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A Review On The Use Of Plastic Waste-Originated Fuels For Compression Ignition Engines

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ABSTRACT

Nowadays, the process of urbanization is an indispensable process of every country in the world. They bring us a civilized and modern life and unintentionally made our life harsher. The environment is increasingly polluted, from air pollution, water pollution to noise pollution. One of the causes of air and water pollution is plastic waste, every day we release a large amount of plastic waste into the environment. According to a projection by the World Economic Forum, there will be one ton of plastic waste in the oceans for every three tons of fish by 2025 and more plastic than fish by 2050. Most man-made plastic waste is concentrated in landfills, buried in the ground or accumulated in the oceans forming giant floating garbage islands. To solve this problem, people need to turn plastic waste into usable goods such as liquid hydrocarbon fuel. Pyrolysis is considered the most suitable technique to convert waste plastics into fuels that serve as an alternative to internal combustion engines. The objective of this review is to highlight the role of pyrolysis techniques in converting waste plastics into waste plastic pyrolysis oil (WPO) fuels. In addition, property assessments of WPO fuels based on relevant literature have been published to confirm the applicability of WPO for compression ignition engines based on the results of engine performance and emission characteristics.

KEYWORDS

waste plastic pyrolysis oil, compression ignition engines, engine performance, emission characteristics

INTRODUCTION

Plastic is an important and indispensable material in recent days. Due to great demand in many fields such as household items, children's toys, packaging materials, automobile parts, electronic components, agricultural supplies, etc., plastic is produced in large quantities. It is the reason why the amount of plastic waste is increasing rapidly [1, 2]. There are 2 types of plastic waste such as municipal and industrial. Due to the more homogeneous and contamination-free, Industrial plastics are generally useful for downcycling into lower-grade plastic products. Municipal plastics tend to be more heterogeneous and contain extraneous materials [3]**.** According to the project [1], the total amount of plastic waste ever generated from primary plastic has reached 5800 million tons. Only in 2015, global plastic emissions reached 302 million tons [4]. The primary plastic waste generated will be assumed around 26,000 Mt by projecting current global waste management trends to 2050 [5].

Moreover, production of plastic packaging is predicted to increase 4 times in 2050 and will reach its peak in 2100, as reported by the Living Lab Zero Waste, shown in Figure 1 [6]. Because of its lower density and higher volumes, several applications of plastics in various industrial sectors created indirect problems of waste disposal. There are many ways to dispose of waste plastic: incineration, land filling and mechanical recycling. Wild animals can be harmed by plastic waste, because they can mistakenly swallow or become trapped in these types of waste. Waste plastic when buried deep in the landfills can release carcinogenic substances [7]. In addition, other toxic substances from waste plastic can contaminate groundwater [8, 9]. Only about 38% of total plastic waste are landfilled, while about 26% are recycled and 36% are used for energy recovery [10]. In 2016, landfilled plastic waste decreased to

27.3% although total plastic waste increased slightly to 27.1 million tons, recycling increased to 31.1% and energy recovery also increased to up to 41.6% [11].

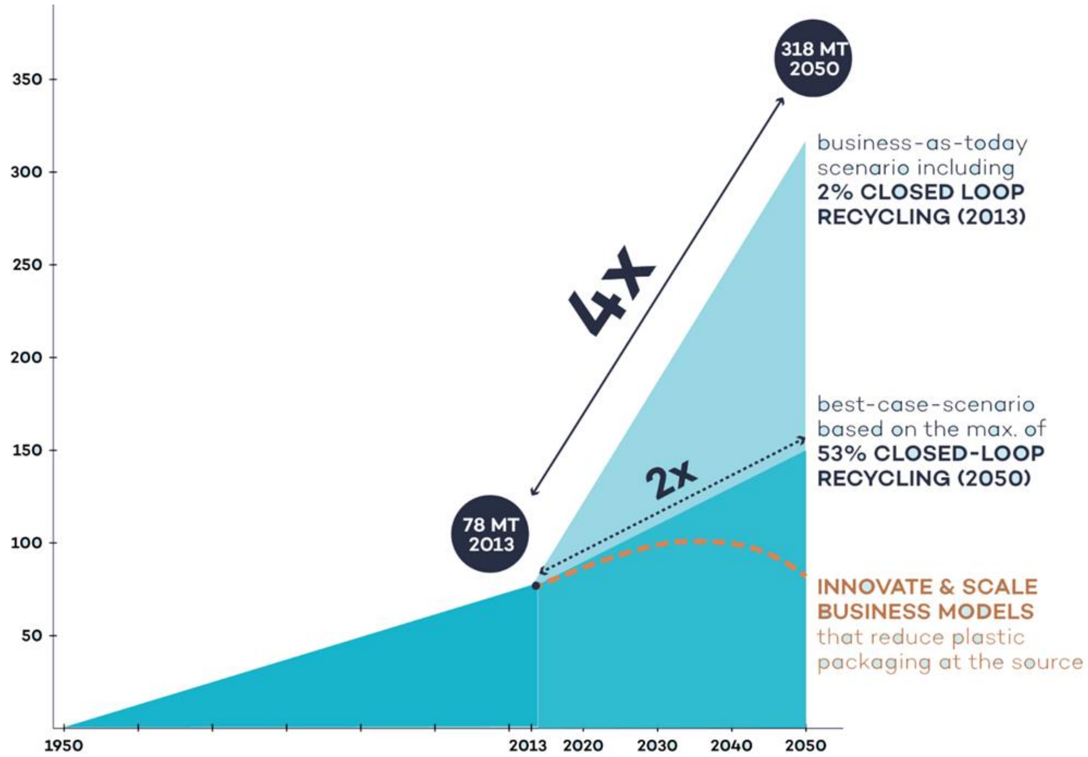

Figure 1. Global plastic packging production quadrouples by 2050 [6]

Besides, other solutions such as catalytic conversion, thermal pyrolysis and co-processing are also used to convert waste plastic into fuel oil. Among them, pyrolysis can reduce the carbon emissions of the transportation industry and optimize waste management towards no landfill, so this is considered as a promising and effective method with high value in making liquid fuels suitable for transportation. Throughout the pyrolysis, the products obtained can be divided into 3 components: gas, liquid and solid fraction. The gas/liquid ratio can vary depending on the process parameters. Researchers have conducted research and investigated various factors affecting plastic waste pyrolysis: type of plastic waste used, temperature, pressure, reaction time, catalyst, reactor type [12-17]. The products obtained from the pyrolysis of plastic waste are polyethylene and polypropylene with a relatively high calorific values comparable to gasoline and diesel oil. Therefore, fuel oil from these sources can be a potential fuel for internal combustion engines, helping to reduce their dependence on traditional fossil fuels that are gradually depleting.

