



Sustainable energy generation from plastic waste: An in-depth review of diesel engine application

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ABSTRACT

Plastic consumption has increased significantly over the previous few decades and it is one of the most significant sources of waste in many countries. Recycling and energy recovery methods are just two methods for dealing with plastic waste. As a result, the process of converting waste plastic into energy and its application in the diesel engine was reviewed in the present study. The pyrolysis process could be utilized to use plastic waste efficiently. The waste plastic is converted to liquid oil, gas, and solid by using this process. This article reviewed the application of plastic pyrolysis oil (PPO) in diesel engines regarding its properties and effects on the fuel's performance, combustion, and emission parameters. PPO typically has a lower sulfur concentration than standard diesel fuel. Plastic pyrolysis oil (PPO) improves cylinder pressure, brake power, and brake thermal efficiency while lowering fuel consumption when blended with diesel. Emissions can also vary depending on combustion characteristics, fuel quality, and engine technology. The literature on emission assessments yields conflicting results regarding nitrogen oxides and hydrocarbon emissions from PPO. However, because of the higher oxygen concentration, carbon monoxide (CO) and particulate matter (PM) often decrease. Finally, the study recommended a 10%–90% mix of PPO-diesel as an alternative fuel for the engine with no modifications; this concentration may be increased by adding additives/nanoparticles in the fuel or modifying the engine.

1. Introduction

The need for energy is currently critical (Nizamuddin et al., 2018) due to rising energy demand (Yaqoob et al., 2021), industrialization, (Agarwal, 2007), depletion of conventional energy, the issues associated with global environmental issues (Nabi et al., 2012; Nabi and Hustad, 2010) and escalating fuel prices (Hossain et al., 2017). Biodiesel (rapeseed, palm oil, and soybean) is not feasible due

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Abbreviations

BP	Brake power
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CD	Commercial diesel
CI	Compression-Ignition
CO ₂	Carbon dioxide
CO	Carbon monoxide
CP	Cylinder pressure
CR	Compression Ratio
DEE	Diethyl ether
DF	Diesel fuel
DI	Direct Injection
HC	Hydrocarbon
HRR	Heat release rate
IC	Internal combustion
ICE	Internal combustion engine
ID	Ignition delay
ID	Indirect ignition
IP	Indicated power
ITE	Indicated thermal efficiency
JME	Jatropha methyl ester
ME	Mechanical efficiency
MI	Main injection
NO _x	Nitrogen oxide
PF	Petrol fuel
PL	Pyrolysis liquid
PM	Particulate matters
PPO	Plastic pyrolysis oil
SI	Sustainability index
SMP	Simulated mixture of plastic
SO ₂	Sulphur dioxide
UBHC	Un burned hydrocarbon
WPO	Waste plastic oil

to deforestation, mainly due to the food-fuel conflict. As a result, converting food crops into fuel could lead to a global food shortage (Lam et al., 2009). Thus, using waste plastic as an alternative energy source could reduce waste worldwide. (Hamid et al., 2021). Plastic waste is a challenging issue with financial and environmental implications (Damodharan et al., 2019). Disposing waste plastic in landfills severely threatens the environment, causing ecological issues (Kalargaris et al., 2017a).

Following the growth of the global plastic manufacturing sector and the absence of a reusing (recycling) program or financing structure, waste plastic and rubbers are additional serious contaminants in terms of open dumping in the land or water channels. According to statistics, 11% of the 19–23 million metric tonnes of plastic waste shipped globally in 2016 ended up in sea-going living places. Considering the severe claims already made by countries, annual discharges might reach up to 53 million metric tonnes by 2030 (Kaimal and Vijayabalan, 2016a). Furthermore, the Coronavirus pandemic's increase in insignificant volume has taken steps to undermine current waste administration frameworks and medical services limitations in recent years. Global waste management strategies are presently unable to respond to existing plastic waste. An emergency clinic or clinical waste provides obvious challenges since it must be removed to eliminate any remaining infections (Klemeš et al., 2020). Plastic is being used at an alarming rate of 4% every year due to its resilience, lightweight, and low cost. The Kingdom of Saudi Arabia (KSA) is one of the world's largest plastic producers, with an estimated 6 million metric tonnes of annual capacity (Miandad et al., 2017). Similarly, China presently delivers about 1 kg of MSW per person each day, with an estimated 150 million tonnes produced annually. In China, landfilling is utilised to dispose of about 90% of the MSW delivered (Lu et al., 2011).

On January 1, 2018, China banned plastic waste imports, leading a few industrialized countries to try to find free plastic waste reuse markets. After China restricted the import of plastic waste, Turkey became one of the world's primary objections to the worldwide plastic waste substitute (Gündoğdu and Walker, 2021). Because plastics are made from petroleum-based components, increased interest in plastics helped to reduce reliance on non-sustainable, unrefined petroleum. Many organisations have put in place plastic waste management frameworks to direct or limit the age of plastic waste to decrease the negative environmental consequences of plastic waste (Vijayakumar and Sebastian, 2018). Annually, Europe alone produces 23 million tonnes of plastic packaging and current projections will see 92 million tonnes by the year 2050 (Guillard et al., 2018). Pyrolysis is a typical innovation for waste plastic reuse that includes the thermochemical process of common and designed materials to produce significant energy at greater

temperatures without oxygen (Syamsiro et al., 2014). Most nations have not widely distributed the guidelines addressing the recycling, reusing, and disposing of garbage. In 2012, Poland and other Europe countries imposed strict waste restrictions to control the waste (Baran, 2021). Waste management is currently a key test in Europe. Growing waste yield has spurred the European Union (EU) to take action since the 1970 s, establishing special measures to speed practical progress (López et al., 2011). Plastic pollution significantly influences biodiversity, particularly in marine environments, and has been recognized as a significant environmental danger (Thushari and Senevirathna, 2020). The challenge associated with nonrenewable energy sources has prompted the creation and commercialization of a few alternative fuels, such as biodiesel, biogas, CNG, LPG, and LNG (Guilayn et al., 2020). It was observed that the properties of plastic oil and diesel fuel are highly similar (Abatneh and Sahu, 2013).

Pyrolysis is classified into two types: thermal pyrolysis and reactive pyrolysis. Thermal pyrolysis necessitates high temperatures and consumes a large quantity of energy. This process, however, lacks an impulse, resulting in a high concentration of low molecular weight hydrocarbons and low-quality output, rendering it unfeasible. Pyrolysis is efficient because of its low-temperature needs and low energy usage. The presence of a catalyst is critical for the pyrolysis process to succeed. ZSM-5 is the most often used catalyst, but other minerals such as zeolite, Y-zeolite, Ti-Al-Beta, FCC, and MCM-41 are also utilized (Anuar Sharuddin et al., 2016; Guilayn et al., 2020; Iyyappan et al., 2019). Phanisankar et al. (Phanisankar and J.E.M., 2020) used a catalyst to convert waste plastic into fuel oil effectively. They used different amounts of zeolite, clay, aluminum, and silicate to catalyze the pyrolysis of mixed polymers at 500 °C, yielding gasoline, light oil, and diesel. They also manufactured coke, radiator oil, and lubricating oil. Several researchers chose pyrolysis because it can produce a large amount of liquid oil, up to 80% by weight, at a temperature of 500 °C. Temperature, reactor type, pressure, duration, fluidizing gas type and rate, and reactor design can affect how much liquid oil is created during pyrolysis (Anuar Sharuddin et al., 2016). The polymers were pyrolyzed in a rotating chamber at different speeds and two distinct temperatures, 700 °C and 900 °C. Diesel is utilized as a reference for the main characteristics of plastic pyrolysis oils produced at 700 °C (PPO700) and 900 °C (PPO900) (Li et al., 2016). Plastics are classified into several categories, each with its qualities. PET, for example, includes benzoic acid, but PVC contains chlorine, which lowers fuel quality. PET and PVC have the lowest calorific values, less than 30 MJ/kg.

Furthermore, the benzoic acid aromatic ring contributes to PET's low calorific value (Anuar Sharuddin et al., 2016). Densities of LDPE and HDPE range from 910 to 925 kg/m³ and 940–965 kg/m³, respectively. Polyethylene's strength improves as its density increases. Polyethylene can also achieve higher physical characteristics and layered stability by increasing density and temperature. Polyethylene melts from 87.8° to 121.2°C (Gebre et al., 2021). While HDPE generally begins to break down at about 121.2 °C, low-density polyethylene softens at roughly 87.8 °C. It demonstrates that HDPE is thermally more stable than LDPE (Bekele et al., 2020). Plastic Pyrolysis Oil should be blended with Diesel Fuel before being used in CI engines designed to run with Diesel Fuel. This research endeavor made use of a comparable structure.

Blends of 10–90% plastic pyrolysis oil with diesel fuel were prepared for use in the CI engine (Babayemi et al., 2019). Plastics are pyrolyzed to produce pyrolysis oil, an easily transported and well-managed liquid. A study was conducted on waste plastic that can be transformed entirely into pyrolysis oil, which can be used to produce environmentally beneficial diesel fuel. The study aimed to examine the physicochemical features of waste plastic and differentiate the fuel injection characteristics of pyrolysis oil and diesel fuel (Kalargaris et al., 2017b; Lakshmana Kumar et al., 2020; Mangesh et al., 2020). Waste-to-energy conversion is more than just a beneficial initiative; it is also naturally developed. Using pyrolysis techniques, municipal plastic waste can be turned into gasoline-range hydrocarbons. To collect enormous amounts of plastic waste, municipal solid waste is exceedingly diversified, necessitating separate disposal at home. Environmental concerns include the development of dioxins during MSW combustion. It is unknown how different plastic additives in plastic waste affect the quality of fuel produced by the pyrolysis process. Naphtha (C₇-C₁₀), petrol (C₈-C₁₀), and light oil (C₁₀-C₂₀) fractions make up the liquid waste products. C₁-C₄ paraffinic hydrocarbons with some olefins are common in the gaseous products. As a result, the majority of the liquid products produced would be perfect for further processing in a petrochemical refinery. At the same time, the gases would be used directly as fuels, notably as fuels for automobiles (Demirbas, 2004).

Several research papers on the application of PPO in diesel have been published. Nonetheless, most have concentrated on its

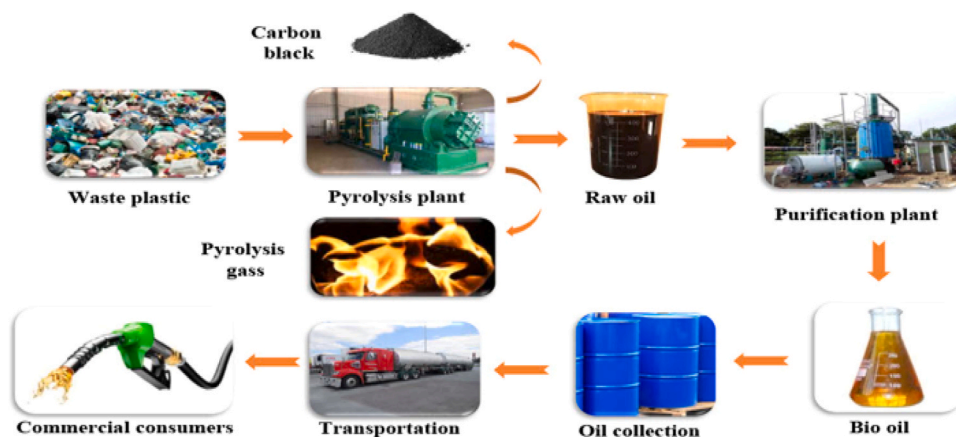


Fig. 1. Waste plastic to pyrolysis oil application and its process diagram.

production and purification rather than an in-depth analysis of its physiochemical, combustion, emission, performance, and economic features. As a result, this evaluation aims to assess PPO's potential as a diesel alternative by providing its combustion, performance, and emission characteristics. As a result, this review study aims to explore PPO's competence as a diesel substitute and its features. The review paper is organized into sections. The problem definition, aims, and possible outcomes of PPO are presented in the first portion of the introduction. The second section concentrates on PPO purification and physicochemical characteristics, such as density, kinematic viscosity, cetane number, and calorific value. The third section discusses the combustion analysis, followed by sections four and five, which look at performance and emission analysis. Furthermore, the sixth segment assesses waste management.

and its economic effects. Fig. 1 displays the outline of the plastic pyrolysis process with different stakeholders.

