Automotive Experiences
Vol. 6 No. 3 (2023) pp. 551-583
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Review Paper

An Overview of Physicochemical Properties and Engine Performance Using Rubber Seed Biodiesel–Plastic Pyrolysis Oil Blends in Diesel Engines

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https://doi.org/10.31603/ae.10136

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang collaboration with Association of Indonesian Vocational Educators (AIVE)

Article Info
Submitted:
02/09/2023
Revised:
07/11/2023
Accepted:
08/11/2023
Online first:
24/11/2023

Abstract

Rubber Seed Biodiesel (RSB) and Plastic Pyrolysis Oil (PPO) deserve to be considered as alternative fuels for diesel engines, because of their advantages such as large raw material resources, derived from free or waste feedstock and the use of plastic waste as fuel can prevent environmental pollution. Due to their almost identical densities, RSB and PPO can be mixed homogeneously. In general, the use of a mixture of RSB and petroleum diesel in diesel engines shows positive performance, both engine performance and emissions, as well as the use of mixed PPO and diesel fuel. Although RSB has a good cetane number and flash point, on the other hand RSB also has disadvantages in its Physicochemical properties, such as low oxidation stability, high acid value, low heating value and high viscosity. Likewise, PPO, PPO has good oxidation stability, acid value, and viscosity, but the flash point, CO and HC emission are also bad. This article tries to describe the opportunity to mix RSB and PPO, to find the best composition between RSB and PPO which shows the best fuel Physicochemical properties and engine performance.

Keywords: Rubber seed biodiesel; Plastic pyrolysis oil; Physicochemical properties; Engine performance

1. Introduction

1.1. Fossil Energy Reserves

Energy serves as both the foundation for human survival and the engine for social advancement. Energy security is crucial for national security of all countries since global energy demand is expected to rise continuously [1]. The total global energy usage has increased significantly based on the findings of the International Energy Outlook for 2016 (IEO2016), where the global total energy usage is projected to rise by 48% from 2012 to 2040 [2]. Total global energy use is also expected to increase exponentially [3]. Environmental pollution, climate change, and energy crisis are all the major issues faced by the world today [4]. The peak of conventional oil production is estimated to have been reached and the production of natural coal and natural gas is expected to pass its peak in the future [5]. The global energy dilemma has gained attention in recent years and has become a major research topic in several nations [6].

Concurrent, the use of fossil fuel energy is still a mainstay in almost all countries. In 2014, according to the World Bank (2018), In the global energy mix, fossil fuel energy remained the dominant source, constituting 81% [7]. In the transportation and industrial sectors, diesel constitutes the largest fuel consumption [8]. Electricity, farming, vehicles, and a number of other industries are fast expanding their usage of high-speed diesel [9]. There is an immediate need for replacement of the use of fossil fuels with biofuels because it is estimated that by 2050 there will only be 14% oil, 72% coal, and 18% gas [10]. According to the Paris Agreement in 2015, in order to prevent a global temperature increase of 2 °C, oil and gas production worldwide must fall by 3% every year until 2050 [11]. New energy sources are now being explored owing to the depletion of fossil fuels [12].

1.2. Biodiesel as a Substitute for Diesel

With the looming fossil energy crisis, almost all countries have developed special policies. For example, in Indonesia, the focus of the Indonesian National Energy Policy is to convert primary energy consumption to a renewable energy mix of at least 23% by 2025 and at least 31% by 2050 [13]. However, in reality, this is not easily accomplished because the conversion of fossil fuel energy to bioenergy requires fuels with special physicochemical properties and suitable for engine operating conditions [14]. Biodiesels are one of the renewable fuel sources which can be used to replace diesel, since their physicochemical qualities are comparable to those of diesel [15]. Biodiesels are also more environmentally friendly than diesel [16]. Biodiesels are nontoxic, biodegradable, and have a higher flash point compared with diesel. In addition, biodiesels have lower carbon emissions compared with diesel. Biodiesels are also very lubricious. These characteristics make biodiesels a possible diesel substitute [6].

Much research has been carried out to produce biodiesels from various raw materials and their properties are found to be equivalent to diesel ones [9]. With new technologies in biodiesel production, Future predictions predict that biodiesel will completely replace fossil fuels [17]. The two primary obstacles faced in the large-scale manufacturing of biodiesels are: selection of nonedible feedstocks with consisting mostly of oil and wide availability and synthesis techniques (enzymatic or chemical) [18]. Various kinds of biodiesel feedstocks are accessible in different quantities in different regions, and these feedstocks will continue to be exploited to meet the increasing demand [19]. The physicochemical characteristics and composition of fatty acids of the feedstock heavily influence the physicochemical characteristics of the biodiesel produced. Each raw material has its own advantages and disadvantages [20]. The main drawbacks of biodiesels are their low-temperature performance and oxidation stability [21]. In reality, most biodiesels have a low oxidation stability, making it challenging to fulfill national regulations. As a result, improving the oxidative stability of biodiesels is critical. Currently, antioxidants being added into biodiesel is the most common approach to enhance oxidation stability [22]. Different feedstocks can be mixed in order to attain the desired biodiesel properties, with the hope that the feedstocks complement one another [23].

1.3. Plastic Waste Pollution

As the globe races toward a more metropolitan future, trash production one of the significant byproducts of rising living standards is growing tremendously [24]. Due to their outstanding physicochemical properties, plastics have become a crucial global commodity in manufacturing and commercial goods. Due to the large societal demands, mass production of plastics has escalated globally. However, the ecosystem suffers from the usage of plastics, considering the lack of plastic waste treatment procedures [25]. Over the next 10 years, it is anticipated that the 381 million tons of plastic trash produced annually around the world will increase twofold. The use of plastics has also increased alarmingly during the COVID-19 outbreak due to the development of personal safety gears, medical equipment, food packaging, and package shipments [26]. The increase in global plastic waste has become a dire problem since plastics degrade into smaller fragments, which pose a tremendous threat to natural biota [27]. Due to the irresponsible handling of plastic trash and the widespread use of plastics, there are enormous environmental concerns that need to be addressed on a global scale [28]. Compared with the overall output, only 9% of garbage gets recycled, which is a relatively small percentage. About 80% of the waste generated is said to build up in landfills or simply dumped in the environment [29]. Plastic pollution has become a major concern in Indonesia's coastal and marine environment today [30]. The stability of marine ecosystems is impacted by marine plastic wastes, which hinders the development of a sustainable blue economy and threatens human health [31]. **Figure 1** shows the 10 countries that release the most plastic wastes into seas and oceans, and it can be seen that Indonesia ranks second after China [27]. It can take more than 400 years for plastics to deteriorate. About 75% of plastic wastes remain on lands and in seas, and only ~10% are physically processed to form other products, and ~12% may be lost. Plastic waste management is essential to prevent the harmful impact of plastics on the environment [32]. Recycling is the most straightforward strategy to reduce the extraction and exploitation of fossil fuels because above 90% of all pure plastics are produced using fossil fuels [33]. One way to recycle is to convert plastic wastes into oils. Fuels can be produced from plastic wastes by means of catalytic pyrolysis [34]. Plastic waste recycling is a hot research topic in plastic waste management [35].

1.4. Utilization of Plastic Wastes into Liquid Fuels

Pyrolysis and gasification are efficient processes for processing plastic wastes, converting them into products that may be used to produce energy. This may somewhat compensate the imminent depletion of fossil fuels [36]. The pyrolysis process offers a way to convert plastic wastes into fuels and is more environmentally friendly than inefficient burning and landfilling [24]. A technology that has promise for the heat decomposition of plastic is pyrolysis [37]. Catalytic pyrolysis is the method of transforming plastic waste into fuel. The plastic trash is heated to 350-450 °C in a reactor. Crude pyrolysis oil is obtained by distillation at dissimilar temperatures. The alkanes in plastic pyrolysis oil (PPO) are transformed into alkanes with physicochemical characteristics similar to those of diesel at a certain temperature [38]. Pacheco-López et al. [39] conducted techno economic analysis of PPO and confirmed that well-to-tank production of propylene was more economically competitive than diesel.

More recently, Lubongo et al. [40] made an economic assessment of plastic pyrolysis into fuel in the USA. They used internal rate of return (IRR) and net present value (NPV) to assess the economic feasibility with lang factor to estimate plant design cost. From their assessment, the plant would be profitable with a minimum of 60 tons per day (TPD) requiring 9.58 years to pay back, considering that the plastic wastes are free.

1.5. Rubber Seeds and Plastics as Fuel Feedstocks

The development of biodiesels is one of the options to address the reduction of fossil energy reserves [41]. Numerous nations continue to do

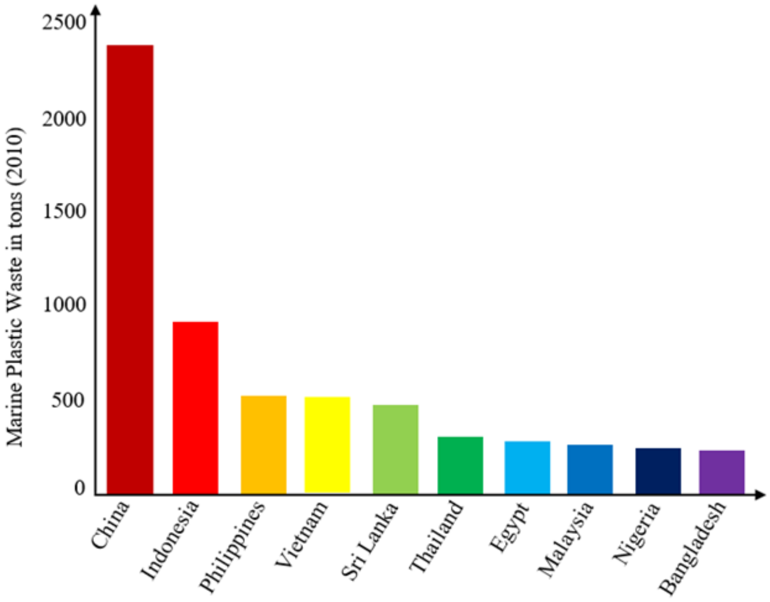

Figure 1. Top 10 countries in the world with the highest marine plastic wastes [27]

research on biodiesel with an emphasis on the study of feedstock and the improvement of process variables, improvement of biodiesel yields, use of different catalysts, evaluation of engine performance, engine longevity, and emission reduction [42]. Biodiesels produced from different raw materials have different purity, composition, and characteristics [43]. Based on the literature survey, even though biodiesels have been produced from various feedstocks, to date, there are no studies on the blending of rubber seed biodiesel (RSB) and PPO. It is expected that blending RSB with PPO will overcome the disadvantages of the individual constituents, this ultimately led to, will improve the overall on the biodiesel's overall quality. In addition, there are no studies on the production and testing of RSB–PPO blends.