Among the reports on the products of waste plastic pyrolysis and their characteristics, the research works on the application of pyrolysis oil in transportation mainly focus on diesel engines [10]. Very few studies report on the use of waste plastic oil (WPO) in compression ignition (CI) engines, as most of them focus on the extraction techniques of fuel oil from waste plastics. Biofuels such as Jatropha oil and seed cake oil have been experimented by many researchers on internal combustion engines, although there are very few studies conducted with waste plastic oil and their mixtures [18]. Studies on the use of WPO in internal combustion engines have shown some remarkable conclusions: The brake thermal efficiency (BTE) of WPO on direct injection (DI) engines is more stable compared to diesel [19]; Common emissions such as CO_2, HC and smoke when using WPO are higher than those of diesel [20, 21]. In the current work, through the implementation of a number of development and improvement strategies, the types of fuel supplied for diesel engines are increasingly growing in quantity and types such as fossil diesel, biodiesel, and biodiesel. chemical, vegetable oil, biogas and bio-alcohol.

Among these, waste plastic can be reused as fuel without affecting the food source by going through the thermochemical process to collect hydrocarbon recovery, although it was originally derived from petroleum products. Therefore, WPO emerges as a promising and attractive alternative fuel because its feedstock is cheap and require immediate disposal. The present study provides an exhaustive review of the use of WPO derived from recycled feedstock in diesel engines that doesn't affect food-based sources.

CONVERSION OF WASTE PLASTICS-TO-FUEL

Waste plastics pyrolysis

Waste plastic processing technologies can be divided into 2 strategies: recycling (includes: physical recycling, energy recovery and resource recovery) and degradation (biodegradation and oxo-biodegradation). The oxo-biodegradation includes 2 methods: abiotic (thermodegradation, photodegradation, mechanochemical degradation...) and biotic degradation. These pyrolysis mechanisms are presented briefly and systematically in Figure 2 [4]. Pyrolysis technology has significant potential in converting various solid materials (including biomass and plastics) into valuable chemical products while remaining environmentally friendly [22, 23]. Therefore, this technology is very suitable for converting WPC into useful chemicals and fuels. This is because plastics can improve the calorific value of pyrolytic oil and reduce the formation of oxygen in a pyrolysis system of biomass as hydrogen-enriched feedstock [13, 24-26]. In addition, the improvement of pyrolysis oil yield and the reduction of coke yield is facilitated by the synergistic effects occurring during the biomass/plastic co-pyrolysis [19]. Pyrolysis oil, which is obtained from the co-pyrolysis of plastics and biomass, is difficult to use directly in engines because it is a very complex mixture of oxygenated compounds and aliphatic hydrocarbons [27, 28].

Depending on the pyrolysis technology, the pyrolysis of plastics typically yields an average of 10–20% tar, 35–40% gas, and 45–50% oil [29]. In some cases, according to previously published studies, the pyrolysis of individual plastics can produce up to 80% liquid, which is higher than the pyrolysis processes of wood biomass in general [30]. The pyrolysis oil can be valorized better if separated into separate fractions with different boiling point ranges: light (0–170◦C), mid-distillate (170–370◦C), and heavy (>370◦C) fractions [31]. Wu, Kuo and Wey [32] presented a two-stage pyrolysis-catalysis of high-density polyethylene. In which, the first stage is the pyrolysis of plastic, the second stage is the catalysis of hydrocarbon pyrolysis gases leading to the production of hydrocarbon oil in the gasoline range (C8-C12). The study results also show that from high density polyethylene can obtain oil product with high yield (83.15 wt %) when using phased catalyst. The use of pyrolysis oil as a fuel for diesel engines has become increasingly important in recent years. In some of the latest studies, the potential of using oil from the pyrolysis of plastics at different temperatures in diesel engines has been meticulously investigated [20,33,19,3].

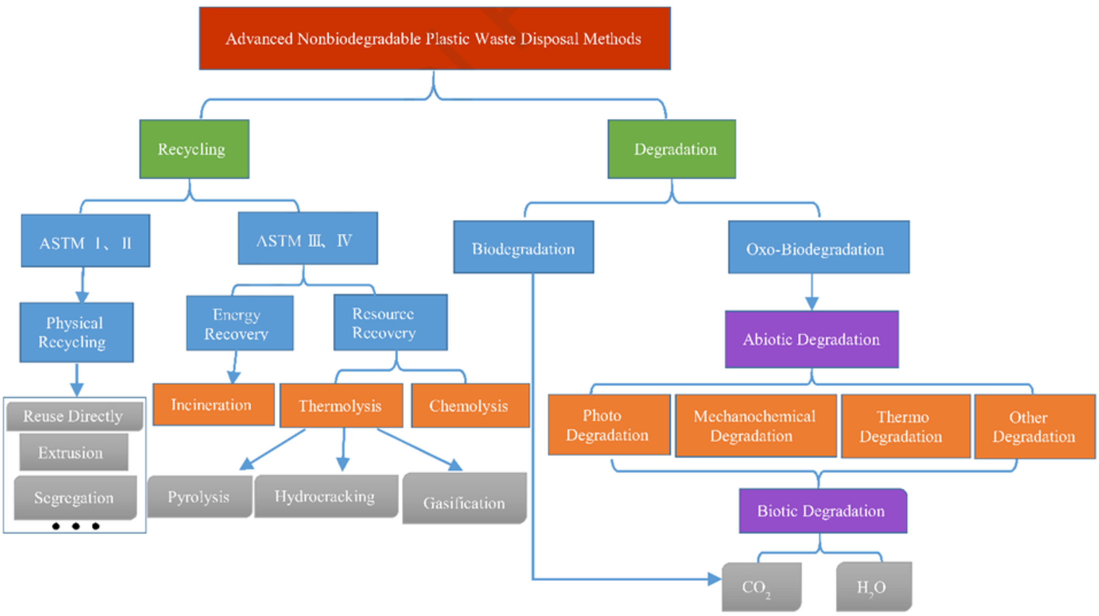

Figure 2. Classification of currently reported advanced NPW disposal methods [4]

