Plastic waste to liquid fuel: A review of technologies, applications, and challenges

Vikas Sharma[a,*], **Abul Kalam Hossain**[a], **Gareth Griffiths**[a], **Ganesh Duraisamy**[b], **Anand Krishnasamy**[c], **Vinu Ravikrishnan**[c], **José Ricardo Sodré**[a]

[a] *College of Engineering and Physical Sciences, Aston University, Birmingham B4 7ET, UK*
[b] *College of Engineering Guindy, Anna University, Chennai 600025, India*
[c] *Indian Institute of Technology Madras (IIT Madras), Chennai 600036, India*

Abstract

One of the most promising approaches for converting waste plastics into oil is fast pyrolysis. This study reviews the current state of the art and recent progress made on the thermal conversion of plastic to oil technologies, and their uses as alternatives to fossil fuels. The fuel properties of waste plastic pyrolysis oil (WPPO) are close to the diesel fuel. The WPPO produced from high-density polyethylene, low-density polyethylene, polypropylene, and polystyrene have higher heating values ranging from 40 to 43 MJ/kg. The thermal efficiency of neat WPPO (or blends) was slightly lower than diesel or gasoline. The WPPO has a shorter ignition delay than diesel due to its high cetane number. The WPPO fuels have a lower peak in-cylinder pressure and heat release rate than diesel. Engine-out emissions such as smoke, CO, and CO_2, are lower than diesel. The NO_x emissions are higher than diesel, which can be reduced with exhaust gas recirculation or use of additives. Our study reveals that the WPPO is a promising alternative fuel for diesel engine applications.

Keywords: Energy; Engine; Environment; Performance; Plastic Oil; Pyrolysis

* Corresponding author.
Email address: v.sharma10@aston.ac.uk (Vikas Sharma)

Nomenclature

ABS	Acrylonitrile butadiene styrene	NZ	Natural Zeolite
AC	Air cooled	PVC	Polyvinyl chloride
bTDC	Before top dead centre	PET	Polyethylene terephthalate
CP	Catalytic pyrolysis	PP	Polypropylene
CD	Combustion duration	PS	Polystyrene
CI	Compression ignition	PA	Polyamide
DTBP	Di-tert-butyl peroxide	PBT	Polybutylene terephthalate
FCC	Fluid catalyst cracking	RP	Rated power
HDPE	High density polyethylene	SoC	Start of combustion
HRR	heat release rate	SC-4s	Single cylinder 4- stroke
ID	Ignition delay	TP	Thermal pyrolysis
LDPE	Low density polyethylene	WC	Water cooled
MEA	Methoxy ethyl acetate	WPPO	Waste plastic pyrolysis oil
Mt	Million tonnes		

Introduction

Plastics are used globally due to their distinctive characteristics such as low cost, adaptability, durability, and high strength-to-weight ratio. Indeed, it is difficult to envisage a future without plastics [1] since they offer substantial economic benefits to various industries including packaging, building, transportation, healthcare, and electronics [2]. However, in recent years, the public perception of plastics has changed from a critical enabler of progress to a primary driver for the depletion of natural resources, waste creation, environmental degradation, climate change and negative impacts on food chains (especially aquatic life) and ultimately human health [3] [2,3]. Plastic production has shifted quickly in recent years from Europe and the United States to Asian countries, and its exponential growth (Fig. 1) shows its success over the last century. Approximately, 400 million tonnes/year (billion kg per day) of plastics are produced worldwide [4]. Figure 1 shows a fourfold increase in projected production capacity by 2050, which raises concerns about increased environmental damage. Policies to dispose of plastics or stop and reverse plastics contamination have proved challenging for policymakers [5]. According to a recent study, 8.3 billion metric tonnes of plastic was produced since 1950, and half of that produced since 2002 [4,6]. Most of the disposable plastics have never been recycled [4,6]. For example, packaging accounts for more than a third of all plastics manufactured globally, often not recycled and instead ends up as waste [4,6]. Out of 6300 Mt of waste plastic produced during 1995-2015, 9 % was recycled, and 12 % was burned [7]. In South Asian countries, India has the highest recycling rate of 47-60 % [7]. Nearly 60% of all plastics produced are being disposed of in the natural environment, and if recent trends continue, then over 12 billion Mt of waste plastics will end up in these depositories by 2050 [8–10]. Furthermore, plastic litter or plastic escaping from landfills often enters the marine environment [11]. Plastic trash production, landfilling, and incineration generates around 400 Mt of CO_2 each year globally [11]. Almost ninety-nine percent of plastics are made from petroleum and out of that about 90% are produced from virgin fossil fuel feedstock. Plastic industries currently utilize 8-9% of worldwide oil and gas production [11–13], and this is projected to grow fourfold by 2050 (Fig. 1). To reduce the GHG emissions, plastic production from bio-based materials are being developed [14]. Generally, these products are richer in oxygen and are easier to degrade since they contain functional groups such as esters, which are more amenable to degradation by microorganisms [15]. However, growing crops for plastic feedstock raises ethical questions about land use for plastics vs. food production [14,16,17]. Plastic recycling is an efficient approach to reduce fossil energy use and GHG emissions [18]. According to one study, mechanical recycling reduces CO_2 emissions by around 0.6 tonnes per year. The thermochemically produced plastic oil can be used for energy production and recovery [18 -20].

