. The pyrolytic liquid was fractionated into light, medium, and heavy fractions, with the medium fraction (56.52%) exhibiting properties similar to diesel fuel, and the light fraction (21.12%) showing gasoline-like characteristics. These findings indicate that thermal pyrolysis under optimized conditions can produce fuel-like products from mixed plastic wastes. These results highlight the potential of thermal pyrolysis as a viable method for converting mixed plastic waste into valuable fuel products. The same study showed that the varying heating rate and temperature influenced the yield percentages towards decreasing yield with the decreasing temperature [9].

Sharuddin et al. have carried out a review to evaluate the effects of critical parameters such as temperature, residence time, heating rate, reactor type, catalysts, and plastic type on product yields and composition. Sharuddin et. al. reported that the temperature strongly influences product distribution, with 400–500 °C favouring high liquid oil yield, while higher temperatures increase gas production. Fast heating rates enhance liquid formation, and longer residence times promote secondary cracking, increasing gas yield. Reactor design affects heat transfer and conversion efficiency, with fluidized-bed reactors providing higher liquid yields than fixed-bed systems. Catalysts, such as zeolites and alumina, improve oil yield, quality, and hydrocarbon selectivity. Plastic type significantly impacts pyrolysis outcomes: polyethylene and polypropylene yield 70–80% liquid oil, polystyrene yields up to 90%, whereas PVC generates corrosive gases requiring pre-treatment. This review further highlighted that optimized pyrolysis conditions can maximize liquid oil recovery, offering an effective strategy for sustainable plastic waste management [10].

Combustion performance and emission characteristics of waste plastics-derived fuel have been analyzed by a quitter few researchers in the past [11-15].

Ioannis Kalargaris et al. has investigated the combustion, performance and emission analysis of plastic pyrolysis oil in a direct injection diesel engine [11]. The plastic pyrolysis oil has been synthesised by waste plastic mixtures mainly consists of styrene butadiene and polyester type of plastics. Around 55% to 60% of pyrolysis oil has been obtained by fast pyrolysis process carried out at 900 °C in a reactor under CO_2 purging. The above liquid has been filtered by 1 μm filter, and used in combustion analysis experiments by blending it with diesel. The blending ratio with diesel was varied from 25% to 100%. A four-cylinder, direct injection, turbocharged water-cooled diesel engine mated to an alternator and then to a load bank to control the load of the engine has been used for their experiments. They have found that the engine was able to operate steadily on 100% plastic pyrolysis oil (PPO) at loads higher than 75% of the full load, on 90% PPO blend for loads higher than 50% and on lower PPO blends for all loads. Also, it was reported that PPO blends have longer ignition delay, higher cylinder peak pressure and higher heat release rate due to the lower cetane number. In addition to that, the engine thermal efficiency decreased by 3 - 4% when PPO blends were used in comparison with diesel. But increasing PPO ratio does not have a significant impact on thermal efficiency. All measured emissions, including NOx, UHC, CO and CO_2, increase with higher PPO blending ratios. For low to medium blending ratios, the increases of NOx and CO are mild. [11]

Hariram Venkatesan et al. has conducted an experimental study on combustion and performance characteristics in a direct injection compression ignition engine fuelled with blends of waste plastic oil. A single feed at the rate of 8 kg of waste plastic consisting 20% LDPE and 80% HDPE in weight basis along with 0.80 kg of coal (10% by weight of waste plastic) and 0.10 kg of silica as catalyst was fed into the pyrolytic reactor and allowed to undergo thermal catalytic cracking between 350 and 425 °C temperature and atmospheric pressure in a reaction time of 4 to 5 hours which yielded 675 ml of pyrolytic oil (PO). The experiments were conducted with straight diesel, PO15% blend (plastic oil 15% and diesel 85%) and PO30% blend in a single cylinder four stroke water cooled direct injection compression ignition engine with a rated power of 3.5 kW and at the rated speed of 1500 rpm, and at no load and full load conditions. The loading was accomplished using eddy current dynamometer with the crank angle encoder detecting the top dead centre. Their findings showed that in-cylinder pressure for straight diesel was noticed to be lower than PO blends at all loads. At full load operation, PO30% blend exhibited higher peak pressure of 75.3 bar. The rate of heat release also showed a drastic increase with PO30% fuelled at full load condition. There was a slight delay in the start of combustion on comparison with straight diesel. The cumulative heat release exhibited an increasing trend with the addition of PO concentration at increasing load due to prolonged premixed combustion period. The peak in-cylinder pressure showed an increasing trend for all fuel blends with PO30% being highest at 76 bar. The brake thermal efficiency showed minimal values at low load but significant improvement was noticed at full load (30.27% for straight diesel, 26.2% for PO15% and 28.4% for PO30%). The mechanical efficiency was found to have minimal effect across all fuel blends at all loads. The BSFC was found to be higher for all fuel blends at no load and the fuel consumption was reduced with increase in load. This experiment hasn't been focused on analysis of exhaust emissions. [12]

