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Waste plastic oil as an alternative fuel: A review

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Abstract

Today, with the high population density of the world, the energy demand is increasing continuously. Global dependency on fossil fuels is very strong and there is a compelling need to reduce our energy consumption in order to offset greenhouse gas emissions. Due to regularly increasing prices of fossil fuels alternative fuels are needed to fulfill the requirements of developing countries like India. Plastics in today's world have become crucial. They are excessively used in industry, as well as in households and other fields due to their lightweight, durability, and design flexibility. Plastic demand is growing day by day, which now poses a huge environmental threat. The current study summarizes the use of WPO (waste plastic oil) in the diesel engine and also concludes the combustion, performance, and emission parameters. After an exhaustive literature search, some interesting results have been found. The study reveals that when using WPO as an alternative source in a diesel engine, the combustion, performance, and emissions are similar to those using conventional diesel fuel. An enhanced BTE (brake thermal efficiency) and reduced emissions of unburned hydrocarbons (UBHC) and carbon monoxide (CO) are reported.

Keywords: Waste plastic oil; Diesel engine; Performance; Emissions and combustion

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1. Introduction

Plastic manufacturing has expanded from 15 million tonnes in 1964 to 311 million tonnes in 2014 and is expected to quadruple again in the next 20 years, with plastics increasingly servicing various applications [1]. Plastic packaging has always been and will remain the major use, and packaging actually accounts for 26% of the overall amount of plastics used. Not only does plastic packaging have direct economic benefits, but it can also lead to improved resource production levels [2].

In India, 1.2 kg/year, per capita plastic waste was generated during 2016–2017 while in 2019–2020 it was 2.5 kg/year, per capita plastic waste generated. It is observed that over the last five years (2016–2020) per capita plastic waste has almost doubled. In 2019–2020, Delhi, Goa and Kerala produced the highest

Nomenclature

Abbreviations and Acronyms

BMEP – brake mean effective pressure
BP – brake power
BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
EGT – exhaust gas temperature
HDPE – high-density polyethylene
HC – hydrocarbons
HRR – heat removal rate
IDP – ignition delay period
LDPE – low-density polyethylene
PP – polypropylene
PPO – plastic pyrolysis oil
PS – polystyrene
PET – polyethylene terephthalate
SFC – specific fuel consumption
UBHC – unburned hydrocarbons
WPO – waste plastic oil

amount of plastic waste per capita while Sikkim, Nagaland and Tripura produced the lowest per capita plastic waste [3]. But in the financial year 2020–2021, Maharashtra generated 443,724 metric tons of waste plastic which is the highest among all the states in India. [4]. As per the CPCB (Central Pollution Control Board) report (2019–20), only 50% of plastic waste is recycled [5]. In India, the plastics market is estimated to be over 8 million tonnes per year. Over 10 000 metric tonnes of plastic each day are manufactured in India, and India imports almost the same amount from most other countries. In India, individuals consume approximately 3 kg of plastic per capita, which is significantly lower compared to developed countries where the per capita plastic intake ranges from 30 kg to 40 kg. Most of them come from the food and packaging industry. Most plastics are recycled. However, this is often not possible because due to a lack of adequate demand control about 43% of non-recycled plastic waste is polyethylene, coming mostly from containers and packaging [6]. Considerable attention was paid to the development of biodiesel as an option to petro-diesel due to concerns about the supply of recoverable fossil fuel supplies and the environmental issues created by the use of these fossil fuels [7]. In order to turn it into liquid fuel to solve the problem of liquid fossil energy depletion, pyrolysis of plastic waste has now been attracting considerable interest from researchers. Studies began with the investigations of the properties of liquid fuel derived from various types of plastics. Plastics are among the most frequently used materials in our everyday lives and contribute greatly to society. They are commonly used in the wrapping and processing of items such as electronics, vehicles, etc. The deterioration of organic waste paper takes 1–3 weeks, and 8–10 weeks for cotton fabric, but it would take a million years for plastic to degrade. Plastics are lightweight and can be shaped simply. They expose non-corrosive behavior. The scenario of plastic waste thermal conversion into liquid fuel has indeed been applied to the combining of different forms of plastics. Two types of plastics are primarily available. The results from either the plastic pyrolysis mixture showed that the liquid produced was less than the individual plastic pyrolysis in contrast.

2. Waste plastic to oil conversion

The process of converting waste plastic into oil involves utilizing techniques like pyrolysis, catalytic cracking, and hydrothermal liquefaction. These methods utilize controlled heat and pressure to break down the complex polymer structures of plastic into smaller hydrocarbon molecules. By addressing the issue of plastic waste accumulation, this conversion process holds the potential to yield both environmental and energy benefits. On the other hand, challenges related to consistent feedstock quality, process optimization, and effective management of byproducts need to be overcome through ongoing research and technological advancements to ensure the efficiency, environmental sustainability, and economic feasibility of this promising alternative solution.