1.6. *Analysis of The Shortcomings of Various Research*

Research on biodiesel including RSB has been carried out a lot, so far almost all researchers report that RSB has advantages including, it is made from free raw materials, has a high cetane number, besides that RSB also has low CO emissions because RSB is rich in oxygen content and has low emissions. HC because it is not a hydrocarbon. However, RSB also has disadvantages, including low heating value and oxidation stability, high viscosity and acid content. Low fuel calorific value will reduce engine performance, increase SFC, low oxidation stability causes a decrease in fuel quality if stored for a long time, because it oxidizes. High viscosity makes it difficult for fuel to flow through the injector nozzles and is difficult to disperse with air, this will also reduce engine performance. From various studies it is also reported that PPO can be used as diesel engine fuel, PPO has a higher calorific value than biodiesel, the viscosity of PPO is also lower than biodiesel. Almost all researchers report that diesel engine performance decreases as the percentage of PPO in diesel increases. PPO is also reported to have high CO and HC emissions because PPO comes from hydrocarbons. Several researchers have made efforts to improve the physico-chemical properties of biodiesel, including by mixing several types of feedstocks, adding catalysts, additives, anti-oxidants and so on, but so far the author has not found any researchers who have tried to mix RSB with PPO. In this paper the author tries to review the advantages and disadvantages of RSB and PPO, examines the feasibility of mixing RSB and PPO to improve the physicochemical properties of the mixed fuel, which ultimately can improve diesel engine performance and emissions.

2. Rubber Seed Oil as Biodiesel Feedstock

2.1. *Potency of Rubber Seed Oil*

With growing awareness of green energy, this is a good opportunity to promote rubber trees as an alternative resource for sustainable development and cleaner production of fuels. In the last few decades, the function of the rubber tree is only to extract the sap. The seeds of the rubber tree are one of the most underappreciated but abundant byproduct [44]. There is great potential to use rubber seed oil (RSO) for biodiesel production [45]. Hevea brasiliensis, generally known as rubber tree, is one of the nonedible, low-cost raw materials found in abundance in the Amazon rainforest. Rubber seeds contain a lot of oil (up to 89.4%) and about 80.5% of the oil is fats that aren't saturated [46]. Indonesia has the largest rubber cultivation land in the globe [47]. According to data from the Directorate General of Indonesian Plantations in 2021, the area of Indonesian rubber plantations will reach more than 3.6 million ha [48]. **Table 1** shows the potential of producing crude oil and biodiesel from rubber seeds in three regions.

Rubber tree seeds, which account for 77% of natural rubber produced worldwide, are currently discarded as biomass wastes in Southeast Asia. Based on the area of rubber tree

Table 1. Potential of producing crude oil and biodiesel from rubber seeds in different regions [48]

Region	Area (hectare)	Seed production (tons/year)	Crude oil (tons/year)	Biodiesel (tons/year)
Southeast Asia	7.5 million	11.6 million	5.8 million	5.2 million
Indonesia	3.6 million	5.5 million	2.75 million	2.4 million
Sub-Saharan Africa	717,000	107,000	17,000	16,000

cultivation in this region (which is 7.5 million ha), it is estimated that 11.6 million tons of rubber seeds are produced per year [49]. In Sub-Saharan Africa (area of rubber tree cultivation: 717,750 ha), it is estimated that 107,662 tons of rubber seeds are produced, which can be used to produce 17,947,339 tons of RSO, and this in turn, can produce 16,691,025 tons of biodiesel [50].

Since the seed kernel contains 40–50% of oil, RSO has promise as a feedstock for the produce of biodiesel [49]. Making use of RSO as a biodiesel feedstock can also reduce the price of biodiesel due to the reduced raw material cost, where the raw material cost accounts for more than 80% of the total production cost [49]. RSO has received much attention recently because it has not been specifically exploited for biodiesel production and rubber trees are abundantly available in most Asian countries [51]. Several investigations have found that the characteristics of rubber seed (biodiesel) are similar to those of diesel [52]. Degumming can be used to purify crude RSO, and the bleaching procedure reduces the oil's peroxide value. The dose of bleaching earth is discovered to be the factor is more important in purification, reaction time follows after and phosphoric acid dose. This process can reduce the peroxide present in the oil and improve oxidation stability [53]. RSO has been researched as a possible Bangladesh's biodiesel production source [54]. **Table 2** shows the physicochemical properties of RSO obtained by several researchers.

The main rubber seed-producing countries are Brazil, Indonesia, Malaysia, Thailand, and India. Brown oil makes up 40–50% of the weight of rubber seed kernels and 50–60% of the seeds themselves. The calorific value, viscosity and density, of RSO are 38.64 MJ/kg, 42.54 mm2/s (at 40 °C) and 917 kg/m3 (at 15 °C), respectively [23]. Fatty acids that are unsaturated such as linolenic acid (16.3%), linoleic acid (39.6%), and oleic acid (24.6%) are abundant in RSO [43].

The physicochemical properties of RSO indicate that the oil can be considered as a potential biodiesel feedstock [55]. Samuel et al. [52] found that the properties of rubber seed ethyl ester (RSOEE) produced in a hydrodynamic cavitation reactor showed good agreement with those of earlier studies and fulfilled biodiesel standards, except for the oxidation stability.

To compensate for these inadequacies, antioxidants may boost oxidation stability to an acceptable limit (> 6 h). For the following reaction conditions, the maximal conversion of methyl ester (biodiesel) from RSO was determined to be 96.8%: (1) alcohol-to-oil ratio: 6:1, (2) catalyst

Table 2. Production Method and Physicochemical properties of RSO.

Ref	Production Method (process)	Density (g/cm^3)	Viscosity (cSt)	Moisture content (wt%)	Acid value (mg KOH/ g)	Iodine value (g I_2/100 g)	Free fatty acid value (%)	Flash point (°C)	Cloud point (°C)	Pour point (°C)
[56]	Extracted with hexane	0.894	7.54	0.013	10.60	—	5.25	—	—	—
[57]	Extracted with hexane	—	—	—	18.19	142.20	9.648	—	—	—
[58]	Hydrodeoxygenation (HDO)	0.839	42.91	—	70	118.3		278	16	12
[59]	Soxhlet extractor	0.91	13.13	0.27	24	113		273	3	2
[60]	-	0.886-0.910	40.18–66.20	—	18.20–83.76	118.8–137.02	—	198–240.3	—	—
[61]	-	0.91	40.86	0.30	83.76	118.8	41.64	—	—	—
[62]	with solvent (n-hexane or isopropanol)	0.869	34	0.23	13.2	72	—	—	—	—
[54]	Mechanical press and cold percolation	0.88	33	0.93		132.6	45	-	—	—
[45]	Mechanical press	0.885	38.9	—	0.42	—	—	—	—	—

concentration: 1%, (3) reaction temperature: 55 °C, and (4) reaction time: 67.5 minutes. The biodiesel's attributes (viscosity, flash point, iodine value, ester concentration, and calorific value) were all within permissible limits [52].

2.2. Biodiesel Based on Rubber Seed Oil

Many research on the utilization of RSO for biodiesel generation have been conducted. Gimbun et al. [63] produced RSB, where a microwave was used during extraction, which reduced the extraction time to 4 min. In contrast, the extraction time using the conventional method took 6 h. There was a potential for a 96.9% success rate in converting free fatty acids (FFA) to biodiesel utilizing a limestone catalyst., and the fuel that was produced complied with the ASTM D6751 standard.

Yang et al. produced RSB using methanol and NaOH/NaPAA catalyst. The RSB physicochemical properties were tested and the results showed that the oxidation stability at 50 °C was 6.5 h, which fulfilled the specifications of the ASTM D6751, DIN V51606, and GB/T20828-2007 standards. They concluded that the biodiesel produced by transesterification of RSO with methanol using NaOH/NaPAA catalyst has potential as diesel substitute [64].

Khazaai et al. [65] converted RSO into methyl ester using a two-step esterification process. The biodiesel's calorific content was 14 percent less than diesel, but its viscosity was close to that of diesel [66].

Dhawane et al. [67] the use of Fe/C catalyst was found to maximize the RSB yield and produce cost-effective biodiesel, with physicochemical properties within the specified limits stipulated by ASTM D6751 standard.

In India, Chhabra et al. [68] optimized the process parameters of RSB production using Box-Behnken experimental design, comprising 29 experimental runs. The following optimal process settings resulted in the highest biodiesel output (98.71%): (1) The molar ratio of methanol to oil is 12 to 1, (2) the concentration of the catalyst is 0.6 weight percent, (3) the temperature of the reaction is 30 degrees Celsius, and (4) the reaction lasts for 75 minutes and 31 seconds. Dhawane et al. [69] performed methanolysis of RSO to produce RSB using lipase enzyme supported by carbon from local materials. They found that the Taguchi technique was effective to recognize the significant parameters that affected the immobilization process and to achieve the optimum conditions for a cost-effective catalyst synthesis, which in turn, minimized the cost of biodiesel synthesis.

Ahmad et al. [69] synthesized biodiesel from RSO having a high FFA concentration (45%). Analyses of the RSB's properties using ASTM D6751 and EN 14214 standards revealed that, in contrast to earlier studies, all of the probed parameters met the requirements established by the biodiesel standard.

Ni et al. [22] assessed the thermal stability of RSB using thermogravimetric analysis and compared the results with those for gasoline and diesel. The RSB was found to comply with the specifications in the EN 14214 standard. The RSB's major components are methyl esters of long-chain fatty acids combined with fats that aren't saturated, that are more susceptible to oxidation. Because peroxides are unstable, this is particularly crucial in storage and transportation procedures. Judging from the ratio of fatty acids and physicochemical properties of the RSO, the oil is suitable to substitute edible feedstock in the manufacturing of biodiesel. **Table 3** shows the comparison of the properties of RSB from several references and diesel as well as the properties specified in the ASTM D6751 standard [59]. RSO, which is made from rubber tree seeds, has shown to be a practical choice for the manufacturing of biodiesel [70].

It is a feasible option to produce RSB from RSO, but studies are needed to improve the method and variables. Jose et al. [59] implemented two-stage esterification utilizing acid and base catalysts. The following properties were investigated: viscosity, calorific value, and carbon residue. However, the induction period of biodiesel from pure RSO without antioxidants was found to be only 0.81 h, which is well below the European EN 14112 standard for biodiesel oxidation stability (8 h) [22]. Oxidation stability is a crucial factor since oxidation alters the physicochemical properties of the biodiesel. The oxidation stability of biodiesel is influenced by the high percentage of fatty acids. Much effort is needed to produce RSB with high oxidation stability [71].

In reality, most biodiesels have low oxidation stability, making it challenging to fulfill national

Table 3. Properties of RSB, compared to ASTM D6751 biodiesel specifications and Diesel.

Physicochemical properties	Unit	Biodiesel ASTM D6751 standard [72]	Diesel [59]	RSB				
				[59]	[73]	[74]	[75]	[76]
Specific gravity		0.86–0.90	0.846	0.883	0.847	0.852	0.876	0.864
Kinematic viscosity	mm^2/s	1.9–6.0	1.9–4.1	3.81	2.05	4.24	4.32	4.3
Calorific value	MJ/kg	37.27	45–46	39.53	40	38.74	40.67	38.7
Iodine number	g I_2/100g	120 (max.)	—	114	87.98	-	85.34	-
Acid number	mg KOH/g oil	0.5 (max.)	0.35	0.4	0.64	0.12	0.56	-
Cloud point	°C	−3 to 12	−15–5	2.5	2	9	−8	3.4
Pour point	°C	−15 to 10	−20	−3	-8	7.2	4.8	−2
Cetane number	—	47 (min.)	40 (min.)	49	35.11	52.5	57	-
Flash point	°C	130	52–96	131	217	136	158	148

regulations. Therefore, there is a critical need to get better the oxidation stability of biodiesels. To date, the addition of antioxidants is the most common method used to enhance oxidation stability of biodiesel [22].