There are many methods to upgrade pyrolysis oil: chemical, physical, thermal and catalytic upgrading technology [34, 35]. In particular, the ones that has attracted great attention of researchers in recent times is the catalytic upgrading technology [36]. In the biomass/plastic co-pyrolysis, the catalyst plays an extremely important role. Various catalysts have been introduced into the biomass/plastic co-pyrolysis to improve the quality of the pyrolysis oil, including: carbon-based catalysts (activated carbon), zeolites (ZSM-5, HY, SBA-15, etc.), metal oxides (Fe_2O_3, Al_2O_3, ZnO, CaO, MgO_2 and TiO_2) [37]. The effect of MgO on rice husk/polyvinyl chloride co-pyrolysis was studied by Yuan et al., the results showed that MgO increased the hydrocarbon content (~35%) and decreased the acid content (~2%) [38]. Similarly, the effect of zeolite-type catalysts (HY(5.1), H-Beta(25), and HZSM-5) on the catalytic pyrolysis of commercial WPCs via the use of Py-GC/MS was studied by Miandad *et al.* [39], and they told that the small-pore HZSM-5 and large-pore HY both negatively affected the formation of aromatics. Another study has also shown that the production of aliphatic and aromatic hydrocarbons in corn stover/LDPE co-pyrolysis is facilitated by the addition of CeO_2 (with the highest selectivity of monocyclic aromatics reached 73% and the maximum yield of hydrocarbons at 85%), according to Ding et al.[40]. In the co-pyrolysis of biomass and plastics, these catalysts (especially HZSM-5) have been widely used. However, due to some disadvantages such as corrosion, easy inactivation (leading to short service life), relatively high cost...so these catalysts are often used in a very limited way in a large scale [41-43].

One of the environmentally acceptable ways to treat waste plastic is pyrolysis. At the same time, this process also contributes to the conservation of petroleum resources [44]. The pyrolysis of high-density polyethylene (HDPE) has been studied by many authors such as Gu *et al* [45] or Hassan, Hameed and Lim [46]. Similarly, the pyrolysis of low-density polyethylene (LDPE) is similar Dobó *et al.* [47, 40]. However, no researcher has analysed the characteristics of the bio-oil obtained by pyrolysis of the film from the fraction not collected selectively from municipal solid waste plants. This type of plastic waste (polyethylene film) is not collected in a specific container in some countries (e.g. Spain). The plastic film (mainly bags) is often mixed with other types of municipal solid waste (mainly organic materials), making the treatment process even more complicated. To obtain liquid fuel, pyrolysis is basically performed on waste plastic (polyethylene film) from the fraction that is not selectively collected. Different oil samples were subjected to experimental studies under different operating conditions to determine their physical and chemical properties. The main objective of these works was to determine whether the quality of these fuels depends on the operating conditions. The results show that the characteristics of the studied fuel do not change with the operating conditions. Except for viscosity (because the research fuel was not fractionated), the oil samples used during the study showed that they have very close chemical and physical properties to commercial gasoline and diesel [48].

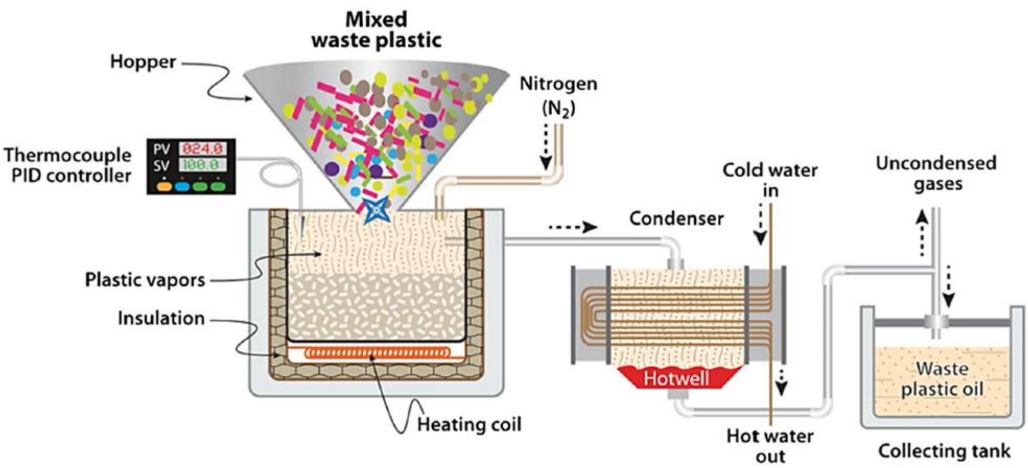

Figure 3. Energy extraction routes from waste plastic [49]

The energy embodied in waste plastic could be recovered by catalytic pyrolysis as waste plastic oil (WPO) and could be recycled as a fuel for diesel engines. Because of its ready availability, Damodharan et al. [49]chose the mixed waste plastic in their studied. The MWP segregated consisted of an assorted mix of plastics like PET, HDPE, LDPE, PVC, PP and PS. Then it was cut into small pieces by shear to approximately 1–1.5 cm^2 in size. Next, the plastic materials were washed to remove dirt and unwanted debris prior to pyrolysis. Figure 3 depicts the layout of the laboratory-scale waste plastic extraction unit. The yield of the oil was around 75% by wt. of the intake MWP. Solid coke residue was found to be 20% by wt. while the remaining 5% comprised the gaseous fraction (5% by wt.).

Properties of waste plastic pyrolysis oil (WPPO)

According to Wathakit *et al.* [50], the chemical composition, quality and quantity of WPO obtained from pyrolysis depends on several factors such as the type of waste resin, the catalyst used and the reaction temperature. Through pyrolysis, according to (Manoj Kumar and Mallikarjuna [51], polystyrene yields the highest oil yield among other plastics. In study by Nalluri, Prem Kumar and Ch Sastry [52], they concluded that HDPE and LDPE gave the lowest oil yield, while other plastics such as PET, PVC and polypropylene gave the average oil yield. The properties such as ash point, density, viscosity and caloric value of HDPE-derived WPOs are quite close to those of diesel [53, 54]. Table 1 summarizes the characteristics of WPOs derived from various sources and tested in diesel engines. In this table, some notable conclusions can be drawn as follows: (1) the cetane number of WPO derived from waste plastic is in the range of 48 - 51, slightly lower than the European emission standard EN590 for ULSD (minimum 51); (2) The viscosity of WPO is about 2.1 - 3; (3) The flash point of WPO is about 42 – 45 ºC, does not satisfy the EN 590 standard (more than 55 ºC required). On the other hand, a study by Ramesha *et al.* [55] also show that the parameters such as density, viscosity and cetane number of pure WPO are lower than that of diesel oil and its blends. WPO has a slightly lower viscosity than diesel but is higher than that of kerosene. The higher viscosity creates problems during atomization, which affects the fuel consumption of the engine. High viscosity fuels will cause the engine to jam due to increased friction between them. On the other hand, low fuel density will make fuel consumption of the engine increased, but if the fuel density is too high, it will cause physical harm to the engine. In addition, the pour point of pure WPO is lower than that of other fuels, which means that pure WPO is not suitable for use in cold weather. Besides, the low flash point of WPO indicates the presence of volatile materials in this fuel.