From Fig. 1 it is shown that the oil extraction journey from waste plastics begins with the collection of waste plastics from

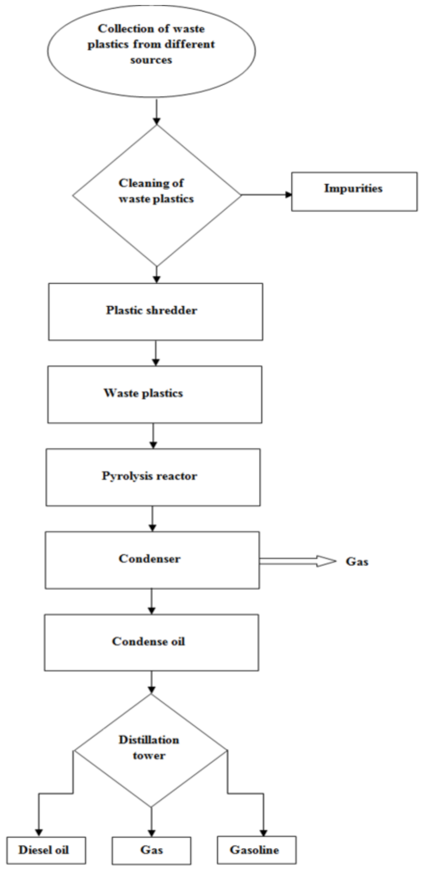

Fig. 1. Flow processes of waste plastic into oil.

diverse sources, such as rivers households, industries, and commercial establishments [8]. The World Bank reports that plastics constitute approximately 5% to 12% of the total global waste generation, which is around 20% to 30% of the waste's total weight [9]. After gathering waste plastics from various origins, it is essential to separate the waste plastics from any additional impurities and materials [10]. Once cleaned, the waste plastics are directed to a plastic shredder. This mechanical apparatus breaks down the plastics into smaller, consistent pieces. Pyrolysis has achieved significant acceptance as a technique that predominantly produces liquid products known as bio-oil. This process also produces char, a solid by-product, as well as a gas. The nature and composition of these liquid and solid products are influenced by the pyrolysis operational circumstances [11]. Dehydration, decarboxylation, and dehydrogenation occur during the initial stage. But in the latter phases, a high-molecular-weight thermal cracking compound occurs, resulting in char and gaseous products such as CO_2 (carbon dioxide), CO (carbon monoxide) and CH_4 (methane) [12].

Plastic waste pyrolysis has emerged as a promising and sustainable solution to address the growing global issue of plastic waste management. Anthony and his colleagues, in their study [13] highlighted the escalating demand for plastic products and the challenges associated with plastic waste disposal. In response, they proposed plastic pyrolysis as an innovative approach to not only manage plastic waste effectively but also harness its potential by converting it into valuable plastic pyrolysis oil. The research compared the technical and economic aspects of substituting diesel oil in diesel engines with WPO and found that it holds substantial promise as a viable alternative. The financial benefits of such a project are substantial, with the potential to significantly boost the economy. Cross et al. [14] highlighted the significance of interdisciplinary collaboration, underlining the need for a strong, cohesive team with a solid engineering foundation. Their project provided valuable practical experience and insights into managing complex tasks.

Mathur et al. [15] emphasized the influence of plastic grades on the pyrolysis process. They conducted pyrolysis using Grade 5 plastic materials (polypropylene) and obtained 1.65 liters of oil from 1.5 kg of plastic waste. This observation underscores the importance of carefully selecting plastic types and grades to optimize oil production, shedding light on the significance of choosing appropriate materials for efficient pyrolysis. Bouaphengphanh et al. [16] delved into the pyrolysis process, exploring the impact of temperature and extraction duration. They found that the process's starting temperature and duration significantly affect oil yields. Among various plastic types, HDPE (High-density polyethylene) emerged as the most productive, achieving approximately 88% conversion, and producing oil that closely resembled diesel. In contrast, PET (Polyethylene terephthalate) failed to yield oil, highlighting variations in plastic behavior during pyrolysis. Desai et al. [17] focused on the environmental and energy benefits of converting plastic waste into synthesis gas emphasizing the potential to mitigate environmental hazards associated with plastic waste and generate components for creating new products.