2. PPO purification and physiochemical parameters

Plastic pyrolysis oil (PPO), derived from the pyrolysis of crude waste plastic, is the liquid component of pure plastics. The liquid form of these mixes produced by pyrolysis has a characteristic look, with a yellowish-brown colour and a pungent odour, indicating the presence of aromatic chemicals in the combination (Budsareechai et al., 2019). Temperatures for pyrolysis of waste plastic can range from 200 °C to 1300 °C, depending on the process and materials used (Maqsood et al., 2021). Red oak and high-density polyethylene (HDPE) were co-pyrolyzed at 525–675 °C temperatures. When the pyrolysis temperature was elevated, it was found that producing 57.6 wt% fluid oil was possible. As the pyrolysis temperature rose, the liquid oil burst, releasing all lighter gases (Xue et al., 2015). According to the investigation's findings, when subjected to the slowest heating rate of 6 °C/min, the polypropylene demonstrated a maximum liquid yield of 82%.

It is also concluded that a slower temperature increase led to higher liquid fuel production. Similarly, slow pyrolysis produced 46%, 70%, 73%, and 80% of liquid fuel from mixed plastic, high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP) from municipal landfills, respectively. It is demonstrated that a lower temperature increase rate resulted in a greater liquid yield (Santaweesuk and Janyalertadun, 2017). The appearance of the oil samples varied significantly, including texture and surface properties. Notably, the oil samples obtained from polystyrene (PS) were dark brown, but the samples obtained from polyethylene (PE) and polypropylene (PP) were lighter brown. The PS oil tests were fluid, whereas the PE oil tests were semisolid and waxy. The PP oil, conversely, had a semiliquid surface and a surface between PE and PS. Sulphur was not found in any of the PPO tests (Quesada et al., 2020). Thermal and catalytic approaches were both found to be effective in the production of pyrolysis. According to the existing literature, plastic pyrolysis employs heterogeneous and homogeneous catalysts. Including these catalysts is intended to reduce operating temperatures, typically between 390 and 425 °C, and shorten the reactor's reaction time (Czajczyńska et al., 2017).

It is shown that the use of PPO in a diesel engine, the substance make-up, quality, and the amount of plastic oil delivered during the pyrolysis cycle are undeniably influenced by various variables, including the type of waste plastic, pressure, and the reaction temperature (Brebū et al., 2004). It is found that the fuel qualities of PPO to those of light fuel (diesel) oil and gas oil, and PPO could replace naphtha, diesel, or gas. Furthermore, it is strongly encouraged because the provided oil has comparable physical properties with commercial petroleum. (Murugan et al., 2008). The dynamic viscosity, kinematic viscosity, density, pour point, freezing point, flash

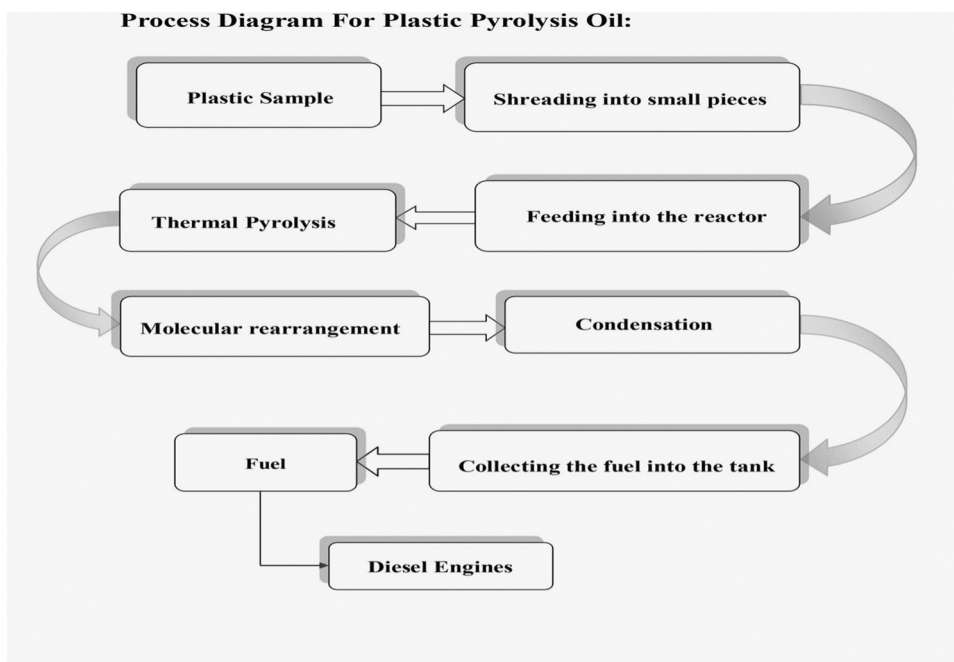


Fig. 2. Waste plastic to pyrolysis oil conversion in the pyrolysis reactor.

point, and HHV of pyrolysis liquid oils closely resemble those of traditional diesel. Consequently, these oils show promise as an alternative energy source for generating electricity. Nevertheless, the elevated levels of aromatic compounds in the liquid oil render it unfit for use as a transportation fuel. To address this limitation, various post-treatment methods, including distillation, refining, or blending with conventional diesel, must be employed to upgrade its suitability (Miandad et al., 2017; Sundar et al., 2022).

The components obtained from the plastics manufacturing industry contain considerable amounts of aromatics and unsaturated hydrocarbons, similar to the mechanism of oil-based cracking operations (Ramesha et al., 2016). The amount of energy needed for the plastic pyrolysis plant is determined by the reactor's temperature and the accuracy of the yield and quality evaluations of the pyrolysis products. Increased temperature reduces viscosity, density, heating value, and C/H ratio, all operating against PPO formation (Khan et al., 2016). Fig. 2 points out the whole process of plastic pyrolysis.

The physicochemical parameters of the fuel, such as its heating value, density, flash point, kinematic viscosity, cetane number, aromatic content, sulphur content, and so on, have a substantial impact on an engine's performance. These fuel attributes directly impact the fuel's performance, emissions, combustion, and tribological properties (Mohammadi and Najafi, 2015). Fuel in the engine should meet the basic requirements of two or three guidelines, such as ASTM, EN, ISO etc. (Arbab et al., 2013). The fuel standards noticed that PPO physicochemical qualities, and it was found that they were inside the scope of the biodiesel and diesel (ASTM 975), generally fuel guidelines (ASTM 6751 and EN 14214) (Rinaldini et al., 2016). Table 1 demonstrates how the standard parameters' fuel characteristics ensure smooth engine start-up, operation, and power. The equal and ternary fuel blends are now required due to their primary fuel properties (Alptekin and Canakci, 2009, 2008; Kim and Lee, 2010). Table 2 includes details of the physicochemical properties of plastic pyrolysis oil (PPO) and compares it with tire pyrolysis oil (TPO) and diesel fuel.

3. Combustion parameters

A number of measures, including ignition delay (ID), cylinder pressure (CP), and heat release rate (HRR), can be used to control the combustion properties. The combustion properties of PPO-diesel mixes in diesel engines are found in Table 3.

4. Performance parameters

The engine's top performance indicators include brake power (BP), output torque, brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC). Table 4 reviews the performance characteristics of PPO-diesel blends in diesel engines and draws some significant findings.

5. Emission parameters

The following are the majority of diesel engine emissions: carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur dioxide (SO₂), particulate matter (PM), smoke and residues. The characteristics of the fuel, as well as the design and utilization of the engine, affect the emission. The outflow properties of PPO-diesel mixes in diesel engines are examined, with outcomes given in Table 5.

6. Waste management and economic aspects

The G7 and the EU have committed to promoting sustainable plastic waste management through reuse and recycling programs. UNEP has also issued global recommendations to combat plastic pollution and encourage sustainable plastic waste management. The Basel Convention on the Control of Transboundary Movements and Disposal of Hazardous Wastes has been signed by 188 countries, making modifications to the convention binding on nearly all governments (Aragaw, 2020). The Extended Producer Responsibility (EPR) waste management system, recognized as highly effective in Canada, South Korea, Europe, and Japan, includes the production of plastic pyrolysis oil (Sadhukhan and Sekar, 2022).

Table 1

Physicochemical properties of different fuels (Chavan and Kalpana, 2023; Gadwal and Rampure, Prasad Baburao, 2015; Hamzah et al., 2015; Jaafar et al., 2022; Mani and Nagarajan, 2009; Sadhik Basha and Anand, 2014; Shaafi et al., 2015; Shahir et al., 2015).

Properties	Diesel	TPO	PPO
Calorific Value (MJ/kg)	42.8–45.8	42.83	40–46.8
Kinematic viscosity @ 40°C (cSt)	2–4.5	3.2	2.52
Density (kg/m ³)	816–890	839–904	839–904
Cetane number	45–56	< 40	51
Flash point °C	50–98	61–73	42–45
Carbon (%)	85.83	87.2	83.49
Hydrogen (%)	13.42	9.65	11.36
Oxygen (%)	0.79	1.76	1.76
Nitrogen (%)	—	0.65	0.65
Sulfur (%)	0.045	0.80–0.95	0.019–0.030
Ash (%)	0.045	0.31	0.00023
Distillation temperature (C) 85%	340	381	362

Table 2
The major findings of the physicochemical properties of the plastic pyrolysis oil.

References	Properties	Findings
(Williams and Slaney, 2007)	Viscosity	<ul style="list-style-type: none"> A dynamic viscosity of liquid oil in the range of 1.66–3.02 mPa·s was produced by all tested parameters. The liquid oil generated under optimum conditions had a viscosity of 1.77 mPa·s for 75 min at 450 °C. The pyrolysis of 75% polystyrene mixtures and 25% polypropylene produces the maximum yield, with a viscosity of 1.12 cSt. Given that it includes a variety of mixes with carbon chains ranging from C₆-C₂₀, this item is recommended as an excellent additional substance specialist for modern applications.
(Miandad et al., 2016; Senthilkumar and Sankaranarayanan, 2016)	Density	<ul style="list-style-type: none"> The density of plastic oil varies with densities of 0.94, 0.92, and 0.93 g/cm³ measured individually at 400, 450, and 500 °C. In the absence of any wax component, it is observed that the volume of oil exhibits an increase as the temperature is raised within the range of 450–500 °C. This increase in volume is accompanied by a slight change in density, from 0.71 to 0.73 g/cm³. However, no significant increase in oil volume is observed when the temperature is further increased to 600 °C. Instead, yield increases by increasing the density from 0.73 to 0.79 g/cm³. This increase in output can be attributed to the arrangement of heavier hydrocarbons, specifically aromatics, within the oil composition.
(Williams and Slaney, 2007)	Calorific value	<ul style="list-style-type: none"> PPO density rises with process temperature; however, volume decreases at lower temperatures, as various indicates. Through the process of plastic pyrolysis, the lower heating value of plastic oil exhibits a range of 41.25–42.00 kJ/kg across a spectrum of temperatures spanning from 400 to 600 °C. PPO, characterized by a calorific value of 42.5 MJ/kg and composed of carbon chain compounds ranging from C₆-C₂₀, is a highly beneficial fuel additive in industrial applications. The calorific value of plastic pyrolysis oil (PPO) surpasses the recycled plastic material from which it originates.
(Khan et al., 2016)	Density	<ul style="list-style-type: none"> The higher oxygen content of PPO causes cylinder pressure (CP) to increase. However, these effects decline after that point because of the poor starting characteristics and increasing density of the PPO-diesel combination
	Calorific value	<ul style="list-style-type: none"> PPO has a slightly lower calorific value than diesel, but this can be increased by blending PPO with diesel. The highest diesel efficiency is 35%, whereas the maximum efficiency of 15 PPO is 28%.
	Flash Point	<ul style="list-style-type: none"> Lower calorific value and thermal losses cause a reduction in brake thermal efficiency (BTE). 15 °C was the flash point for PPO. Low flash points indicate the presence of gasoline mixtures that are highly unpredictable and pose a severe risk to handling and delivery. Diesel, lamp oil, and heater oil all have more flash points than PPO. The (PPO-Diesel) mixture's flashpoint, which ranges from 42 °C (PPO 40%) to 23 °C (PPO 90%) drops as the PPO percentage in the mixture increases. Removing lighter components (like naphtha/gas) raises the flash point of PPO.
(Ramavathu and Kota, 2020)	Calorific value	<ul style="list-style-type: none"> PPO's high calorific value increases the cylinder pressure. The input mixture should be optimized by adding additional PS or PP to raise the aromatic or alkene contents for a higher calorific value or octane number. Alternatively, a suitable catalyst may promote the formation of a specific molecule type (aromatics, alkenes, or alkanes).
(Padmanabhan et al., 2021)	Viscosity	<ul style="list-style-type: none"> Low BSFC and BTE are caused by PPO kinematic viscosity's adversarial influence on the atomization and dissipation characteristics of the fuel splashing during ignition.
(Mani et al., 2011)	Density	<ul style="list-style-type: none"> PPO is more dense than diesel and other additives. To lower the BSFC and BTE, it is justified to atomize the fuel, which is undesired but essential. Compared to commercial diesel, which has a density of 832 kg/m³, PPO has a density of 837.4 kg/m³ at 15 °C.
(Mani et al., 2011)	Calorific value	<ul style="list-style-type: none"> Engine power decreases as a result of PPO's high oxygen share and low calorific value. The brake thermal efficiency decreases under all load settings because waste plastic oil has a lower calorific value than diesel fuel.
(Güngör et al., 2015)	Cetane number	<ul style="list-style-type: none"> The PPO is blended with diesel fuel in the engine, wherein the diesel fuel possesses a comparatively lower cetane number. As per the EN 590 Diesel Fuel Standard, it has been observed that the fuel compositions PPO15%, PPO20%, and PPO100 exhibit reduced cetane values. Conversely, the fuel blends PPO5% and PPO10% demonstrate cetane numbers that meet the minimum requirement of 51, thus being deemed acceptable.
(Irawan et al., 2019)	Density	<ul style="list-style-type: none"> PE and PP have densities relatively similar to gasoline and diesel fuels.
(Sharuddin et al., 2018)	Heating Value	<ul style="list-style-type: none"> The heating values of liquid oils derived from PVC, PET, LDPE, HDPE, PP and PS are 21.1, 28.2, 39.5, 40.5, 40.8 and 43 MJ/kg, respectively. The petrol and diesel heating values are 42.5 and 43 MJ/kg, respectively.
(Ahmad et al., 2015)	Density	<ul style="list-style-type: none"> The API gravities of the PPO produced from PP and HDPE were 33.03 and 27.48, respectively, and their corresponding densities were 0.86 and 0.89 g/cm³. The numbers correspond to hydrocarbons' density and API gravity in the diesel series (C₁₂-C₁₆).
	Heating value	<ul style="list-style-type: none"> The heating values for liquid items made of PP and HDPE were 35.5 and 30.6 MJ/kg, respectively. According to sources, the heating values of gasoline and diesel oil vary from 41 to 43 MJ/kg, which is lower than the expected heating values, which are relatively high in energy usage at more than 45 MJ/kg.

