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Production of Fuel Oil from Waste Low Density Polyethylene and its Blends on Engine Performance Characteristics

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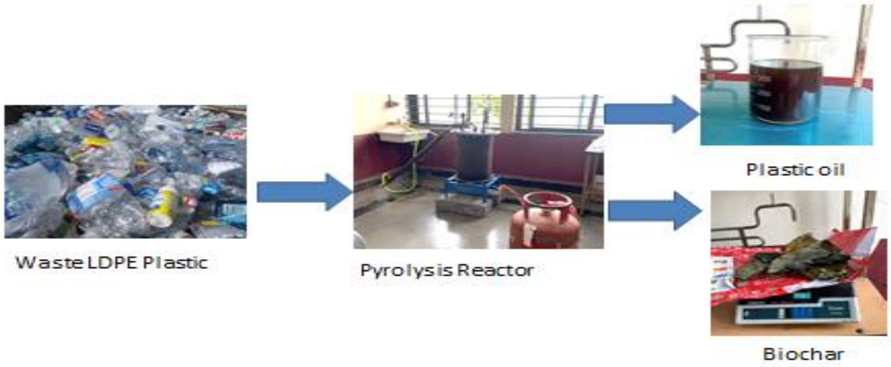
Abstract: Driven by dwindling oil resources and rising energy demands, researchers are exploring ways to convert waste products into high-quality fuels that can replace fossil fuels. Plastic waste, a growing concern, can be a valuable resource. This study investigates the potential of fuel oil (FO), derived from waste plastic (low-density polyethylene), as a fuel source. Fuel oils were produced from low-density polyethylene at 340°C and 450°C, respectively. The properties of these oils and their blends with commercial diesel were analysed using the American Society for Testing and Materials (ASTM) Method. Engine tests were then conducted using fuel oil and compared to diesel. The blend also resulted in slightly higher carbon dioxide (CO_2), oxides of nitrogen (NO_x), and unburned hydrocarbons (HC). However, there is a similarity in brake thermal efficiency, specific fuel consumption, and carbon monoxide emissions of fuel oil and diesel. Notably, adding diesel to fuel oil improves engine performance. The fuel properties of the fuel oil obtained from LDPE were comparable to diesel, suggesting potential direct use as engine fuel or refinery feedstock. The engine runs smoothly and is conducted up to a 30% blend, with improved brake thermal efficiency and lower fuel consumption than pure diesel. This highlights the need for further research on fuel fractionation or engine modifications to optimise performance and minimise emissions.

Keywords: Pyrolysis, Waste plastic oil, Thermal degradation, Fuel Oil, Solid waste management, Fuel characterisation, Engine performance, Thermal efficiency.

Graphical Abstract



1. Introduction

The twenty-first century is the "Era of plastic," a necessary evil integrated into human life. Coined in the early 17th century from the Latin "plasticus" and the Greek "plastikos," both meaning "to mould," plastic describes materials that can be shaped and formed into various designs [1]. Plastics can be tailored to various applications because of their diverse properties, including strength-to-weight ratio, stiffness, toughness, corrosion resistance, thermal stability, and electrical insulation [1, 2]. The low cost, versatility, and durability of plastics have led to soaring demands in emerging markets [3, 4]. Over 300 plastic types are used in daily applications and categorised as general-purpose or engineering plastics [5, 6]. Plastic packaging use is rising, and there are concerns about its safety; a database catalogues 900 chemicals linked to plastic packaging, sixty-three of these chemicals are ranked high risk for human health and sixty-eight for environmental harm [7]. There are challenges to understanding the risks of these chemicals. First, plastic packaging can include many different kinds of plastic and additives. Second, many chemicals in plastic packaging are not well documented. Common general plastics include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyurethane (PU). A UN report suggests a shift from durable plastics to SUPs, with packaging dominating SUP production [7]. This has driven global plastic production to 360 million metric tons in 2018, with SUPs accounting for half of plastics used [6, 8]. PP and PE are widely used in disposable products like packaging and bottles [9, 10]. These single-use plastics (SUPs) are also used in agriculture, particularly mulching film and greenhouses. Most SUPs are discarded after a single use [11], ending up in landfills, incinerators, or polluting our oceans, rivers, and soils [10, 12]. This plastic waste harms the environment, prompting action from governments and international agreements [5, 13, 14].

Plastic's incredible variety and affordability have revolutionised daily life; from packaging to building materials, countless applications rely on common types like polyethylene (PE) and polypropylene (PP). Table 1 elucidates common types of plastics and their properties used in packaging to building materials.

The flow diagram (Figure. 1.) illustrates the flow and accumulation of plastics in China. Focusing on the "Major Five" plastics (due to better data availability), the diagram tracks their journey from production (1978-2017) through manufacturing into various products. These products are then used in six different sectors and finally reach their end-of-life stage, where they may be recycled or enter waste management. The Boxes represent different stages in a plastic's life cycle, and the arrows show the movement of plastic between these stages. The dotted line defines the system boundary.