2.3. *Engine Performance and Exhaust Emissions using RSB*

Increasing the PPO ratio has been shown to have no significant effect on the thermal efficiency. For low to medium mixing ratios, there was only a little rise in the nitrogen oxide (NOx) and carbon monoxide (CO) emissions. In the long term, the most promising combination to obtain optimum performance engine of and reduced emissions was 60–70% of PPO [77]. In order to enhance performance of diesel engines with one cylinder Geo et al. [78] injected ethanol into the intake port during the intake stroke. In their investigation, RSO, rubber seed oil methyl ester (RSOME), and diesel were all examined as fuels. For dual fuel operation, the injection timing and ethanol injection duration were optimized. According to the findings, adding more ethanol to RSO and RSOME improved thermal efficiency and decreased smoke emissions. The greatest thermal efficiency at full load for diesel, RSOME, and RSO, with corresponding ethanol percentages of 35.2, 33.5, and 31.6%, was 31, 29.9, and 29.3%. For RSO, RSOME, and diesel, respectively, the reduction in smoke emissions was 44.26, 43.63, and 26.47% at the greatest thermal efficiency. However, as the proportion of ethanol grew at all loads, the emissions of UHC, CO, and NOx increased as well. As the amount of ethanol grew, so did the peak pressure and top rate of pressure increase. The burning period was shortened by ethanol infusion, which in turn increased the rate of heat emission.

According to engine tests done by Vishal et al. [76], found that RB blended with diesel reduced fuel consumption by 50.23% for RB10 (10% rubber oil) and 47.74% for RB20 (20% rubber oil). Thermal efficiency decreased by 12.16 and 14.74%, UHC emissions rose by 22.3 and 41.72%, CO_2 emissions reduced by 46.3 and 49.54%, NOx emissions decreased by 21.5% and 21.7%, respectively. CO emissions rose by 25 and 37.5%, respectively, when pure RSO was used and the highest when it was combined with hydrogen, ethanol, and diethyl ether (DEE). A study by Edwin [79] compared various methods to boost performance levels achieved by a diesel engine when fuelled with RSO. They found that using hydrogen and DEE as dual fuels effectively increased performance.

Sudalaiyandi et al. [12] tested a mixture of flaxseed oil biodiesel, RSB, and diesel in a diesel engine. The experimental results showed that the performance of the diesel engine fueled with Mixture 1 (5% linseed biodiesel + 5% RSB + 90% diesel) and Mixture 2 (10% flaxseed biodiesel + 10% RSB + 80% diesel) was optimal compared with other mixtures. The heating value for Mixture 1 and Mixture 2 was found to be 42.33 and 41.95 MJ/kg, respectively. The cetane number (CN) for Mixture 1 and Mixture 2 was 51 and 52, respectively, where the values were similar to that for diesel. At higher loads, there was a minor difference in the specific fuel consumption (SFC) between the tested mixtures and diesel. The nitrogen dioxide (NO_2) and CO emissions for the ternary mixtures were lesser compared with those for diesel. However, the nitrogen monoxide (NO) and carbon dioxide (CO_2) emissions for the ternary mixtures were higher.

Sai Bharadwaj, et al. [80] investigated three biodiesel blends made from RSO (B10, B20, and B30), where calcined eggshell was used as the catalyst. The B10 blend, which contained 10% biodiesel and 90% diesel, had the lowest SFC (0.3895 kg/kWh). The B10 blend had a maximum thermal efficiency of 73.26%. There was a progressive increase in the NOx (275 ppm for the B30 blend), CO_2 (1.9% for the B30 blend), and UHC (36 ppm for the B10 blend) emissions. There was a decrease in the CO emissions (0.0275% for the B30 blend). The results demonstrated that A competitive substitute for traditional diesel is synthetic RSB [80].

In their 2018 study, Vamsi Krishna et al. [81], made use of a semi-adiabatic diesel engine (SADE) that included a thermal insulator, eight YSZ (yttria-stabilized zirconia) cylinder heads, and a ceramic-coated liner with a NiCrAl bond coat as an intermediary layer. At a continuous rotation of 10%, Exhaust gas recirculation (EGR) was used to power the engine. Dieselsa with a 15% diethyl ether additive plus 85% RSB made up the test fuel, which was a volumetric mix known as A15B85. At 18:1, 190 bar, and 1800 rpm, respectively, the compression ratio, fuel injection pressure, and engine speed were maintained constants. It was looked into how the SADE and regular diesel engine (ODE) performed when powered by the test fuels in terms of cylinder pressure and emissions. All of the tested characteristics, with the exception of NOx emissions, were shown to be improved by commencement of injection (SOI), according to the data. Based on the findings of ODE, the fuel mix performed better than diesel. It was discovered that diesel at 340 BTDC with greater loads was the ideal ODE setup.

Sudalaiyandi et al. [12] found that Blend 2 (10% linseed biodiesel + 10% RSB + 80% diesel) performed well compared with other test fuels. Blend 1 was composed of 5% linseed biodiesel, 5% RSB, and 90% diesel.

Murugapoopathi and Vasudevan tested RSB blends at an injection pressure of 160 bar, compression ratio of 20:1, engine load of 80%, and supercharging settings, finding that supercharging leads to improved qualities regarding both performance and emissions [82].

Varuvel et al. [83] looked at how a hybrid vegetable oil blend might impact the emissions, performance, and combustion characteristics of a twin-cylinder tractor engine using compression ignition. RSO, babassu oil (BSO), and their blends had lower BTEs than diesel, which had a BTE of 32.2%. The blend consisting of 75% RSO and 25% BSO produced the lowest BTE (27.7%). If we compare diesel at every load, the RSO, BSO, and their mixes had greater HC, CO, and smoke emissions. Due to inefficient combustion, NOx emissions were lower than those for diesel. It was discovered that the mixes' combustion started slowly with less premix combustion, which led to more diffusion combustion. The optimal mixture was determined to be 50% RSO/50% BSO.

Performance indicators for diesel engines using RSB from several references are shown in **Table 4**. It can be seen that, compared to diesel, the overall BTE using RSB has decreased, this could be because the calorific value of RSB is lower than the calorific value of diesel, or the viscosity of RSB is higher than diesel (**Table 3**). Some references show that the use of RSB in diesel engines reduces Opacity and CO emissions [75], reducing NOx in certain mixtures [12], [76], [79], [82], reduce HC [79], [82]. This shows one of the advantages of RSB, RSB like biodiesel in general, is rich in O2 content so it reduces CO emissions, it is not a hydrocarbon so it reduces HC emissions, so it is called environmentally friendly.

3. Pyrolysis of Plastics into Fuels

3.1. Types of Plastics

Plastics are increasingly being used in both home and industrial settings. Plastics have many advantages including ease of forming, low weight, and relatively cheap price [84]. There are various types of plastics used for different purposes in industrial products. One of the things that affect the quantity and characteristics of pyrolysis products is the types of plastics [85]. Hence, it is necessary to first identify the types of plastics. **Table 5** shows several types of plastics, their characteristics, and pyrolysis products.

The types of plastics that are commonly used to support industrial products include [86]:

3.1.1. Polystyrene (PS)

The characteristics of this type of plastic are: good heat resistance, light weight, high strength,

Table 4. Diesel engine performance and emissions using RSB

Ref	Fuel	Performance			Emissions			
		BTE	**BSFC**	**Opacity**	**NOx**	**CO**	**CO$_2$**	**HC**
[76]	B10, B20	B10: ↓12.16% B20: ↓14.74%	B10: ↓50.23% B20: ↓47.74%	-	B10: ↓21.5% B20: ↓21.7%	B10: ↑25% B20: ↑37.5%	B10: ↓46.3% B20: ↓49.54%	B10: ↑22.3% B20: ↑41.72%
[79]	B100, B70	B100 ↓ B70 ↓	B100 ↑ B70 ↑	B100 ↑ B70 ↑	B100 ↓ B70 ↓	B100 ↑ B70 ↑	-	B100 ↑ B70 ↑
[80]	B10, B20, B30	B10: ↓ 0.055% B10: ↓ 0.083% B10: ↓ 0.33%	B10: ↑0.025% B20: ↑0.026% B30: ↑0.025%	-	B10: ↑ B20: ↑ B30: ↑		B10: ↑ B20: ↑ B30: ↑	B10: ↓62% B20: ↓ B30: ↓
[12]	B5, B10, B15, B20, B25	B5: ↓ B10: ↓ B15: ↓ B20: ↓ B25: ↓	B5: ↑ B10: ↑ B15: ↑ B20: ↑ B25: ↑	-	B5: ↑ B10: ↓ B15: ↑ B20: ↓ B25: ↓	B5: ↓ B10: ↓ B15: ↓ B20: ↓ B25: ↓	B5: ↑ B10: ↑ B15: ↑ B20: ↑ B25: ↑	-
[82]	VCR engine B20, B40, B60, B80	B20: ↑ B40: ↑ B60: ↓ B80: ↓	B20: ↓ B40: ↓ B60: ↑ B80: ↑	-	B20: ↓ B40: ↓ B60: ↑ B80: ↑	B20: ↑ B40: ↑ B60: ↑ B80: ↑	B20: ↑ B40: ↑ B60: ↑ B80: ↑	B20: ↓ B40: ↓ B60: ↑ B80: ↑
[75]	B10, B20, B30, B50, B100	B10: ↓ B20: ↓ B30: ↓ B50: ↓ B100: ↓	B10: ↑ B20: ↑ B30: ↑ B50: ↑ B100: ↑	B10: ↓ B20: ↓ B30: ↓ B50: ↓ B100: ↓	B10: ↑ B20: ↑ B30: ↑ B50: ↑ B100: ↑	B10: ↓ B20: ↓ B30: ↓ B50: ↓ B100: ↓	B10: ↑ B20: ↑ B30: ↑ B50: ↑ B100: ↑	B10: ↑ B20: ↑ B30: ↑ B50: ↑ B100: ↑

and high durability. PS is usually used in toys, medical devices, food packaging, electronics, and construction goods.

3.1.2. *Low-density Polyethylene (LDPE)*

The characteristics of LDPE include low tensile strength, low hardness, and good water resistance. LDPE is a favored polymer for a variety of purposes and is commonly used in trash cans, packaging foil wrappers, and plastic bags.

3.1.3. *High-density Polyethylene (HDPE)*

The characteristics of HDPE include long chain polymer, high strength, and high crystallinity. HDPE is typically used for milk bottles, oil containers, detergent bottles, and toys.

3.1.4. *Polypropylene (PP)*

Good hotness and chemical counter, low density, high stiffness, and high hardness are just a few characteristics of PP. PP is typically used to make buckets, carpets, mebel, storage boxes, office folders, flower pots, and car bumpers.