(continued on next page)

Table 2 (continued)

References	Properties	Findings
(Nizami et al., 2016)	Viscosity Catalyst selection	<ul style="list-style-type: none"> The liquid products made from PP and HDPE had kinematic viscosities of 4.09 and 5.08 mm²/s, respectively. The values follow premium fuel criteria when compared to the viscosities of petroleum fuels. This characteristic is crucial to how the fuel injection system functions. Additionally, it influences the fuel's atomization quality and subsequent combustion characteristics. Natural zeolites are ideal for use in WTE technologies because of their high thermal stability, unique ion exchange, adsorption, high surface area, and porosity. This is especially true for the pyrolysis process used to turn waste plastic into liquid fuel because the highly stable structure of these materials maintains its integrity at high process temperatures (300–600 °C).

The United Nations introduced the Sustainable Development Goals (SDGs) in September 2015 as a follow-up to the Millennium Development Goals, aiming to address the most significant global economic, environmental, and social challenges. Among the 169 targets and 17 SDGs, only one explicitly focuses on plastic pollution. Global plastic production has surged from 1.5 million tonnes in 1950–370 million tonnes today (Walker, 2019). Asia accounted for 51% of global plastic production in 2019, followed by NAFTA members (the United States, Canada, and Mexico; 19%), Europe (16%), the Middle East and Africa (7%), Latin America (4%), and the Commonwealth of Independent States (Azerbaijan, Armenia, Belarus, Georgia, and others; 3%). The United Nations Environment Programme (UNEP) highlights that single-use plastics, including items like plastic bottles, lids, cigarette butts, grocery bags, caps, stirrers, straws, and food packaging, indicate insufficient waste management practices and our environmental attitude. These plastics have severe health and social consequences, including the presence of hazardous compounds in plastic particles that can lead to cancer and harm the neurological, reproductive, and respiratory systems (Pratelli et al., 2022).

According to Plastics Europe, a significant portion (75.1%) of plastic waste collected from European landfills undergoes recycling (42.6%) or is utilized for energy recovery (32.5%). It's important to note that bio-based polymers derived from oil are not inherently biodegradable or compostable. Common waste management approaches for bio-based polymers encompass chemical recycling, waste-to-energy (WTE/incineration), biological and thermochemical conversion into fuel, and chemical blending. When considering the environmental impact, bioplastics demonstrate a 12% lower global warming potential and a 30% reduction in non-renewable energy consumption compared to traditional plastics, as indicated by life cycle assessments (LCA). However, it's worth noting that bioplastics are over 11% more expensive than regular plastics. Consequently, bio-based plastics, also referred to as bio-polymeric plastics, tend to be pricier than conventional plastics (Galafassi et al., 2019; Wojnowska-Baryła et al., 2020).

A financial analysis of a waste plastic pyrolysis cycle for producing fuel was conducted in Australia. This study focused on managing waste plastic at a facility with a daily feed rate of 40 tonnes. It considered both the pyrolysis process and the utilization of the produced fuel. The financial assessment of the proposed waste plastic-to-fuel facility revealed a remarkable 54% profit relative to the initial capital investment, indicating that the value generated exceeded the costs involved. The relatively high practicality observed in the pyrolysis of plastic materials underscores its economic viability, highlighting the ability of the facility to turn all preparations into revenue (Ghodrat et al., 2019). Additionally, this process is significantly more cost-effective than the diesel price of US\$ 1048 per ton (Jacob et al., 2022). Fig. 3 illustrates the process of utilizing waste plastic, and it was discovered that 29% of plastic waste was either discarded or sent to a landfill (Evide et al., 2021).

The PPO technology can convert up to 73% of plastic waste into fuel oil, with 15% being transformed into gas and the remaining 12% converted into inert solid waste (usually soil mixed with the waste). The resulting fuel oil can be immediately used for power generation or further fractionated into a roughly equal mix of transportation-grade diesel and high-octane, lead- and sulfur-free fuel (Sharul et al., 2020). The process is environmentally friendly, with no odor, gaseous emissions, or liquid effluents produced compared to conventional petrochemical practices. The processing plants have high-quality fuels that meet or exceed current industry standards for transportation fuels (Chung et al., 2003). The cost of plastic pyrolysis oil is lower than that of both biofuel and diesel. Nonetheless, the widespread adoption and advancement of plastic pyrolysis oil face several challenges in India. Despite its potential to address plastic waste problems and serve as an alternative fuel source, various impediments hinder its progress. These include the absence of regulatory frameworks, technological limitations, issues with infrastructure and distribution, public perception and awareness challenges, economic feasibility concerns, and complications related to waste separation. To surmount these hurdles, it necessitates a coordinated effort involving society, stakeholders in the industry, and government intervention. Such collaborative endeavors will create an environment conducive to the commercialization of pyrolysis-derived oil from plastic (Kumar et al., 2024).

7. Assessments and discussion

This study found the noteworthy characteristics of diesel engines utilizing PPO. The following are the key conclusions for each of these attributes:

Unrefined PPO with a high sulphur content must be properly desulfurized and refined. Oxidative desulfurization and hydro-desulfurization are the two most efficient processes for desulfurizing unrefined PPO. PPO includes a high quantity of Sulphur when compared to DF and biodiesel, but the refinement process can eliminate Sulphur. Among these, oxidative desulfurization is seen to be the most successful and feasible, as it can reduce sulphur levels to very low levels. Furthermore, the filtration process is used to achieve the final purification of the crude PPO, which is enhanced with various additives. Some physicochemical properties are shared by PPO

Table 3
The significant findings of the combustion characteristics of the plastic pyrolysis oil.

References	Properties	Findings
(Singh et al., 2020)	Ignition delay (ID)	<ul style="list-style-type: none"> Rapid combustion results in a higher rate of heat release, an accumulation of fuel, and a low cetane value, which prolongs the ignition delay. Maximum heat output from diesel is 115.41 J/°CA at 2°CA. For blends with PPO increases, the maximum heating rate is 136, 141.33, 144.96, 147.59, and 149.18 J/°CA for 10%, 20%, 30%, 40%, and 50%. Biodiesel's high oxygen content and quick ignition delay have improved combustion and high in-cylinder temperatures. Premixed combustion accounted for most of the heat output in the case of PPO mixtures. The delayed ignition of premixed combustion allows for greater heat release.
(Senthilkumar and Sankaranarayanan, 2016)	Cylinder pressure	<ul style="list-style-type: none"> Premixed combustion was utilised to investigate the effect of crank angle on cylinder pressure for four fuels: diesel, waste plastic oil, PJ10 (10% PPO, 90% Jatropha methyl ester (JME) oil), and PJ20. The study discovered that introducing JME into the fuel, which has a higher cetane number and is blended with waste plastic oil, reduces the ignition delay time. Peak pressures for conventional diesel, waste plastic oil, PJ10, and PJ20 were the highest, at 63.82, 68.05, 67.09, and 64.62 bar, respectively. The results reveal that increasing the proportion of waste plastic oil in the JME blend reduces peak cylinder pressure, despite the fact that the combustion process remains the same for all test fuels and includes premixed and diffusion combustion.
	Heat release rate and Ignition delay	<ul style="list-style-type: none"> Diesel, waste plastic oil, PJ10, and PJ20 have maximum heat release rates of 71.56, 91.93, 86.50, and 79.32 J/CA°, respectively. It can be seen that the majority of the heat release in waste plastic oil occurs only during the premixed combustion. A longer ignition delay causes more heat to be released during the premixed combustion phase. Because of the greater fuel-air ratio, the heat release rate of waste plastic oil is higher. The ignition delay will be reduced when the cylinder temperature drops. The reduction in ignition delay period reduces the rate of heat release of waste plastic oil-JME mixes.
(Mani et al., 2011)	Ignition delay	<ul style="list-style-type: none"> Because of the lower cetane number, a DF with a greater aromatic percentage has poor self-igniting qualities when used as fuel in a diesel engine. It is also influenced by engine load since it shrinks as engine load increases. The PPO-Diesel (50–50%) blend has the highest cylinder peak pressure (CPP) of any blend percentage because it has the best available air-fuel ratio for ignition. Because of the longer ignition delay, PPO's peak pressure is 5 bars higher than DF's, and PPO's ignition delay is around 2–2.5 CA longer than DF's.
	Cylinder pressure	<ul style="list-style-type: none"> It shows how different loads affect the differences in cylinder peak pressure of the tested fuels. When the load is increased, PPO-DF mixes outperform DF in terms of cylinder peak pressure. The cylinder peak pressure for DF and WPO 10 rises as pressure rises from 56 bar at low load to 66 bar at full load, and from 57 bar to 67 bar at full load, respectively. When compared to DF, PPO has 1.5% more oxygen, which improves combustion and raises peak pressure. PPO-DF blends operating at full load have higher peak pressure due to a longer ignition delay and more heat generated during premixed combustion.
(Jatadhara and Chandrashekar, 2018)	Ignition delay	<ul style="list-style-type: none"> The higher NOx content of PPO may possibly be due to delayed combustion and a protracted injection interval before ignition. The high aromatic concentration of the mix, which shortens combustion duration and increases ignition delay, is to account for the high UHS emissions.
(Faisal et al., 2023)	Ignition delay	<ul style="list-style-type: none"> PPO has a longer ignition delay during the premixed combustion phase. PPOs have a longer ignition delay than diesel fuel due to their higher viscosity, lower cetane number, low volatility, change in spray characteristics, and longer hydrocarbon chain compounds (C15-C30), which require more energy to break. They also have longer self-ignition temperature compounds.
	Heat release rate	<ul style="list-style-type: none"> Due to PPO's longer ignition delay, higher calorific value, higher air-fuel ratio, higher oxygen content, and lower atomization during premixed combustion, net heat release is higher for PPO compared to diesel fuel. As a result of PPO and diesel blends' higher calorific value, longer ignition delay, lower cetane number, and higher oxygen content compared to diesel, an increase in heat release rate was also attained.
(Maithomklang et al., 2023)	Cylinder pressure	<ul style="list-style-type: none"> The study showed that at full load conditions, diesel fuel resulted in a lower cylinder pressure of 62.52 bar at 1°CA, while the 50% PPO mix exhibited a maximum cylinder pressure of 67.87 bar at 4°CA. The occurrence of a delayed peak pressure for all blends, particularly after top dead centre (TDC), leads to reduced availability of fuel for auto-ignition. Consequently, the delayed combustion and diffusion combustion phases become critical. The augmentation of engine load resulted in a commensurate boost in fuel delivery to the cylinder, causing an elevation in-cylinder pressure.
(Singh et al., 2020)	Heat release rate	<ul style="list-style-type: none"> The blend of PPO-diesel (15–90%) released heat faster than diesel. Although quick combustion can increase the heat release rate, a prolonged ignition delay is caused by a high fuel accumulation and low cetane value. At a 2°CA, diesel is estimated to emit heat at a maximum rate of 115.41 J/°CA. For blends with PPO increases, the maximum heating rate is 136, 141.33, 144.96, 147.59, and 149.18 J/°CA for 10–50% with an increment of 10%.