Table 1. *Comparing Plastics: Key Traits for Different Types [15]*

Type of plastic	**Chemical formula**	**Density** (g/cc)	**Melting point** °C	**General Properties**	**Uses**
PS	$(C_8H_8)_n$	0.96-1.04	240	The long chain of hydrocarbon attached to the Phenyl group is light in weight, durable, and resistant to heat.	Toys, electronics, and medical items
PET	$(C_{10}H_8O_4)_n$	1.38	>250	Chemical resistant, hard, strong, transparent, also opaque, and off-white	Water and soft drink bottles, food jar
PVC	$(C_2H_3Cl)_n$	1.4	100-260	Resistant to fire	Electrical insulations, packaging, credit cards, shoes, frames of windows, artificial leather
PP	$(C_3H_6)_n$	0.855-0.946	130-171	Higher melting point, rigid and hard	Bottle caps, chip packs, medicine bottles
LDPE	$(C_2H_4)_n$	0.88-0.96	115-135	Consists of more branches, making it weaker in intermolecular force, less hardness, tensile strength, and Ductile.	Garbage containers, PE bags for carrying fruits, vegetables, groceries, and water pipes (hose).
HDPE	$(C_2H_4)_n$	0.93-0.97	120	Side branching, less crystalline structure, thus easy to mould, resistant to water, higher strength	Plastic bags, foils, oil containers, bottles, and toys.

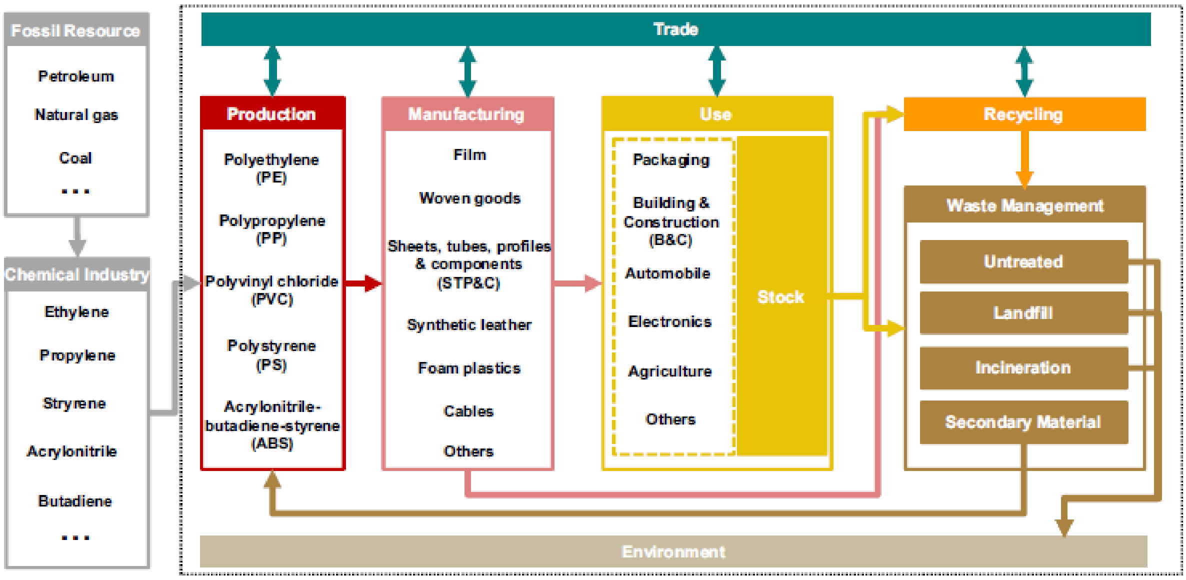


Figure. 1. *Illustration of the flow and accumulation of plastics in China [16]*

A UN report indicates annual plastic waste generation has surpassed 400 million tonnes since 2020. This alarming trend is projected to continue, with plastic production doubling to 800 million tonnes by 2035 and reaching a staggering 1600 million tonnes by 2050 [17]. The world's largest plastic consumer, China, uses five common plastic categories extensively:

polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and acrylonitrile-butadiene-styrene (ABS). These five categories account for 74% of China's total plastic consumption. A dramatic rise in plastic use is evident, with consumption surging from 1 million tons/year in 1978 to 63 million tons/year in 2017. This rapid growth has led to a significant waste problem, with 44 million tons of plastic waste generated in 2017 alone, 29% of this waste is recycled [16]. China consumed nearly 1 billion tons of PE, PP, PVC, PS, and ABS from 2000-2019. However, only 27% of the resulting 590 million tons of plastic waste was recycled. Recycling rates varied by plastic type, with PP and PE at 28-30% and PS/ABS (lowest consumption) at 26% [18]. Singapore generated 868,600 tonnes of plastic waste in 2020, with a meagre 4% recycled [1]. Economic development in emerging economies like India and South Africa has fueled a shift from lower-consumption lifestyles to reliance on convenience items like plastic bags and packaging. This trend has resulted in the consumption of over 15 billion tons of single-use plastics in these countries over the past four decades [19-21].