3.1.5. *Polyvinyl Chloride (PVC)*

PVC has fire-resistant characteristics and it is a versatile plastic. Common applications include plumbing, car interiors, credit cards and other cards, packaging, medical gadgets, food wrapping, boots, and window frames.

3.1.6. *Polyethylene-terephthalate (PET)*

The characteristics of PET are light weight, pressure resistance, and greater capacity. PET is a versatile polymer and it is typically used in window frames, magnetic tapes, X-ray films, electrical insulation, food packaging, and photographic films. Solid wastes such as plastic wastes are a major part of fossil-based wastes that can be converted into commercially profitable renewable fuels or add-on chemicals [87]. Due to their high calorific value, hydrocarbons, which are present in plastics, are a great source of energy. Plastic trash disposal offers substantial prospects for energy conservation and resource recovery [88].

3.2. *Plastic Pyrolysis Oil as Fuel*

Numerous studies have been done to turn plastic garbage into fuel since doing so would cut down on plastic waste and the fuel may be made from easily accessible resources.

Most of the materials used in everyday life are plastics because of their light weight, durability, and usability. Various combinations of polymers have been used to strengthen plastics, which will

Table 5. Types of plastics and their characteristics [86]

Type of plastic	Characteristics	Used on	As pyrolysis feedstock	Composition of pyrolysis oil
Polystyrene (PS)	• Heat resilience Lightness • High strength • Reasonable durability	• Toys • Medical devices • Electronics • Food packaging • Construction goods	• Requires low temperature compared with PP and PE • Produces less viscous oil compared with PE and PP	• Styrene • Toluene • Ethylbenzene • Benzene • Xylene • Cumene • Benzene • Naphthalene • Anthracene • Di and triphenylbenzene
Polyethylene (PE)	High-density polyethylene (HDPE) • Long polymer chain • Highly crystalline • High-strength polymer Low-density polyethylene (LDPE) • Less tensile strength • Less hardness • Excellent water resistance • Desirable polymer for various applications	• Toys • Oil containers • Detergent bottles • Milk bottles • Trash bags • Wrapping foil for packaging • Plastic bags	• Due of its lengthy chain structure, it must be heated over 500 °C. • Converts into wax instead of liquid fuel in thermal pyrolysis • Wax develops on the catalyst's exterior surface, while additional splitting of the wax into gases and liquids occurs on the catalyst's interior surface.	• 1- and 3-ethylcyclopentene • 1-hexene • Cyclohexene • 1-octene • 1-nonene • 1-decene • Benzene • Toluene • Xylene
Polypropylene (PP)	• Good heat and chemical resistance • Low density • High rigidity • High hardness	• Pail • Carpets • Furniture • Storage box • Office folder • Flower pot • Car bumpers	• Requires high temperature • Difficult to degrade under thermal pyrolysis • Catalytic pyrolysis yields a liquid with a high aromatic content.	• Acenaphthene • Benzene • Toluene • Xylene • Ethylbenzene • Indene • Biphenyl • 1-heptene • 1-octene • 2-methy l-1-pentene
Polyvinyl chloride (PVC)	• Resistant to fire • Versatile plastic	• Automotive interior • Cards • Medical appliance • Packaging • Electrical covering • Food foil • Boots • Window frames	• Produce risky chlorine gas • Physical or chemical dechlorination at low temperatures (250-320 °C) adsorption • The existence of chlorine and coke deposition have an impact on the catalytic activity of the catalyst.	• Azulene • Biphenyl • Phenanthrene • 9H-fluorene • Naphthalene and its monomers
Polyethylene terephthalate (PET)	• Lightweight • Pressure resistance • Larger capacity • Versatile polymer	• Food packaging • Electrical insulation • Magnetic tapes • X-ray films • Printing sheets • Photographic films	Contains heteroatoms	• Propanone • Benzoic acid • Biphenyl • Fluorene • Diphenylmethane • Anthracene • Benzophenone • 1-butanone

lead to problems in the recycling process. Plastic wastes are usually recycled and made into fuel using the plastic pyrolysis method. The high amount of plastic consumption every day results in great amounts of wastes. Plastic pyrolysis is a technique for recycling plastic trash to create fuel [89].

Janarthanan and Sivanandi [90] used the thermal cracking method was used to produce gasoline from plastic trash among 370 and 380 °C, resulting in 78 wt% of liquid fuel with 38.53 MJ/kg of caloric content, the hydrocarbon molecules were found to be within the C_7–C_{40} range. As indicated in **Table 7**, the outcomes also revealed that the oil created by the pyrolysis of plastic waste exhibited physicochemical characteristics comparable to those of diesel.

Abnisa and Alaba [91] who evaluated the pyrolysis approaches for recovering liquid fuels from solid waste derived from fossil fuels, the optimal temperature for creating high liquid yields is the same for all wastes, ranging between 400 and 500 °C under high heating rates. Except for PET, most plastics may provide high liquid yields of more than 50%, however the yield of oil produced from tyres is found to be lower owing to the large proportion of recovered charcoal. **Figure 2** shows the pyrolysis of plastics into fuels.

With the low recycling rate and the exponential increase of plastic production, there is an increase in plastic wastes. Thus, new methods are required to treat plastic wastes. Only ~10% of plastic trash is now recycled in Europe, primarily by mechanical recycling. Unlike mechanical recycling, chemical recycling such as pyrolysis can considerably boost recycling capacity because various plastic wastes are used in the latter method. Pyrolysis can be used to clean up garbage made of a variety of modern materials including composites, which will reduce waste sorting time and costs. Pyrolysis offers an environmentally friendly alternative to inefficient burning and stockpiling. The main obstacles currently faced in the pyrolysis process are the lack of raw materials and their variable quality, ineffective and expensive sorting process, absence of a market due to the absence of standardized products, and the lack of clear regulations regarding plastic waste management. To ensure a steady supply of raw materials (both quantity and quality), there is a need for a strong collaboration between raw material suppliers and converters. To standardize the liquid oil as a product, the pyrolysis liquid must be classified as a product rather than a waste and registered under Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). In addition, it must be kept sustainable [92]. Plastic wastes are not the main problem; rather, the problem is how the plastic wastes are handled. Hence, it is the public's responsibility to be smart in dealing with plastics, whether plastics are treated as pollution or as an economical resource [93].

Kalargaris at al. [77] produced oils from different kinds of plastics using a quick pyrolysis process. The results showed that the oils had similar characteristics as diesel. They used a direct injection and four cylinders diesel engine to evaluate several PPO-diesel blends (PPO concentration: 0-100%) at varied engine loads (25-100%). The studied fuel mixtures' engine performance, exhaust emissions, and combustion characteristics were contrasted with those of diesel. According to the findings, PPO-diesel blends may be utilised to drive engines at high loads and are comparable to diesel in operation.

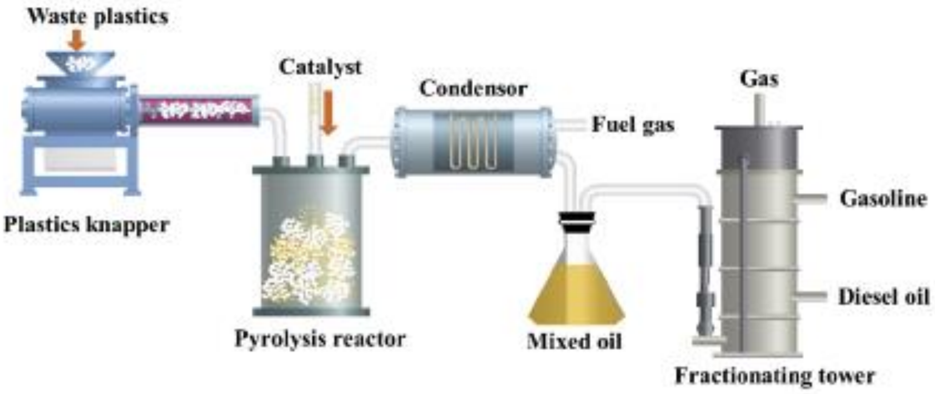

Figure 2. Schematic of pyrolysis of plastics waste into diesel and gasoline fuels [85]

However, the PPO-diesel blends had longer ignition delay time at low engine loads. Wiriyaumpaiwong and Jamradloedluk [94] conducted rapid pyrolysis of plastic wastes at a temperature of 500–800 °C, producing a dark brown liquid.

There are three types of reactors used for plastic pyrolysis: (1) batch reactor, (2) fixed bed reactor, and (3) fluidized bed reactor. Batch reactor is commonly used at the initial stage to study the reaction conditions. Plastic waste is poured into a closed system and heated at 400-600 °C and 1-2 bar pressure, with constant stirring. The product can be taken manually after the reaction and analyzed with liquid chromatography (LC) or the product can be separated using a condenser. However, this type of reactor is time-consuming and labor-intensive because of the large number of batches, and therefore, a semi-batch reactor is preferred with the possibility to add plastic wastes during the reaction [95]. A very high temperature is required due to the absence of a catalyst in the reactor and thus, some researchers added a catalyst to reduce the reaction temperature. However, the formation of coke and the wide product distribution are the challenges of catalytic pyrolysis.

Fixed bed reactor has a different configuration compared with a batch reactor. The reactant has its own way-in and product own way-out. The benefit of this reactor is especially obvious for gas-catalytic reactions in which the catalyst does not need to be separated from the reaction mixture. In plastic pyrolysis, a fixed bed reactor has no stirring function and a slower heating rate, and therefore, it requires a longer reaction time. The gradient temperature in this reactor makes it appropriate for large reactant volumes with char and syngas as the major and minor products, respectively. Some researchers used this reactor for secondary pyrolysis by feeding the first pyrolysis product as the reactant [96], [97].

Fluidized bed reactor is commonly used in the petrochemical industry with continuous reactant flow to regenerate the catalyst active site. The plastic wastes are fed to a solid bed with gas carrier to the pyrolizer. Char, which is formed during the pyrolysis reaction, is separated with cyclones to prevent further secondary cracking. In this reactor, temperature and residence time play a crucial role in determining product selectivity for the oil yield and syngas product [98]. To further improve the process, Zhou et al. [99] proposed continuous microwave-assisted pyrolysis (CMAP) that has higher energy efficiency than traditional fluidized bed reactor for plastic waste recycling. **Figure 3** shows several types of plastic pyrolysis reactors.

Using a diesel engine with four cylinders, Kalargaris et al. [100] tested the impact of thermochemical effects of polypropylene pyrolysis on engine performance, combustion parameters, and exhaust emissions. Results showed that diesel had a lower BTE, longer ignition delay time, longer combustion duration, greater levels of NOx, UHC, and CO, but lower levels of CO_2.

In the previous year, Kalargaris et al., [101] converted polyethylene (LDPE700), the most widely used plastic, and ethylene-vinyl acetate (EVA900) into pyrolysis oils at a pyrolysis temperature of 700 and 900 °C. The performance of the engine, combustion parameters, and emissions of the pyrolysis oils were then evaluated using a diesel engine with four cylinders, and the findings were compared to diesel. The results revealed that the engine could run with both types of pyrolysis oils even in the absence of diesel. The combustion and thermal efficiency of the LDPE700 fuel were nearly identical to those for diesel, and the fuel emitted less NOx, CO, and CO_2. However, the LDPE700 fuel emitted more UHC. The EVA900 fuel resulted in a longer ignition delay, reduced efficiency (1.5–2%), higher NOx and UHC emissions, and lower CO and CO_2 emissions. The overall engine performance for the EVA900 fuel was not considerably enhanced by the addition of diesel.