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Table 3 (continued)

References	Properties	Findings
(Devaraj et al., 2015)	Ignition delay	<ul style="list-style-type: none"> The delay period for PPO and diesel engines is observed under varying engine loads. An increase in the diethyl ether (DEE) ratio within the fuel mixture reduces the duration of the ignition delay period. This behaviour becomes increasingly apparent when the engine operates under larger rather than lower loads. In this context, it is essential to consider the potential impact of DEE's elevated cetane number and latent heat of vaporization. As the latent heat of vaporization grows, the effect or magnitude of the phenomenon also increases. The evaporation process is anticipated to significantly impact both the increase in cylinder temperature and the ignition delay. Compared to other fuels, the extended delay time in waste plastic pyrolysis oil can be attributed to the elevated cylinder pressure.
	Cylinder pressure	<ul style="list-style-type: none"> PPO's highest heat release rate is 43.28 J/°CA, while diesel demonstrates a maximum heat release rate of 39 J/°CA. On the other hand, the maximum heat release rates for WD05 and WD10 were documented as 36.57 J/°CA and 32.85 J/°CA, respectively.
	Heat release rate	<ul style="list-style-type: none"> The heat release rate of PPO is observed to reach a maximum value of 43.28 J/deg CA, whereas diesel exhibits a maximum heat release rate of 39.00 J/deg CA. In contrast, the peak heat release rates for WD05 and WD10 were 36.57 J/°CA and 32.85 J/°CA, respectively. When compared to fuel, waste plastic oil produces far more heat. Premixed combustion is the only method by which waste plastic oil releases the most heat. Due to the greater fuel-to-air ratio, the waste plastic oil releases heat more quickly. The ignition delay will vary to changes in-cylinder temperature.
(Mangesh et al., 2020)	Ignition delay	<ul style="list-style-type: none"> Waste plastic oil takes substantially longer to ignite than diesel. Peak pressure inside the cylinder rises proportionally to waste plastic oil delay time. It's also important to note that waste plastic oil has a peak pressure of 5 bar higher than diesel because of the longer ignition delay. Waste plastic oil also has an ignition delay of 2–2.5 CA longer than diesel. Because the amount of the air-fuel mixture being altered at this moment is inversely connected to the ignition delay period, it increases the HRR through the incomplete burning stage.
	Heat release rate (HRR)	<ul style="list-style-type: none"> Diesel has the most minimal starting heat release rate and extended ignition length at evaluated power. heat release rate for diesel is 65 J/CA, and waste plastic oil is 85 J/CA. Compared with diesel, waste plastic oil's greatest heat release rate is significant. It tends to be seen that most of the heat release rate in waste plastic oil happens exclusively during premixed burning. A more extended start postponement delivers a higher heat release rate during the premixed ignition stage.
(Kalargaris et al., 2018)	Cylinder pressure	<ul style="list-style-type: none"> The increased heat release rate raises the temperature of the fumes gas. Several variables can influence the highest pressure a compression ignition (CI) engine achieves. The factors under consideration include the amount of fuel expended in the early phases of combustion, the duration of the delay period, the amount of fuel consumed during the controlled combustion phase, and the composition of the fuel mixture formed during the delay period.
(Kalargaris et al., 2018)	Ignition delay	<ul style="list-style-type: none"> The significance of the ignition delay is deemed negligible due to its minimal duration and lack of adverse impact on combustion stability. The engine combustion stability assessment involved quantifying the coefficient of variation of indicated mean effective pressure (COVIMEP), which was afterwards compared to the performance observed during diesel operation. The study's findings revealed that the COVIMEP exhibited a slightly elevated value of 2, although it remained within the low range, suggesting favourable combustion stability. The ignition delay gets shorter for all fuel mixes as the load increases. When the cylinder is fully loaded, the heat inside can spontaneously explode the fuel-air combination.
(Imtenan et al., 2015)	Heat release rate (HRR)	<ul style="list-style-type: none"> Because J20 had a higher cetane rating than diesel, it produced more in-cylinder pressure. The addition of n-butanol and DEE did, however, decrease pressure due to the additives' delayed SOC and greater latent heat of evaporation. In 10% additive mixtures, as opposed to 5% additive blends, the impacts of the additions were more noticeable. The enhancements decreased HRR during the combustion's premixed phase. However, the adjusted mixes outperformed J20 in the diffusion-controlled zone regarding HRR.
(Devaraj et al., 2015)	Cylinder pressure, HRR, and Injection	<ul style="list-style-type: none"> PPO expresses the injection of a sizable amount of PPO in the shifted injection scenario. When PPO is injected during the pilot injection, the main injection's ignition delay time is shortened, which leads to less intense premixed combustion and main injection PPO that burns more like diesel. The achievement of low specific fuel consumption can be attributed to enhancements in fuel atomization, enhanced mixing, and the utilization of high in-cylinder temperatures during operations at elevated loads. Increased engine speeds enhance fuel and air homogenization, facilitating improved fuel combustion.
	Heat release rate	<ul style="list-style-type: none"> When the PPO introduced during the pilot injection started to burn, a change resulted in a higher rate of heat release. The rate of heat emission is reduced by reducing the ignition delay time.

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Table 3 (continued)

References	Properties	Findings
(Ren et al., 2006)	Ignition delay	<ul style="list-style-type: none"> • Diesel-ethanol blends can benefit from adding a CN improver by having a shorter ignition delay, a slower rate of pressure increase, a lower maximum cylinder pressure, and reduced combustion noise and cycle-by-cycle fluctuations.
	Heat release rate	<ul style="list-style-type: none"> • The initial phase of the heat release process is delayed as the amount of ethanol in the mixtures rises, but the maximum heat release rate increases as well. • Since PPO fuel achieves a peak in the rate of heat release and in-cylinder pressure a little bit earlier than diesel fuel, it is evident that PPO fuel begins to burn before diesel fuel. PPO fuel, on the other hand, seems to provide the highest start-combustion inhibition. This trend persists when the engine is operated at higher load ranges of 50, 70, and 90 N.
(Arjham et al., 2022)	Ignition delay	<ul style="list-style-type: none"> • PPO is greater for the cetane index, representing the ignition's simplicity. • This analysis suggests the possibility of a reduced igniting delay compared to diesel fuel. The combustion properties of WPO fuel exhibit an inverse trend, which necessitates an explanation based on bulk modulus. However, it should be noted that this explanation is only applicable to small amounts of PPO fuel. Due to its comparatively lower density among the three fuels, PPO fuel has a heightened susceptibility to the lower bulk modulus.
(Sekar et al., 2021)	Ignition delay & HRR	<ul style="list-style-type: none"> • Ignition delay is the primary component that influences the rate of heat emission. • Getting the fuel-air combination for PO and P25A, which exhibit higher viscosities than diesel, presents a little more challenging task. The process of combining with the air is prolonged, resulting in a delay in the occurrence of combustion. Consequently, the process of polymerization releases thermal energy rapidly. Moreover, oxygen content in P25A leads to a substantial increase in combustion. The heat release rates for PO and P25A were measured to be 147 J/CA and 132 J/CA, respectively.
	Cylinder pressure	<ul style="list-style-type: none"> • It examines the effects of PO and P25A on in-cylinder pressure under varied load conditions and varying brake mean effective pressures (BMEPs). The study revealed that P25A and PO exhibited the greatest peak pressures, positively correlated with the applied load. The fuel known as PO has more viscosity and heating value than diesel fuel. It attained its maximum peak pressure at a level of 68 bar. Conversely, the fuel referred to as P25A, which had a larger quantity of oxygenated compounds and a faster combustion rate, achieved its highest peak pressure at 71 bar. Moreover, it was observed that the peak pressure value exhibited a positive correlation with the combustion rate, indicating an increase in the former as the latter intensified.
(Kalargaris et al., 2017c)	Cylinder pressure	<ul style="list-style-type: none"> • The cylinder pressure profiles at 100% and 75% load are depicted after conducting the tests. EVA900 and EVA900 at 75% exhibit significantly extended ignition delay durations and reduced peak cylinder pressures, LDPE700 has a similar pressure profile under full load but with a bit lower peak pressure. Because of the difference in heat release rates at 100% (a) and 75% (b) load, combustion starts much later, resulting in slightly lower peak pressures. I. The higher the cylinder capacity at maximum combustion. The fact that the EVA900, EVA900 75, and LDPE700 have later peak cylinder pressures (CA after TDC) than diesel lends credence to this theory.
(Kalargaris et al., 2017c, 2017a)	Heat release rate	<ul style="list-style-type: none"> • The HRR peak values of LDPE700 are marginally lower than diesel for both 75% and 100% load. This behaviour can partly be explained by the increased viscosity, which results in poor atomization and a slower heat release rate.
(Kalargaris et al., 2017c)	Injection mechanism	<ul style="list-style-type: none"> • When using plastic pyrolysis oil as fuel, it is preferred to use diesel engines that have mechanical injector systems and indirect injection mechanisms.
(Ramesha et al., 2019)	Cylinder peak pressure	<ul style="list-style-type: none"> • The peak cylinder pressure rises as the load rises. It is higher for blended fuels than for straight diesel. Because of the presence of AL2O3 nanoparticles, it is more in B20H WPO+AL2O3 than in B20N. The increased peak cylinder pressure is due to the strong catalytic activity of AL2O3 nanoparticles and the shortened ignition delay, which promotes full combustion by boosting cylinder pressure.
(Kim et al., 2002)	Combustion characteristics	<ul style="list-style-type: none"> • The combustibility of waste polyethylene at a given distance from the tuyere might be enhanced by increasing both blast temperature and the level of oxygen enrichment, as well as decreasing particle size. The efficiency of coal combustion was also observed to diminish with the addition of plastics; however, the combustion efficiency of the mixture might be equivalent at a greater distance from the tuyere.

and DF. The PPO-diesel mix has a significant density concern since PPO has a higher density than DF, which draws in more fuel to the chamber for starting and builds the chamber's CP and HRR, which benefits the engine's Brake thermal efficiency (BTE) and Brake power (BP). PPO's high viscosity and oxygen content reduce fuel atomization while improving combustion. PPO's calorific value is increased by its low C and H content and high sulphur level.

An increase in oxygen concentration in PPO affects heating value and engine brake power (BP). Because of its similar physico-chemical properties will generally be used in ICE alone or in mixes with DF and biodiesel. Increased PPO content and injection pressure, together with the use of PPO fuels, resulting in better performance indicators such as brake thermal efficiency (BTE), braking power (BP), and mechanical efficiency (ME). Because of their lower hydrogen and oxygen content and poorer PPO igniting capabilities, hydrocarbon (HC) fuels have less spectacular exhaust metrics than diesel. CO emissions will be decreased since PPO contains more oxygen and converts CO into CO₂. PPO with higher nitrogen concentration and viscosity emits more NO_x, demonstrating an increasing tendency in PPO fuel improvement. However, in both instances, the overall impact is reduced by the lower cetane number

Table 4
The significant findings of the performance characteristics of the plastic pyrolysis oil.