Plastic waste is a growing problem globally; India is no exception [22]. In 2019, India generated around 9.4 million tonnes of plastic waste annually, contributing about 3.1% to the global total of over 380 million tonnes [23]. Plastic consumption in India has skyrocketed, growing twice as fast as the GDP. Polyolefins comprise most plastic use (60%), with packaging being the most prominent consumer (42%). A "master curve" based on global trends was used to estimate future plastic consumption in India, assuming similar development to Western Europe. This model projects a sixfold increase in plastic consumption by 2030 compared to 2000. Currently, 47% of plastic waste is recycled in India, significantly higher than in most countries. However, with a growing number of long-lasting plastic products, the recycling rate is expected to drop to 35% by 2030. Plastic waste for disposal (excluding recycling) is projected to increase tenfold by 2030, reaching over 13 million tonnes [24]. Plastic production is a growing environmental concern, currently consuming 6% of global oil production and is projected to reach 20% by 2050 if trends continue. With a growth rate of around 4%, global plastic production is on track to reach significant volumes [25]. The distribution of plastic product use across various industries and global plastic consumption by region in 2016 are presented in Figure. 2(a) and 2 (b).

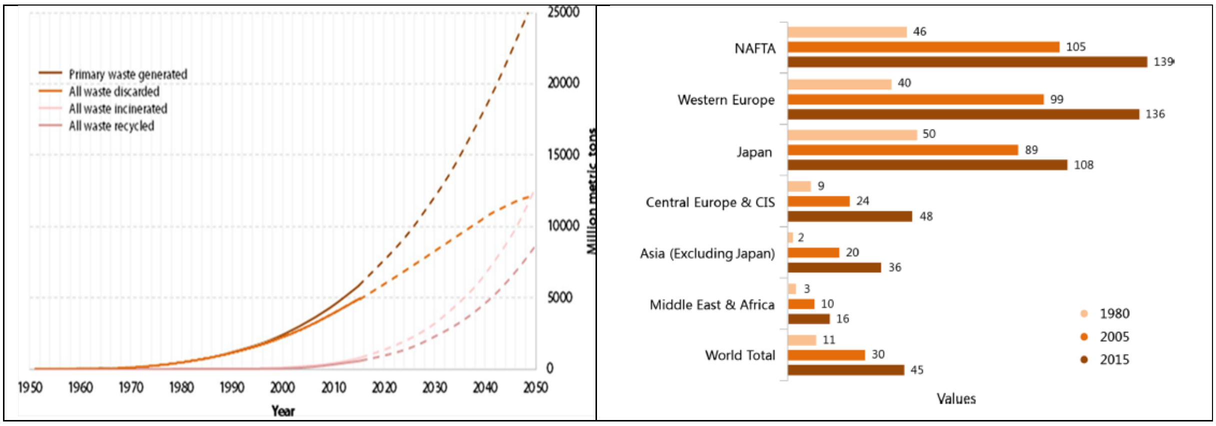


Figure. 2(a) & (b). *Global Plastic Use: A comparison of plastic consumption patterns [26]*

Effective waste management is critical for sustainable development, including exploring alternatives to landfills such as source reduction, reuse, recycling, and energy recovery through incineration or processed fuel applications [27]. While research on biodegradable/green polymers is ongoing, they are currently limited in replacing non-biodegradable plastics [28, 29]. Growing environmental awareness has led to a more aggressive approach to waste management in the US. Plastics, a key waste component, are seeing a significant rise in recycling. Inefficient waste management systems lead to improper collection and disposal of plastic waste, resulting in environmental and public health hazards [30]. Plastic waste can be converted into a valuable resource by adopting scientific collection, recycling, and disposal in an environmentally friendly manner. Recycling presents a significant potential for resource conservation and greenhouse gas reduction, making it economically viable by generating in-demand resources like diesel fuel from plastic waste [31]. India’s plastic consumption has soared, increasing from 5 million tons/year in 2005 to a projected 24 million by 2020. While 94% of this plastic waste is technically recyclable, limited collection and infrastructure leave a significant portion unmanaged, ending up in landfills. PET bottles, PE plastics, and shopping bags are significant contributors to this growing waste stream [31].

1.1 Technologies for Plastic Degradation

While traditional methods like incineration and landfilling exist for plastic waste disposal, incineration releases harmful gasses, and landfills offer limited biodegradation due to low oxygen levels. While plastic waste can be incorporated into road construction, and biodegradation offers an eco-friendly solution, these methods are not universally applicable.

Bioremediation using engineered microbes and enzymes shows promise but requires further research [32-34]. Upcycling plastics represents an exciting possibility but necessitates significant research in solvent development for polymer separation, novel catalyst design, and efficiency-enhancing techniques. Existing biomass conversion methods might also be adaptable to plastics, but a thorough environmental impact assessment is crucial before widespread adoption [35].