Table 1. Properties of WPO extracted via pyrolysis with some extraction parameters

Catalyst used	Reaction temperature	Density at 15ºC	Kinematic viscosity at 40ºC	LHV	Cetane number	Flash point	Fire point	Cloud point	Pour point	Ref.
	ºC	kg/m³	mm²/s	kJ/kg		ºC	ºC	ºC	ºC	
Silica	350–400	830	2.64	44,200	50	40	44	-	-	[57]
Acid treated Kaolin	450	790	2.10	40,170	66	- 2	5	12	-1	[29]
NA	400	835.5	2.52	44,340	51	42	45	-	< -7	[58]
Sodium aluminium silicate	400	788	2.34	45,468	43	< 100	-	-	18	[49]
Kaolin	500	777	2.27	47,095	65	< -12	< -12	< -45	-45	[59]
Patented	450–700	800.7	2.97	46,292	72	-	-	-	-	[60]
Patented	350	780	-	42,900	44	72	-	-	15	[61]
NU	900	981.3⁺	1.92	38,300	-	13	-	-	-	[62]
NA	400	798	-	45,216	51	42	45	-	-	[14]
NA	320–500	835–	3.25	43,388	48	41	49	-	-	[63]
NU	300–900	790	2.52	43,340	51	42	45	-	-	[5]
MWP mixed waste plastic, HDPE high density polyethylene, NA not available, NU not used, LHV low heating value, ZSM zeolite socony mobil										

APPLICATION OF WASTE PLASTIC PYROLYSIS OIL IN COMPRESSION IGNITION ENGINES

Neat PPO fuel

In the current period, fuel oil derived from waste plastic is attracting more and more attention from scientists, being studied and applied in many fields such as industrial heating equipment and internal combustion engines. Although pyrolysis oil from waste plastic is considered a potential alternative fuel for engines in the field of transportation, there is currently very little research on the use of single-plastic derived pyrolysis oils on spark ignition (SI) or compression ignition (CI) engines [64]. However, the use of 100% waste plastic oil has been successfully applied by a few scientists on CI engines with different capacities. Even so, engine performance will be degraded at all load conditions when 100% waste plastic oil is used. However, some other studies have shown the opposite: the performance of the engine when using pure waste plastic oil is almost equivalent or slightly improved when compared with pure diesel [65]. For example, the thermal efficiency of engines running on waste plastic oil has been found to be about 4-9% higher than when using diesel, according to Janyalertadun, Santaweesuk and Sanongraj [65] and Mani and Nagarajan [66].

Regarding emissions, published works show that there are many differences when studying common engine emissions such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), oxides of nitrogen (NOx) and smoke emissions [67]. There are some works reporting that when using plastic oil in the engine, the emissions of HC, CO, and CO_2 decrease but NOx emissions increase [68]. However, several others have reported the opposite trend [69]. In addition, the combustion characteristics of CI engines when using waste plastic oil have received very little attention from research and evaluation. Kaimal et al. [57] conducted a study on the use of waste plastic oil in CI engines to evaluate combustion parameters such as in-cylinder pressure, peak pressure, ignition delay and combustion duration. The results show that the peak pressure of the engine has increased by about 6%, but the thermal efficiency is slightly reduced when the engine was operated with plastic oil. Similarly, the combined effects of fuel injection timing and exhaust gas recirculation (EGR) on the combustion characteristics of CI engines when running on waste plastic oil were reported by Damodharan et al. [49, 70]. Experiments were conducted at three injection timings (21°, 23° and 25°CA bTDC) with different EGR ratios (10, 20 and 30%) at the engine's rated power output. Combustion was occurred close to the TDC (top dead center) with the delayed injection timing from 25°CA bTDC to 21°CA bTDC. The results showed that the advanced injection timing of 25°CA bTDC and low EGR rate of 10% was found to simultaneously reduce smoke and NOx emissions by 46% and 38% respectively.

Using thermochemical depolymerization during mass production with a capacity of 0.5 tons/batch, MPW was used to produce plasto oil (PO1 and PO2) by Chintala et al.[71]. These oils are then used in single cylinder CI engines rated at 3.7 kW to evaluate the combustion and emission characteristics. Tests were carried out with engines using plasto oil at loads corresponding to different brake mean effective pressures (BMEPs) of 1.8, 3.8, 5.8, 7.8 and 10.8. bar, then compare to pure diesel. The results show that the brake thermal efficiency of the engine operated with plasto oil was almost equivalent to that of the original diesel at all engine loads. In terms of emission characteristics, the above study has also shown that the CO, HC and exhaust emissions of the engine at BMEPs 3.8–10.8 bar when using plasto oil are slightly higher than those of diesel, simultaneously, NOx emissions decreased slightly at medium and high BMEP (5.8–10.8 bar). However, the emission characteristics of the engine (CO, HC, NOx and smoke) were the same for all test fuels (PO1, PO2 and diesel) at lower BMEP loads (1.8–3.8 bar). Overall, the above studies all showed that plasto oil exhibits comparable performance to conventional diesel fuel. This helps confirm with certainty that this is a potential fuel candidate for CI engines.

To reduce environmental pollution, the treatment of waste plastic accumulated in the soil is a very important issue. Through catalytic pyrolysis in the form of waste plastic oil (WPO), the energy contained in waste plastic can be recovered and recycled to fuel diesel engines. As global plastic production and waste plastics expand, this approach is seen as a sustainable solution in managing plastic waste. In this regard, Damodharan et al. [49] investigated the combined effects of injection timing and exhaust gas recirculation (EGR) on the combustion and emission characteristics of diesel engines using neat WPO. Experiments were conducted at different injection timing (21°, 23° and 25°CA bTDC) and different EGR ratios (10, 20 and 30%) at rated engine power. The combustion event occurred closer to the TDC when the injection timing is delayed from 25°CA bTDC to 21°CA bTDC compared to diesel. As the injection timing was delayed from 25°CA bTDC to 21°CA bTDC, the peak in-cylinder pressures and HRRs dropped gradually at all EGR rates. The fuel consumption of the engine when using WPO is similar to that of diesel, but the brake thermal efficiency is 5.1% higher. When WPO was injected into the engine at 21°CA bTDC with an EGR of less than 30%, NOx emissions decreased up to 52.4%. With WPO at early injection timing at 25°CA bTDC, the smoke density was still 46% and 9.5% lower for 10% and 20% EGR, respectively. Also at this time of early injection (25°CA bTDC), the CO and HC emissions of WPO are also lower than that of diesel. Thus, it can be seen that when injecting WPO at an elevated injection time of 25°CA bTDC and a low EGR of 10%, the smoke and NOx emissions decreased by 46% and 38%, respectively.