Chavan et al. [18] investigation into thermal pyrolysis highlighted its efficiency, cleanliness, and effectiveness in dealing with plastic waste. Polypropylene and polystyrene were identified as top oil producers, while PET offered high gasoline yields. This process effectively addressed the dual challenges of managing plastic waste and mitigating fuel shortages by converting plastics into a valuable fuel source. Santaweesuk et. al [19] underscored the importance of precise temperature, time, and energy control in pyrolysis. This ensured controlled and less reactive processes while employing waste plastics to derive WPO using both conventional pyrolysis and distillation methods. Patni et al. [20] conducted an experiment to address key challenges in plastic waste pyrolysis. Their endeavors emphasized the need to scale up the process, minimize waste handling costs, and reduce production costs. With the right infrastructure and financial support, large quantities of plastic waste could be efficiently converted into viable alternatives to fossil fuels. Jha et al. [21] demonstrated the effectiveness of catalytic pyrolysis in converting various plastic waste types into clean fuel, significantly reducing carbon emissions and environmental burdens. Srinivas et al. [22] confirmed that pyrolysis effectively converts waste plastic into valuable fuel, addressing the problem of plastic waste and its environmental impact. Fivga et al. [23] assessed the technical and economic viability of plastic waste pyrolysis, highlighting its fuel energy efficiency and self-sufficiency in thermal energy. Sensitivity analyses were conducted to determine the impact of waste disposal charges on fuel production costs, emphasizing the cost-effectiveness and environmental benefits of utilizing plastic waste for sustainable fuel production. Medrano et al. [24] explored the potential of mechanical material separation processes before pyrolysis to enhance the efficiency and quality of pyrolysis oil production from diverse plastic waste streams. Sharuddin et al. [25] highlighted the flexibility and adaptability of the pyrolysis process in converting substantial energy from plastic waste into valuable products, making it a practical solution for plastic waste management. Chiwara et al. [26] successfully designed a laboratory-scale pyrolysis unit for converting plastic solid waste into pyrolysis oil, achieving optimal process throughput. Tahir et al. [27] conducted experiments aimed at optimizing the production of liquid fuel through pyrolysis. Their study emphasized the crucial correlation between temperature variations and the resulting quality of liquid fuel products. Walendziewski et al. [28] explored the impact of temperature on the pyrolysis process and the efficiency of thermal and catalytic cracking. Higher temperatures were found to increase conversion rates and gasoline fraction production, and the use of cracking catalysts improved the process's overall efficiency.

In conclusion, plastic waste pyrolysis has gained considerable attention as a sustainable solution for plastic waste management and the production of valuable resources. These studies collectively emphasize the potential of this technology to not only address environmental challenges but also provide economic and energy benefits. Through precise control of process parameters, careful material selection, and innovative approaches, plastic waste pyrolysis holds the promise of mitigating the negative environmental impacts of plastic waste while offering solutions to energy and economic challenges.

3. Physical properties of extracted oil from waste plastics

The physical characteristics of liquid oil generated from different plastic waste types can vary significantly, impacting their suitability for various applications and necessitating tailored processing and treatment approaches.

3.1. Density

Density is a crucial parameter that quantifies the relationship between an object's mass and its known volume. Calculating density holds significant importance in various applications, especially in the context of fuel and engine performance. A higher fuel density can significantly impact engine performance, while a lower density can contribute to the rapid evaporation of oil. In either scenario, there exists the potential for severe damage to the engine [29]. Figure 2 presents data illustrating the density values of various waste plastic oil samples in comparison to diesel fuel. Specifically, the density of LDPE (Low-density polyethylene) is measured at 0.778 g/cm³, whereas PE (Polyethylene) bags and diesel fuel exhibit densities of 0.854 g/cm³ and 0.838 g/cm³, respectively [30].

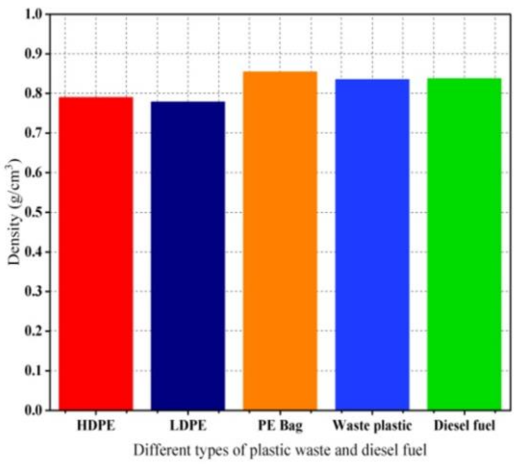

Fig. 2. Density of liquid oil produced from different types of plastic waste.

3.2. Kinematic viscosity

The kinematic viscosity of bio-oil is conventionally assessed at a temperature of 40°C as a means of gauging its fluidity characteristics. This viscosity measurement plays a crucial role in assessing the stability of liquid fuel while it is in storage [31].