The low plastic recycling rate highlights the need for improvement. Separating plastic types is expensive and complex, hindering recycling efforts [36]. Landfills overflow with plastic, polluting our environment. Direct recycling offers a more straightforward solution, but this process sorts and transforms plastic into lower-quality new products. To address this, manufacturers often blend recycled materials with virgin plastic. Modified regeneration offers an alternative by enhancing recycled plastic properties [37]. Waste-to-Energy (WTE) technology eliminates sorting and mixed plastic waste’s high heat content, making it a viable fuel source. Incineration offers efficiency, but it releases harmful pollutants. WTE and incineration pose health and environmental risks [38, 39]. Like plastic production, pyrolysis converts plastic waste into valuable fuel and can potentially replace fossil fuels.

The thermal degradation of plastic with a bentonite catalyst at optimal conditions produces fuel oil, gas, and charcoal [40-42]. Gasification offers the most flexibility, transforming end-of-life plastic waste into energy or fuel production. Gasification with fluidised bed reactors is a promising recycling method for end-of-life plastics [43]. Simulations of gasification of polyethylene using AspenPlusTM software showed that a gasifier operated at 900°C ratio of steam to feed 1.5 produces a maximised output of 21 kmol/hr [44]. Pyrolysis and gasification hold promise for plastic waste treatment. The development of models that integrate reaction kinetics, reactor design, and the variability of real-world feedstocks through experimentation and computational tools will help minimise the environmental impact of plastic waste processing [45-47].

2. Experimental Setup

This study investigated the conversion of waste plastics, specifically low-density polyethylene (LDPE), into fuel oil (FO) using pyrolysis. A lab-scale semi-batch pyrolysis reactor was designed, commissioned, and used to study the thermo-chemical conversion of plastic wastes into valuable products such as pyrolysis oil. A pilot-scale mild steel reactor assembly was designed and fabricated for this purpose (Figure. 3). The assembly consisted of a cracking reactor body, a double pipe type heat exchanger for condensation, thermocouples for temperature measurement and control, a digital temperature indicator, PID controllers, and a manometer for pressure drop measurement. The reactor itself is a vessel with a diameter of 260 mm, a height of 570 mm, and a capacity of 30.3 L. Thermocouples, pressure gauges, and PID controllers were used for monitoring and control during the process. Electrical band heaters with insulation minimised heat loss and provided uniform heating throughout the pyrolysis process, which ranged from 350 to 450°C. Nitrogen gas (N_2) was purged through the reactor at a constant rate of 0.5 L/s at a pressure of 5 PSI. The reactor, made of mild steel and capable of withstanding temperatures up to 1000°C, can process 5 kg of raw materials in a single batch.

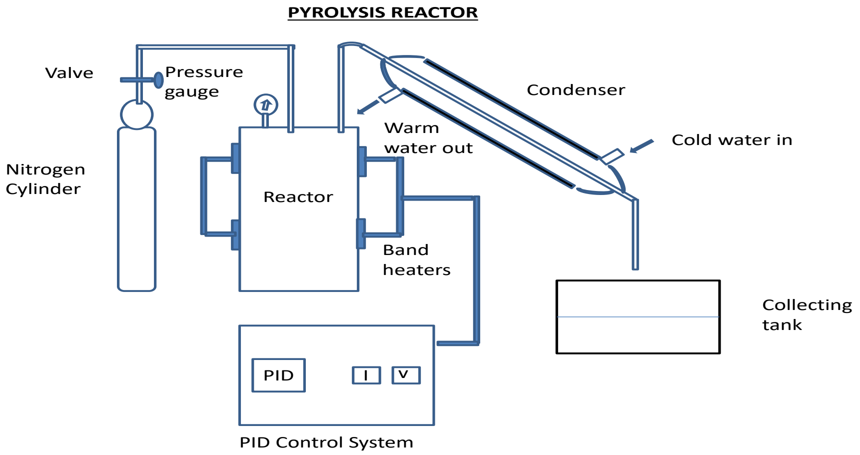


Figure 3. *Schematic diagram of conversion of LDPE waste to fuel oil.*

The pyrolysis process involved heating pre-cleaned and dried LDPE milk pouches (1000 g) in the reactor. The endpoint of the process, signified by a reduction in condensate collection over time, began at 127°C and lasted for 3 hours. The organic vapours generated in the reaction chamber were condensed and collected as liquid oil. In a typical experiment, 1000 g of waste plastics were fed into the reactor and heated to a reaction temperature of 450°C at 10°C/min. LDPE pyrolysed at a lower temperature of 450°C yielded a lower viscosity fuel oil with superior fuel properties. The LDPE-derived fuel oil resembled diesel in density, heating value, carbon, and hydrogen content. However, it had higher acidity, ash, oxygen, and aromatic content.