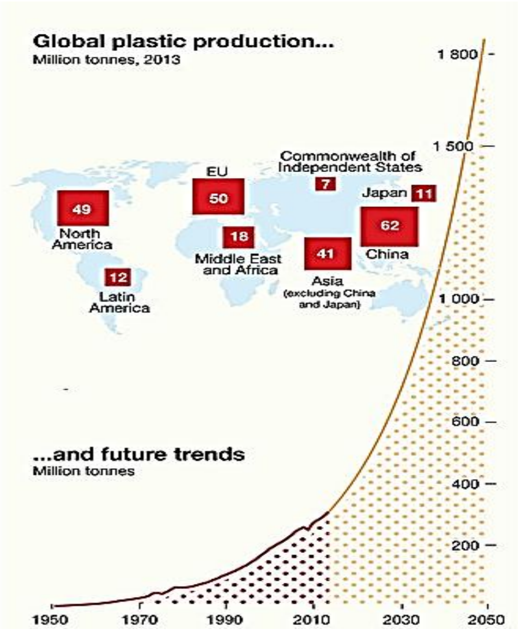


Fig. 1. Global plastics production 1950-2013 [19].

Chemical kinetic models for recycling solid plastic waste focusing on pyrolysis, co-pyrolysis, and gasification and improving conversion efficiency through reactor design have been developed [20]. The performance of numerous catalytic co-pyrolysis reactors for various feedstock-catalyst-ratios, process temperature, and other functioning factors have been examined by various research groups [19-22]. Wong et al. [21] studied the technical aspects of transforming waste plastic into gasoline using microwaves, thermal, catalytic pyrolysis and co-pyrolysis. Quality of the oil yield obtained from low-density polyethylene (LDPE) plastic waste utilizing three different types of pyrolysis reactors were investigated [22]. They employed LDPE-White, LDPE mixed-plastic, and LDPE blend-plastic as feedstock [22]. They reported that better quality plastics gave reduced reaction time and higher oil yields. At 250℃ reaction temperature, the oil yield of three LDPE mixtures were reported as 99.78%, 75.60%, and 50.29% when pyrolyzed for 110, 180, and 270 mins, respectively [22]. Sharuddin et al. [23] examined the pyrolysis procedures for several plastics and the critical process parameters that affect product yield [23]. Most plastics could provide good oil yields at lower temperatures with proper catalyst selection [23]. Pyrolysis and gasification are two methods for producing fuels from waste plastics [23–25]. By-products of pyrolysis, such as gas, can produce heat and power; while char can be used to enhance soil quality, or as ‘green’ materials for road construction, or as absorbents for wastewater treatment [23,26]. WPPO exhibit fuel properties similar to fossil diesel, suggesting that they could be employed in diesel engines as suitable alternatives [27]. However, in the application of plastic pyrolysis oil in internal combustion engines, there is a knowledge gap. In the present review, the current state-of-the-art on use of plastic pyrolysis oil in diesel engines in terms of performance, combustion, emissions, and the issues and opportunities that it brings are examined.