References	Topics	Findings
(Faisal et al., 2023)	Brake thermal efficiency	<ul style="list-style-type: none"> Because PPO releases heat more quickly than diesel fuel, it has been shown to have better brake thermal efficiency. Due to the higher calorific value of PPO-diesel blend than diesel, BTE for PPO and diesel blends were slightly higher or closer to diesel until 80% load.
	BSFC	<ul style="list-style-type: none"> BSFC was seen to increase (the largest increase recorded was 17.14% by using blends of PPO and Jatropa methyl ester (JME) compared to using diesel fuel) and decrease depending on the blend ratios when PPO and diesel were used. However, combining oxygenated chemicals with PPO has mostly been found to boost BSFC.
(J and Watwe, 2007)	Brake Thermal efficiency	<ul style="list-style-type: none"> Waste plastic oil releases heat at a slower rate and somewhat higher exhaust gas temperatures than diesel and gasoline when operating at full load. Each WPO-DF mixture generates less heat overall than diesel. As a result, the thermal efficiency of the WPO-DF (diesel fuel) and WPO-PF (petrol fuel) brakes is reduced.
	Brake specific fuel consumption	<ul style="list-style-type: none"> PPO mixtures specifically use more fuel than diesel. The primary explanation for this could be that heat losses contribute less to fuel consumption at higher loads, which reduces the percentage rise in brake power. PPO-Diesel (10–90%) should be used because of its reduced fuel consumption.
(Maroa and Inambao, 2018)	Brake power (BP)	<ul style="list-style-type: none"> For all test fills, the BP increases directly as the engine load rises. Among the blended fuels of PPO, diesel encountered the greatest ascent in BP values. At 20% engine load, the BP incentive for Compact disc was 1.45 kW while the incentive for PPOB10 was 1.350 kW, bringing about a 6.8% distinction in BTE between the two fills. The increase in blending percentage brought about an immediate drop in BP in a directly moderate relationship. The engine BP of the blended fuels decreased considerably as the fraction of WPO blends increased when compared to diesel. Using the EGR% stream rate brought about no recognizable change in BP. Except for the mix PPO10, which had almost the same worth as commercial diesel (CD), there was a minor misfortune in engine brake influence with the effect of the EGR stream rate.
(Ananthakumar et al., 2017)	Brake specific fuel consumption	<ul style="list-style-type: none"> As load and compression ratio increase, specific fuel consumption (SFC) falls. The temperature within the cylinder rises as the amount of load increases, which causes the combustion temperature to rise along with it. Thus, while running at higher loads and compression ratios, this effect improves combustion efficiency. The thermal efficiency of the braking process for all fuels was seen to vary between 26.03% and 28.56% when using a compression ratio of 20. The findings of this study indicate that waste plastic oil and its mixtures, especially when higher compression ratios are used, have thermal efficiency that is comparable to diesel fuel. By effectively raising the temperature and pressure of the intake air, higher compression ratios can improve fuel combustion.
	Brake thermal efficiency	<ul style="list-style-type: none"> With a 20:1 compression ratio, the brake thermal efficiency for all fuel types ranged between 26.03% and 28.56%. This research suggests that when waste plastic oil and its blends are subjected to higher compression ratios in brake systems, they exhibit thermal efficiency that is comparable to diesel fuels. Compression ratios are increased to produce improved fuel combustion, which raises intake air temperature and pressure levels. As the load rises, the thermal efficiency of braking for all fuels shows an ascending trend. However, compared to diesel fuel, waste plastic oil (WPO) and its mixtures have been found to demonstrate somewhat lower levels of efficiency. The reduced calorific value and higher viscosity of the substance, which have a negative impact on the atomization and vaporisation processes during combustion, are the main causes of this phenomena. Diethyl ether (DEE) can be used as an ignition enhancer to improve the combustion process in order to allay this worry.
(Sekar et al., 2021)	Brake specific fuel consumption	<ul style="list-style-type: none"> BSFC is higher since PPO has a high density and a low heating value. When compared to alternatives, the P25A blend (25% PO+ 75% diesel with 25 ppm of Al₂O₃) performs better according to Brake Specific Fuel Consumption (BSFC). It is important to raise the oxygen content in order to lower the brake-specific fuel consumption (BSFC). The amount of oxygenated compounds in the fuel rises with the addition of P25A. Because less fuel is needed to produce the same amount of output when there is a high concentration of oxygen and energy, the P25A mix has a lower BSFC.
	Break Thermal Efficiency (BTE)	<ul style="list-style-type: none"> The most crucial role parameter for improving BTE is fuel air mixing. Diesel and PPO were outperformed in terms of efficiency by the nano-catalyst mixtures. As the BMEP and load increase, the BTE increases as well, eventually reaching full load conditions. When the full load is applied, the BTE for PPO and P25A slightly declines. The P25A still performs better, though.
(Dillikannan et al., 2020)	Brake specific fuel consumption	<ul style="list-style-type: none"> It has been amply demonstrated that, for all test fuels, brake-specific fuel consumption falls as the load increases. It has been demonstrated that adding more n-hexanol to a mixture decreases the cetane number, extends the ignition delay time, and increases the amount of fuel required to participate in fuel combustion in order to produce a comparable output of braking power.
	Brake thermal efficiency	<ul style="list-style-type: none"> As engine load increases, more fuel is added to the cylinder, intensifying the combustion process and causing an increase in heat release. The brake thermal efficiency (BTE) of all test fuels increases with temperature. D50-W40-H10 is the ternary mixture with the greatest Brake Thermal Efficiency (BTE). The cetane number specifically falls as the amount of n-hexanol increases, which may lead to higher fuel input into the combustion chamber and a subsequent decrease in BTE. The latent heat of vaporisation that n-high hexanol exhibits is another possible explanation for the cooling effect.

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Table 4 (continued)

References	Topics	Findings
(Kaewbuddee et al., 2020)	BSFC & BTE	<ul style="list-style-type: none"> The fuel flow rate, brake thermal efficiency, and exhaust gas temperature all showed positive correlations with engine load, suggesting that these variables increased as the engine's load increased. It is noticeable, nevertheless, that under these circumstances, the fuel reserved solely for the brakes reduced. When using biodiesel generated from waste plastic oil, the brake-specific fuel consumption (BSFC) was relatively higher. In general, it was found that utilising biodiesel in petrol mixes increased brake-specific fuel consumption, owing to the lower heating value of biodiesel.
(Bui et al., 2021)	Brake thermal efficiency & BMEP	<ul style="list-style-type: none"> PPO-DF blends outperform diesel fuel in terms of brake thermal efficiency up to 80% load. Aside from that, diesel fuel economy is improving. Diesel has a lower BMEP than other fuel mixes due to a change in high heating value, which enhances the fuel's heat release rate and hence boosts BMEP. When compared to diesel engines, the thermal efficiency of engines using waste plastic oil increases by about 4–9%.
(Venkatesan et al., 2020)	Brake specific fuel consumption	<ul style="list-style-type: none"> Brake-specific fuel consumption ranges from 0.4 to 0.3 kg/kWh for diesel, 0.45–0.27 kg/kWh for WPO, 0.385–0.225 kg/kWh for D50WPO30H20, 0.42–0.24 kg/kWh for D50WPO20H30, and 0.44–0.245 kg/kWh for D50WPO30H40, respectively, from low to full load. It shows that when load increases, brake-specific fuel consumption decreases for all test fuels. It was found that raising the n-hexanol proportion in the blend decreased the cetane number, which lengthens the ignition delay period, requiring more fuel to participate in the combustion fuel to provide the equivalent braking power output.
(Ramesha et al., 2019)	BTE	<ul style="list-style-type: none"> The BTE for all test fuels has been found to be higher than the neat diesel. B20H+WPO has the highest BTE (45.74%), whereas diesel has the lowest (36.996%). This demonstrates that BTE increases by 8.2% and 4.7% when compared to diesel and B20N, respectively. This is due to improved air-fuel mixing and combustion. Alumina oxide nanoparticles, which offer oxygen for combustion, contribute to the increase in BTE.
	BSFC	<ul style="list-style-type: none"> The graph clearly shows that SFC reduces as load increases. At full load, diesel has the highest SFC (5.3 kg/kw-hr) and B20H WPO+AL2O3 has the lowest (3.5 kg/kw-hr). As a result, the SFC of B20H WPO+AL2O3 is 33.65% lower than that of diesel. This is due to the decreased calorific values of blended oils, as well as improved combustion due to the high atomization of AL2O3 nanoparticles.
(Singh et al., 2020)	Performance output	<ul style="list-style-type: none"> It has been determined that PPO containing up to 50% diesel can be utilized in diesel engines with just a slight increase in CO emissions at higher loads.
(Walendziewski, 2005)	Brake power	<ul style="list-style-type: none"> Polypropylene wastes are regarded as the best feed in terms of cracking plant operation efficiency due to variables such as the maximum liquid output, low temperature freezing products, and minimal solid carbon residue and gas yields. In compared to commercial 'fresh' plastics, the cracking process of the waste plastic combination generates much lower yields of the most valuable liquid products, 80–85 instead of ca. 92–93 wt%, and higher gas and solid carbon residue yields.
(Mangesh et al., 2020)	Brake thermal efficiency	<ul style="list-style-type: none"> Waste plastic oil had a thermal efficiency of 27.4% at rated power while diesel had a thermal efficiency of 28.2%. According to the findings, waste plastic oil has brake thermal efficiency that is comparable to diesel up to 75% of rated power before it starts to degrade. Due to slightly higher exhaust gas temperatures and a slower rate of heat release in waste plastic oil compared to diesel, diesel fuel demonstrates marginally superior efficiency at full load.
(Awang et al., 2022)	Torque	<ul style="list-style-type: none"> Diesel fuel and other blends produced the maximum torque at 1800 rpm, whereas PPO-biodiesel-diesel (10%–10%–80%) delivered the best torque yield of 278 Nm at 1600 rpm. With the addition of 10% PPO, the torque output of the biodiesel-diesel blend significantly increased. Of all the fuels tested, diesel fuel provided the least torque, which is significant.
	Brake-specific fuel consumption (BSFC)	<ul style="list-style-type: none"> It is found that PPO-biodiesel-diesel (10%–10%–80%) blend has a lower Brake Specific Fuel Consumption (BSFC) of 343 g/kWh compared to diesel fuel, which is 450 g/kWh at full throttle and no load conditions. The PPO-biodiesel-diesel mix (10%–10%–80%) has a brake-specific fuel consumption (BSFC) that is comparable to that of the biodiesel-diesel blend (10%–90%) but less than that of pure diesel fuel. When the engine speed was set to 1600 rpm, the PPO-biodiesel-diesel fuel mixture showed the lowest Brake Specific Fuel Consumption (BSFC) and highest torque outputs.
(Zhang et al., 2020)	Energy and Exergy efficiency	<ul style="list-style-type: none"> The total energy efficiency of plastic pyrolysis varies depending on the filling ratio and is between 59.6% and 66.0%, which is less than the corresponding total energy efficiency. At 15% heat carrier loading, the efficiency peaked before afterwards declining. As was already said, the lower intake of electric energy is the main cause of the initial increase. Even if it further decreased oil production, raising the filling ratios was still better than reducing the amount of electric energy used. Under a heat carrier loading of 15%, the overall exergy efficiency of the pyrolysis of PE, PP, PS, and SMP is 68.1%, 65.0%, 64.7%, and 66.0%, respectively. To produce a high liquid oil yield with a high H/C ratio and higher energy recovery, a heat carrier loading ratio of 15% is recommended. Under the same operating conditions, the energy content of gas products from PE pyrolysis was 23.4 MJ/kg, which was higher than the energy content of other polymers.
(Devaraj et al., 2015)	Brake thermal efficiency	<ul style="list-style-type: none"> Plastic pyrolysis oil was blended with 5% and 10% diethyl ether and used as fuel for a single-cylinder, water-cooled, DI engine. The atomization of the air-fuel combination was enhanced by the reduction of viscosity caused by the addition of DEE and WPO. This was the rationale

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Table 4 (continued)