Figure 3 provides a visual representation of the kinematic viscosity values for converted waste plastic oils and diesel fuel. Specifically, diesel fuel exhibits a kinematic viscosity of 3.37×10^{-6} m²/s, whereas PP (Polypropylene), HDPE (High-density polyethylene), and PS (Polystyrene) show kinematic viscosities of 2.27×10^{-6} m²/s, 1.63×10^{-6} m²/s and 1.1×10^{-6} m²/s, respectively [32].

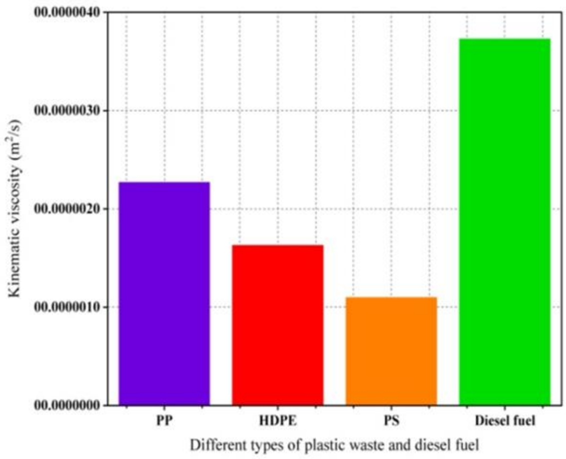

Fig. 3. Kinematic viscosity of liquid oil produced from different types of plastic waste.

3.3. Higher heating value (HHV)

The heating value of a fuel can be expressed in two ways: the higher heating value (HHV), also known as the gross calorific value, and the lower heating value (LHV), or net calorific value. The HHV signifies the heat liberated during fuel combustion when both the original water and the water produced during combustion are in a condensed state [33].

Figure 4 illustrates a comparative analysis of the higher heating values between diesel fuel and various waste plastic oils. Specifically, the HHV for diesel fuel is measured at 46.67 MJ/kg, whereas waste plastic oils such as LDPE, PE bags, tires, and mixed plastic exhibit HHV values of 38.45 MJ/kg, 41.45 MJ/kg, 43.22 MJ/kg, and 44.4 MJ/kg, respectively [34].

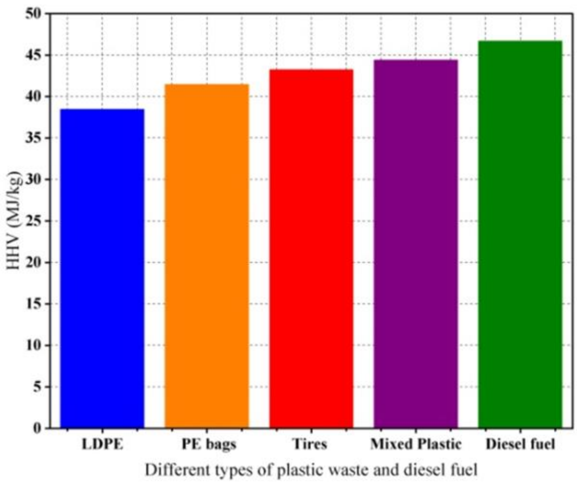

Fig. 4. Higher heating values of liquid oil produced from different types of plastic waste.

3.4. Viscosity

Viscosity is a property that undergoes fluctuations based on factors like feedstock, pyrolysis conditions, temperature, and various other variables.

It is worth noting that as viscosity increases, fuel consumption, engine temperature, and the overall engine workload tend to rise as well. Conversely, if the oil's viscosity becomes excessively high, it can lead to undesirable consequences such as heightened friction within the system [35]. The viscosity measurement for LDPE has been determined to be 1.73 mm²/s, which is notably lower than the viscosities of all the other fuels depicted in Fig. 5.

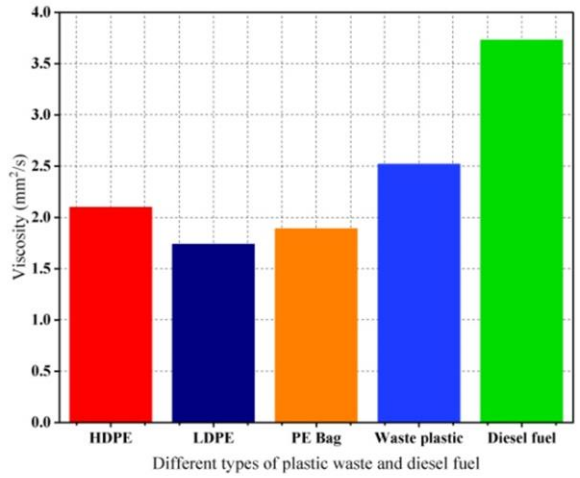

Fig. 5. Viscosity of liquid oil produced from different types of plastic waste.

3.5. Flash point

The flash point is defined as the minimum temperature at which a fuel can ignite. To assess the flash point of petroleum and related products, the Indian standard IS1448, P20 is commonly employed. Typically, any flash point measurement below 60°C is indicative of the substance's combustibility [29].