Venkatesan et al. [102] pyrolyzed 8 kg of plastics and obtained 675 cm^3 of pyrolytic oil. The properties of the pyrolytic oil fulfilled the requirements of the ASTM standard despite having a greater carbon residue and higher kinematic viscosity. The pyrolytic oil was then mixed with diesel specifically, for these volume fractions: (1) PPO15 (85% diesel + 15% pyrolytic oil) and (2) PPO30 (70% diesel and 30% pyrolytic oil). Tests were performed on a single-cylinder engine under no-load and full-load circumstances to establish the practicality of the pyrolytic oil as a diesel alternative. Under full-load conditions, the PPO30 fuel had higher pressure in the cylinder

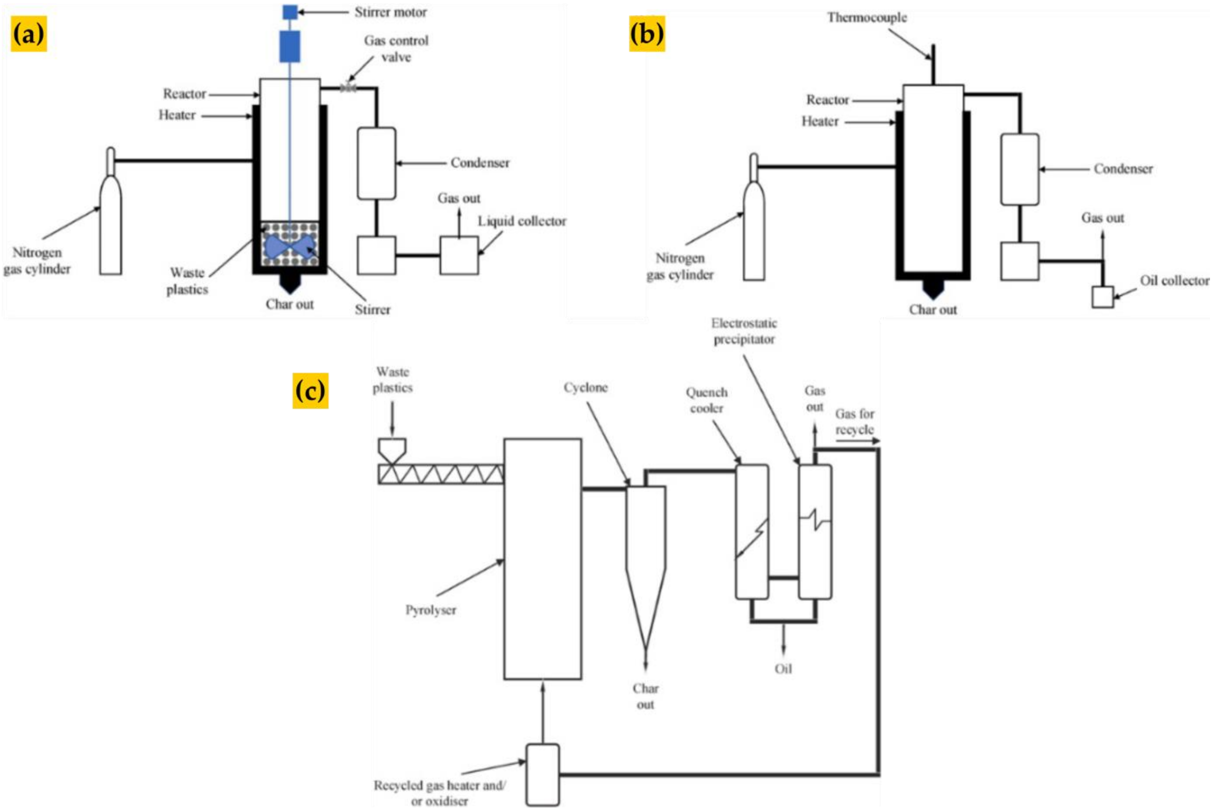

Figure 3. Types of reactors used for plastic pyrolysis: (a) batch reactor, (b) fixed bed reactor, and (c) fluidized bed reactor [103]

and its rate of rise, heat release rate, and maximum pressure than diesel. With a large increase in fuel consumption, the efficiency of thermal was marginally higher for the PPO–diesel blends compared with that for diesel. The physicochemical properties of the PPO had a considerable effect on the combustion characteristics and engine performance.

Kareddula and Puli [104] converted plastic trash into PPO and conducted tests using a Maruti 800 multi-cylinder petrol engine to evaluate engine performance and pollution levels. PPO was mixed with gasoline at a rate of 15% while ethanol additive was added at a rate of 5%. Both the overall performance and the emission parameters were compared to those of regular gasoline and pure ethanol. Based on the experimental results, pure gasoline has a higher thermal efficiency than the fuel blend containing 15% PPO; however, the NOx were considerably higher. The overall performance of the engine was enhanced. upon the addition of ethanol, which reduced the NOx emissions compared with those for pure gasoline and fuel blend containing 15% PPO. The CO and NOx emissions were greatly reduced.

Kalargaris et al. [105] studied the results in the long run of using PPO as the a diesel engine's main fuel. The results show that PPO could be a fuel, but the adding of diesel is required to gain a satisfactory level of engine performance. In this study, the engine was tested for durability with the following blend (75% PPO + 25% diesel). The piston fractured and the engine failed using the PPO–diesel blend after 36 h.

Waste plastic oil (WPO) was used in an experimental investigation by Bridjesh et al. [106] as a diesel substitute. The findings demonstrated that altering the hardware of the engine or enhancing the physicochemical characteristics of the WPO could not improve engine performance. The findings of adding composite additives and changing the combustion chamber imply that the SFC, thermal efficiency, and exhaust emissions of the diesel engine may be enhanced by carefully matching the combustion chamber geometry with the physicochemical characteristics of the WPO.

Mariappan et al. [107] focused on efficiently recovering the available energy from plastic wastes and identifying the best diesel substitute. LDPE wastes were catalytically pyrolyzed to produce gasoline after meticulous calculations were made to optimize the reaction time, reaction temperature, and catalyst concentration. The PPO was then used to power a diesel engine with one cylinder and common rail direct injection.

Mariappan et al. [107] was used the Taguchi method to optimize the operating parameters of the test engine, including compression ratio, injection time, and injection pressure. Average effective pressure values were calculated using the performance of engine, characteristics of combustion and emission readings at an injection pressure of 800 bar and advanced injection timing (27° before TDC). The results showed that an increase in the PPO concentration affected the combustion characteristics, resulting in a decrease in the performance parameters, especially when the PPO concentration was more than 40%. To improve engine performance, the P40 blend was mixed with methanol and DEE in varying amounts. With this adjustment, the thermal efficiency increased significantly by 31.25%, while the UHC, NOx, CO, and smoke emissions reduced to 2.3, 20.28, 34.61 g/h, and 44% respectively, at full load. The findings demonstrated that PPO can replace diesel up to a maximum of 40%, and that the addition of methanol and DEE can completely offset the drawbacks of using PPO [107].

Oni et al. [108] investigated the qualities of gasoline made from used tires and plastics and compared the results with those for diesel. To make PPO, several materials (PET, PP, HDPE, PS, LDPE, and PVC) were combined in different ratios with used Dunlop tire pyrolysis oil. The engine performance was assessed in terms of the BTE, combustion characteristics, and exhaust emissions. The mixes of pyrolyzed polystyrene and tyres produced minimal emissions and the greatest BTE, 36.9%.

Ağbulut et al. [109] tested four fuels, which were a mixture of diesel + tire pyrolysis oil + waste biodiesel, with the respective ratios of: (1) 100% + 0% + 0%, (2) 80% + 20% + 0%, (3) 80% + 10% + 10%, while the 4th fuel is 10% waste tire pyrolysis oil + 80% diesel + 10% waste fusel oil. The thermal efficiency was reduced by up to 9.13% for the blend composed of waste tire biofuel and diesel, but this was offset by increasing the amount of biodiesel. The brake specific fuel consumption (BSFC) increased by 21.78% when the oil from pyrolysis of scrap tyres was combined with diesel, while the BSFC increased by 8.89 and 12.57% when waste biodiesel and waste fuel oil were used instead. High oxygen content of waste biofuels reduced CO emissions by 7.69% and 19.23% for waste biodiesel and waste fuel oil. Waste tire pyrolysis oil also resulted in higher NOx emissions, but this increase reduced to 4.64%. The results suggest that a ternary combination should be used for diesel engines.

Mangesh et al. [110] investigated the combustion, efficiency, and emissions of a diesel engine running on hydrogenated polypropylene pyrolysis oil. PP was transformed into HPPO with the use of a catalyst called ZSM-5. The results demonstrated that the HPPO met the criteria of the EN 590 standard. The effectivity of hydrogenation to complete the change of alkenes into alkanes was investigated using GC-MS on polypropylene pyrolysis oil and HPPO. The HPPO was then mixed with diesel at quantities of 10, 20, 30, and 40% by weight. The performance of the engine, combustion properties, and exhaust emissions of fuel blends containing 10 and 20% wt% HPPO were equivalent to diesel. The usage of HPPO as a diesel alternative represents a more ecologically responsible method of managing plastic waste.

Singh et al. [111] have developed and used laboratory scale plastic pyrolysis and processing of plastics with a 3-1.5 cm^2 size for the particles. The samples were evaluated with and without a catalyst in a pyrolysis factory at an outside temperature of 500 ± 30 °C. A 1:10 catalyst addition ratio was used. Based on the results, the liquid fraction yield from the pyrolysis of plastic bottles without catalyst was highest with an average of 24% whereas a lower liquid fraction yield (16–22%) was obtained from pyrolysis with catalyst. A liquid fraction yield of 22% was obtained by pyrolysis of plastic bags using zeolite catalyst, with a 47% conversion rate. In contrast to the uncatalyzed samples, the use of a catalyst reduced the liquid fraction yield while improving oil quality. Analysis of the engine characteristics revealed that the cylinder pressure of the D80PO20 fuel blend (80% diesel + 20% PPO) was identical to that of diesel. A higher thermal efficiency and lesser specific energy usage were also noted when the engine was tested with the fuel blends. Compared with pure diesel, the fuel blends had lower NOx emissions and UHC emissions by 19 and 26%, respectively.

Mallick et al. [26] formulated three fuels for engine tests: (1) 80% diesel + 20% waste pyrolysis oil (WPO), (2) 60% diesel + 20% WPO + 20% ethanol, and (3) 80% diesel + 20% WPO + 100 ppm nanographene. Compared with diesel, the WPO fuel blends contained more ethanol, resulting in higher EGT, lower SFC, and lower energetic efficiency. Compared with other fuel blends at higher engine loads, the WPO fuel blend containing nanographene resulted in higher energy and energy efficiency values. The energy of WPO fuel blend containing nanographene increased by 18.57 compared with that for diesel at the highest load. However, compared with those for diesel at the highest load, the annihilation and exhaust exergy of this fuel blend reduced by 34.97 and 14.03%, respectively. In addition, the energetic efficiency was 18.9% higher than for diesel at maximum load.