M. Mani et al. reported in their experiments to analyse performance, emission and combustion characteristics of a direct injection diesel engine using waste plastic oil that, the engine was able to run with 100% waste plastic oil, ignition delay was longer by about 2.5 °CA in the case of waste plastic oil compared to diesel. Also, NOx is higher by about 25% for waste plastic oil operation than that of diesel operation. CO emission increased by 5% in waste plastic oil compared to diesel operation and unburned hydrocarbon emission is higher by about 15%. Smoke reduced by 40% at rated power in waste plastic oil compared to diesel operation. Engine fuelled with waste plastic oil exhibits higher thermal efficiency up to 75% of the rated power. The exhaust gas temperature was found to vary from 221 °C, at no load to 417 °C, at rated power for diesel whereas in the case of waste plastic oil it varies from 240 °C, at no load to 450 °C, at rated power. The waste plastic oil for their experiments has been produced by assorted waste plastic that was fed into a reactor along with 1% catalyst and 10% coal (by weight), and maintained at a temperature of 300 °C to 400 °C, at atmospheric pressure for about 3 hours to 4 hours. Combustion analysis experiments were carried out in a single cylinder, four stroke, air cooled, direct injection, compression ignition engine with a rated power of 4.4 kW at the rated speed of 1500 rpm. [13]

Christine Cleetus et al. has investigated the performance of petroleum-based fuel derived from waste plastics in a compression ignition engine. Waste Polythene was selected as the source of waste plastics and converted into plastic oil in a reactor system. The catalysts identified for the study include silica alumina, zeolites, barium carbonate, titanium chloride, and their combinations. The pyrolysis reaction was carried out in the polymer to catalyst ratio of 4:1. The reaction temperature was ranging between 350 and 450 °C. The inert atmosphere for the pyrolysis was provided by using nitrogen as a carrier gas. The maximum loading capacity of the reactor was 1.5 kg of waste plastics and liquid yields were ranging from 50 to 145 ml depending on the catalyst and operating conditions. The experimental setup consists of a single cylinder compression ignition (CI) engine (5 hp, 1500 rpm, 4 stroke, and 500 CC), which is mechanically loaded by means of a brake drum dynamometer has been used for the experiments. The performance of plastic oil blends in a CI engine was investigated and compared with pure diesel. Five blends of the plastic oil which includes B10 (10% oil and 90% diesel), B20, B30, B50, and B80 were prepared. It was reported by Christine Cleetus et al that the fuel consumption was increased with increasing concertation of plastic oil and that was due to the low calorific value of plastic oil compared to diesel [14]. The brake thermal efficiency was found to increase with brake power only up to a limit beyond which it drops due the incomplete combustion taking place. Here, with increase in the concentration of plastic oil in the blends, the efficiency decreases which is due to the higher fuel consumption, and the pure plastic oil gives the least efficiency. The air fuel ratio was found to decrease with increasing plastic oil concentration, which is due to the increasing fuel consumption with increasing plastic oil concentration. Exhaust gas temperature and emission characteristics of B20 were compared with diesel and showed close similarities. The exhaust gas temperature of B20 was slightly higher than that of diesel. Also, NOx emission was slightly higher while CO emission was slightly lesser for B20 compared to diesel.

Digambar Singh et al. has done a review on use of waste plastic oil as an alternative fuel in compression ignition engine. LDPE (low density polyethylene) and EVA (ethylene-vinyl acetate) were used as feed stocks and converted into high quality oils via the pyrolysis process at temperature of 300-350 °C by using a catalyst [15]. The catalyst used in this system will prevent formation of all the dioxins and furans. From the study it was found that engine is able to run with only plastic oil but emissions are higher compared to blend of waste plastic oil (WPO) and diesel. It was also found that the brake thermal efficiency of waste plastic oil is higher with the retardation of injection timing and the brake thermal efficiency is decreased with increasing percentage of exhaust gas recirculation (EGR). Engine fuelled with WPO exhibits higher thermal efficiency up to 75% of rated power. It was found that for the WPO, the exhaust temperature is higher than diesel due to high heat release rate and the fuel consumption is higher for WPO blend at the full load. WPO emits 15% higher unburned hydrocarbon than diesel fuel and CO emission is 5% more than diesel. The CO_2 and NOx concentrations decrease with increasing percentage of EGR.

Therefore, what has not been invested so far is a simultaneous study of waste plastics to fuel conversion process, analysis of composition and properties of derived hydrocarbon fuel from different types of waste plastics, analysis of combustion performance and emission characteristics of derived fuel. This study focused on investigation of waste plastics to fuel conversion process, investigation of composition and properties of derived hydrocarbon fuel from different types of waste plastics, analysis of combustion performance and emission characteristics of derived fuel to determine their usability in different combustion applications. Experimental results suggest that the waste plastics derived fuel in the form of a crude oil blended with diesel is having engine performance and emission characteristics very close to diesel and also for some blends the performance and emission characteristics are better.

3 Methodology

This study consists of investigation of waste plastics to fuel conversion process, analysis of composition and properties of derived hydrocarbon fuel, analysis of combustion performance and emission characteristics of derived hydrocarbon fuel from different types of waste plastics.

3.1 Waste Plastics to Fuel Conversion Process

A waste plastic to fuel conversion experimental setup mainly consists of three devices: a semi batch reactor, a condenser and a liquid-gas separator was used for the experiments. The semi batch reactor made of stainless steel having a loading capacity of 3 kg (polyethene bags) is the heart of the system. The semi batch reactor was heated by a set of electric heaters of 7.5 kW fitted on the outside body. A pressure gauge with 0.02 bar sensitivity and a thermocouple inserted into a thermo well was fitted on the reactor lid. A condenser was used to condense gasses generated in the cracking process under the water cooling at room temperature and atmospheric pressure. A liquid-gas separator equipped with a demister was used to separate liquid and gasses after the condenser.