Plastic Waste Generation and Management

Plastic waste generation

In 2015, 407 Mt of primary plastics were manufactured, with 302 Mt of primary garbage created [28]. Figure A.1 (see Appendix) depicts the generation of plastic waste by sector - packaging, institute products, and electrical/electronic garbage produced most waste. Figure 2(a) illustrates the major types of plastic wastes and their accelerated production. By 2050, 2000 Mt of additives, 6000 Mt of PP and Acrylic (PP&A), and 26000 Mt of resins will have been created if current production rates continue [28,29]. Over 9000 Mt of plastic garbage has been recycled, 12,000 Mt has been burned, and 12,000 Mt has been thrown in landfills (Fig. 2(b)) [28,29].

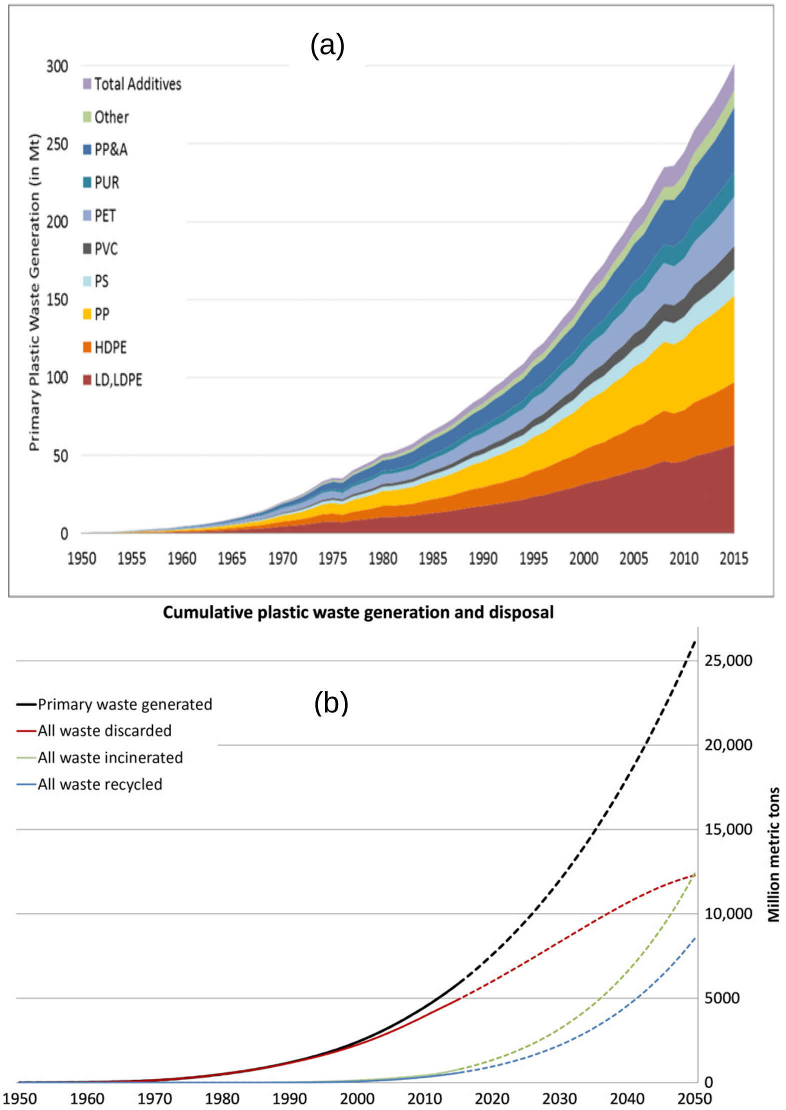


Fig. 2. (a) plastics waste generation (b) plastic waste generation and disposal (solid lines show historical data) [7].