According to Rinaldini et al.[14], a current production, indirect injection, naturally aspirated diesel engine, has been tested, without any modification, running on standard CDO and WPO derived from recycled plastic pyrolysis. The combustion and emission characteristics of the engine such as efficiency, fuel consumption, cylinder pressure and particulate matter emissions have been measured and studied. The results showed that the volumetric fuel ratio of WPO was lower than that of diesel at full load. As a result, the torque and power output of engine when using WPO were also lower, with the difference between the two fuels varying from 5 to 10%. When using WPO at low and medium speeds, specific fuel consumption was found to decrease, but it increased slightly at high speeds. The WPO global efficiency is always higher than diesel. At full load, the test results showed that the engine performance was the same with the 2 test fuels because the pump provides the same fuel volume, but WPO's BSFC is always lower than diesel because of its lower density . WPO efficiency is still higher. Soot emissions are consistently significantly lower when WPO is used as an engine fuel, and this difference can be as high as 50% at full load. The above studies have shown that waste plastic oil can be used for currently produced diesel engines without changing the engine structure. However, more tests need to be carried out to fully assess the reliability and operational durability of the engine.

PPO blends

Due to similar properties to petroleum products, PPO has the potential to be used as an alternative fuel in various types of internal combustion engines. Due to their excellent drivability and high performance for large loads, since the beginning of the 20th century, diesel engines have grown more and more. Moreover, diesel engines are robust and desirable for testing alternative fuels with the potential to replace petroleum diesel. However, there are limited studies on the use of WPO in diesel engines, and most of these works focus on the use of PPO-diesel blends in single cylinder diesel engines [72, 51]. Kalargaris, Tian and Gu [58] investigated the use of a medium PPO-diesel blend in larger and more multi-cylinder diesel engines. The results show that the diesel engine can produce an acceptable performance on the average mixture with diesel. However, because different pyrolysis parameters and raw materials have the potential to affect the quality of PPO, comparing engine performance results has been challenging throughout the research process. The potential of using oils that have been derived from the pyrolysis of plastics at different temperatures in diesel engines has been evaluated by Kalargaris, Tian and Gu [58]. The results of the analysis show that the oils produced have similar properties to diesel fuel. The plastic pyrolysis oil is then used during testing on a four-cylinder, direct-injection diesel engine to determine its combustion and emission characteristics to compare with pure diesel fuel.

The results show that the engine performs better on pyrolysis oil at higher loads. Since the oil produced at a lower temperature has a higher brake thermal efficiency and a shorter ignition delay at all loads, it can be seen that the temperature of the pyrolysis does not have a significant effect on the combustion process of PPO in engine. Compared with diesel, the brake thermal efficiency of the PPO900 and PPO700 fuels was 3-4% and 2-3% lower, respectively. Although the HC, CO, CO_2 and NOx emissions of these oils were higher than that of diesel, their emissions were found to be lower than that of oils produced at higher temperatures. The NOx emissions of the PPO900 are much higher than those of diesel and PPO700. More specifically, the NOX emissions of PPO900 are 45% higher than diesel at 100% load, and 65% higher at 75% load. Through the catalyzed pyrolysis of High Density Poly Ethylene (HDPE), Kumar et al. [73, 10] obtained plastic oil from waste plastic, and also analyzed the performance and emission characteristics of the diesel-plastic mixture at different loads. The results show that the brake thermal efficiency of plastic oil was lower than that of diesel at all loads. When adding the concentration of waste plastic oil, it can be seen that the BSFC of the engine increases, and CO and NOx emissions are also higher.

PROSPECTS AND CONCLUSION

Waste plastic has been and is a leading threat to the environment and the survival of species on earth. Recovering waste plastic to convert into value-added products such as fuel, recycled products, nano-additives, has been the goal of many recent studies. Technological solutions to convert waste plastic into waste plastic pyrolysis oils are considered as the key to reducing the negative effects of waste plastic on the environment and enhancing its economic value in society. This review has focused on clarifying the issues related to pyrolysis technology for the production of plastic pyrolysis oil which has been seen as a potential alternative fuel for diesel engines. Furthermore, analyzes and discussions of engine characteristics, combustion characteristics and emissions were reviewed to highlight the role of plastic pyrolysis oils. Recent studies all agree that catalytic pyrolysis has brought the highest efficiency in converting waste plastic into value-added products including plastic pyrolysis oil. Referring to the published literature on the properties of resin pyrolysis oils, it was concluded that it is quite suitable for use in compression-ignition engines.

It is possible to use WPO on CI engines without the need for structural and fuel system adjustments. Researches included a slightly lower cetane number than diesel, a flash point within safe limits, and a fairly adequate viscosity for the fuel system. In terms of engine characteristics, thermal efficiency is slightly improved compared to diesel fuel, while specific fuel consumption is higher. In terms of emissions, pure WPO used for diesel engines has shown higher concentrations of NOx, CO and HC emissions. However, WPO is blended in more appropriate proportions in diesel fuel, emission characteristics can be improved. With a participation rate of about 10-75% of WPO in diesel fuel, CO and HC emissions have been reduced almost by that of diesel fuel. In addition, the addition of certain additives can clearly improve the environmental and economic properties. The issue of engine durability when using WPO long-term fuel also needs to be considered in future studies before appropriate policies can be developed to widely deploy this potential fuel. As such, more extensive and diverse research may be needed to make WPO widely used and commercialized. Technical, environmental and economic factors should be combined to accurately assess the ability to use WPO fuel for engines equipped with vehicles.

REFERENCES

[1] B. Kunwar, H. N. Cheng, S. R. Chandrashekaran, and B. K. Sharma, “Plastics to fuel: a review,” Renew. Sustain. Energy Rev., vol. 54, pp. 421–428, 2016, doi: 10.1016/j.rser.2015.10.015.

[2] J. J. Klemeš, Y. Van Fan, and P. Jiang, “Plastics: friends or foes? The circularity and plastic waste footprint,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 43, no. 13, pp. 1549–1565, Jul. 2021, doi: 10.1080/15567036.2020.1801906.

[3] M. Q. Chau, A. T. Hoang, T. T. Truong, and X. P. Nguyen, “Endless story about the alarming reality of plastic waste in Vietnam,” Energy Sources, Part A Recover. Util. Environ. Eff., pp. 1–9, Aug. 2020, doi: 10.1080/15567036.2020.1802535.

[4] F. Zhang et al., “Current technologies for plastic waste treatment: A review,” J. Clean. Prod., vol. 282, p. 124523, 2021, doi: 10.1016/j.jclepro.2020.124523.

[5] M. Chandran, S. Tamilkolundu, and C. Murugesan, “Numerical simulation of diesel engine using waste plastic oil blends,” SN Appl. Sci., vol. 2, no. 9, 2020, doi: 10.1007/s42452-020-03417-3.