Figure 6 provides a clear depiction of the flash points for various waste plastic oils and diesel fuel. Specifically, the flash points for PVC (Polyvinyl chloride), HDPE, and diesel fuel are recorded at 40°C, 48°C, and 52°C, respectively [36].

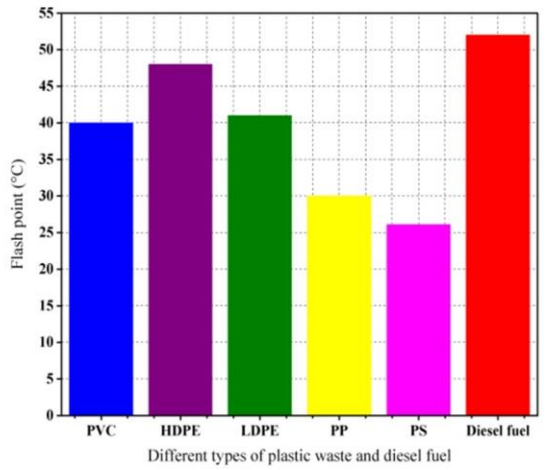

Fig. 6. Flash point of liquid oil produced from different types of plastic waste.

3.6. Pour point

The pour point is defined as the temperature at which oil no longer flows when cooled at a standardized rate within a prescribed apparatus. This parameter is critical in assessing the suitability of oil for use in low-temperature environments and applications [35].

The pour points of PP, HDPE and PS are < −45°C, −15°C and −67°C, respectively, as shown in Fig. 7. Lower value of the pour point shows that the fuel is not suitable in cold weather areas [36].

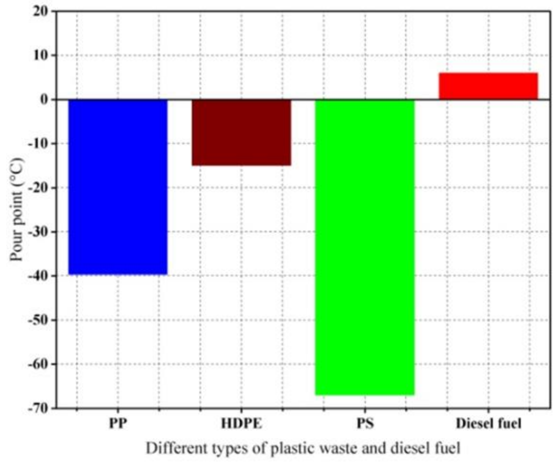

Fig. 7. Pour point of liquid oil produced from different types of plastic waste.

3.7. Ash content

The ash content in oil refers to the noncombustible residue it contains. From Fig. 8 it is clear that the ash content of LDPE is much higher than for other extracted waste plastic oil and diesel.

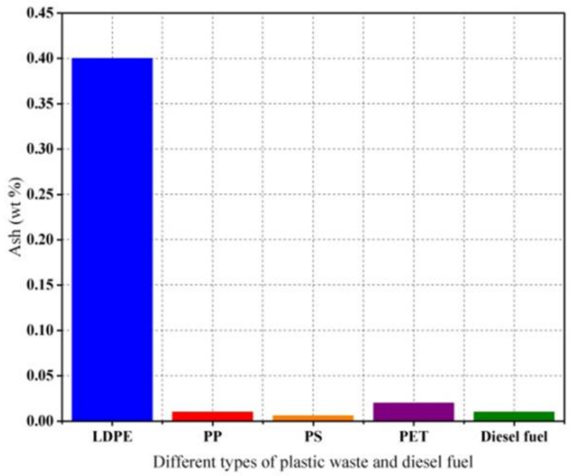

Fig. 8. Ash content of liquid oil produced from different types of plastic waste.

3.8. Water content

Water content in waste plastic oil hampers its fuel efficiency by disrupting combustion, lowering energy output, and raising emissions. It corrodes equipment, forms clogging sludge, reduces energy density, causes ignition issues, and affects stability. Proper handling and treatment are essential to enhance the utility of waste plastic oil as a fuel.

Figure 9 clearly shows that the PS and PET have the highest water content as compared to other extracted plastic waste oil and diesel fuel. The water content of PS, PET and diesel fuel is 0.67 ppm, 0.57 ppm and 0.05 ppm, respectively [32, 34, 36].