Plastic waste management

Plastic waste management involves three different recycling processes - mechanical, biological and thermo-chemical conversion (Fig. A.2 – see Appendix) [29,30]. Non-recycling route, landfilling, is the most common solid waste management strategy, creating short-term and long-term environmental and health issues [29]. The excessive utilization of landfilling contaminates groundwater and soil, leading to increased air pollution, wildlife disruption and GHG emissions [29]. Plastics, with time, degrade, generating smaller sized fragments and are termed macro, meso and microplastics with the latter having sizes <5 mm, and this process can be accelerated by photo-beaching [29]. These microplastics pollute sea and river water [29].

Mechanical recycling involves separating single plastic, shredding, washing and drying and quenching [30]. Due to the limitations on feedstock type, only about 15-20% of the total plastic waste can be recycled through this means [31]. Hence, mechanical recycling is not sustainable to manage the vast amount of plastic wastes [31]. Chemical recycling can decompose most plastic waste types [32]. Thermal decomposition (gasification and pyrolysis), and hydrocracking are two main chemical recycling techniques. Fast pyrolysis is preferred for producing bio-oil as the principal product. The amount of gas and char increases at lower heating speeds (intermediate and slow pyrolysis). Catalytic cracking and hydrogenation are both hydrocracking processes [32]. Heavy hydrocarbon cracking happens at high temperatures and pressures in the presence of hydrogen and catalyst [32].

Another route for plastic waste management is incineration, resulting in complete decomposition and offers thermal energy recovery with a concomitant high volumetric reduction in plastic waste [32–34]. However, there are numerous pollution and health issues associated with the incineration of plastics, including the release of toxic gases (e.g. polycyclic aromatic hydrocarbons, polychlorinated biphenyls, dioxins, and phosgene) and dust, which are harmful to the ecosystem and pose significant health risks to human [32,35]. Dioxin has been associated with increased cancer rates and reproductive abnormalities [35].

In Singapore, Khoo [36] used eight distinct scenarios to conduct a life cycle assessment of plastic waste recovery into recyclable materials, electricity, and fuel. These scenarios consider various recycling rates and technologies. According to the authors, 822.2 Mt of plastic waste was produced in 2016; and out of this product, only 7% was recycled (Fig. A.3(a) – in Appendix). Plastics waste generation and recycling rates varies widely. Countries such as Singapore and the United States have the lowest recycling rates; whereas, 78% of the waste plastics are recycled in Japan. [36]. Out of 8 scenarios examined, scenario 7 showed the highest net potential with the suggestion of a waste pyrolysis plant, which showed 54% energy recovery (Fig. A.3(b)) [36]. The net GHG emissions is dependent on the recycling and conversion technology used (Fig. A.4 – in Appendix). Sustainable plastic waste management focuses on the 3R and 3E methods: “R’s” **R**educed, **R**euse, **R**ecycle (energy recovery) and 3E- Energy, Economy, and Environment security [36]. Strategies of modern energy recovery could reduce plastic waste by 90% (vol.) by converting it into liquid oil through pyrolysis [35,36]. Hence, from both ‘R’ and ‘E’ point of view, pyrolysis process is preferable for waste plastic recycling.

Chemical recycling - pyrolysis

Pyrolysis is a viable method for recycling waste plastics. Thermal pyrolysis (TP) is a non-catalytic endothermic pyrolysis process [37,38]. Cross-linking, chain stripping, random chain, and end chain scission are the four separate chemical mechanisms [38,39]. Catalytic pyrolysis (CP) is better for producing more liquid oil from waste plastic [39,40]. It can proceed at lower temperatures and retention times, requiring less energy than thermal pyrolysis [39,40]. However, plastic oil generated through CP contains lower carbon chain length products, reduced liquid oil yield and increased gas generation [40,41]. Microwave pyrolysis, a thermal decomposition method [42], in which microwave radiation heats and pyrolyzes the feedstock at temperatures of between 300 and 800 ℃ [43]. Microwave pyrolysis provides various advantages over traditional heat sources like an oven or furnace, including faster heating, better heat distribution, and a higher production rate [44]. This technique enables direct heating and processing of big, wet feedstocks without pre-treatment requirements like drying or size reduction, resulting in decreased operating costs [42–44]. Employing microwave pyrolysis poses an additional danger of microwave radiation exposure, which can be avoided by using a Faraday cage [42–44].