[6] Living Lab Zero Waste, “Plastic Pollution Fact: Plastic packaging production is predicted to quadruple by 2050,” 2020. [Online]. Available: https://www.greenpeace.org/usa/myths-about-ending-plastic-pollution/global_plastic-packaging-projections_2050czerowastelivinglab-by-enviu/.

[7] K. R. Bukkarapu, D. S. Gangadhar, Y. Jyothi, and P. Kanasani, “Management, conversion, and utilization of waste plastic as a source of sustainable energy to run automotive: a review,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 40, no. 14, pp. 1681–1692, Jul. 2018, doi: 10.1080/15567036.2018.1486898.

[8] D. Damodharan, B. Rajesh Kumar, K. Gopal, M. V. De Poures, and B. Sethuramasamyraja, “Utilization of waste plastic oil in diesel engines: a review,” Rev. Environ. Sci. Biotechnol., vol. 18, no. 4, pp. 681–697, 2019, doi: 10.1007/s11157-019-09516-x.

[9] J. Li, S. Chen, and L. Jiang, "Dynamic Strength and Accumulated Plastic Strain Development Laws and Models of the Remolded Red Clay under Long-Term Cyclic Loads: Laboratory Test Results," Polish Marit. Res., vol. 22, no. s1, pp. 89–94, 2015, doi: doi:10.1515/pomr-2015-0038.

[10] S. Bezergianni, A. Dimitriadis, G. C. Faussone, and D. Karonis, "Alternative diesel from waste plastics," Energies, vol. 10, no. 11, pp. 1–12, 2017, doi: 10.3390/en10111750.

[11] L. Lebreton and A. Andrady, "Future scenarios of global plastic waste generation and disposal," Palgrave Commun., vol. 5, no. 1, pp. 1–11, 2019, doi: 10.1057/s41599-018-0212-7.

[12] K. Ragaert, L. Delva, and K. Van Geem, "Mechanical and chemical recycling of solid plastic waste," Waste Management. 2017, doi: 10.1016/j.wasman.2017.07.044.

[13] P. T. Williams, "Hydrogen and Carbon Nanotubes from Pyrolysis-Catalysis of Waste Plastics: A Review," Waste and Biomass Valorization, vol. 12, no. 1. 2021, doi: 10.1007/s12649-020-01054-w.

[14] C. A. Rinaldini, E. Mattarelli, T. Savioli, G. Cantore, M. Garbero, and A. Bologna, "Performance, emission and combustion characteristics of a IDI engine running on waste plastic oil," Fuel, vol. 183, pp. 292–303, 2016, doi: 10.1016/j.fuel.2016.06.015.

[15] S. Budsaereechai, A. J. Hunt, and Y. Ngernyen, "Catalytic pyrolysis of plastic waste for the production of liquid fuels for engines," RSC Adv., vol. 9, no. 10, 2019, doi: 10.1039/c8ra10058f.

[16] Y. Zhang, G. Ji, C. Chen, Y. Wang, W. Wang, and A. Li, "Liquid oils produced from pyrolysis of plastic wastes with heat carrier in rotary kiln," Fuel Process. Technol., vol. 206, 2020, doi: 10.1016/j.fuproc.2020.106455.

[17] F. Wang, X. Deng, and Y. Li, "Elastic-Plastic Analysis for Circumferential through Crack at Boundary of Semi'S Brace under Beam Wave," Polish Marit. Res., vol. 25, no. 4, pp. 106–113, 2019, doi: doi:10.2478/pomr-2018-0137.

[18] S. Soulayman and D. Ola, "Synthesis parameters of biodiesel from frying oils wastes," Int. J. Renew. Energy Dev., vol. 8, no. 1, pp. 33–39, 2019, doi: 10.14710/ijred.8.1.33-39.

[19] R. K. Gopidesi, G. K. R. Kakunuri, J. Y. Manideep, C. P. Kalyan, and R. Rambabu, "Production of waste plastic oil and its impact on a diesel engine used as a fuel," in AIP Conference Proceedings, 2020, vol. 2311, doi: 10.1063/5.0033971.

[20] Sunaryo, P. A. Sesotyo, E. Saputra, and A. P. Sasmito, "Performance and fuel consumption of diesel engine fueled by diesel fuel and waste plastic oil blends: An experimental investigation," Automot. Exp., vol. 4, no. 1, 2021, doi: 10.31603/ae.3692.

[21] P. Sambandam, H. Venu, and B. K. Narayanaperumal, "Effective utilization and evaluation of waste plastic pyrolysis oil in a low heat rejection single cylinder diesel engine," Energy Sources, Part A Recover. Util. Environ. Eff., 2020, doi: 10.1080/15567036.2020.1803453.

[22] U. Pandey, J. A. Stormyr, A. Hassani, R. Jaiswal, H. H. Haugen, and B. M. E. Moldestad, "Pyrolysis of plastic waste to environmentally friendly products," WIT Trans. Ecol. Environ., vol. 246, 2020, doi: 10.2495/EPM200071.

[23] S. Mushtaq, S. Munir, J. A. Awan, and J. Akhtar, "Co-pyrolysis and hydrogenation of Thar coal, waste plastic and waste oil blends for fuel oil production," Energy Sources, Part A Recover. Util. Environ. Eff., vol. 40, no. 13, pp. 1604–1612, Jul. 2018, doi: 10.1080/15567036.2018.1486481.

[24] T. A. Hoang and V. Van Le, "The Performance of A Diesel Engine Fueled With Diesel Oil, Biodiesel and Preheated Coconut Oil," Int. J. Renew. Energy Dev., vol. 6, no. 1, p. 1, 2017.

[25] V. T. Bui, V. V. Pham, M. T. Pham, and T. H. Le, "A brief review on hydrogen as a potential fuel for internal combustion engines," J. Mech. Eng. Res. Dev., vol. 44, no. 7, pp. 120–130, 2021.

[26] T. R. Ayodele, A. S. O. Ogunjuyigbe, O. Durodola, and J. L. Munda, "Electricity generation potential and environmental assessment of bio-oil derivable from pyrolysis of plastic in some selected cities of Nigeria,"

Energy Sources, Part A Recover. Util. Environ. Eff., vol. 42, no. 10, pp. 1167–1182, May 2020, doi: 10.1080/15567036.2019.1602226.

[27] H. Jeswani et al., “Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery,” Sci. Total Environ., vol. 769, 2021, doi: 10.1016/j.scitotenv.2020.144483.

[28] T. S. Le, T. H. Le, and M. T. Pham, “A review of the indirect solar dryer with sensible heat storage mediums,” J. Mech. Eng. Res. Dev., vol. 44, no. 7, pp. 131–140, 2021.