Devaraj et al. [112] subjected mixed plastic trash to noncatalytic pyrolysis at 450 °C to produce high-quality PPO with a content comparable to petroleum fuels. FTIR spectroscopy was conducted on the PPO and the results were compared with that for diesel. As the engine load increased, the fuel blend with a higher PPO content had higher BTE and lower SFC. The PPO resulted in a strong heat release and delayed ignition, increasing the cylinder pressure. In addition, Singh et al. [43] found that the high concentration of oxygenated molecules of the PPO contributed to a reduction in combustion-related pollutants. Diesel engines may utilize PPO with a mix that has up to 50% diesel; however, larger loads would result in a minor rise in carbon monoxide output. An engine with a single cylinder and direct injection running on waste plastic pyrolysis oil (WPPO) mixed with 5% and 10% DEE was studied for performance, emissions from the exhaust, and combustion characteristics. The BTE increased, the smoke levels decreased, the WPPO blends reduced CO and NOx emissions, and the combustion process was improved, according to the results. Additionally, compared to pure diesel, a blend of WPPO, DEE, and diesel had a better cetane rating.

Das et al. [113] studied the efficiency and emissions of a diesel engine with a single cylinder and four strokes fueled with PPO. The PPO was produced by burning plastic wastes where zeolite-A was used as the catalyst. An engine trial run was performed after the PPO was blended with petroleum diesel at compositions of 10, 20, and 30 vol%. According to the findings, pure diesel performed worse than a fuel mix containing 20% PPO with relation to the BTE and the BSFC. The PPO-diesel fuel blends had reduced low load emissions of NOx and UHC and greater levels at higher loads. With an increase in engine load, the fuel's exergetic efficiency fell while the fuel's exergetic efficiency increased. According to the findings, 20 vol% of PPO was appropriate as a diesel alternative.

Mangesh et al. [84] examined the qualities of polypropylene pyrolysis oil (PPPO) made from HDPE, LDPE, PP, and styrene to determine if it was suitable for use as a diesel substitute. PPPO had better physicochemical properties than the other three plastic waste pyrolysis oils, and was chosen for engine performance emission tests. As the amount of PPPO in the blend grew, the cylinder pressure and heat release rate of the PPPO-diesel fuel blends increased, but the NOx, UHC, and CO emissions increased.

Hürdoan et al. [114] Diesel was mixed with PPPO at a 5, 10, and 15% ratio. The results revealed that as the amount of PPPO in the blend grew, the cylinder pressure and heat release rate of the PPPO-diesel fuel blends also increased. However, the NOx, UHC, and CO emissions increased.

Rajesh and Rajesh [115] discovered that a tri-charged engine might outperform conventional diesel engines by operating at maximum load capacity while using waste plastic pyrolysis oil (WPPO). However, a higher WPPO content led to reduced fuel economy and more CO and UHC emissions. This shows that technology with three charges is a workable technology and that WPPO is feasible as an alternate energy source for various engine implementations.

In order to produce liquid gasoline, Boonnoun et al. [55] conducted pyrolysis of a plastic wastes (polyethylene films). The physicochemical properties of several oil samples were characterized for various operating conditions. The objective was to examine the fuel quality and determine whether the fuel quality was dependent on the operating conditions. The findings indicated that the operating circumstances had no influence on the quality of the fuel. The physicochemical properties of the oil samples were shown to be quite close to those of commercial fuels (gasoline and diesel) [55]. Kumar et al. [116] pyrolyzed HDPE at 330–490 °C for 1–2 h after the HDPE was extracted with solid waste, liquid oil, and flammable hydrocarbon gas. The pyrolysis fuel was found to satisfy all requirements. The characteristics of the combustible include a kinematic viscosity (40 °C) of 1.98 cSt, length of 0.75 gm/cc, sulfur content of 0.25 wt%, carbon residue of 0.5%, and a high calorific value, which were a considerable improvement over diesel.

In the experiments that Kareddula and Puli [104] the performance and emission characteristics of a Maruti 800 gasoline engine with many cylinders fed by PPO were assessed via studies. Both with and without the addition of ethanol, PPO was mixed with gasoline at a rate of 5 and 15%. Although the BTE of the 15PPO fuel mix was lower than that of pure gasoline, NOx emissions increased significantly. However, ethanol enhanced engine performance while reducing NOx and CO emissions.

In order to manufacture PPO, Song et al. [117], thermally aged a variety of typical Useless plastic materials, like polyethylene, polypropylene, and polyvinyl chloride. According to the findings, the PPO had a change in composition as a consequence of thermal ageing, and the kind of plastic used significantly affected the outcome. Random cutting of the heavy oil portion of PE and PP led to structural faults and a mild browning of the PVC samples. After 128 hours of thermal agethe maximal rate of weight reduction fell by 35.8%, while there were variations in the ratios of the C5-C9 and aromatic components.

With the inclusion of 2-methoxy ethyl acetate (MEA) and DEE, Bridjesh et al. [118] performed a research to replace at least 50% of diesel with waste pyrolysis oil (WPO). The 50D40W10MEA sample enhanced BTE, decreased BSFC, decreased UHC, CO, and smoke emissions, but had no impact on NOx emissions, according to the results.

Through a fast pyrolysis procedure, Kalargaris et al. [77] created PPO from a variety of polymers. In order to evaluate various PPO-diesel blends (PPO content: 0-100%) at varying engine loads (25–100%), a four-cylinder direct injection diesel engine was employed. The findings demonstrated that the PPO could operate the engine at high engine loads, but at low engine loads, it caused longer ignition delay times and stability problems. In spite of the fact that the BTE was somewhat less than diesel's at maximum load, the NOx emissions were noticeably greater for PPO-diesel mixes. The results show that PPO is a viable substitute fuel for diesel engines.

Damodharan et al. [119] explored implications of including a custainable oxygen Source (n-butanol) to waste plastic oil (WPO) produced by the pyrolysis of a sample in a batch reactor of a laboratory size. Three blends were prepared where D denotes diesel, WPO denotes waste plastic oil, and B denotes n-butanol. The engine performance and emissions of a direct injection diesel engine fueled with these blends were compared with those fueled with WPO and pure diesel. The D50–WPO40–B10 blend resulted in lower NOx emissions and improved engine performance. The amount of fuel used by ternary fuel mixtures was superior to that for WPO.

Ayodhya et al. [120] found that PPO blends had a modest reduction in engine performance due to their increased viscosity and decreased heating value, but there was a reduction in UHC, CO, and the release of soot. The results showed that PPO-diesel blends perhaps utilised successfully as a diesel alternative with no engine changes required.

Pal et al. [121] used a fixed bed reactor with a temperature range of 400-550 °C to pyrolyze mixed plastic trash. The physicochemical properties of the plastic fuel (PF) and plastic fuel–diesel blends (PF10, PF20, and PF30) were found to be below ASTM standards. At two distinct angles, a diesel engine with a single cylinder was put through its paces using various plastic fuel mixtures to observe how injection time affected engine performance and exhaust emissions. The findings revealed that BSFC and NOx emissions depleted as the engine load increased, while BTE, and CO, UHC, and there was a rise in the amount of smoke emissions.

Kalargaris et al. [122] found that the pyrolysis temperature plays an important role in engine performance. A four-cylinder direct injection diesel engine was used to evaluate the PPO's combustion, performance, and emission properties. Higher loads were found to improve the engine performance, while lower temperatures resulted in lower NOx, UHC, CO, and CO_2 emissions. Kalargaris et al. [105] investigated the consequences of prolonged use of PPO on diesel engines. After 36 h of running using a PPO–diesel blend, the engine failed and the pistons were fractured. After examining the EGT at the time of failure, they found that fuel injector failure was the primary cause of the piston fracture. Analysis of the lubricating fluid revealed that the severe wear was brought on by excessive contamination. After collecting and analyzing the deposits from the piston heads, the results indicated that the combustion was incomplete.

Jha and Kannan [123] separated plastic garbage from municipal wastes, classified the wastes into categories, and then chopped them into uniform pieces. The pyrolysis process was carried out by mixing the plastics with a catalyst and heating the mixture to 320-600 °C with high pressure. Product physicochemical properties as compared to petroleum, and the processing cost was low.

Researchers Miandad et al. [86] investigated how several kinds of discarded plastics, including Polystyrene, Polyethylene, polypropylene, and Polyethylene Terephthalate, influence the amount and oil in its liquid form in terms of its qualities produced by pyrolysis. They found that PS-derived liquid oil had the greatest oil production rate (80.8%), least amount of gas produced (13.2%). The physicochemical characteristics of the liquid oils were comparable to diesel, with kinematic viscosity between 1.92-2.09 cSt, density between 0.91-0.92 g/cm^3, pour point between 11-60 °C, freezing point between 15-65 °C, flash point between 28-30.2 °C. Post-treatment procedures are necessary to make the oils usable in the transportation industry, and they have the potential to serve as chemical precursors for the polymerization of styrene monomers in the industrial sector.

Tulashie et al. [93] performed pyrolysis of plastic garbage in a fixed bed reactor at 350 °C 2 h with nitrogen gas flow of 200 mL/min and cracking period of 40 min. The final crude product was examined using FTIR spectroscopy and GC-MS. There were 21 functional groups identified in the fuel oil, with aliphatic compounds being the most prevalent. The kinematic viscosity of the fuel oil decreased with an increase in temperature, indicating its potential to be used as an alternative fuel.

Zeolite is an aluminosilicate compound used in plastic catalytic pyrolysis. Miandad et al. [124] compared the activity of natural and synthetic zeolite for several plastic types such as PP, PS, PE, and plastic mixtures. The results showed that PS had the highest oil yield (50-54 wt%), while PP and PE had a low oil yield of 14 and 16 wt%, respectively. The oil yield was increased for PS–PP and PS–PE mixtures due to easier hydrogen transfer, and the oils obtained had similar properties to conventional diesel.

Sivagami et al. [125] recently used commercial and synthetic ZSM-5 as a catalyst for pyrolysis of several plastic types. They compared thermal (without catalyst) and catalytic pyrolysis of LDPE. The maximum oil yield was 37 and 70% for pyrolysis that is both thermal and catalytic, respectively, at 450 °C in a 2-kg batch-scale reactor. ZSM- 5 has strong acid sites and small porosity, and hence, it is easier for the large molecules to crack and isomerize into gas and liquid product. Meanwhile, the oil yield was lower for other types of plastics such as PET and laminated metalized plastic. The oil yield can be increased by adding graphite that has a large amount of surface area and certain functional groups to assist the cracking process. The results of the GC-MS, the hydrocarbon distribution of the oil yield was C_{11}–C_{20}, which was similar to diesel.

The yield of PPO obtained from pyrolysis of various types of plastic with different pyrolysis techniques is shown in **Table 6**. It can be seen that the yield obtained varies greatly from 0.45% - 95%, depending on the type of plastic, pyrolysis technique, pyrolysis temperature and use of catalyst. The lowest yield (0.45%) was obtained from PVC using the slow pyrolysis technique at a temperature of 220-520 °C [126], while the highest yield (95%) was obtained from LDPE using the fast pyrolysis technique at a temperature of 500 °C [127]. Overall, it can be concluded that the potential for PPO from plastic pyrolysis is quite large.