Chemical compositions and architectures differ across plastics - Table 1, and Fig. A.5 and A.6 (in Appendix). For liquid oil generation, plastics with a high volatile matter and low ash content are better [23,45]. Polypropylene (PP) and polystyrene (PS) are suitable for liquid oil production at higher temperatures (700-800℃) and without the need for a catalyst [23,45,46]. At high temperatures (700-800°C), polyethylene (PE) generates wax, necessitating the employment of a catalyst to produce liquid oil [45,46]. Polyvinylchloride (PVC) is unsuitable for pyrolysis since it produces a high % of hazardous chemicals such as hydrochloric acid and chlorine gas; this require a de-chlorination process, which would increase operation and capital costs [47].

Table 1
Proximate and ultimate analysis of various plastics.

		Proximate %				**Ultimate %**						
Types of Plastic	**Identify Marks**	**Moisture (wt.%)**	**Fixed carbon (wt.%)**	**Volatile (wt.%)**	**Ash (wt.%)**	**C %**	**H %**	**N %**	**S %**	**O* %**	**Remarks**	**Ref.**
PET	♳	0.46-0.61	7-13	86-91	0-0.02	65	5	0.05	0.01	32	Not suitable for pyrolysis Contains heteroatoms	[3, 47]
HDPE	♴	0.00	0.01-0.03	97-99	0.18-1.40	84	14	0.08	0.02	0.30	Excellent for pyrolysis. Temperature of >500 ℃ is necessary, due to branched chain structure Converts into wax instead of liquid oil.	[3, 47]
LDPE	♶	0.30	0.00	99	0.00-0.40	81	13	0.07	0.02	0.20		
PVC	♵	0.74-0.80	5-7	93-95	0.00	-	-	-	-	-	Unsuitable for pyrolysis. Dechlorination is required	[3, 47]
PP	♷	0.15-0.18	0.1-1.3	95-97	1-4	85	13.5	0.06	0.03	0.20	Excellent for pyrolysis. Requires a high temperature. In catalytic pyrolysis, oil with aromatic compounds generated.	[3, 47]
PS	♸	0.25-0.30	0.12-0.20	98-99.65	0.00	90	9	0.07	0.01	0.00	Better fuel properties. Required lower temperature then PP and PE Produces less viscous oil than PP and PE	[3, 47]
Other (ABS, PA, PBT)	♹	0.00-0.2	0.05-3	97-99.6	0-1.5	-	-	-	-	-		[24]

ABS –, **PA**- Polyamide, **PBT**- Polybutylene terephthalate

Pyrolysis parameters

One of the major operating parameters in pyrolysis is temperature, which influences the quantity and quality of bio-oil produced [47,48]. The plastic melts, and the high-energy molecules vaporizes as temperature inside the reactor rises [49]. Carbon chain fragmentation occurs when the energy produced by Van der Waals forces in the polymer chain rises above the constituent C-C bonds [49,50]. The effect of temperature on waste plastic pyrolysis can be seen in Fig. 3, and in Tables 2 and 3. Literature reported that PS, LDPE, and PP show a higher liquid oil yield fraction than PET and PVC (Fig. 3). The liquid oil fraction increases gradually with an increase in the temperature (350-500℃), and a further rise in temperature decreases the oil yield [47,51,52]. At very high temperatures, the retention time was short of converting wax into bio-oil molecules [47,51,52].