[29] R. Kumar, M. K. Mishra, S. K. Singh, and A. Kumar, “Experimental evaluation of waste plastic oil and its blends on a single cylinder diesel engine,” J. Mech. Sci. Technol., vol. 30, no. 10, pp. 4781–4789, 2016, doi: 10.1007/s12206-016-0950-7.

[30] A. T. Hoang and V. V. Pham, “2-Methylfuran (MF) as a potential biofuel: A thorough review on the production pathway from biomass, combustion progress, and application in engines,” Renew. Sustain. Energy Rev., vol. 148, p. 111265, 2021.

[31] K. M. Wyss et al., “Converting plastic waste pyrolysis ash into flash graphene,” Carbon N. Y., vol. 174, 2021, doi: 10.1016/j.carbon.2020.12.063.

[32] S. L. Wu, J. H. Kuo, and M. Y. Wey, “Thermal degradation of waste plastics in a two-stage pyrolysis-catalysis reactor over core-shell type catalyst,” J. Anal. Appl. Pyrolysis, vol. 142, 2019, doi: 10.1016/j.jaap.2019.104641.

[33] S. P. Venkatesan, J. J. Jeevahan, J. Hemanandh, S. Ganesan, R. Rajakavieswaran, and V. Saravanan, “Performance and emission characteristics of diesel engine using waste plastic oil with N-hexanol as an additive,” in AIP Conference Proceedings, 2020, vol. 2311, doi: 10.1063/5.0034393.

[34] C. Muhammad, J. A. Onwudili, and P. T. Williams, “Thermal degradation of real-world waste plastics and simulated mixed plastics in a two-stage pyrolysis-catalysis reactor for fuel production,” Energy and Fuels, vol. 29, no. 4, 2015, doi: 10.1021/ef502749h.

[35] N. N. Pratama and H. Saptoadi, “Characteristics of waste plastics pyrolytic oil and its applications as alternative fuel on four cylinder diesel engines,” Int. J. Renew. Energy Dev., vol. 3, no. 1, pp. 13–20, 2014, doi: 10.14710/ijred.3.1.13-20.

[36] I. Dubdub and M. Al-Yaari, “Pyrolysis of mixed plastic waste: I. kinetic study,” Materials (Basel)., vol. 13, no. 21, 2020, doi: 10.3390/ma13214912.

[37] Q. Jin et al., “Synergistic effects during co-pyrolysis of biomass and plastic: Gas, tar, soot, char products and thermogravimetric study,” J. Energy Inst., vol. 92, no. 1, pp. 108–117, 2019.

[38] A. T. Hoang et al., “Rice bran oil-based biodiesel as a promising renewable fuel alternative to petrodiesel: A review,” Renew. Sustain. Energy Rev., vol. 135, p. 110204, Jan. 2021, doi: 10.1016/j.rser.2020.110204.

[39] R. Miandad, M. A. Barakat, M. Rehan, A. S. Aburiazaiza, I. M. I. Ismail, and A. S. Nizami, “Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts,” Waste Manag., vol. 69, 2017, doi: 10.1016/j.wasman.2017.08.032.

[40] K. Ding et al., “Improving hydrocarbon yield via catalytic fast co-pyrolysis of biomass and plastic over ceria and HZSM-5: An analytical pyrolyzer analysis,” Bioresour. Technol., vol. 268, 2018, doi: 10.1016/j.biortech.2018.07.108.

[41] S. Jamilatun, Budhijanto, Rochmadi, A. Yuliestyan, H. Hadiyanto, and A. Budiman, “Comparative analysis between pyrolysis products of Spirulina platensis biomass and its residues,” Int. J. Renew. Energy Dev., vol. 8, no. 2, pp. 133–140, 2019, doi: 10.14710/ijred.8.2.133-140.

[42] B. Żółtowski and M. Żółtowski, “A Hydrogenic Electrolyzer for Fuels,” Polish Marit. Res., vol. 21, no. 4, pp. 79–89, 2015, doi: doi:10.2478/pomr-2014-0044.

[43] N. Jeyakumar and B. Narayanasamy, "Investigation of performance, emission, combustion characteristics of municipal waste plastic oil fueled diesel engine with nano fluids," Energy Sources, Part A Recover. Util. Environ. Eff., pp. 1–22, Apr. 2020, doi: 10.1080/15567036.2020.1745958.

[44] Y. Zheng et al., "Preparation of aromatic and bio-char by pyrolysis of biomass and plastics catalyzed by modified HZSM-5," Nongye Gongcheng Xuebao/Transactions Chinese Soc. Agric. Eng., vol. 36, no. 17, 2020, doi: 10.11975/j.issn.1002-6819.2020.17.023.

[45] J. Gu, H. Fan, Y. Wang, Y. Zhang, H. Yuan, and Y. Chen, "Co-pyrolysis of xylan and high-density polyethylene: Product distribution and synergistic effects," Fuel, vol. 267, 2020, doi: 10.1016/j.fuel.2019.116896.

[46] H. Hassan, B. H. Hameed, and J. K. Lim, "Co-pyrolysis of sugarcane bagasse and waste high-density polyethylene: Synergistic effect and product distributions," Energy, vol. 191, 2020, doi: 10.1016/j.energy.2019.116545.

[47] Z. Dobó, Z. Jakab, G. Nagy, T. Koós, K. Szemmelveisz, and G. Muránszky, "Transportation fuel from plastic wastes: Production, purification and SI engine tests," Energy, vol. 189, 2019, doi: 10.1016/j.energy.2019.116353.

[48] D. Zhang, X. Lin, Q. Zhang, X. Ren, W. Yu, and H. Cai, "Catalytic pyrolysis of wood-plastic composite waste over activated carbon catalyst for aromatics production: Effect of preparation process of activated carbon," Energy, vol. 212, p. 118983, 2020, doi: 10.1016/j.energy.2020.118983.

[49] D. Damodharan, A. P. Sathiyagnanam, D. Rana, B. R. Kumar, and S. Saravanan, "Combined influence of injection timing and EGR on combustion, performance and emissions of DI diesel engine fueled with neat waste plastic oil," Energy Convers. Manag., vol. 161, no. December 2017, pp. 294–305, 2018, doi: 10.1016/j.enconman.2018.01.045.

[50] K. Wathakit et al., "Characterization and Impact of Waste Plastic Oil in a Variable Compression Ratio Diesel Engine," Energies, vol. 14, no. 8, 2021, doi: 10.3390/en14082230.

[51] Manoj Kumar and J. M. Mallikarjuna, "Experimental Investigation on a Compression Ignition Engine with Blends of Plastic Oil and Diesel as Fuel," 2021, doi: 10.1007/978-981-15-5996-9_7.