Fig. 1. Developed waste plastics to fuel conversion plant

In a typical experiment, waste plastic sample was loaded to the semi batch reactor as received and reactor lid was closed. The condenser was connected to the reactor and the heater was switched on. The temperature and pressure were measured at every 5 min. In the first phase of the experiment, the reactor outlet valve was closed and the temperature of the sample was allowed to increase until 300 °C in order to melt them. The reactor valve was opened after reaching 300 °C temperature and the generated gasses were allowed to pass through the condenser where condensation of gasses takes place at room temperature and atmospheric pressure under water cooling allowing the reactor pressure to maintain near atmospheric slightly positive pressure (around 0.02 bar). Heating was continued at the above pressure until the gas generation is stopped. The condensed liquid in the liquid-gas separator and the solid residue left in the reactor were collected after the experiment and measured by a scale for weight. No N_2 purging or vacuuming was used during the experiments by successfully escaping atmospheric air at the loading of the sample to the reactor and maintaining sealed and slightly positive pressure environment in the reactor during the experiments.

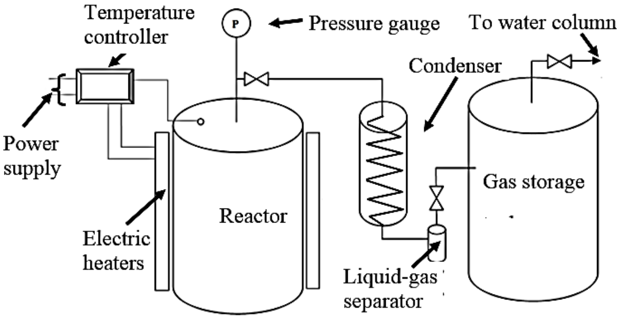


Fig. 2. Schematic of developed waste plastics to fuel conversion plant

3.2 GC/MS Analysis of Liquid and Gaseous Fuel

Liquid and gaseous products obtained by the pyrolysis of waste plastics were analyzed for the percentages of different compounds by a gas chromatograph/mass spectrometer (5975 series GC-MSD) consist of Agilent tech 7890A type GC equipped with Agilent 5975C inert XL EI/CI type MSD.

3.3 ASTM Distillation Test, Determination of Density, Flash Point and Pour Point

Distillation tests of liquid fuel were conducted according to the ASTM-D 86 method. ASTM boiling point curves for the liquid fuels were obtained by the results of distillation test. Density at 15 °C, flash point, and pour point were determined according to the ASTM-D 1298, ASTM-D 93, and ASTM-D 97 respectively.

3.4 Determination of Calorific Value and Viscosity

Calorific value of the liquid and gaseous fuel was determined by the 6100 Oxygen Bomb Calorimeter (fully automated) unit and P5615 Boys gas calorimeter respectively. Viscosity of liquid fuel was determined by the Broofield digital viscometer (Model DV-E) at the temperature of 25 °C.

3.5 CI Engine Experimental Setup

A single-cylinder, 4-stroke, direct injection diesel engine coupled with a 3000 rpm synchronous speed generator was used for the experiments carried out to analyse the combustion performance and emissions characteristics of waste plastics derived fuel blended with diesel. The rated power of the engine and generator are 7 kW and 5 kW respectively. The generator was connected to a load panel which consists of electrical resistive loads. An external fuel supply unit capable of measuring fuel consumption in a given period of time was connected with the engine. A thermocouple with temperature measuring device was used to measure the temperature of exhaust gas leaving 3 m long exhaust pipe. A gas analyzer capable of measuring the amount of CO, CO_2, NOx, and NO in the emission was used to analyse the emission.

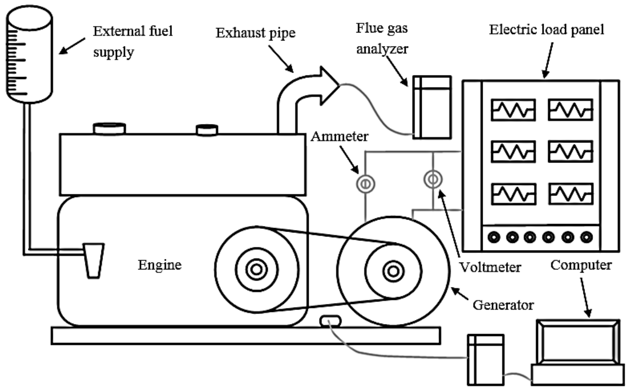
The liquid fuel extracted from waste plastics was blended with diesel and used in the experiments. In a typical experiment the fuel supply unit was filled by a sample of fuel and the engine was started and allowed to warm up. Time taken to consume a constant volume (20 ml) of fuel, voltage produced by the generator and current drawn by the electrical loads, engine vibration and temperature of exhaust gas were measured at different loads varying from no load to 5000 W load while the engine is running at its full speed. At the same time, the exhaust gas emitted from the engine was allowed to enter the gas analyzer and the percentage of CO and CO_2, the amount of NOx and NO of the emission were measured at each load. Same procedure was followed for diesel and various blends.