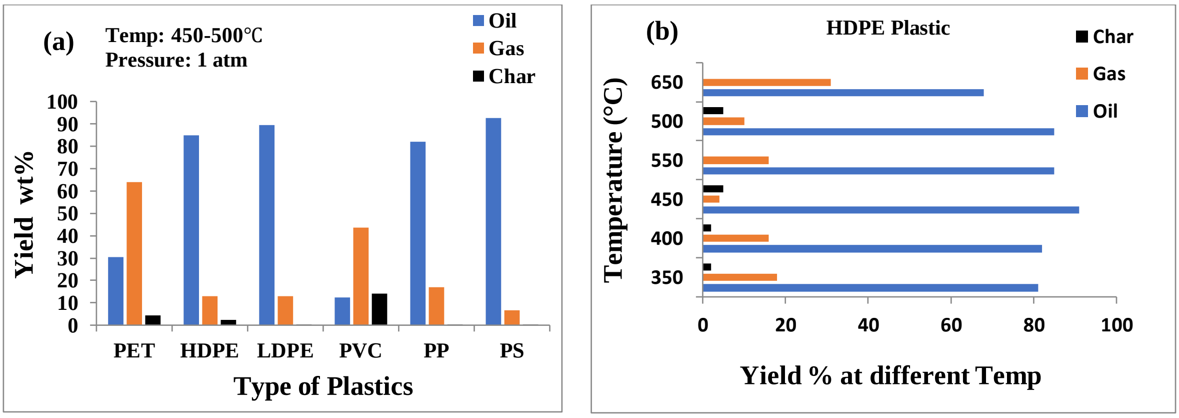


Fig. 3. Effect of temperature on yield: (a) various plastics, (b) HDPE [47,51–53].

Conversely, increasing the pyrolysis reactor pressure shows negative impacts on oil yield at elevated temperatures (Table 2); high pressure decreases the formation rate of double bonds and generates lower molecular weight products [47,51–53]. Murata et al. [54] investigated the impact of pressure on HDPE pyrolysis at 0.1-0.8 MPa, they reported that oil output was significantly affected at high pressures.

Table 2
Impact of process characteristics on oil yield.

Types of plastic	Reactor	Process Parameters				Effect of Yield			Ref.
		Temp (℃)	Pressure	Heating rate (℃/min)	Duration (min)	Oil (wt.%)	Gas (wt.%)	Char (wt.%)	
PET	Fixed bed	500	-	10	-	23	76	0	[47]
PET	Horizontal steel	500	1 atm	6	-	38	52	9	[32]
HDPE	Horizontal steel	350	-	20	30	81	18	2	[23]
HDPE	Semi batch	400	1 atm	7	-	82	16	2	[55]
HDPE	Semi batch	450	1 atm	25	-	91	4	5	[55]
HDPE	Batch	450	-	-	60	74	6	20	[56]
HDPE	Batch	550	-	5	-	85	16	0	[57]
HDPE	Fluidized bed	500	-	-	60	85	10	5	[58]
HDPE	Fluidized bed	650	-	-	22	68	31	0	[58]
LDPE	Pressurised Batch	425	4MPa	10	60	90	10	0.5	[59]

LDPE	Batch	430	-	3	-	76	8	7	[60]
LDPE	Batch	550	-	5	-	93	14	0	[61]
LDPE	Fixed bed	500	-	10	20	95	5	0	[61]
LDPE	Fluidized bed	600	1 atm	-	-	51	24	0	[38]
LDPE	Fixed bed	500	1 atm	6	-	81	20	0.15	[60]
PVC	Fixed bed	500	-	10	-	12	87	0	[27]
PVC	Vacuum bed	520	2 kPa	10	-	13	0.4	28	[27]
PP	Horizontal steel	300	-	20	30	69	29	1.4	[45]
PP	Semi-batch	400	1 atm	7	-	85	13	2	[39]
PP	Semi-batch	450	1 atm	25	-	92	4	3.5	[39]
PP	Batch	380	1 atm	3	-	80	6.6	13	[62]
PP	Batch	740	-	-	-	49	50	1.5	[23]
PP	Fixed bed	500	1 atm	6	-	82	17	0.13	[23]
PS	Batch	500	-	-	150	96	3.27	0	[57]
PS	Batch	581	-	-	-	89	10	0.5	[23]
PS	Semi-batch	400	1 atm	7	-	90	6	4	[23]
PS	Pressurised Batch	425	1 MPa	10	60	97	2.5	0.5	[63]

Effect of catalytic cracking on pyrolysis products

Catalysts are classified into two main categories: homogeneous, involving one phase; and heterogeneous, involving two or more phases [64]. Heterogeneous catalysts are preferable because they can be easily removed from mixtures for reuse [21,64]. Natural zeolite (NZ), Silica-alumina (SA), and fluid catalyst cracking (FCC) are three heterogeneous catalysts commonly employed in waste plastic pyrolysis [59,65]. A summary of the effects of catalysts on pyrolysis products is described in Table A.1 (presented in Appendix). Catalyst enhances reaction rates by reducing the system's activation energy, thereby generally lowering temperature and pressure requirements, which has an economic benefit on the process (Table A.1) Catalysts are also utilized to increase the hydrocarbon distribution in pyrolysis oil, which improves the quality of the pyrolysis liquid oil [66].