References	Topics	Findings
(Güngör et al., 2015)	Brake power	<ul style="list-style-type: none"> behind improving BTE. 10% PPO had a higher BTE when compared to 5% PPO. The BTE of 10% PPO was higher than PPO's at full load. There were no observable differences in measured engine power output between 5% PPO and diesel fuel at low engine speeds. The fuel type has no effect on the power curve's specifications. At an engine speed of 2400 rpm, all fuels produced the maximum power.
(Kumar et al., 2024)	Optimization	<ul style="list-style-type: none"> Experiments were carried out under various conditions, including a partial full load of 80% with different percentages of PPO (0%, 10%, 20%, 30%, and 40%), Al₂O₃ concentrations (0, 25, 50, 75, and 100 ppm), compression ratios (CR) of 16, 17, 18, 19, and 20, and ignition timings (IT) of 17, 19, 21, 23, and 25°bTDC. The engine's response characteristics that needed optimization for optimal performance encompassed BSFC, BTE, CP, HRR, ID, HC, and NOx. Statistical analysis, specifically ANOVA, was employed to assess the significance of the mathematical (quadratic) models utilized for each output response using the regression coefficient. The ideal operating parameters for the input variables were determined to be a compression ratio of approximately 18.06, a PPO volume fraction of approximately 16.56%, an Al₂O₃ concentration of approximately 53.53 ppm, and an ignition timing of around 20.95°bTDC.
(Das et al., 2020)	BTE	<ul style="list-style-type: none"> The 20% WPO-Diesel blend excels among all combinations, with a notable efficiency boost at full load. However, increasing WPO beyond 20% leads to efficiency decline. This is because, while WPO has a higher calorific value than diesel, the blend's equivalent number is also higher. Moreover, higher WPO proportions in the blend increase viscosity, reduce density, and decrease total heat release rate compared to diesel, impacting fuel atomization, vaporization, and subsequently, lowering BTE.
(Kumar and Sankaranarayanan, 2016)	BSFC	<ul style="list-style-type: none"> BSFC decline is more prominent at lower loads, with 20% WPO vs. diesel showing a 4% decrease at 25% load, following a similar pattern at full load.
	Brake power	<ul style="list-style-type: none"> WPO's brake power, reaching 75% at full load and a 20% blend, may be attributed to better blend atomization and depends on engine efficiency and load variation.
	Exhaust gas temperature (EGT)	<ul style="list-style-type: none"> The exhaust gas temperature (EGT) fluctuates between 235 °C at 25% load and 470 °C at full load for diesel, while for WPO, it ranges from 250 °C at 25% load to 480 °C at full load. Additionally, as engine load increases from 25% to full load, EGT also rises. The decline in EGT in emulsions is attributed to the lower heat release rate, and the presence of water molecules in WPO emulsions initially evaporates due to thermal degradation. This helps in regulating the temperature of the working fluid in the combustion chamber.
	BTE	<ul style="list-style-type: none"> At rated load conditions, WPO has slightly lower Brake Thermal Efficiency (BTE) compared to diesel, mainly due to higher EGT and heat loss. Emulsion fuels have a lower heating value than diesel and WPO, resulting in reduced energy release during combustion and, consequently, lower brake power output. However, emulsion fuels still achieve higher BTE than diesel, thanks to the micro-explosion of water droplets, which breaks down larger oil droplets, accelerating fuel evaporation, air mixing, and combustion.

and cold pour point. Also, the PPO's higher density than the DF directly contributes to enhanced smoke. With technological improvement, the intercooler significantly impacts the in-chamber temperature, which governs the release of HC.

When the injection timing was delayed, NO_x emissions were reduced at all loads, while CO emissions were reduced by 25%. The timing of waste plastic oil injection has a substantial impact on emissions as compared to traditional injection. The ignition properties of waste plastic-derived fuel (WPDF) were compared to diesel fuel, showing that diesel engines can run on 100% PPO with modifications in the engine. Overall, the results indicate that WPDF has ignition properties more similar to diesel fuel than other fuels. The arrangement of NO_x and CO₂ grows as the amount of nano-added substance in the fuel increases. Diesel engines may use up to 20% plastic pyrolysis oil without modification. In any instance, changes to the injections in higher PPO fractions are indicated to accommodate for the increased ignition delay. Plastic pyrolysis oil is feasible due to the low raw material cost and production cost than the other conventional resources.

Plastic pyrolysis oil (PPO) is recommended as an alternative fuel based on a detailed investigation of its physicochemical features, impact on combustion, performance, and emission parameters, and economic and functional compatibility with engines. However, there is a huge research gap and future opportunity in researching the application of various additives and nanomaterials in PPO-diesel blends at higher PPO concentrations.

Table 6 compiles the engine characteristics, test conditions, and the expected outcomes of the numerous evaluations of diesel engines' PPO diesel and biodiesel blends, including utilization and operation. PPO-diesel up to 20% can be used in IC engines without requiring any modifications, whereas PPO-diesel (10%–90%) may be recommended due to its better performance response than diesel fuel.

8. Conclusions and future recommendations

Plastic pyrolysis has gained attention due to its effectiveness in addressing several environmental and economic issues. It provides a long-term solution to plastic waste management, lowers reliance on traditional fossil fuels, and has the ability to contribute to the local economy. The review covers a wide range of PPO topics, such as purification and physicochemical parameters, combustion, performance, emissions, and economic concerns, giving readers an in-depth knowledge of the fuel source.

Table 5
The major findings of the emission parameters of the plastic pyrolysis oil.

References	Topics	Findings
(Das et al., 2020)	HC	<ul style="list-style-type: none"> As engine loads increase, HC emissions have been seen to rise. As the PPO component of the diesel blend grows, so does the pattern of HC emission. Higher hydrocarbon emissions are caused by lean F/A mixture areas, low exhaust temperature, and heterogeneous fuel distribution. As the load is increased from lowest to highest, the HC emission ranges from 19 ppm to 42 ppm for diesel, 20–44 ppm for 10% PPO, 24–42 ppm for 20% PPO, and 28–46 ppm for 30% PPO. Furthermore, consumption of a rich F/A combination during periods of high load results in an increase in unburned hydrocarbon.
	CO ₂	<ul style="list-style-type: none"> At all loads, following increases in WPO concentration in diesel yielded marginally equal or greater CO₂ emissions than diesel. This could be because the combined fuels have greater exhaust temperatures, resulting in better combustion.
	NO _x	<ul style="list-style-type: none"> NO_x emission was observed to increase with the addition of WPO to diesel. This could be attributed to a longer combustion delay period caused by the long hydrocarbon chain enhanced in WPO. NO_x levels rise with increasing load and temperature.
	CO	<ul style="list-style-type: none"> In diesel engines, CO emission varies from 0.08% at 25% load to 0.058% at full load. However, for the 20% PPO blend, CO levels are 0.083% at 25% load and 0.06% at full load. This suggests that the 20% PPO mix is environmentally favorable only at high load conditions, as other blends have a more significant impact on emissions. Insufficient oxygen levels during lower loads and lean air-fuel mixture preparation can lead to inefficient combustion and increased CO emission.
(Kumar and Sankaranarayanan, 2016)	HC	<ul style="list-style-type: none"> The higher hydrocarbon emissions of WPO and its blends compared to diesel oil at all load conditions are attributed to their higher water content, which results in prolonged ignition delays and incomplete combustion.
	CO	<ul style="list-style-type: none"> A substantial change in CO levels is evident during full load conditions, primarily attributed to increased brake-specific fuel consumption (BSFC). The introduction of water in emulsion fuel leads to a lower flame temperature compared to diesel, preventing adequate conversion of CO to CO₂. Consequently, emulsion fuel exhibits higher CO emissions across all load conditions.
	Smoke	<ul style="list-style-type: none"> The increased smoke percentage in the exhaust gas is attributed to the plastic oil derived from the pyrolysis process. It is believed that the micro-explosions in the emulsion fuel enhance fuel evaporation and air mixing, leading to reduced smoke formation. Additionally, the presence of pre-mixed waste plastic oil inside the combustion chamber, with a longer ignition delay, contributes to smoke reduction.
(Dillikannan et al., 2020)	HC	<ul style="list-style-type: none"> Unlike DF, the PPO-DEE blend exhibits notably higher hydrocarbon emissions across all loads, especially at lower loads. HC emissions can serve as a measure of ignition quality, with levels varying based on engine load. For diesel, HC levels range from 25 to 61 ppm, PPO from 46 to 74 ppm, D50PPO30H20 from 30 to 62 ppm, D50PPO20H30 from 36 to 65 ppm, and D50PPO10H40 from 38 to 70 ppm. In comparison to diesel, PPO and most HC emissions are higher, while the D50WPO30H20 combination yields superior results.
(Venkatesan et al., 2019)	HC	<ul style="list-style-type: none"> The presence of plastic oil in the blend led to a reduction in unburned hydrocarbon emissions. While there are temperature ranges where HC emissions increase and CO emissions decrease, lower temperatures typically result in higher emissions of unburned HC and CO.
	CO	<ul style="list-style-type: none"> These emissions are a result of incomplete fuel combustion, often caused by insufficient oxygen or flame quenching. Additionally, CO emissions showed a slight increase with higher amounts of plastic oil in the blend.
	NO _x	<ul style="list-style-type: none"> NO_x emissions increase with rising peak cylinder temperatures, which, in turn, occur as the load increases. NO_x emissions exhibit fluctuations in response to changes in the air-to-fuel ratio, although the air-fuel ratio in an engine does not significantly vary with load. As anticipated, NO_x emissions increased with higher loads.
	Smoke	<ul style="list-style-type: none"> These two components, solid hydrocarbon particles responsible for smoke emissions, are detectable in exhaust gas emissions. For all PPO combinations, there was a noticeable increase in smoke emissions; however, compared to CD, both the quantity and intensity were significantly reduced.
(Dillikannan et al., 2020)	CO	<ul style="list-style-type: none"> CO emissions as a percentage of engine load, with the application of EGR and various WPPO and commercial diesel (CD) fuel mixtures, displayed a

(continued on next page)

Table 5 (continued)

References	Topics	Findings
		trend where they decreased up to intermediate loads of 50%. However, beyond that point, CO emissions notably and slightly increased.
	Smoke opacity	<ul style="list-style-type: none"> At 0% engine load, conventional diesel exhibited a 0.051% value, which decreased to 0.03% at 50% engine load. However, as the engine load surpassed 50%, the volume proportion of carbon emissions increased steadily and marginally, regardless of the EGR flow rate. Changes in smoke emissions or opacity percentages at full engine load were observed with different WPPO and CD blends, influenced by the application of EGR flow rates. The use of EGR flow rates significantly increased smoke and particulate matter emissions for all test fuels. With a 0% EGR flow rate, the WPPOB10 blend had 7.2% lower smoke emissions compared to CD, while CD smoke emissions were 11.5% higher than WPPOB100 blend at a 30% EGR flow rate.
(Venkata Subbaiah et al., 2019)	HC	<ul style="list-style-type: none"> The pyrolysed fuel has a lower cetane number compared to conventional diesel, leading to enhanced combustion and reduced hydrocarbon emissions.
(Arjham et al., 2022)	SOOT	<ul style="list-style-type: none"> Smoke levels typically vary based on the carbon atom content of fuels, with higher levels of smoke indicating incomplete combustion. WPO fuel exhibits a lower smoke index, which further decreases at higher engine loads. Smoke levels are influenced by the quantity of carbon atoms in the fuel and the fuel injection rate, as well as the presence of chemical groups like aromatics. In this experiment, both pyrolysis fuels have fewer aromatic groups compared to conventional diesel fuel, resulting in a reduced smoke index due to fewer available compounds for soot particle growth and particle formation. WPO fuel, which contains a portion of naphtha, has a shorter carbon chain length, resulting in fewer solid particles remaining in the smoke. Moreover, improved combustion at higher loads burns more soot and contributes to a lower smoke index.
	NO _x	<ul style="list-style-type: none"> NO_x emissions are a significant pollutant resulting from the combustion of diesel engines, primarily because diesel engines typically burn with an excess of air. The presence of N₂ in the air charge plays a crucial role in the formation of NO_x, as a substantial amount of heat energy at high temperatures is needed to dissociate N₂ molecules into radical atoms that contribute to NO_x formation. This suggests that higher NO_x emissions indicate more heat generated during combustion. Notably, NO_x emissions saw a significant increase when using waste plastic oil distilled (WPOD) fuel, whereas WPO fuel led to only a slight increase in NO_x emission levels. WPOD shares a similar calorific value with diesel fuel but has a higher cetane index. This results in more advanced combustion initiation, leading to a higher peak in-cylinder pressure at the top dead center. This prolonged combustion duration generates additional heat, contributing to higher NO_x emissions. Conversely, WPO fuel, with its less effective and more constrained combustion, emits less NO_x.
	CO	<ul style="list-style-type: none"> Utilizing WPO fuel at low engine loads leads to a significant increase in CO emissions, but at higher engine loads, the disparity between WPO and diesel fuel is minimal. In comparison to WPOD fuel, WPO fuel results in higher CO and HC emissions. As engine load rises, the gap in HC emissions between WPO and WPOD diminishes due to increased thermal processes. These emissions are affected by heat transfer between combusted gas and cylinder walls, as well as charge inhomogeneity. Heat loss plays a role in reducing combustion chamber temperatures at low loads, which can lead to premature flame quenching and incomplete hydrocarbon combustion. Nevertheless, in high-load conditions, the impact of heat transfer is diminished, thanks to elevated thermal reactions that result in higher in-cylinder temperatures.
(Kaewbuddee et al., 2020)	HC	<ul style="list-style-type: none"> The process of converting waste plastic oil into fuel generated higher hydrocarbon emissions compared to diesel fuel.
	CO	<ul style="list-style-type: none"> The biodiesel-waste plastic oil blends exhibited a drawback in terms of carbon monoxide emissions due to their higher viscosity and lower calorific value. This ineffective atomization of the fuel blends resulted in a reduction in combustion temperature, consequently leading to an increase in carbon monoxide emissions.
	NO _x	<ul style="list-style-type: none"> With increasing engine load, the overall nitrogen oxide (NO_x) emissions increased, and waste plastic oil demonstrated higher NO_x emissions compared to diesel fuel. Among waste plastic oil and its blends, biodiesel showed lower NO_x emissions.