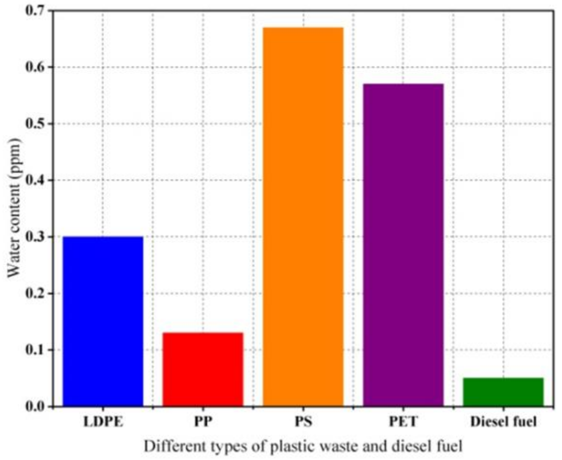

Fig. 9. Water content of liquid oil produced from different types of plastic waste.

4. Diesel engine fuelled with waste plastic oil

The utilization of waste plastic oil (WPO) as an alternative fuel source for diesel engines represents a groundbreaking innovation with substantial environmental benefits. This approach not only mitigates plastic waste but also maximizes the use of existing diesel engine infrastructure. The process of converting waste plastics into usable fuel not only aligns with sustainability efforts but also holds the potential to reduce fuel costs significantly. Table 1 compiles a selection of research studies that delve into the application of waste plastic oil in diesel engines. These investigations scrutinize various facets of engine performance, emissions, and fuel properties when integrating WPO as a fuel source. The collective findings underscore the promise of WPO as a greener fuel alternative, emphasizing its role in plastic waste reduction and the enhancement of engine efficiency.

The studies included in Table 1 collectively demonstrate a growing interest in the utilization of waste plastic oil as a sustainable alternative fuel for diesel engines. These research endeavors reveal that WPO derived from various plastic sources through different conversion methods can be effectively incorporated into diesel engines, offering notable benefits such as improved brake thermal efficiency, reduced emissions of carbon

Table 1. Studies on the utilization of waste plastic oil (WPO) in diesel engines.

Authors	Findings	Ref.
Janarthanan et al.	Diesel engine running on plastic pyrolysis-derived fuel, 6% improvement in brake thermal efficiency (BTE), reduced emissions of unburned hydrocarbons (UBHC) and CO emission.	[37]
Churkunti et al.	In-cylinder temperatures increase during high loads, while nitrogen oxides decrease with diesel content. Variations occur due to the pyrolysis method and the plastic type.	[38]
Singh et al.	Plastic pyrolysis oil (PPO) combustion with delayed ignition and high in-cylinder pressure. Oxygen in PPO reduces emissions. Up to 50% PPO blend effective with slight CO increase.	[39]
Maithomklang et al.	WPO is not favourable for direct use in diesel engines, suggested as a blend component. WPO has a lower soot oxidation temperature, promoting sustainability.	[40]
Peng et al.	Catalysts offer benefits over thermal cracking in fuel production, but more upgrading is needed. Techno-economic evaluation conducted for commercial viability.	[41]
Chowdhury et al.	The review highlights challenges in biomass conversion using pyrolysis and emphasizes the need for complete energy and material balances.	[42]
Naima et al.	The engine runs efficiently on 100% WPO with a slightly longer ignition delay. Oil derived from waste engine oil is suitable as fuel for diesel engines.	[43]
Mani et al.	WPO results in higher cylinder peak pressure and efficient combustion, but increased NOx emissions. Higher hydrocarbon levels with more fuel.	[44]
Harshal et al.	Waste plastic pyrolysis oil is a viable substitute for diesel engines, with significantly higher thermal efficiency. Promising and efficient fuel option.	[45]
Ghorpade et al.	Blends with up to 50% WPO effective, but higher percentages lead to engine issues and increased emissions.	[46]
Anup et al.	WPO demonstrates higher thermal efficiency and lower UHBC emissions but a 5% increase in CO emissions compared to diesel.	[47]
Saleem et al.	Investigation into using microwave technology to extract oil from plastic waste for efficient energy and material resource production.	[48]
Sasikumar et al.	Focus on the pyrolysis process for mixed plastic waste, offering a holistic and sustainable approach to waste management and recycling.	[49]
Bockhorn et al.	Exposure of polypropylene to fractional pyrolysis at varying temperatures alters product composition, influencing reaction mechanisms.	[50]
Nakhate et al.	Successful experiments using plastic waste to produce plastic oil, with a potential for distillation to enhance properties.	[51]
Miandad et al.	Catalytic pyrolysis with modified natural zeolite catalysts enhances liquid oil production from plastic waste.	[52]

Table 2. Studies on pyrolysis of waste plastics and its environmental impact.