Characterization of Plastic Pyrolysis Oil

Pyrolysis fuel produced from waste plastics must meet fuel standards such as the American standard (ASTM), European standards (EU), or those of many other countries where WPPO could be used as a transportation fuel [58] [67]. The physical and chemical qualities of fuel are split into two categories, both of which are important for improving diesel engine performance, combustion, and pollution [55]. The ignition, combustion, and emission formation of fuel are affected by fuel quality and associated thermophysical properties [68]. The essential fuel properties that influence diesel engine performance include cetane number, density, viscosity, and calorific value (Table 3).

Table 3
Characteristics of WPPO [67-96].

Properties	PET	HDPE	LDPE	PVC	PP	PS	Mix	Gasoline	Diesel
Calorific Value (MJ/kg)	28	40	40	21	40	43	41	42.5	43
API° gravity	n.a	28	48	39	33	n.a	38.98	55	38
Viscosity at 40°C (mm^2/s)	n.a	5.08	5.55	6.36	4.09	1.4	2.52	1.17	1.9-4.1
Density at 15 °C (g/cm^3)	0.9	0.89	0.78	0.85	0.86	0.85	0.83	0.78	0.807
Ash content (wt.%)	n.a	0	0.02	n.a	0	0.006	1.04	0	0.01
Octane Number	n.a	85	n.a	n.a	87	n.a	n.a	81-85	15-25
Cetane Number	n.a	95	85	n.a	97	90-98	60	93-97	52
Pour Point (°C)	n.a	-5	-7	-15	-9	-67	-42	0	6
Flash Point (°C)	n.a	48	41	40	30	26	30	42	52
Aniline Point (°C)	n.a	45	n.a	n.a	40	n.a	n.a	71	77.5

Physical Properties of WPPO

Viscosity and density

Viscosity directly affects engine performance by influencing fuel spray penetration, atomization, vaporization, and ultimately combustion efficiency [69,70]. Generally, plastic oils have higher viscosity than diesel and gasoline (Table 3). The PS and mixed plastic oils have higher viscosity than gasoline but lower than diesel fuel [71]. Due to feedstocks' varied compositions and structures, plastic oils from PET, HDPE, LDPE, PVC, PP, PS, and mixed polymers have variable viscosities [72]. Ates et al. [73] examined various catalytic pyrolysis processes of municipal plastic waste in a batch reactor. They found a high percentage of aromatic compounds produced from long-chain aliphatic molecules in the presence of catalysts (Y-zeolite, zeolite, equilibrium FCC, Molybdenum oxide (MoO_3), Ni-Mo-catalyst, HZSM-5, and $Al(OH)_3$) resulting in a slight increase in viscosity [73]. Plastic oil shows a higher density than fossil fuel (Table 3). It means mechanically operated fuel pumps inject a higher mass of WPPO than fossil fuel due to volumetric operation [74]. Hence density affects the air-fuel ratio, energy content, in-cylinder temperature and engine-out emissions. The relative densities of petroleum liquids are commonly compared and analysed using API° gravity scale. If the API° gravity exceeds 10, it is classified as a light oil. If the number is less than 10, the oil is classified as heavy oil [75].