Fig. 3. CI engine experimental setup used for the experiments

Table 1
Specification of the Engine

Make	Yanmar diesel engine, Japan
Type	Single cylinder, direct injection, CI engine
Continuous output	6.3 kW at 2400 rpm
Maximum output	7 kW
Displacement	0.450 liters
Generator max: output	5 kW
Loading device	Electrical resistive load

Fig. 4. Schematic of CI engine experimental setup used for the experiments



4 Results and Discussions

Results and discussion on waste plastics to fuel conversion process, analysis of composition and properties of waste plastics derived fuel, analysis of engine performance and emission characteristics of waste plastics derived fuel are presented under the results and discussions.

4.1 Waste Plastic to Fuel Conversion Process

Set of experiments were carried out to determine the optimum process parameters towards taking highest product yield from different types of waste plastics. The optimum pressure and the batch size were found to be 0.02 bar (near atmosphere slightly positive pressure), and 3 kg (full loading of the reactor) respectively for all types of waste plastics [2]. The optimum set temperature was found to vary according to the type of the waste plastics sample. Repeated experiments were also carried out for each sample to check the consistency of results. Table 2 shows optimum temperatures and product yield for different types of waste plastic at the optimum pressure of 0.02 bar and optimum batch size of full loading of the reactor.

Table 2
Optimum set temperature for different types of waste plastics and the product yield

Material	Sample size* (g)	Set Temperature (°C)	Reaction Time (min)	Liquid Yield		Gas Yield	Solid Residue
				Mass (g)	Percentage		
Waste PP	3000	425	170	2665	66.4%	30.8%	2.8%
Waste PE	3000	475	225	1822	60.7%	12.8%	26.5%
Waste PS	750	400	200	504	67.2%	30.0%	2.8%
Waste PET	1200	450	125	8	0.6%	77.7%	21.7%
Waste PP + waste PE (50% each)	3000	450	230	1699	56.6%	20.4%	23.0%

*Sample size at the full load of the reactor

Experimental results showed that the optimum set temperature for waste PP is 425 °C, the reaction time was 170 min at this set temperature. Also, the liquid yield, gas yield, and solid residue percentages at the optimum conditions were found to be 66.4%, 30.8%, and 2.8% respectively.

The optimum set temperature for waste PE was found to be 475 °C, the reaction time was 225 min at this set temperature. The liquid yield, gas yield, and solid residue percentages at the optimum conditions were found to be 60.7%, 12.8%, and 26.5% respectively. Reaction time was considerably increased with waste PE compared to waste PP. Also, solid residue amount was heavily increased at the expense of gaseous yield in case of waste PE compared to waste PP.

The optimum set temperature for waste PP and PE mixture (50% each) was found to be 450 °C, the reaction time was 230 min at this set temperature. The liquid yield, gas yield, and solid residue percentages at the optimum conditions were found to be 56.6%, 20.4%, and 23.0% respectively. Reaction time was almost similar to that of PE while having slightly smaller liquid yield and solid residue amount compared to PE. In contrast, the gaseous yield was considerably increased to 20.4% compared to 12.8% with waste PE.

In case of waste PS, the optimum set temperature was found to be 400 °C, the reaction time was 200 min at this set temperature. The liquid yield, gas yield, and solid residue percentages at the optimum conditions for waste PS were found to be 67.2%, 30.0%, and 2.8% respectively. Reaction time was slightly increased compared to waste PP while having almost similar product yield. In contrast to waste PP, the sample size of PS was 750 g in order to match the full loading capacity of the reactor.

A single experiment was carried out with waste PET to determine its suitability for thermal pyrolysis process. The experiment was carried out at 450 °C set temperature, around 0.06 bar operating pressure in a reaction time of 125 min. The liquid yield, gas yield, and solid residue percentages for waste PET were found to be 0.6%, 77.7%, and 21.7% respectively. The liquid yield was drastically decreased with PET compared to the other types of waste plastics tested. Apart from that some operational issues to the process like line clogging was experienced. Formation of waxy materials and condensation of them inside the gas lines at the operating temperature during the conversion process was the reason for line clogging. Highly unfavourable and hard smell was presented during the experiments.

4.2 Analysis of Composition and Properties of Derived Fuel

GC/MS analysis of waste plastics derived liquid and gaseous fuel was carried out in a gas chromatograph/mass spectrometer (5975 series GC-MSD) consist of Agilent tech 7890A type GC equipped with Agilent 5975C inert XL EI/CI type MSD. Approximately similar compositions were observed in all liquid fuel samples in this analysis. Abundant compounds in the waste plastics derived liquid fuel are shown in the table 3 below.

According to the composition, the liquid fuel obtained from waste plastic is flammable. Compound such as benzene, xylene and toluene contain in the liquid show some toxicity. However, the combustion of benzene, xylene, toluene and other aromatics hydrocarbon in a plentiful supply of O_2 would release CO_2 and H_2O to the environment.

Therefore, this liquid fuel is acceptable to be used as a fuel in different combustion applications.

GC-MS analysis showed that the gases derived from waste plastics is non condensable at ambient temperature and mainly consists of methane, propene, isobutane and 1-propene, 2-methyl (isobutylene). The percentages of methane, propene, isobutane and isobutylene were found to be 80%, 13%, 3% and 3% of total respectively. This is flammable, combustion of this gas mixture in atmosphere would release CO_2 and H_2O to the environment and can be acceptable as a gaseous fuel to be used in different combustion applications.