Authors	Findings	Ref.
Shah et al.	Gasification and pyrolysis compared to incineration, with environmental and efficiency benefits. Challenges with product gas removal and CO emissions.	[53]
Wongkhorsub et al.	Plastic pyrolysis oil effectively replaces diesel but results in slightly lower engine performance. Oil quality is linked to desulfurization cost.	[54]
Khan et al.	Thermal pyrolysis of mixed plastic offers a cost-effective method for resource recovery with minimal char production.	[35]
Miandad et al.	Pyrolysis produces valuable liquid oil and char, influenced by factors like temperature, retention time, feedstock, and catalysts.	[55]
Ibrahim et al.	Pyrolysis has applications in carbon dating, thermal cleaning, refining, and petrochemical industries for gasoline and aromatic compound production.	[56]
Fahmy et al.	Combining solar pyrolysis with hydrogen production as an environmentally friendly approach for the future.	[57]
Verma et al.	Pyrolysis process, its products, and efforts to upgrade bio-oil for various practical uses.	[58]
Xun Hu et al.	Summary of bio-oil production through slow, fast, and catalytic pyrolysis techniques, with a focus on the reaction pathway.	[59]
Yansaneh et al.	Extensive interest and research efforts in thermal and catalytic pyrolysis of plastic waste, highlighting its potential for waste management.	[60]
Bridgwater et al.	Fast pyrolysis as a technology for liquid fuel production and the challenges of upgrading the produced liquids for various applications.	[61]
Li et al.	Bio-pyrolysis liquefaction technology and its adaptability, rapid reaction rates, and conversion efficiency.	[62]
Pandey et al.	Pyrolysis as an efficient method for recovering monomers or pyrolysis liquid from plastic waste, influenced by factors such as catalysts and temperature.	[63]
Uzochukwu et al.	Pyrolysis as an environmentally friendly method for plastic waste disposal and resource recovery.	[64]
Miandad et al.	Factors influencing the efficiency of catalytic pyrolysis; highlighting the potential of catalysts to improve product quality.	[65]
Oasmaa et al.	The need for REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) registration of pyrolysis liquid and the importance of ensuring positive sustainability impacts.	[66]
Papuga et al.	Growing academic and industrial interest in pyrolysis, particularly catalytic pyrolysis, and its potential for plastic waste management.	[67]
Xayachak et al.	Experiment evaluating the cetane number of oil produced through pyrolysis of plastic waste, showing potential as an alternative fuel.	[68]
Sasikumar et al.	An investigation into technologies and operational conditions for the recovery of plastic waste, emphasizing the role of operating temperature.	[69]

monoxide (CO) and unburned hydrocarbons (UHBC), and the potential for lower fuel costs. Notably, the use of catalysts in the pyrolysis process and the blending of WPO with diesel have been identified as methods to enhance combustion efficiency and address some of the challenges associated with direct WPO utilization.

Table 2 compiles a selection of research studies focusing on the pyrolysis of waste plastics and its environmental consequences. Pyrolysis, a thermal degradation process, has gained prominence as a promising approach to address the burgeoning challenge of plastic waste management. The studies presented here investigate various aspects of pyrolysis, including the use of different catalysts, feedstocks, and reaction conditions, and delve into the subsequent environmental implications. As the world grapples with mounting concerns related to plastic pollution, understanding the effects of plastic pyrolysis on emissions, energy recovery, and the fate of by-products is essential. The studies assembled in Table 2 collectively underscore the significance of pyrolysis as a viable technology for transforming plastic waste into valuable resources while also addressing environmental concerns. From investigating the influence of catalysts to assessing the composition of pyrolysis products, these studies offer valuable insights into the optimization of pyrolysis processes. Furthermore, an improved understanding of emissions, energy recovery, and the potential uses of by-products plays a pivotal role in enhancing the sustainability of this waste management approach. As the world seeks sustainable solutions to the plastic waste crisis, these studies provide a foundation for informed decision-making and further research endeavors in the field of pyrolysis technology.

In Table 3, we present an overview of studies focused on the operation of diesel engines using waste plastic oil and various blends with conventional diesel fuels. These studies investigate a range of parameters, including engine performance, emissions, and combustion characteristics. The use of WPO and its blends in diesel engines is a compelling area of research, offering potential environmental and economic advantages. This table summarizes key findings and trends from the selected studies, providing valuable insights into the utilization of WPO and its impact on engine operation.

The amalgamation of findings across various research papers (Table 3) reveals consistent patterns and certain notable inconsistencies. The bulk of the research suggests a notable enhancement in brake thermal efficiency (BTE) when WPO is blended with conventional diesel fuel. However, when it comes to the trends in carbon monoxide emissions, the literature paints a less clear picture. Some studies demonstrate a decrease in CO emissions, but, conversely, the majority reports an increase.

Similarly, the in-cylinder pressure results exhibit variability and lack a fixed pattern across these studies. Regarding emissions parameters, there is a consistent trend of increased levels

Table 3. Brief of diesel engine operated with waste plastic oil and blends; BSFC – brake specified fuel consumption, BTE – brake thermal efficiency, CD – combustion duration, SFC – specific fuel consumption , HRR – heat removal rate, EGT – exhaust gas temperature, IDP – ignition delay period.