Additionally, it had a lower cetane index (indicating a slightly lower self-ignition potential) but a lower distillation temperature (suggesting lighter components) than diesel. Tests were conducted to evaluate performance in stationary diesel engines and indicated the suitability of fuel oil derived from LDPE for applications in power generation and marine engines. The thermo-chemical conversion of waste plastic follows a specific reaction pathway.

2.1 Engine Performance Characteristics with Fuel Oil (FO) Blends

This section explores the performance of a single-cylinder, four-stroke diesel engine running on blends of fuel oil (FO) and commercial diesel. The engine was tested with pure diesel and FO-diesel blends at 25%, 50%, 75%, and 100%. Higher FO concentrations were not used due to detonation issues within the engine.

2.2.1 Experimental Setup:

A Kirloskar TV1 model single cylinder, 4-stroke cycle, engine with a power output of 3.50 kW, an operational speed of 1500 RPM was used for the fuel testing. The combustion chamber geometry are mentined in Table 2.

Table 2. *Engine Details: Courtesy: Apex Innovations Pvt. Ltd. Kupwad, Sangli, India*

Parameter	**Specification**
Model	Make Kirloskar, Model TV1, Type 1
Power	3.50 kW
RPM	1500
Cylinder	Single cylinder, 4-Stroke
Bore X Stroke	87.50 mm X 110.00 mm
Compression ratio	18: 1
Swept volume	661.45 (cc)
Density of fuel	830 Kg/m^3
Calorific value of fuel	42000 kJ/Kg

3. Results and Discussion

Blending fuel oil (FO) with diesel impacts engine performance and emissions. It focuses on three key areas: combustion, blending of diesel and FO, and exhaust emissions. The study compares pure diesel to blends of 10%, 20%, and 30% FO. The tests also explored engine performance with FO blends ranging from 25% to 100%, limited by noise and vibration constraints.

Evaluating engine performance with blended fuel oil (FO) and diesel focuses on Brake Thermal Efficiency (BTE) and Brake-Specific Fuel Consumption (BSFC). BTE reflects the usable work output as a percentage of fuel energy input, while BSFC indicates fuel consumption per power output unit. Lower BSFC signifies better fuel economy. The evaluation compares the BTE and BSFC of the engine running on pure diesel (B0) to various FO blends (e.g., 10%, 20%, 30%). Ideally, both BTE and BSFC improve with increasing FO, suggesting efficient burning and lower fuel consumption.

Engine noise, vibration and exhaust emissions (NO_X, CO, CO_2, smoke) are crucial. Increased noise, vibration, or incomplete combustion can outweigh efficiency gains. Even if fuel economy improves, a rise in harmful pollutants negates environmental benefits. Analysing these parameters determines the optimal FO-diesel blend for an engine, balancing fuel efficiency, engine health, and emission output.

3.1 Comparative Analysis of Fuel Oil and Diesel

Fuel oil derived from the thermal degradation of low-density polyethylene (LDPE) plastic waste through a pyrolysis reactor was analyzed and compared to commercially available diesel fuel meeting Bharat Standard (BS) specifications from Bharat Petroleum, as well as findings from a previous study by Khan et al. [48] are described in Table 3. This comparison aims to assess the potential of this FO as a viable alternative to diesel.

3.2 Physical Property Analysis

Density: The FO density (741.7 kg/m^3) aligns closely with Khan et al. [48], suggesting consistency in processing methods. This lower density compared to conventional diesel (840–880 kg/m^3) offers potential advantages in storage and transportation.

Kinematic Viscosity: The measured value of FO 2.18 cSt falls within the range reported by Khan et al. [48] 1.98 cSt and is significantly lower than standard diesel 5 cSt. This indicates superior flow characteristics and potentially improved engine combustion efficiency.

Gross Calorific Value: The FO demonstrates a high value (44,141 J/kg), exceeding standard diesel (42,000 J/kg) and aligning with Khan et al. [48] findings, suggesting efficient energy release during combustion.

Flash Point and Fire Point: Slight variations from standards and Khan et al. [48] results exist, potentially due to feedstock or processing differences. However, the higher fire point suggests improved safety during handling and transportation compared to diesel fuel.

Pour Point: The pour point of -5°C indicates exceptional low-temperature fluidity, advantageous for cold weather operability.

Aniline Point: This suggests a moderate aromatic hydrocarbon content, aligning with high-quality diesel fuel standards.

Sulfur Content: The lower sulfur content translates to reduced soot formation and cleaner emissions.

Carbon Residue: The lower carbon residue indicates a reduced propensity for carbon deposits, potentially improving engine performance.

Ash Content: The ash content is higher than standard values, suggesting the presence of non-combustible materials that could hinder combustion efficiency and increase emissions. Further research is needed to optimize the pyrolysis process and minimize ash content.

Acidity: The low pH value suggests lower corrosivity compared to standard values, though variations may exist due to processing methods.