Table 3
Abundant linear and aromatics hydrocarbons in the waste plastics derived liquid fuel

Linear Hydrocarbons		Aromatics Hydrocarbons	
Compound Name	**Formula**	**Compound Name**	**Formula**
2,4-Dimethyl-1-heptene	C_9H_{18}	Xylene	C_8H_{10}
2-Heptene, 4-methyl	C_8H_{16}	Toluene	C_7H_8
Heptane,4-methyl	C_8H_{18}	Cyclohexane, 1,3,5-trimethyl	C_9H_{18}
Hexene,3,3-dimethyl	C_8H_{16}	Benzene, 1,2,3-trimethyl	C_9H_{12}
2-Decene,4-methyl	$C_{11}H_{22}$	Cyclopentane,1,1,3,4-tetramethyi-trans	C_9H_{18}
Decane,4-methyl	$C_{11}H_{24}$	Cyclooctane,butyl	$C_{12}H_{24}$

ASTM Distillation tests were carried out according to the ASTM-D 86 method and the ASTM boiling point curves for the liquid fuels were obtained. Density at 15 °C, flash point, and pour point were determined according to the ASTM-D 1298, ASTM-D 93, and ASTM-D 97 respectively. Calorific value of the liquid and gaseous fuel was determined by the 6100 Oxygen Bomb Calorimeter (Fully automated) unit and P5615 Boys gas calorimeter respectively. Viscosity was determined by the Broofield digital viscometer (Model DV-E) at the temperature of 25 °C.

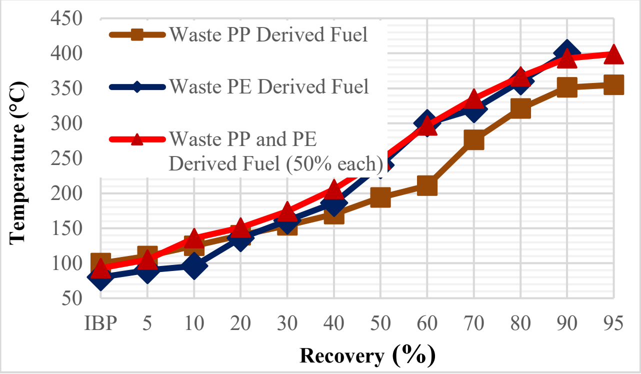


Fig. 5. ASTM boiling point curves of the waste plastics derived fuel

According to the ASTM boiling point curve (figure 5), 90% to 95% of total of liquid fuel was able to recover in the distillation test for all samples. In case of waste PP derived fuel, 95% of the sample was recovered when temperature reached 355 °C whereas 95% of the sample was recovered in waste PP and PE mixture derived fuel when the temperature reached 400 °C. In case of waste PE derived fuel, 90% was recovered when the temperature reached 400 °C. According to the results, liquid fuel samples consist of around 40% to 55% of light distillates, around 30% to 40% of middle distillates and around 5% to 20% of heavy distillates. Waste PE derived fuel consists of around 45% of light distillates, around 35% of middle distillates and around 20% of heavy distillates. Waste PP and PE mixture derived fuel consists of around 40% of light distillates, around 40% of middle distillates and around 20% of heavy distillates.

Density at 15 °C, flash point, and pour point were determined according to the ASTM-D 1298, ASTM-D 93, and ASTM-D 97 respectively. Calorific value of the liquid and gaseous fuel was determined by the 6100 Oxygen Bomb Calorimeter (Fully automated) unit and P5615 Boys gas calorimeter respectively. Viscosity was determined by the Broofield digital viscometer (Model DV-E) at the temperature of 25 °C.

Almost similar densities, flash points, and calorific values were observed in waste PP, waste PE, and waste PP, PE (50% each) derived fuel samples whereas pour points are slightly different. These results are shown in Table 4 below.

Table 4
Properties of waste plastics derived fuel

Property	Method /Apparatus	Waste PP	Waste PE	Waste PP, PE mixture (50% each)
Density at 15 °C (kg/m^3)	ASTM-D 1298	813.8	817.8	806.1
Flash point (°C)	ASTM-D 93	< 30	< 30	< 30
Pour point (°C)	ASTM-D 97	0	3	9
Calorific value of liquid (MJ/kg)	6100 Oxygen Bomb Calorimeter	43.5	43.2	43.5
Calorific value gas (MJ/kg)	P5615 Boys gas calorimeter	42.6		
Viscosity at 25 °C (m Pa s)	Broofield digital viscometer (Model DV-E)	2.5	79	55

4.3 Analysis of Engine Performance and Emission Characteristics of Derived Fuel

Experiments were carried out with waste PP derived fuel, waste PE derived fuel, and waste PP and PE mixture (50% each) derived fuel in order to determine the engine performance and emission characteristics.

The engine was shown consistent performance without considerable variations in running conditions up to 50% blended fuel mixture of waste plastics derived fuel with diesel (50/B/PE/D and 50/B/PP/D). The engine speed was slightly fluctuated with 60% blended fuel mixture and heavily fluctuated and sometimes the engine was tended to stop when it was running with 70% blended fuel mixture.