In research conducted by Haryadi et al. reported that the color of PPO obtained from plastic pyrolysis is very dependent on the pyrolysis temperature as seen in **Figure 4** [128]. This research also reports that the largest yield was obtained when pyrolyzing 6000 g of LDPE at 250 °C for 110 minutes.

Table 6. PPO yield from plastic pyrolysis

Plastic	Pyrolysis	Temperature (°C)	Oil yield (wt%)	Others	Reference
PS	Fixed bed	50-600	53.4	wax	[129]
PP			20		
LDPE			25.1		
HDPE			16		
HDPE	Slow	300 - 400	80.88	Nitrogen	[130]
LDPE	Slow	300 - 450	86.5	135 min	[131]
LDPE	Fast	500	95	20 min	[127]
PVC	Slow	220-520	0.45 – 12.79	10 °C/min	[126]
PET	Slow	400 - 500	26 - 28	10 °C/min	[132]
PS	Slow	360 - 460	91.65	Nickel/Silica catalyst	[133]
PE	Flash	800	6.8	HZSM-5 catalyst	[134]
HDPE	Fast	640 - 850	68.53	3 - 4 g/min	[135]
LDPE	Flash	780 - 825	5.0 – 8.0	0.3 - 0.6 s	[136]
LDPE	Slow	450	3.2	10 °C/min	[137]
PP	Slow	430	91.5	> 20 min	[138]
HDPE	Flash	500 - 900	14.7	-	[139]
PE	Slow	450 - 515	37.1 – 38.3	FCC catalist	[140]

Figure 4. The difference in PPO color obtained depends on the pyrolysis temperature of: (a) LDPE Plastic-P; (b) LDPE Plastic-M [128]

Despite the good performance of ZSM-5 in catalytic pyrolysis, its small pore size also causes problem where reaction takes place on the surface without penetration into the internal cavities. This in turn, generates coke, which deactivates the catalyst. For this reason, Mousavi et al. [141] investigated the effect of crystallization time on zeolite crystallinity and modified with metal oxide. The modification was conducted by incorporating MIL-53 (Cu) and catalytic pyrolysis was then carried out under nitrogen atmosphere. The correlation between zeolite crystallinity and fuel type was also examined. Gasoline was the main product at 400 °C with a yield of 37% using MZY18 catalyst (MIL-modified zeolite Y with a crystallization time of 18 h) . Meanwhile, diesel and jet fuel were produced at a reaction temperature of 450 and 500 °C, respectively, using zeolite catalyst with fast crystallization. Plastic conversion to fuel was initiated by free radical pathways that produce oligomer via random scission. Radical formation was accelerated by co-existence of Cu^0 and Cu_2O. At first, hydrogen was adsorbed on the catalyst surface and formed unstable species of Cu-H, which then hydrogenated the radical species. The carbon trace in this catalyst serves as a sealing agent, which can prevent agglomeration of the active site and prolong catalyst lifetime.

Liu et al. [142] found that plastics could be selectively converted into fuel at a mild temperature (225 °C) using a bifunctional catalyst. The catalyst consisted of $Pt/WO_3/ZrO_2$ and zeolite Y, producing a liquid fuel mixture with a yield of 85% within 2 h of reaction. Unlike monofunctional catalyst, the balance between acid and metal sites of the bifunctional catalyst facilitates polymer conversion. As shown in **Figure 5a**, the liquid selectivity could be tuned by the zeolite acidity. As an example, reducing the Al content of the HY zeolite increases diesel (C_9–C_{22}) from 11% to 27% and decreases gasoline (C_5–C_{12}) from 72% to 32%. Based on the results, they proposed the following reaction mechanism. First, the polymer feed was hydrocracked over $Pt/WO_3/ZrO_2$ to olefins or alkane with $C_n \geq 13$. Next, the intermediate penetrated into the acid sites of zeolite, then cracked to C_5–C_7 alkanes because of its micropore nature, as presented in **Figure 5b**. In addition, they also confirmed that certain shape selectivity of zeolite directed to certain major product due to secondary cracking.

Thermal and catalytic procedures are potential means of producing oils from plastic wastes, and much effort has been made to develop and overcome the difficulties in pyrolysis oil production. Plastic garbage has accumulated more over time with the rapid growth of plastic production worldwide. Thus, it is crucial to turn plastic trash into usable energy in order to mitigate environmental issues. In addition, the usage of pyrolysis oil is possible without the need to modify the engine design [143].

3.3. *Performance and Emissions of Diesel Engine Fueled with PPO*

Based on the literature survey so far, the majority of the studies decided that PPO may be utilised as a diesel alternative. As a result, several research have been conducted to evaluate the fuel economy and pollution levels produced by diesel engines running on PPO.

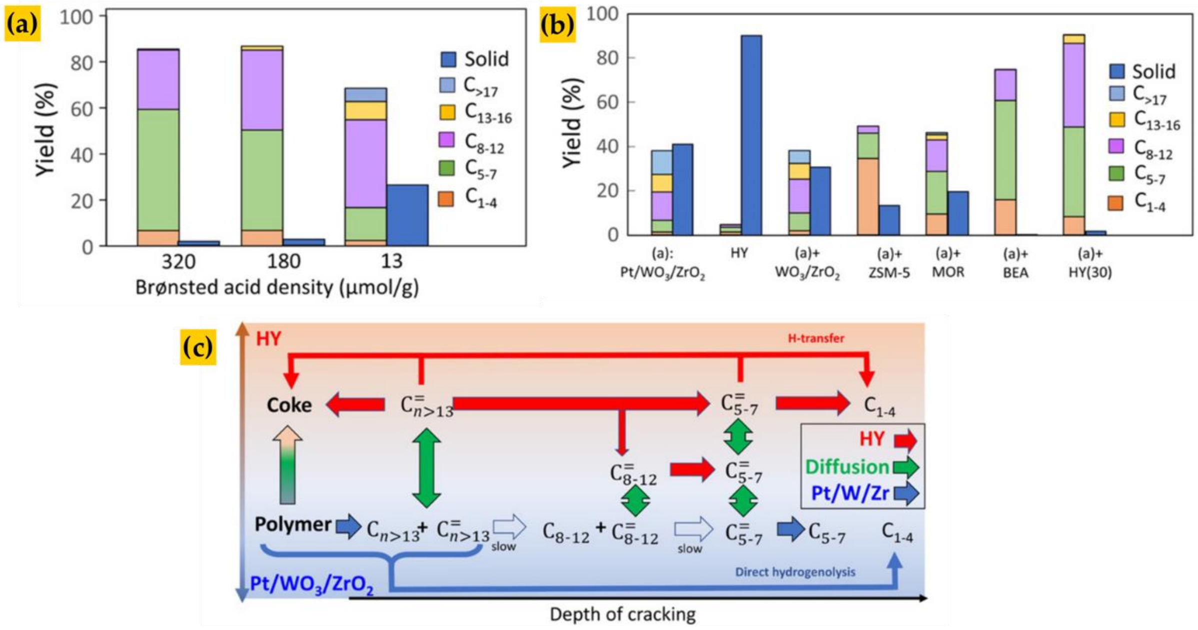

Figure 5. (a) How the acidity of HY zeolite affects product production; (b) For two hours, LDPE was depolymerized over Pt/WO3/ZrO_2 using a variety of solid acid catalysts; (c) Reaction network illustrating the HY zeolite's contribution to deep cracking speed [142]

Table 7. Comparison of the physicochemical properties of PPO with those for diesel specified in the ASTM standards [90]

No.	Property	ASTM standard	PPO	Diesel
1	Viscosity (kg/ms)	D445	4.3	2–4
2	Calorific value (kcal/kg)	D240	9201.72	10191.20
3	Fire point (°C)	D92	55	52
4	Flash point (°C)	D93	53	40
5	Moisture (%)	D7261	0.21	0.05
6	Sulfur (wt%)	D7039	0.0046	0.05
7	Specific gravity	D1298	0.8517	0.85
8	Carbon (%)	D4530	0.044	0.035
9	Density (kg/L)	D1298	0.8654	0.8600

Singh et al. [144] studied the engine performance and emissions of diesel engine for five PPO–diesel blends (PPO: 10, 20, 30, 40, and 50%). A higher part of PPO in the fuel mix was shown to boost the BTE and reduce SFC. The PPO resulted in a high heat dissipation and delayed ignition, both of which increased the in-cylinder pressure. A higher concentration of PPO in the fuel blend was found to reduce engine emissions. According to the findings, PPO may be utilised in diesel engines up to a 50% concentration. However, at higher engine loads, the PPO–diesel blends resulted in a minor increase in CO emissions. The results showed that the D80PO20 blend (80% diesel + 20% PPO) resulted in the same cylinder pressure as diesel. Compared with pure diesel, the PPO–diesel blends had lower UHC and NOx emissions by 19 and 26%, respectively.

Quesada et al. [145] pyrolyzed PE, PP, and PS at 500 °C. The resultant oil was dark brown for PS, while the oils were light brown for PP and PE, attributed to their different viscosity and API gravity. The kinematic viscosity at 45 °C of the oils produced from PP, PE, and PS were 3.09, 381 and 1.45 cSt, respectively. Meanwhile, the flash point for the oils produced from PE, PP and PS was 123, 115, and 55 °C, respectively. The composition of the oil produced from PE was C_7–C_{35}, which was similar to diesel, whereas the oil produced from PS was more suitable for production of basic chemicals rather than fuel.

Most of the researchers in **Table 8** report that, compared to the use of diesel, the use of PPO in diesel engines causes BTE to decrease, but there are some researchers who report that BTE increases by 4.03% in diesel + PPO (50% blend) [144], increased 4% in the mixture of PPO + 10% diethyl ether [77]. From **Table 8** it can be concluded that the opportunity to increase BTE is still open in further research.

Das et al. [146] used engine load, compression ratio, and fuel blend ratio as parameters in order to optimize engine performance (maximum BTE and minimum NOx emissions). The optimum parameters were determined to be: (1) engine load: full load, (2) compression ratio: 17:1, and (3) fuel blend ratio: 10% waste plastic oil + 90% diesel. A BTE of 28.8% and NOx emissions of 162.45 ppm were gained using the multi-response optimization technique. Sensitivity analysis was too conducted to understand the relative importance of the various parameters and their

Table 8. Diesel engine performance using PPO

Fuel	Load	BSFC (g/kWh)	BTE (%)	BSEC (MJ/kWh)	Reference
Diesel	Full	-	30.9	-	[147]
PPO		-	11 % ↓	-	
PO5		-	9.71 % ↓	-	
PO10		-	4.85 % ↓	-	
PO15		-	2.82 %↓	-	
Diesel	Full	-	30.86	11.9	[148]
PPO		-	11.37 %↓	10.08 %↑	
PO25		-	3.21 %↓	2.52 %↑	
PO50		-	5.48 %↓	5.04 %↑	
PO75		-	8.43 %↓	8.4 %↑	
Diesel	Full	-	30.5	12	[149]
PPO (HDPE):diesel (50:50)		-	↑	0.83 %↓	
Diesel	Full	353	-	16.07	[150]
PPO (PP+PS)		↑	↓	7.59 %↓	
PPO (PE, PP and PS)		17.88 %↓	-		
Diesel	Full	274	30.01	-	[144]
Diesel + PPO (50 % blend)		0.73 % ↓	4.03 %↑	-	
Diesel	Full	276	28	-	[77]
PPO		50.80%↑	0.89 %↓	-	
PPO + 5 % diethyl ether		6.52 %↑	1.75 %↓	-	
PPO + 10 % diethyl ether		9.06 %↑	4 %↑	-	
Diesel	-	-	31.4	11.4	[151]
PPO + diesel blend (25, 50, 75, 90, 100) %PPO		↑ -	- 15.92 %↓	- 8.77 %↑	

major contributions. The compression ratio was shown to be the most important aspect, followed by engine load and fuel blend ratio.