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Table 5 (continued)

References	Topics	Findings
(Ananthakumar et al., 2017)	Smoke	<ul style="list-style-type: none"> • Combustion of biodiesel blends delayed the rise in combustion temperature, which was less favorable for NOx formation and reduced the peak of heat release during the premixed combustion phase. The addition of biodiesel resulted in NOx levels similar to those of diesel fuel blends, contributing to NOx reduction. • Combusting waste plastic oil resulted in significantly lower smoke emissions compared to diesel fuel. However, the addition of biodiesels to waste plastic oil increased smoke emissions in these fuel blends. Smoke emissions further increased under higher engine load conditions. When comparing castor oil biodiesel to palm oil biodiesel, it was evident that castor oil biodiesel produced reduced smoke emissions. • The effects of the two main variables on particulate matter emissions, which were directly linked to smoke emissions, were opposite. Firstly, the higher viscosity of castor oil biodiesel made fuel injection more challenging. This led to inadequate fuel atomization, resulting in more incomplete combustion and subsequently more smoke emissions.
(Ananthakumar et al., 2017)	HC	<ul style="list-style-type: none"> • At full load, WPO and diesel had HC emissions of 27 ppm and 20 ppm, respectively. This occurred because the fuel spray did not penetrate the combustion chamber, causing gaseous hydrocarbons to accumulate along the cylinder wall and crevice.
(Kalargaris et al., 2018)	NO _x	<ul style="list-style-type: none"> • The production of NOx is influenced by factors such as cylinder temperature, oxygen levels, and the duration of the reaction. • Nitrogen oxides are generated through oxidation within the cylinder at temperatures around 2200 K. Breaking the triple bond of nitrogen requires a substantial amount of energy, and NOx formation is promoted by the high combustion temperatures. • NOx, a combustion byproduct, consists of 10–30% NO₂ and NO. Its production is influenced by oxygen levels and cylinder temperature. • Combustion theory recognizes three mechanisms for NOx production: the heat mechanism, the prompt mechanism, and the fuel mechanism. • In diesel engines, the thermal mechanism is the primary contributor to NOx emissions, owing to higher in-cylinder temperatures and increased oxygen availability. Results indicate that adding diesel to PP700 and PP900 reduces NOx emissions. • The longer ignition delay duration of PP700, which leads to a higher proportion of premixed combustion, might be responsible for the greater NOx emissions. • Furthermore, the lower polypropylene blend of PP900 burns more smoothly, possibly due to higher oxygen levels and reduced viscosity, which enhance air-fuel mixing.
(Hossain and Davies, 2013)	NO _x	<ul style="list-style-type: none"> • Compared to diesel, pyrolysis liquid has a higher water content, which may result in lower NOx emissions. However, the higher density of PL might sometimes lead to increased NOx emissions.
(Murugesan et al., 2023)	HC	<ul style="list-style-type: none"> • Across all loads, there was a slight increase in HC emissions, suggesting some incomplete combustion.
(Murugesan et al., 2023)	Smoke	<ul style="list-style-type: none"> • The incorporation of water particles in the fuel, resulting in micro-explosions and secondary atomization, effectively prevented smoke production. Consequently, the addition of 20% PPO with carbon nano-additives led to reduced smoke emissions. However, PPO, under normal conditions, produced 35% more smoke at full load compared to diesel.
(Murugesan et al., 2023)	NO _x	<ul style="list-style-type: none"> • Under peak load conditions, standard engine operation resulted in the highest NOx emissions from PPO, showing a 15.5% increase compared to the low heat rejection (LHR) engine with 20% PPO + CNT30 (30 ppm Carbon nano tubes). In contrast, experiments with the LHR engine revealed that emulsions of 20% PPO with varying CNT blends (10, 20, and 30 ppm) had NOx emissions 2.7%, 6.8%, and 7.7% lower, respectively, than 20% PPO alone. These results align with the property of water having a high specific heat capacity, which reduces peak cycle temperatures and enhances the catalytic activity of CNT particles, leading to reduced NOx emissions.
(Ananthakumar et al., 2017)	Smoke Opacity	<ul style="list-style-type: none"> • At full load, smoke opacity measured 26% for diesel and 47% for waste plastic oil, mainly due to the absence of a homogeneous charge within the engine cylinder. Smoke emissions were lower with higher compression ratios but higher with lower compression ratios. As the load increased and a rich mixture was burned in the cylinder, smoke levels significantly rose.
(Ramesha et al., 2019)	CO	<ul style="list-style-type: none"> • Diesel exhibits the highest CO emissions, while B20H WPO has the lowest. This indicates that B20H WPO reduces CO emissions by 16.66% compared to diesel. The reduced CO emissions in B20H WPO are attributed to the fuel's fine atomization and high oxygen content, enabling complete

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Table 5 (continued)

References	Topics	Findings
		combustion. Additionally, Al_2O_3 nanoparticles act as a catalyst, providing oxygen to the fuel and converting CO to CO_2 .
	NOx	<ul style="list-style-type: none"> Nitrogen reacts with oxygen primarily at high temperatures and pressures, and the elevated temperature within the cylinder promotes this reaction, leading to increased NOx emissions as the temperature rises. The graph illustrates the highest and lowest NOx emissions for B20H WPO+Al_2O_3 (550 ppm) and diesel (410 ppm), respectively, resulting in a 140 ppm difference compared to diesel. This difference is attributed to the greater surface-to-volume ratio of Al_2O_3 nanoparticles, which enhances combustion by elevating cylinder temperature and consequently increasing NOx emissions.
	HC	<ul style="list-style-type: none"> In comparison to pure diesel, all the test fuels exhibited lower UBHC emissions across all loads. Diesel had the highest UBHC emissions at 14.2 ppm, while B20H WPO+Al_2O_3 had the lowest at 7.1 ppm. The significant reduction in UBHC emissions in the presence of Al_2O_3 nanoparticles, resulting in a 50% decrease compared to diesel, is attributed to the nanoparticles' excellent catalytic capability, which supplies oxygen for complete combustion.
(Venkata Subbaiah et al., 2019)	CO_2 & NOx	<ul style="list-style-type: none"> The elevated CO_2 emissions observed in PPO blends are primarily a result of the increased availability of oxygenated chemicals within PPO. This availability leads to improved combustion at higher loads, resulting in higher CO_2 emissions compared to diesel fuel. Nitrogen Oxide (NOx) is produced as a byproduct of the oxidation of nitrogen content present in the air drawn into the combustion chamber during the combustion of an air-fuel mixture. Blends with lower percentage levels have reduced oxygen content and consequently emit lower levels of NOx.
(Padmanabhan et al., 2022)	HC	<ul style="list-style-type: none"> The more significant part of hydrocarbon emissions are caused by insufficient mixing of fuel and air particles during combustion and incomplete combustion of the fuel itself. Under different load conditions, hydrocarbon emissions decrease by 11.76–16.39%, 4.41–8.82%, and 1.47–1.72%, respectively. When a fuel is burned, the higher oxygen content is mixed with the air in the combustion chamber in the proper amount. Therefore, more fuel particles than diesel are consumed in the combustion chamber.
(Güngör et al., 2015)	CO , CO_2 , NOx	<ul style="list-style-type: none"> A 5% PPO blend results in a 20.63% reduction in CO emissions, along with a 3.34% increase in CO_2 emissions. However, NOx emissions increase by 9.17% compared to diesel fuel with the same blend.
(Shrivastava et al., 2019)	NOx	<ul style="list-style-type: none"> NOx emissions increased with higher engine loads for all fuels due to elevated temperatures and longer combustion times. Biodiesel and its blends produced lower NOx emissions at higher loads compared to diesel, as NOx formation is closely tied to temperature, which rises with increased engine load.
	Smoke	<ul style="list-style-type: none"> Smoke emissions increased with higher engine loads for all fuels. Oxygenated gasoline led to a slight reduction in smoke emissions across all engines. Smoke is primarily generated because unburned carbon particles accumulate near the cylinder wall surface in lower temperature, fuel-rich zones. Inadequate fuel-air mixing in these rich zones leads to smoke production in the engine exhaust. Fuel properties like lower volatility and higher viscosity can impact the combustion process, contributing to smoke formation.
	CO	<ul style="list-style-type: none"> The PPO-biodiesel-diesel blend (10%–10%–80%) exhibited lower CO emissions compared to diesel fuel. The inclusion of 5–10% PPO in biodiesel-diesel blends significantly reduced CO emissions.
	CO_2	<ul style="list-style-type: none"> Combustion theory suggests that the combination of carbon (C) and hydrogen (H) with oxygen (O) initiates fuel combustion, producing energy, H_2O, CO_2, and more. Consequently, as the energy content increases (on an energy basis), CO_2 emissions decrease. CO_2 emissions for pure diesel, biodiesels, and their blends decreased with increasing engine load, signifying greater fuel entry into the combustion chamber. CO_2 emissions from engine exhaust serve as an indicator of combustion quality, with higher CO_2 emissions indicating more complete fuel combustion.
(Singh et al., 2020)	CO & CO_2	<ul style="list-style-type: none"> PPO mixed fuel emits higher levels of CO compared to diesel fuel. This increase in CO concentration is primarily attributed to greater fuel consumption at higher loads. Additionally, a lower in-cylinder temperature during combustion leads to increased CO emissions.

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Table 5 (continued)

References	Topics	Findings
(Munaf et al., 2021)	NO _x	<ul style="list-style-type: none"> Complete fuel oxidation generates significant heat and CO₂. From a sustainability standpoint, it is imperative to minimize CO₂ emissions as they contribute to the greenhouse effect. NO_x emissions for pure plastic oil are measured at 300, 400, 700, and 800 ppm for different loads. In comparison, the B100 blend at full load emits lower NO_x than other loads. The 25–75% blend reveals that NO_x increases due to the reactivity of nitrogen (N₂) at high temperatures.
	CO	<ul style="list-style-type: none"> Waste plastic oil B50 blends exhibit reduced CO emissions. The high injection pressure results in a more efficient fuel mixture in the combustion chamber, which converts CO into CO₂.
	CO ₂	<ul style="list-style-type: none"> B25 emitted lower CO₂ levels at full load and various applied loads. This can be attributed to the complete combustion of B25, resulting in reduced CO₂ emissions compared to other blend ratios.
(Singh et al., 2020)	NO _x	<ul style="list-style-type: none"> The inclusion of DEE in PPO enhances combustion duration by increasing the cetane number, which helps in reducing nitrogen oxides. Another contributing factor to elevated NO_x levels could be delayed combustion and prolonged injection times before ignition.
(Mondal et al., 2023)	Exhaust Gas	<ul style="list-style-type: none"> In the absence of a catalyst, HDPE and LDPE produce 43.5% and 37.3% of exhaust gas, respectively.
(Avinash, Kumar Agarwal, Dhananjay, Kumar Srivastava, Atul, Dhar, Rakesh, Kumar Maurya, Pravesh, Chandra Shukla, Akhilendra, 2013)	NO _x	<ul style="list-style-type: none"> In extreme conditions, NO_x formation is significantly influenced by factors such as the highest temperature of burning gases, oxygen concentration, and the available residence time for reactions to occur. Increasing engine load leads to reduced NO_x emissions, primarily because the rise in power production outpaces the increase in raw NO_x emissions.
(Devaraj et al., 2015)	HC, NO _x , CO	<ul style="list-style-type: none"> The addition of DEE to PPO led to an increase in HC emissions. Higher Cetane number values and the high heat of DEE evaporation contributed to a reduction in NO_x emissions. DEE blends exhibited lower CO emissions compared to PPO.
	Smoke opacity	<ul style="list-style-type: none"> Combining DEE with WPPPO results in reduced smoke opacity. This is attributed to DEE's higher oxygen concentration, which inhibits smoke generation during the diffusion phase of combustion.