[52] P. Nalluri, P. Prem Kumar, and M. R. Ch Sastry, "Experimental study on catalytic pyrolysis of plastic waste using low cost catalyst," Mater. Today Proc., vol. 45, 2021, doi: 10.1016/j.matpr.2021.02.478.

[53] B. G. Sudershan, N. R. Banapurmath, M. A. Kamoji, P. B. Rampure, and S. V. Khandal, "Experimental investigation of a CRDI engine in terms of performance and emission under the effect of injection strategy using a moderate percentage of plastic pyrolysis oil and its blends with diesel and ethanol," Biofuels, vol. 12, no. 4, 2021, doi: 10.1080/17597269.2018.1493563.

[54] A. T. Hoang and V. V. Pham, "A review on fuels used for marine diesel engines," J. Mech. Eng. Res. Dev., vol. 41, no. 4, pp. 22–32, 2018.

[55] D. K. Ramesha, G. P. Kumara, Lalsaheb, A. V. T. Mohammed, H. A. Mohammad, and M. A. Kasma, "An experimental study on usage of plastic oil and B20 algae biodiesel blend as substitute fuel to diesel engine," Environ. Sci. Pollut. Res., vol. 23, no. 10, 2016, doi: 10.1007/s11356-015-5981-6.

[56] L. Quesada, M. Calero, M. A. Martín-Lara, A. Pérez, and G. Blázquez, "Characterization of fuel produced by pyrolysis of plastic film obtained of municipal solid waste," Energy, vol. 186, no. 2019, 2019, doi: 10.1016/j.energy.2019.115874.

[57] V. K. Kaimal and P. Vijayabalan, "A detailed study of combustion characteristics of a DI diesel engine using waste plastic oil and its blends," Energy Convers. Manag., vol. 105, pp. 951–956, 2015, doi: 10.1016/j.enconman.2015.08.043.

[58] I. Kalargaris, G. Tian, and S. Gu, "Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil," Fuel Process. Technol., vol. 157, pp. 108–115, 2017, doi: 10.1016/j.fuproc.2016.11.016.

[59] I. Kalargaris, G. Tian, and S. Gu, “Experimental evaluation of a diesel engine fuelled by pyrolysis oils produced from low-density polyethylene and ethylene–vinyl acetate plastics,” Fuel Process. Technol., vol. 161, pp. 125–131, 2017, doi: 10.1016/j.fuproc.2017.03.014.

[60] D. Damodharan, A. P. Sathiyagnanam, D. Rana, B. Rajesh Kumar, and S. Saravanan, “Extraction and characterization of waste plastic oil (WPO) with the effect of n-butanol addition on the performance and emissions of a DI diesel engine fueled with WPO/diesel blends,” Energy Convers. Manag., vol. 131, pp. 117–126, 2017, doi: 10.1016/j.enconman.2016.10.076.

[61] R. K. Singh, B. Ruj, A. K. Sadhukhan, P. Gupta, and V. P. Tigga, “Waste plastic to pyrolytic oil and its utilization in CI engine: Performance analysis and combustion characteristics,” Fuel, vol. 262, no. May, p. 116539, 2020, doi: 10.1016/j.fuel.2019.116539.

[62] P. Bridjesh, P. Periyasamy, A. V. Krishna Chaitanya, and N. K. Geetha, “MEA and DEE as additives on diesel engine using waste plastic oil diesel blends,” Sustain. Environ. Res., vol. 28, no. 3, pp. 142–147, 2018, doi: 10.1016/j.serj.2018.01.001.

[63] P. Senthilkumar and G. Sankaranarayanan, “Effect of Jatropha methyl ester on waste plastic oil fueled DI diesel engine,” J. Energy Inst., vol. 89, no. 4, pp. 504–512, 2016, doi: 10.1016/j.joei.2015.07.006.

[64] C. Wongkhorsub and N. Chindaprasert, “A comparison of the use of pyrolysis oils in diesel engine,” Energy Power Eng., vol. 5, no. 04, p. 350, 2013.

[65] A. Janyalertadun, C. Santaweesuk, and S. Sanongraj, “Fuel production, performance, and emission of a CI engine using waste plastics oil,” World J. Eng., vol. 14, no. 2, 2017, doi: 10.1108/WJE-08-2016-0044.

[66] M. Mani and G. Nagarajan, “Influence of injection timing on performance, emission and combustion characteristics of a DI diesel engine running on waste plastic oil,” Energy, vol. 34, no. 10, 2009, doi: 10.1016/j.energy.2009.07.010.

[67] C. Güngör, H. Serin, M. Özcanl, S. Serin, and K. Aydin, “Engine performance and emission characteristics of plastic oil produced from waste polyethylene and its blends with diesel fuel,” in International Journal of Green Energy, 2015, vol. 12, no. 1, doi: 10.1080/15435075.2014.893873.

[68] A. K. Panda, S. Murugan, and R. K. Singh, “Performance and emission characteristics of diesel fuel produced from waste plastic oil obtained by catalytic pyrolysis of waste polypropylene,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 38, no. 4, 2016, doi: 10.1080/15567036.2013.800924.

[69] S. Kumar, R. Prakash, S. Murugan, and R. K. Singh, “Performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine,” Energy Convers. Manag., vol. 74, 2013, doi: 10.1016/j.enconman.2013.05.028.

[70] V. T. Bui, T. H. Le, P. Van Viet, and X. P. Nguyen, “A study evaluating the ability to recover cooling water waste heat using organic Rankine cycle on marine engines,” J. Mech. Eng. Res. Dev., vol. 44, no. 4, pp. 19–25, 2021.

[71] V. Chintala, P. Godkhe, S. Phadtare, M. Tadpatrikar, J. K. Pandey, and S. Kumar, “A comparative assessment of single cylinder diesel engine characteristics with plasto-oils derived from municipal mixed plastic waste,” Energy Convers. Manag., vol. 166, no. April, pp. 579–589, 2018, doi: 10.1016/j.enconman.2018.04.068.

[72] N. G and C. Thamotharan, “Performance and Emissions Characteristics of twin cylinder Diesel Engine Fueled with Waste Plastic Oil & Diesel Blends with multi functional diesel fuel Additive,” IOSR J. Mech. Civ. Eng. Ver, vol. 12, no. 2, 2015.

[73] A. K. Das, M. R. Padhi, D. Hansdah, and A. K. Panda, “Optimization of Engine Parameters and Ethanol Fuel Additive of a Diesel Engine Fuelled with Waste Plastic Oil Blended Diesel,” Process Integr. Optim. Sustain., vol. 4, no. 4, pp. 465–479, 2020, doi: 10.1007/s41660-020-00134-7.