Sekar et al. [152] conducted a number of engine tests using pyrolysis oil (PO), P25 (25% PO + 75% diesel + 25 ppm Al_2O_3), and diesel at various average effective pressures (1.3, 2.6, 3.9, and 5.2 bar). The use of Al_2O_3 nanoparticles was found to boost power by 35% and reduce UHC and CO_2 emissions by 45 and 60%, respectively. The NOx emissions of the P25 blend were found to decrease by 15 and 9%, respectively, compared with those for diesel and PO. The P25 blend was shown to have a positive impact on the combustion and emission characteristics compared with PO.

Singh et al. [153] conducted engine tests at a wide range of rpms:1200, 1500, and 1800 rpm, and different loads: low, medium, and full, so that analyze how well the diesel engine performs and how much emissions it produces fueled with diesel–PPO blends. The D80PO20 blend (80% diesel + 20% PPO by volume) resulted in the same cylinder pressure as that for diesel. The results demonstrated that increasing the engine speed increased the thermal efficiency and cylinder pressure.

Rajak et al. [154] blended a base fuel (BF) with PPO so that evaluate the suitability of the blends in compression ignition engine. The results indicate that PPO is a promising alternative fuel that can enhance the efficiency, characteristics of diesel engines' combustion and emissions when blended with diesel at a rate of up to 20%.

Devaraj et al. [112] studied the engine performance, exhaust emissions, and combustion characteristics of a single-cylinder water-cooled diesel engine fueled with waste plastic pyrolysis oil (WPPO) blended with 5 and 10% DEE. Based on the experimental results, the smoke emissions decreased when WPPO was used as a starting point. The BTE of the WPPO blends was higher compared with those for pure WPPO and diesel. The levels of both CO and NOx in the air were lowered. because to the WPPO mixes. The results indicate that the combustion process is enhanced and the emissions is reduced by the addition of oxygenates. The addition of DEE into the WPPO was found to increase the cetane rating, with a value above diesel.

Kalargaris et al. [77] blended PPO with diesel and conducted engine tests using a four-cylinder direct injection diesel engine at various engine loads (25–100%). The engine performance, combustion characteristics, and exhaust emissions for the PPO–diesel blends compared to diesel. Based on the results, the engine could run with the PPO–diesel blends at upper loads and deliver performance comparable to petroleum diesel. However, with lower loads, longer delay before igniting times led to stability issues. At full load, the NOx emissions were significantly higher and the BTE for the PPO was somewhat lower than that of diesel. Kaewbuddee et al. [132] also found that the properties of combustion of WPO were comparable to those for diesel at all engine loads.

4. Advantages and Disadvantages of RSB and PPO

Based on the literature survey, there are advantages and disadvantages of RSB and PPO. Biodiesel has poor oxidation stability. The induction period of RSB without additional antioxidants was found to be 0.81 h, which is well below the European EN 14112 standard for biodiesel oxidation stability (8h) [22]. The primary issue is crude RSO's high FFA content (37.46%) [76]. In addition, RSB has a high acid content (4 mg KOH/g), which is undesirable as this can lead to corrosion of the engine components [12]. RSB has a lower heating value (38–39 MJ/kg) [59], low pour point and cloud point (−3 and 2.5 °C), high flash point (131 °C), high kinematic viscosity (13.13 mm^2/s), and low RSB density (0.88 g/mL) [155].

The high kinematic viscosity of RSB can reduce engine performance [59]. Owing to the higher viscosity of biodiesels, using just one biodiesel in a diesel engine can reduce its performance [156]. Compared to diesel, RSB has a greater flash point and thus, it is safer to store RSB compared with diesel [155]. The cetane number of RSB (49–54) is higher than that of diesel [155]. Blending RSB with diesel can reduce CO and HC emissions [80]. **Table 9** shows the comparison of the advantages and disadvantages of the physicochemical properties of RSB and PPO.

5. PPO–Biodiesel Blends

Among the issues faced in replacing fossil fuels with biofuels are the high production cost and availability of feedstock [127]. Even though numerous studies have shown that PPO can be

Table 9. Comparison of the advantages and disadvantages of the physicochemical properties of RSB and PPO

Properties	Unit	RSB		Ref.	PPO		Ref.
		Value	Category		Value	Category	
Oxidation stability	h	0.81	Bad	[17]	18.1–20.1	Good	[157]
Acid value	mg KOH/g	4	Bad	[146]	2.79	Good	[158]
Calorific value	MJ/kg	38-39	Low	[146]	40–43	High/Good	[124]
Pour poin	°C	−3	Bad	[56]	−5 s/d −67	Good	[119]
Cloud point	°C	2.5	Bad	[56]	—		
Flash point	°C	131	Good	[56]	30–42	Bad	[112]
Kinematic viscosity	mm^2/s	13.13	Bad	[56]	1.4–6.3	Low/Good	[12]
Cetane number		49–54	Good	[47], [56]	60–68	High/Good	[112]
Density	g/ml	0.88		[47]	0.77–0.79		[112]

used as a diesel substitute, CO, NOx, and UHC emissions are greater than diesel. Plastic wastes pose a very serious environmental challenge associated and efforts are being made to improve plastic waste management [113], [126], [132]. Many studies have recommended the use of biodiesel as an alternative to conventional fuel since it is environmentally friendly and results in lower exhaust emissions [133], [134]. However, biodiesels are not without disadvantages, especially since they have low oxidation stability and high acid value [135], [136]. However, based on the advantages of PPO and biodiesels, it can be reasonably assumed that blending both of these fuels can exploit the advantages offered by each fuel and compensate the disadvantages of each fuel.

Senthilkumar and Sankaranarayanan [129] found that the BTE of the diesel engine fueled with WPO–Jatropha curcas biodiesel blend was higher by 2.24% than that compared with WPO at full load. The BSFC increased with an increase in the proportion of biodiesel in the blend and decrease in engine load. A reduction in the amount of biodiesel in the mixture led to an increase in CO and HC emissions. The NOx emissions increased slightly with an increase in the proportion of biodiesel in the blend. The smoke emissions decreased by 11.4% for the WPO–Jatropha curcas biodiesel blend compared with those for WPO.

Awang et al. [137] formulated a quaternary fuel from commercial diesel, used cooking oil biodiesel, palm oil biodiesel, and waste plastic pyrolysis oil. The results demonstrated that brake power and BTE of all quaternary fuel blends increased by 2.78 and 9.81%, respectively, relative to those for B30 fuel (30% biodiesel +70% diesel). All quaternary fuels demonstrated a 6.31% decrease in BSFC compared with B30, as well as a decrease in CO and carbon emissions of 19.66 and 4.16%, respectively. They concluded that The usage of the quaternary fuel in diesel engines has enormous potential.

Quaternary fuel mix may soon replace next-generation fuels due to the rising need for alternative fuels and to overcome the drawbacks of biodiesel–diesel blends. Awang et al. [137] showed that waste plastic pyrolysis oil (WPPO) and waste cooking oil biodiesel (WCOB) can be used with diesel–palm biodiesel blends to enhance specific fuel properties, without the need for engine modifications. Blending WPPO and WCOB with diesel–palm biodiesel enhanced as well as engine performance, emission and wear characteristics.

Sharma and Murugan [138] conducted research to determine how the compression ratio at the appropriate injection time and nozzle opening pressure influenced the performance of diesel engines that ran on the fuels listed below: 80% biodiesel produced from Jatropha seeds + 20% oil produced from waste tire pyrolysis. The experimental results suggested that the engine performance, characteristics of combustion, and exhaust emissions of the fuel blend improved at a higher compression ratio of 8.5:1 compared with those at standard operating conditions. The exhaust emissions were slightly higher but still within a tolerable level and the results were comparable with those for diesel. According to Senthilkumar and Sankaranarayanan [129], PPO can be used as a diesel substitute without engine modifications, though it produces more emissions such as CO, NOx, and UHC than diesel. Kaewbuddee et al. [132] found that the mixing of biodiesel into WPO increased CO and smoke emissions. However, the presence of castor oil in the WPO resulted in lesser CO and smoke emissions compared with the other biodiesels be examined in their study. Based on the findings of previous studies, it can be deduced that PPO and RSB have great potential as a fuel for the automotive sector. However, PPO and RSB each has their own disadvantages and therefore, blending PPO with RSB appears to be a solution to overcome the disadvantages of each fuel. It is also expected that blending PPO with RSB will improve the physicochemical properties of biodiesel, as well as enhance the performance and reduce the emissions of diesel engines.

6. Conclusion

Environmental pollution due to plastic waste is increasingly worrying, therefore if plastic waste can be utilized as a fuel raw material it will help reduce environmental pollution due to plastic waste. Plastic waste can be processed into a fuel called Plastic Pyrolysis Oil (PPO). Rubber seed can be used as raw material for biodiesel which is called Rubber Seed Biodiesel (RSB). RSB and PPO can be blended with petroleum diesel and used as diesel engine fuel. Due to their almost identical densities, RSB and PPO can be mixed homogeneously. RSB and PPO each have advantages and disadvantages in their physicochemical properties and terms of performance and emissions when blended with petroleum diesel and used as diesel engine fuel. To be able to complement each other, RSB and PPO need to be mixed. It is necessary to study the mixing method and the best composition between RSB and PPO, to get the best physicochemical properties of the mixed fuel and also to find the best performance and exhaust emissions when the mix of RSB and PPO is used as diesel engine fuel.

Acknowledgement

The authors wish to acknowledge the Indonesian Ministry of Education, Culture, Study, and Technology's Directorate General of Higher Education, Research, and Technology under the Doctoral Dissertation Research Scheme (No. 9417/UN5.1.R/PPM/2022 and No. 12/UN5.2.3.1/PPM/KP-DRTPM/TI/2022). The authors would like to convey their heartfelt appreciation to Universitas Negeri Medan, Universitas Sumatera Utara, and Politeknik Negeri Medan.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

Indonesian Ministry of Education, Culture, Study, and Technology's Directorate General of Higher Education, Research, and Technology under the Doctoral Dissertation Research Scheme (No. 9417/UN5.1.R/PPM/2022 and No. 12/UN5.2.3.1/PPM/KP-DRTPM/TI/2022).

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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