Hence, the different engine performance parameters such as brake specific fuel consumption (BSFC), break power (BP), break thermal efficiency (BTE), vibration of the engine and exhaust gas temperature were measured and calculated up to 50% blended fuel mixtures and compared with that of diesel. Brake specific fuel consumption measures how efficiently an engine is using the fuel supplied to produce work. BSFC decreases for all fuels as expected as the load increases as shown in the figure 6 and figure 7. It was observed that BSFC is 2% to 50% higher at low loads (1000 W to 2000 W) and 4% to 28% lower at high loads (3000 W to 500 W) with waste PE derived blended fuel mixtures whereas it was almost similar (maximum of ±10% deviation) at all loads with waste PP derived blended fuel mixtures.

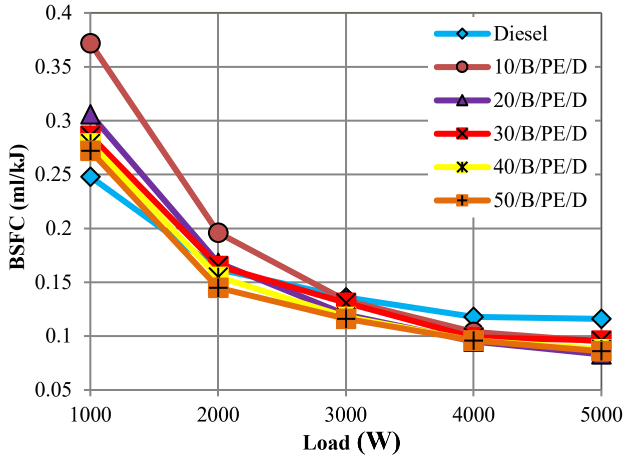


Fig. 6. Load vs. Brake specific fuel consumption (BSFC) for waste PE derived fuel

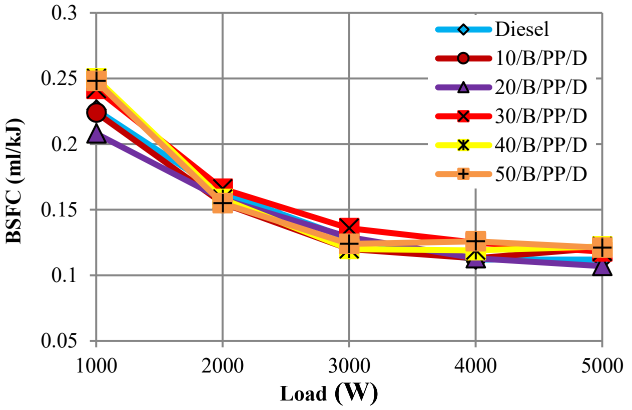


Fig. 7. Load vs. Brake specific fuel consumption (BSFC) for waste PP derived fuel

Brake power measures how efficiently an engine is producing power with the fuel supplied. It is clear from the figure 8 and figure 9 that, as the load increases the BP also increases for all fuels as expected. At the same time, it was observed that BP is almost similar (maximum of ±7% deviation) for all blended fuel mixtures at low loads and slightly higher or lower (maximum of ±15% deviation) at high loads depending on the relative proportions of the blended fuel mixture, with waste PE derived fuel whereas it was almost similar (maximum of ±9% deviation) for all blended fuel mixtures at all loads with waste PP derived fuel.

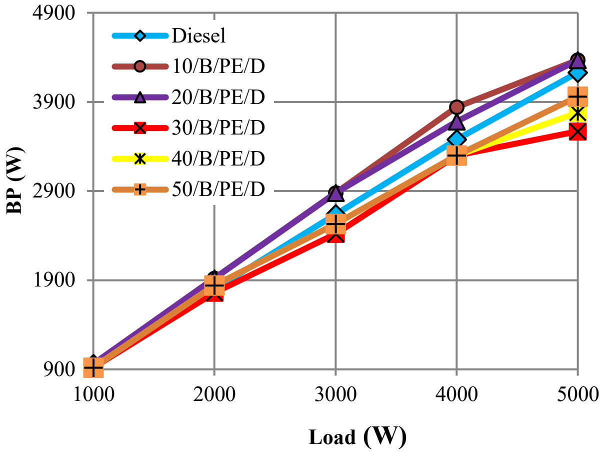


Fig. 8. Load vs. Brake power (BP) for waste PE derived fuel

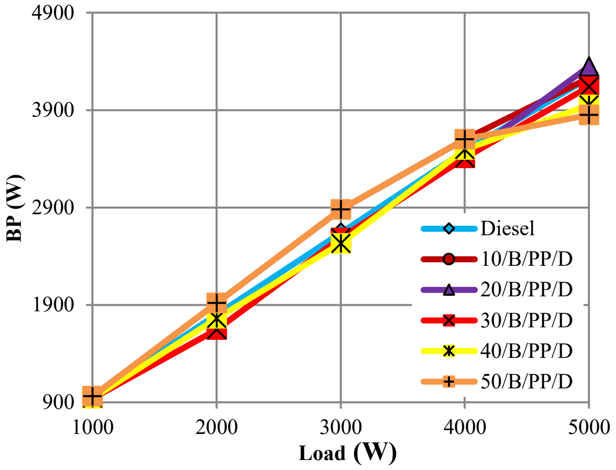


Fig. 9. Load vs. Brake power (BP) for waste PP derived fuel

Brake thermal efficiency measures how efficiently an engine is running with the fuel supplied to produce work. It can be seen in the figure 10 and figure 11 that, as the load increases the BTE increases for all fuels as expected. At the same time, it was observed that BTE is slightly higher or lower (maximum of ±15% deviation) for all blended fuel mixtures at low loads and 9% to 33% higher at high loads with waste PE derived blended fuel mixtures whereas it was almost similar (maximum of ±10% deviation) for all blended fuel mixtures at all loads with waste PP derived fuel.