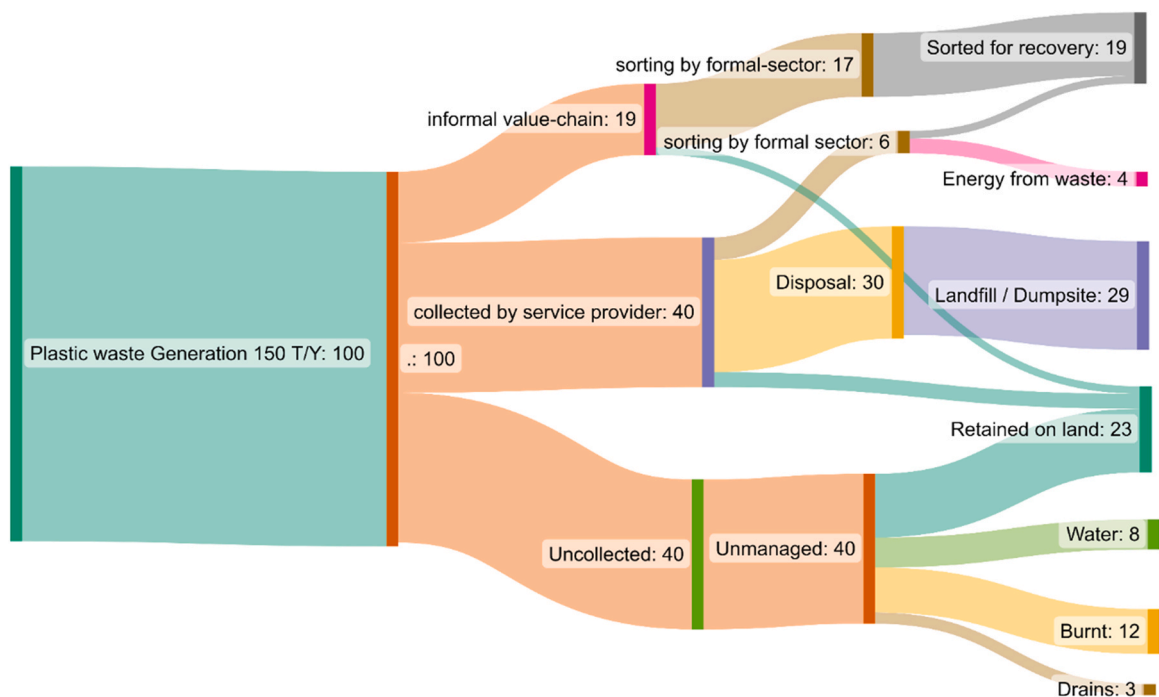


Fig. 3. Visualizing the Pathway to Sustainable Plastic Waste Utilization (Evide et al., 2021).

Table 6
A summary of different studies conducted on PPO-diesel blends in engine.

Engine Specification	Test Condition	Composition of Fuel (%)			Ref Fuel/ Add	Combustion Parameters	Performance Parameters	Emission Parameters	References
		PPO	Diesel	Others					
CR 17.5:1,4 Stroke CI, DI, RP: 5.2 kW, RS: 1500 rpm, WC, Single Cylinder	Fixed speed and varying loads	10 20 30 40 50	90 80 70 60 50		Diesel	↑: ID ↑: HRR	↑: BTE ↓:SFC	↑: CO ↑: HC ↑: NO _x	(Singh et al., 2020)
CI, single cylinder Four Stroke, DI CR 18:1 RS:3200 rpm,	Fixed speed and varying loads	60 80	40 20		Diesel	————	↑: BSFC ↑: BTE —: Torque —: Power	↑: CO ↑: CO ₂ ↑: HC ↑: NO _x	(J and Watwe, 2007)
CI, Four Strokes, DI, Cylinder Single, CR 17.5:1, RP: 4.4 kW,	varying speed and varying loads	30 50 70 100	70 50 30 00		Diesel	↑: CP ↑: HRR ↑: ID ↑: Tem.	————	↑: NO _x ↑: HC ↑: CO ↓: CO ₂	(Mani et al., 2011)
CI, Four strokes, Cylinder four,	Fixed speed and load	50 70	50 30		Diesel	————	↑: BSFC ↑: BTE ↑: BMEP	↑: HC ↑: CO ↑: NO _x	(Sankar et al., 2016)
CI, Two Cylinder, 4 Stroke, RP: 7.4 kW, CR 17.5:1, DI, RS: 1500 rpm,	Fixed load and varying speed	10 20 30 40	90 80 70 60		Diesel	↑: CP ↑: ID ↑: HRR	↑: BTE ↓: BSEC ↓: BSFC	↑: CO ↑: HC ↓: NO _x	(Kumar et al., 2013)
CI, DI, 1 Cylinder, 4 Stroke CR 17.5:1, RS: 1500 rpm, RP: 4.4 kW	Varying speed and fixed loads	90–10	10–90		Diesel	—: ID,	↑: BSFC ↑: BTE	↑: HC ↓: NO _x ↓: CO ↓: CO ₂	(Mani and Nagarajan, 2009)
CI, CR 16.5:1, One Cylinder RS: 1500 rpm Four Stroke, DI, RP: 3.7 kW, WC,	Varying speed and fixed loads	95 90		05 10 (diethyl ether)	Diesel	↑: HRR	↑: BTE ↓: BSEC	↑: CO ₂ ↓: NO _x ↓: CO ↑: HC	(Devaraj et al., 2015)
CI, One Cylinder, Four Stroke, RP: 50.7 kW, DI, WC, CR 22.1:1, RS: 2600	Varying speed and fixed loads	80	20			↑: T	↓: BSFC ↑: BTE	↑: CO ₂ ↑: NO _x ↓: CO ↑: HC	(Mustayen et al., 2023)
CI, One Cylinder, CR 12–18:1, Four Stroke, WC, DI, RS: 1500 rpm, NA, RP: 3.5 kW,	Fixed speed and Varying loads	90		10(palm oil)	Diesel	————	↑: BP ↑: BTE ↓: BSFC	↑: CO ₂ ↓: NO _x ↑: CO ↓: HC	(Kaewbuddee et al., 2020)
CI, DI, One Cylinder. RS: 1500 AC, Four Stroke, RP: 5.20 kW, rpm, CR 18:1,	Fixed speed and varying loads	90	10		Diesel	↑: CP ↑: HRR ↑: ID	↑: BTE ↓: BSFC	↑: CO ₂ ↓: NO _x ↓: CO ↓: HC	(Das et al., 2020)
CI, DI, One Cylinder, WC, Four Stroke, CR 17.5:1, RS: 1600 rpm, NA, RP: 5.5 kW	Fixed speed and varying loads	25	75	25 ppm of Al ₂ O ₃	Diesel	————	↓: BSFC ↑: BTE ↑: BMEP	↑: HC ↓: CO ↑: NO _x	(Sekar et al., 2021)
CI, DI, One Cylinder NA, RS: 1500 rpm 4 S, AC, RP: 4.4 kW, CR 18.5:1	Fixed speed and varying loads	40	50	n- butanol (B) 10	Diesel	—: CP —: HRR	↓: BSEC ↑: BTE ↑: BMEP	↑: NO _x ↓: HC ↓: CO	(Damodharan et al., 2017)
CI, RP: 43.7 kW, One Cylinder RS: 1500 rpm, 4 S, CR 16.5:1, DI, WC	Fixed speed and varying compression ratios	25 50 75	75 50 25		Diesel	↑: PP ↑: HRR ↓: ID	↓: BTE ↓: BSEC	NA	(Kaimal and Vijayabalan, 2015)

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Table 6 (continued)

Engine Specification	Test Condition	Composition of Fuel (%)			Ref Fuel/Add	Combustion Parameters	Performance Parameters	Emission Parameters	References
		PPO	Diesel	Others					
CI, CR 16.5:1, One Cylinder, RS: 1500 WC, 4 S, DI,	Varying speed and varying load	100 95 90	— 05 10	—	Diesel	↓: HRR	↑: BTE —BSFC ↑: BP	↑: HC ↓: CO ↓: NO _x	(Devaraj et al., 2015)
CI, 1-Cylinder RP: 4.4 kW, DI, AC, Four Stroke, RS: 1500 rpm, CR 17.5:1,	Fixed speed and varying loads	PPO 90 80	— 10 20	JME	PPO	—	↑: BTE ↑: BSFC JME (↑:BP, ↓: EGT)	↑: NO _x ↓: CO ↓: HC	(Senthilkumar and Sankaranarayanan, 2016)
CI, 4-Cylinder, DI, WC, 4 S, RP: 3.7 kW, RS: 1500 rpm, CR 16.5:1,	Fixed speed and varying loads	25 50 75	75 50 25	—	Diesel	—	↓: BP ↓: BSFC ↑: BTE	↓: NO _x ↑: CO ↑: HC ↓: CO ₂	(Kaimal and Vijayabalan, 2016a)
CI, 4-Cylinder, DI, WC, 4 S, RP: 89 kW, RS: 3200 rpm, CR 16.5:1	Varying speed and varying load	05 10 15 20	95 90 85 80	—	Diesel	—	↑: BP ↑: BSFC	—: HC ↓: CO ↑: NO _x ↑: CO ₂	(Güngör et al., 2015)
CI, RP: 3.7 kW, 1-Cylinder NA, 4 S, AC, RS: 1500 rpm DI	Fixed speed and varying loads	100 95 90 85	0 05 10 15	—	Diesel	↑: HRR ↑: ID	↑: PP ↑: BTE ↓: BSEC	↓: CO ↓: NO _x ↑: HC	(Kaimal and Vijayabalan, 2016b)
CI, One Cylinder RS: 1500 rpm, NA, 4 S, RP: 3.7 kW DI, CR 16.5:1,	Varying load fixed speed	100 00	00 100	—	Diesel	—	↓: BTE ↓: BTE	—	(Kaimal and Vijayabalan, 2017)
CI, One Cylinder RS: 1500 rpm, NA, 4 S, RP: 3.7 kW DI, CR 16.5:1,	Varying load fixed speed	100 2.5 7.5 12.5	00 97.5 92.5 87.5	—	Diesel	— HRR —PP	↓: BTE ↑: BSFC	—: HC ↑: CO ↑: NO _x	(Ananthakumar et al., 2017)
CI	Compression ignition		HRR			Heat removal rate		BP	Brake power
DI	Direct ignition		BTE			Brake thermal efficiency		JME	Jatropha methyl ester
RP	Rated power		BSFC			Brake specific fuel consumption		HC	Hydrocarbon
RS	Rated speed		BSEC			Brake specific energy consumption		CP	Cylinder pressure
AC	Air cooled		BMEP			Brake mean effective pressure		PP	Peak pressure
WC	Water cooled		IG			Ignition delay		PPO	Plastic pyrolysis oil
CR	Compression Ratio		EGR			Exhaust gas recirculation		CO ₂	Carbon dioxide
CO	Carbon monoxide		NOx			Nitrogen oxides		↑	Increase
NA	Not available		—			No change		↓	Decrease

- Various purification methods, such as acid washing, activated carbon treatment desulphurization, and distillation, have been employed to remove impurities and enhance the quality of PPO. Physicochemical parameters such as viscosity, density, and calorific value of PPO are improved by the purification method and the type of plastic used.
- In terms of combustion properties, PPO has a longer ignition delay and a faster heat release rate than diesel fuel. Although blending PPO with diesel fuel reduces BTE, utilising n-butanol as an additive can improve PPO combustion characteristics.
- Due to its higher density, calorific value, and lower viscosity, PPO outperforms diesel fuel in terms of power output and engine efficiency.
- If additives are added to the blends of PPO-diesel, NO_x and CO emissions are reduced, but hydrocarbon emissions are increased. However, carbon monoxide (CO) and particulate matter (PM) frequently decrease as a result of the increased oxygen content.
- Due to its cheap production cost and high yield, PPO has the potential to be a fuel source that is cost-effective. However, the commercialization of PPO faces difficulties because to the absence of set purification criteria and policies.
- The study indicates that a blend of up to 70% plastic pyrolysis oil (PPO) and an engine operating at 80–90% load can result in the most promising outcomes in terms of engine performance and emissions reduction without any or slight modification of the engine.

In conclusion, PPO as a fuel source has suitable parameters that require careful consideration when assessing its suitability for various applications. Further research is needed to develop purification standards, optimize combustion and performance parameters, and reduce emissions to make PPO a viable alternative to traditional fossil fuels. Moreover, the nanoparticles and additives are blended in the fuel to increase the favorable physicochemical properties that affect the combustion, performance, and emission characteristics.

CRedit authorship contribution statement

Yaqoob Haseeb: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tan Ee Sann:** Funding acquisition, Investigation, Resources, Software, Supervision, Validation. **Ali Hafiz Muhammad:** Investigation, Resources, Supervision, Validation, Visualization. **Farooq Muhammad Umar:** Data curation, Formal analysis, Methodology, Project administration, Resources, Software, Writing – original draft. **Jamil Muhammad Ahmad:** Resources, Software, Supervision, Validation, Writing – original draft. **Ong Hwai Chyuan:** Supervision, Writing – review & editing.

Data Availability

No data was used for the research described in the article.

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Declaration of interests

The authors reiterate that they are unaware of any personal or financial conflicts that may have looked to have influenced the research disclosed in this study.

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