Used engine specification	Combustion and performance parameters	Emission parameters	Ref.
Single cylinder, 4-stroke, water-cooled, variable speed 1500-180 rpm, with a fuel injection pressure of 220 bar.	BTE (↓), SFC (↑), HRR (↑), EGT (↓), IDP (↑)	NO (↑), smoke (↓), CO_2 (↑)	[70]
Single cylinder, 4-stroke, Common Rail, Bosch CP4.1, direct injection, with a fuel injection pressure of 180 MPa.	In-cylinder pressure (↓), HRR (↑)	CO (↑), HC (↑)	[71]
Single cylinder, 4 strokes DI, air-cooled diesel engine @constant speed, with an injection time of 23°CA bTDC and injection pressure of 21 MPa	BTE (↑), BSFC (↓), In-cylinder pressure (↑), HRR (↑)	smoke (↑), CO (↑), NOx (↑), HC (↑)	[72]
Kirloskar TV1, water-cooled, 1500rpm constant speed, 5.2 kW, single cylinder, 661.45 CC with a compression ratio of 17.5:1	In-cylinder pressure (↓), IDP (↓), CD (↑), HRR (↑), BTE (↑)	NOx (↑), CO (↑), HC (↑),	[73]
Kirloskar, 240 PE, VCR, Single Cylinder and 4-stroke Engine, Water-cooled, 3.5 kW at 1500 rpm, with Displacement Volume 661 CC.	BP (↑), BTE (↑), BMEP (↑)	CO (↓), CO_2 (↑), NOx (↑)	[74]
Single cylinder, 4 S, Diesel Engine, Kirloskar, model: TV1, 1500 rpm constant speed, with 5.2 kW rated power	IDP (↑), BTE (↑), SFC (↓), HRR (↓) BTE (↑)	NOx (↑), CO (↑), CO2 (↑)	[75]
4 cylinder in-lines T/C, DI, rated power 70 kW, CR 17.5:1, with injection timing 12°CA bTDC and Nozzle opening pressure 23 MPa.	In-cylinder pressure (↑), BSFC (↓), BTE (↑) HRR (↑)	CO(↑), NOx (↑)	[76]
4-stroke, CI, air-cooled, single-cylinder, constant-speed diesel engine.	BTE (↓)	CO_2 (↑), NOx (↓), CO (↓)	[77]
AKSA, 4 cylinder, Diesel engine, constant RPM@ 1500, Rated power 68 kW.	IDP (↑), HRR (↑), BTE (↓)	CO_2 (↑), NOx (↑), CO (↑)	[78]

of nitrogen oxides, hydrocarbons, and various other emissions constituents when waste plastic oil is introduced into diesel engines. These findings collectively provide valuable insights into the complex interplay between WPO and diesel engines, shedding light on performance enhancements, emissions variations, and the need for further research to optimize this eco-friendly fuel source.

6. Conclusions

Overall, after the exhaustive literature, it is found that fuel from plastic pyrolysis has the potential to be a viable alternative to conventional diesel fuel, with improvements in engine performance and reduced emissions. However, further studies are needed to explore the long-term effects of using pyrolysis fuel, as well as to optimize the pyrolysis process for commercial application. Some findings are listed below.

- The utilization of waste plastic oil (WPO) in diesel engines shows promising results, with improvements in BTE (brake thermal efficiency) and reductions in UBHC (unburned hydrocarbons) and CO emissions.
- The characteristics of plastic pyrolysis oil (PPO) have been analyzed, and the compound analysis confirms the presence of alkanes and aromatic components.
- Different types of plastics yield varying amounts and qualities of pyrolysis oil, with HDPE (high-density polyethylene) and PS (polystyrene) showing higher oil yields compared to other types.
- The use of catalysts in pyrolysis processes, such as zeolites and base catalysts, offers advantages over thermal cracking, but further upgrading is needed for commercial application.
- Pyrolysis presents a viable remedy for the management of waste plastic as it converts plastic waste into valuable liquid oil and gas fuels, reducing environmental pollution.
- The direct use of waste plastic oil in diesel engines may require blending with diesel fuel to reduce engine performance issues but blends up to 50% have shown promise.
- The pyrolysis process can produce oil, gas, and char, which can be used in various applications, such as energy production and environmental remediation.
- The pyrolysis process is influenced by factors such as temperature, feedstock composition, catalysts, and reaction time, which affect the quality and quantity of the products.
- Pyrolysis technology requires optimization in terms of energy efficiency, waste handling costs, and production costs to make it economically viable and sustainable.
- Further research is needed to address challenges in scale-up, waste handling, and product quality as a waste management and fuel production technology.

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