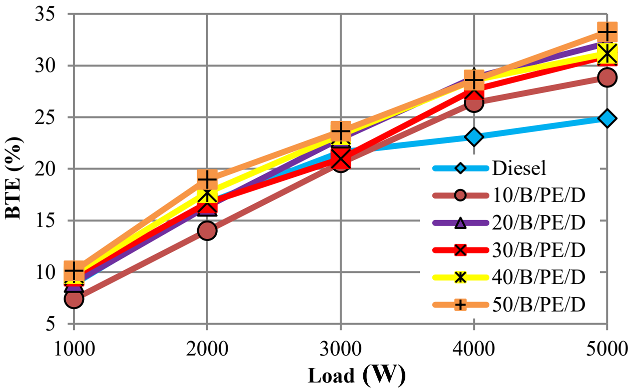


Fig. 10. Load vs. Brake thermal efficiency (BTE) for waste PE derived fuel

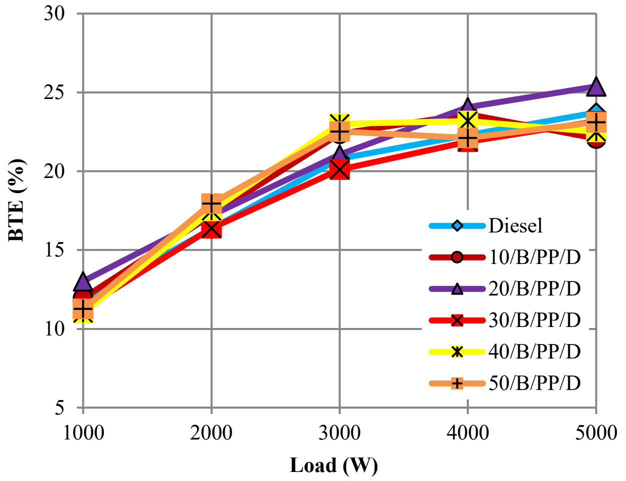


Fig. 11. Load vs. Brake thermal efficiency (BTE) for waste PP derived fuel

In the emission analysis, CO percentage was found to decrease and CO_2 percentage was found to increase with increasing load as expected. CO emissions with 10% to 40% waste PP derived blended fuel mixtures were found to be almost similar or higher (33% to 100%) than that of diesel whereas that were drastically higher (500% to 1000%) with 50% and 60% waste PP derived blended fuel mixtures. This behaviour is caused by the increase of incomplete combustion in the engine which is due to the low purity of waste plastics derived fuel that is in the form of a crude oil and/or inappropriate injector settings according to the type of fuel. CO_2 emissions were found to be almost similar (maximum of ±9% deviation) to that of diesel. NO and NOx amounts were observed to be decreased with increasing concentration of waste plastics derived fuel in the blended fuel mixtures. NO amount was found to be decreased by 16% to 49% compared to diesel whereas NOx amount was decreased by 14% to 52%. The reason for having low NO and NOx amounts with blended fuel mixtures is the low temperature combustion inside the engine with the blended fuel mixtures as evident in the variation of exhaust gas temperature. The exhaust gas temperature was observed to be decrease with the increasing percentage of waste plastics derived fuel in the blended fuel mixture compared to diesel.