Table 3. *Comparison of FO Properties with Standard Diesel and as reported by Khan et al.[48].*

S. No	Parameter	Unit	Value (Analysis of 300 ml sample)*	Std. Data from IS 1460:2005 Bharat Stage IV [49]	Characteristics of WPPO[48]	Test Method[48]
1	Ash	%	<0.10	0.01	0.036	ASTM D 48
2	Density, at 20ºC	Kg/m^3	785.1	820 - 845	0.7477	IP 131/57
3	Pour Point	ºC	-5	3-15	<−15	ASTM D 93
4	Acidity (Total)	mg KOH/gm.	0.087	To report	--	Titration method
5	Viscosity at 40∘C	cSt	2.18	2.0 - 4.5	1.980	ASTM D 415
6	Sulphur	mg / kg	32	< 50	0.246 (% of wt.)	
7	Flash point (Pensky Martens closed cup)	ºC	68	66	15	ASTM D 93
8	Fire Point	ºC	74	56	20	ASTM D 93
9	Carbon residue	%	0.07	0.30	0.5	ASTM 189-65
10	Gross Calorific value	J/Kg	44,141	42,000	41127	Bomb Calorimeter 12/58
11	Aniline point	ºC	75	45-55	--	ASTM D 93

3.3 Engine Performance with Fuel Oil - Diesel Blends

3.3.1 Brake Thermal Efficiency

Engine performance, specifically its ability to convert thermal energy into usable work, was evaluated using Brake Thermal Efficiency (BTE). Figure. 4 depicts the variation of Brake Thermal efficiency with load. The blends containing 10% and 20% FO displayed a slight BTE advantage over pure diesel at specific load conditions (25% load for both blends and 75% load for the 20% blend). However, this benefit diminished at full load, where pure diesel achieved a BTE of 20.83%, while FO blends (25% to 100%) ranged from 18.84% to 19.31%. Despite their potentially higher calorific value, this decrease in BTE for FO blends can be due to two factors.

Firstly, marginally higher heat losses at full load, possibly caused by increased exhaust gas temperatures, could have reduced efficiency. Secondly, the higher viscosity of FO blends may have led to poorer fuel atomisation, hindering complete combustion and resulting in unutilised fuel energy. While exhaust gas temperatures were comparable between blends and pure diesel, the higher heat release rate observed with FO blends suggests incomplete combustion and potentially contributes to the lower BTE. Overall, these findings highlight a trade-off when using FO blends. While some blends show promise at specific loads, their inherent properties can lead to slightly lower BTE, particularly at full load, compared to pure diesel.

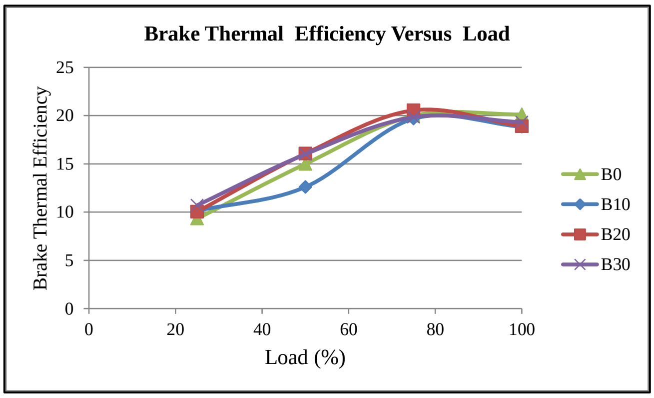


Figure 4. *Variation of Brake Thermal Efficiency with load*

3.3.2 Brake-Specific Fuel Consumption

Brake-Specific Fuel Consumption (BSFC) is an indicator of fuel efficiency. Figure. 5 depicts the variation of brake-specific fuel consumption with load. As expected, BSFC decreased with increasing engine load for all fuels (diesel and FO blends). The blends with higher FO content slightly improved BSFC compared to pure diesel, which can be attributed to the higher calorific value of FO blends requiring less fuel for the same power output and, potentially, the presence of oxygenated compounds in the FO that might enhance premixed combustion. FO blends improved fuel efficiency, but balancing noise, vibration, and emissions with BSFC is crucial for finding the optimal blend ratio for each engine.

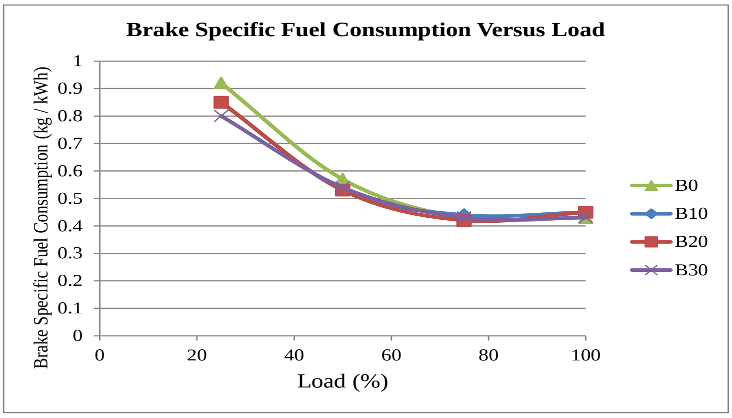


Figure 5. *Variation of Brake-Specific Fuel Consumption with load*

3.3.3 Emission Analysis

Engine emission parameters (NO_x, CO, CO_2, smoke) are crucial metrics for engine performance in determining the blending of fuels with alternatives. Incomplete combustion caused by FO blends can negate any BTE gains. Even if fuel efficiency improves, a rise in harmful pollutants nullifies the environmental benefits. Analysing both BTE and emissions allows engineers to determine the optimal FO-diesel blend for an engine, balancing fuel efficiency, engine health, and minimising air pollution. The comparison of emissions between FO blends and diesel revealed significant differences.