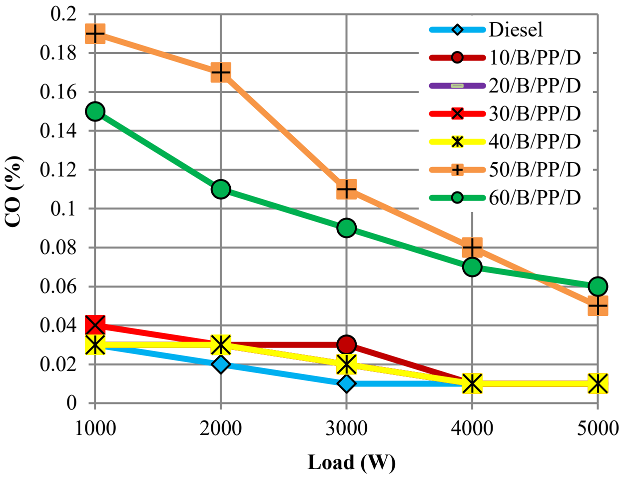


Fig. 12. Load vs. Carbon monoxide (CO) percentage for waste PP derived fuel

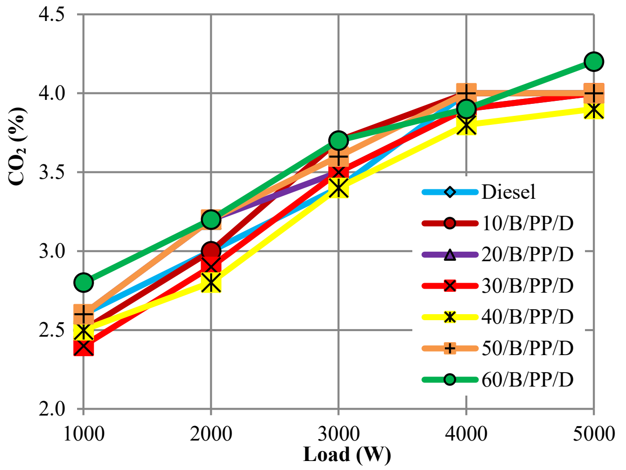


Fig. 13. Load vs. Carbon dioxide (CO_2) percentage for waste PP derived fuel

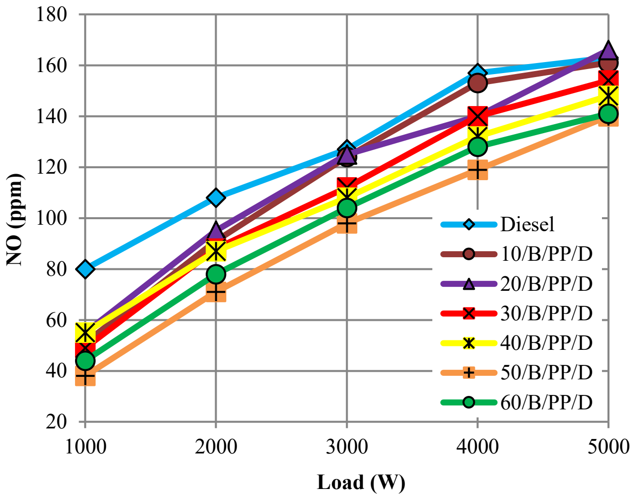


Fig. 14. Load vs Nitrogen oxide (NO) amount for waste PP derived fuel

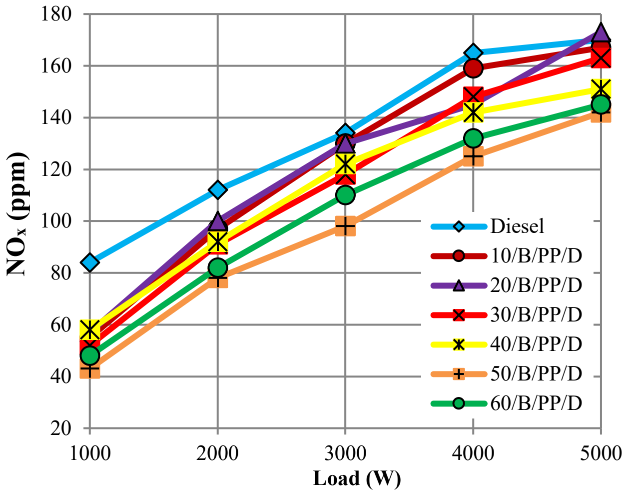


Fig. 15. Load vs Oxides of nitrogen (NOx) amount for waste PP derived fuel

5 Conclusion

The optimum pressure and the batch size were found to be 0.02 bar and full loading capacity of the reactor for all types of waste plastics. The optimum set temperature was found to vary according to the type of the waste plastic sample. It was found that N_2 purging or vacuuming is not essential in the thermal pyrolysis process as long as atmospheric air is successfully escaped at the loading of the sample into the reactor, and sealed and slightly positive pressure environment is maintained in the reactor during the pyrolysis process.

The liquid fuel derived from waste plastics was found to consist of light distillates, middle distillates and heavy distillates. This fuel was found to comprise of linear, branched, and aromatic hydrocarbon compounds. Aromatic compounds such as benzene, xylene and toluene contained in the liquid fuel show some toxicity and combustion of these aromatics hydrocarbon in a plentiful supply of O_2 would release CO_2 and H_2O to the environment.

Gaseous fuel derived from waste plastics is non condensable at ambient temperature and mainly consists of methane, propene, isobutane and isobutylene. Combustion of this fuel in atmosphere would release CO_2 and H_2O to the environment.

The calorific value of the liquid fuel was found to be similar to that of commercial gasoline and diesel. Calorific value of gaseous fuel was found to be similar to that of liquid petroleum (LP) gas.

Therefore, the waste plastics derived liquid fuel and gaseous fuel are acceptable as a fuel to be used in different combustion applications.

The engine was able to perform consistently up to 50% waste plastics derived fuel mixture blended with diesel whereas the engine was not performed well above 60% waste plastics derived blended fuel mixture.

Slight deviations were observed in BSFC, BP, and BTE with waste PE derived blended fuel mixtures whereas that was almost similar at all loads with waste PP derived blended fuel mixtures.

Slight increase in CO emissions was observed with 10% to 40% blends of waste PP derived fuel and dramatic increase were observed with 50% and 60% blends compared to diesel. This behaviour is caused by the increase of incomplete combustion in the engine and/or inappropriate injector settings according to the type of fuel. CO_2 emissions were found to be almost similar to that of diesel. Also, NO and NOx emissions were decreased with increasing concentration of waste PP derived fuel in the blended fuel mixtures since low temperature combustion take place inside the engine with the blended fuel mixtures. The performance of waste PP derived fuel in terms of having low amount of NO and NOx emissions is better and further improvements of fuel quality is required to reduce CO emissions.

The properties of waste plastics derived liquid fuel are closed to that of commercial diesel. The combustion performance and emission characteristics of the waste plastics derived fuel blended with diesel up to the volume percentage of 50% are close to that of diesel. The net energy return of the conversion process was found to be 16,521 kJ/kg of waste plastics. Therefore, the conversion of waste plastics into hydrocarbon fuel using the developed reactor system is a sustainable approach for waste plastics recycling in terms of having usable hydrocarbon fuels and positive net energy return.

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