Oxides of Nitrogen (NO_x): NO_x emissions increased with FO blends due to extended ignition delay periods, resulting in higher premixed combustion portions and in-cylinder temperatures. NO_x emissions comprise nitric oxide (NO) and nitrogen dioxide (NO_2). Their formation depends highly on in-cylinder temperature, stoichiometry (fuel-air ratio), oxygen concentration, and the residence time available for the reactions. Figure. 6 shows that NO_x emissions increase marginally when running the engine with fuel oil. At 25% load, emissions vary from 267 ppm for diesel to 435 ppm for the 10% FO blend. Similarly, at 100% load, emissions range from 143 ppm for diesel to 491 ppm for the 10% FO blend.

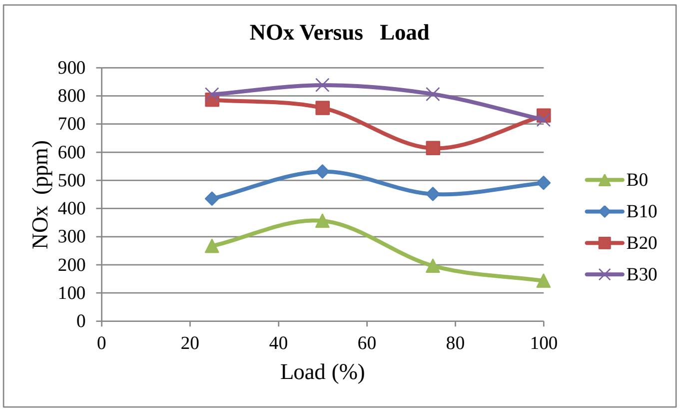


Figure 6. *Variation of NO_x with load*

3.3.4 Unburned Hydrocarbon (UHC):

Higher unburned hydrocarbon (UHC) emissions signify incomplete combustion, a characteristic of FO blends (Figure. 7). This may have resulted from longer ignition delays and aromatic content in the fuel oil, even with some improvement from its higher oxygen content. As the FO concentration increased, UHC emissions rose. At 25% load, diesel UHC ranged from 15-5 ppm, while the 30% FO blend emitted 79-65 ppm. The two factors likely to contribute to high UHC emissions are 1) fuel spray failing to penetrate deeply enough and 2) the presence of harder-to-break-down unsaturated hydrocarbons in the FO.

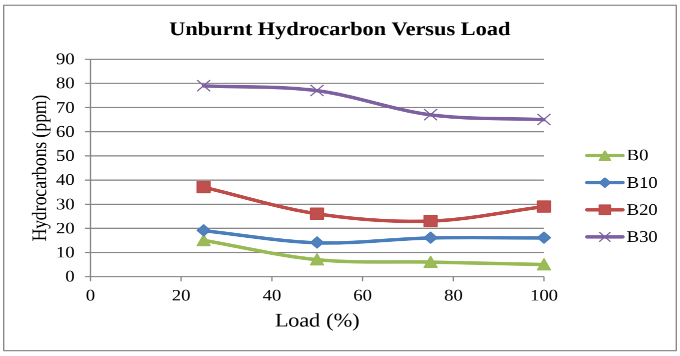


Figure 7. *Variation of unburnt hydrocarbons with load*

3.3.5 Carbon Monoxide (CO):

Carbon monoxide emissions and carbon dioxide were significantly higher for FO blends than diesel, particularly at higher engine loads and blend concentrations (Figure. 8 and Figure. 9). This is likely due to poorer air-fuel mixing within the cylinder, creating localised fuel-rich regions. CO typically forms due to incomplete combustion caused by a lack of oxygen or inadequate mixing. As the figure shows, CO emissions for diesel range from 0.07% at 25% load to 0.02% at full load. In contrast, the 30% FO blend exhibits CO emissions as high as

0.29% at low load, remaining elevated even at full load (0.27%). These results confirm that waste plastic oil blends generate considerably more CO than diesel, especially under higher loads and with higher FO content. This can be attributed to the poorer fuel-air mixing observed with FO blends, leading to incomplete combustion and increased CO formation.

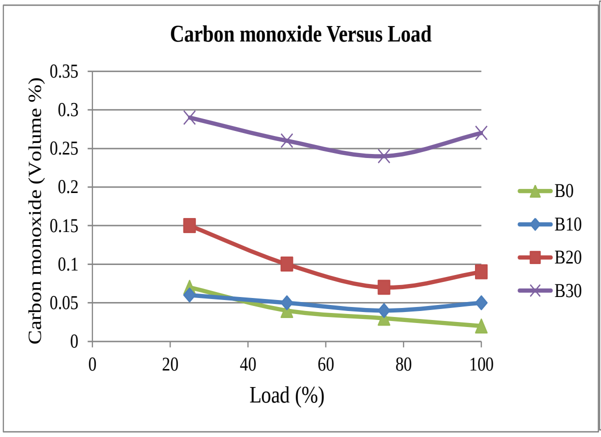


Figure 8. *Variation of carbon monoxide with load*

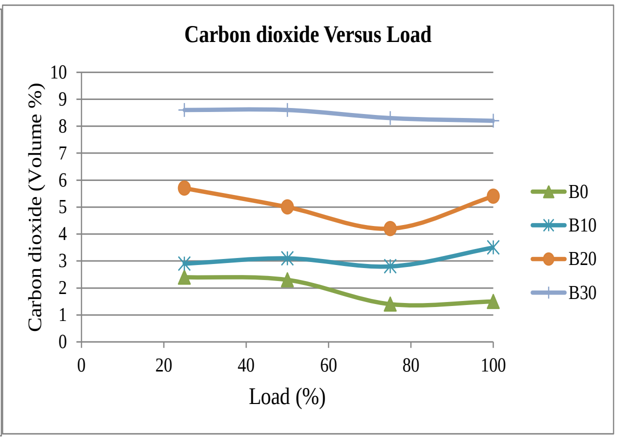


Figure 9. *Variation of carbon dioxide with load*

Smoke: Smoke emissions were significantly higher for FO blends than diesel (Figure. 10). This is attributed to reduced combustion duration and rapid flame propagation. The smoke itself consists of soot particles suspended in exhaust gas. Diesel smoke emissions range from 2.7 BSU to 15.1 BSU, while FO blends show a range of 0.0 BSU to 4.6 BSU (30% FO blend) as load increases.

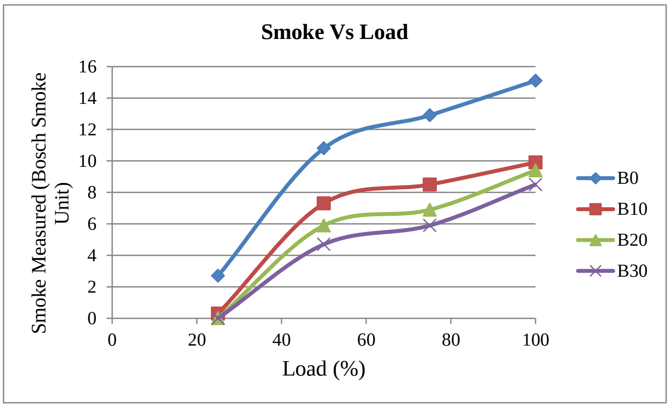


Figure 10. *Variation of unburnt hydrocarbons with load*

4. Conclusion

This experimental study explored pyrolysed low-density polyethylene fuel oil (FO) as a potential alternative to diesel fuel in a CI engine. The engine ran stably on FO blends, exhibiting combustion characteristics similar to diesel with some key differences. Brake thermal efficiency (BTE) was marginally lower with FO blends at full load, possibly due to increased heat loss. However, the blends displayed lower brake-specific fuel consumption (BSFC) (ranging from 0.0 units to a specific value for a blend) compared to diesel, indicating better fuel efficiency, which is due to FO blends higher calorific value (energy content). BTE for some FO blends (10% and 20% at 25% load, 20% at 75% load) surpassed diesel, potentially due to oxygenated compounds. While FO blends offered improved fuel efficiency (lower BSFC and potentially lower overall fuel consumption), a significant increase in engine noise and vibration occurred when FO content exceeded 30%. Therefore, a 20% FO blend seems like a practical compromise for long-term use, balancing performance gains with engine behaviour.

However, trade-offs exist regarding emissions. FO blends produced higher NO_x, CO, CO_2 and UHC emissions than diesel, likely due to slower ignition. The oxygenated compounds in FO blends might contribute to improved premixed combustion, leading to some overall gains in fuel efficiency. This study suggests promise for FO blends, particularly up to 20% concentration, as an alternative fuel for diesel engines. They offer advantages like improved fuel efficiency and potentially lower fuel consumption. However, further research is needed to address long-term considerations such as the acidity of FO, ignition delay period, cylinder peak pressures, combustion period, and potential engine modifications for optimal performance and emission reduction.

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Nomenclature:

ASTM	American Society for Testing and Materials
BTE	Brake Thermal Efficiency
CI	Compression-Ignition
CO	Carbon monoxide
HC	Hydrocarbon
HCV	Higher Calorific Value
NO	Nitric Oxide
NOx	Oxides of Nitrogen

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