Calorific value and ignition quality

The calorific value (CV) of HDPE, LDPE, PP, PS, and mix plastics are 40, 40, 40, 43, and 41.2 MJ/kg respectively (Table 3), close to fossil diesel fuel. The CV oils produced from PET and PVC are 28 and 21 MJ/kg respectively, which is below the permitted fuel standard limit of 30 MJ/kg [76–79]. Presence of benzoic acid and chlorine in PET and PVC accounted for the lower CV of PET and PVC. Due to the presence of aromatic rings, which have lower combustion energy than aliphatic hydrocarbons, PP and mixed plastic have somewhat lower CV than PE and PS [80]. Fuel with a higher CN results in better combustion, particularly during cold-start conditions [81]. Generally, plastic oils have higher cetane and octane numbers than fossil fuels. The WPPO sourced from HDPE and PP gave higher cetane numbers of 95, and 97 compared to other plastic oils [82]. Mixed waste plastics fuel shows lowest cetane number compared to single plastic oil, but it is still higher than fossil fuel (Table 3). The range of distillation products obtained at low temperature for various plastics are shown in Table A.2 (in Appendix). The HDPE and LDPE gave similar profiles (Table A.2), rich in paraffins and olefins except 2,4-dimethyl-1-heptene, which is generally not detected in LDPE [59,65]. Paraffins often have lower octane number than olefins. The PP oil includes predominantly branched hydrocarbon chains, but the PS oil has a significant aromatic component, resulting in high octane rating [76–79]

WPPO Application in Diesel Engines

Waste plastic pyrolysis oil (WPPO) offers big potential for both transportation and stationary engine applications. Literature data on engine performance and combustion characteristics of WPPO fuel in diesel engines have been collated and summarized in Tables 4 and 5.

Engine Performance Characteristics

The BSFC and BTE are directly influenced by the physio-chemical properties of the fuel. Venkatesan et al. [83], investigated the engine performance of WPPO15% and WPPO30% blends (blended with diesel). They found that at full load, the BTE for WPPO30% blend was slightly higher and BSFC was significantly increased than neat diesel (Table 4). Chintala et al. [78], examined the effects of WPPO-diesel blends (WPPO25%, WPPO50%, and WPPO75%) in a diesel engine. The WPPO was extracted from municipal waste plastics. Due to lower CV and higher viscosity, the BTE of WPPO blends were lower than diesel and neat WPPO at all engine load conditions. Studies with high WPPO concentration in blends demonstrated variations in BTE with various WPPO-diesel blends; the BTE of WPPO10%, WPPO30%, WPPO50%, WPPO70%, neat diesel, and neat WPPO was roughly 28.2 %, 27.95 %, 27.42 %, 26.5 %, 28%, and 27.4 % respectively at full load. The BTE of WPPO10% was found near to diesel fuel (Fig. 4(a)) [84].

Kumar et al. [85] studied the HDPE plastic oil with diesel in a diesel engine and observed lower BTE than diesel. The BSFC increased as the WPPO concentration in the blend increased. Kalargaris et al. [86] synthesized WPPO at two different elevated temperatures, WPP700 at 700 ^{o}C and WPP900 at 900 °C. These samples were tested in a diesel engine and exhibited a 2 % increase in BTE at full engine load compared to 75 % load for all fuel blends. With increased EGR flow rate and at full load, BTE value reduced by around 2% [87]. Another study looked at performance of the WPPO (30%) blend with fossil diesel in a two-cylinder common rail direct injection engine by varying EGR flow rates (0, 10, and 20%) and at variable loads from 0 to 80 % (in 20 % increments) [77].

A slight loss in engine performance was observed while running with WPPO blends because of higher viscosity and lower CV. Dilution of charge due to high EGR % resulted in reduced oxygen content during combustion and a drop in BTE. Furthermore, a higher EGR flow rate reduced the average combustion temperature [77,87]. The influence of injection timing (23, 20,17, and 14 °bTDC) on engine performance with WPPO as fuel at various engine loads revealed that the injection timing of 14 °bTDC gave higher BTE than conventional injection timing of 23 °bTDC [88]. The WPPO blends (10,2 0 & 30%) tested in single-cylinder diesel engines with varied injection timings (10^{o} retard and 8^{o} advance bTDC) [83]. They found that the BTE increased with increasing load under advanced injection timing conditions. Studies on the effects of WPPO on indirect injection (IDI) engines running on partial and full load at various engine speeds (ranging from 1500-3000 rpm) found that the WPPO resulted in lower engine performance, but with improvement in BSFC of up to 8% [75].

Table 4

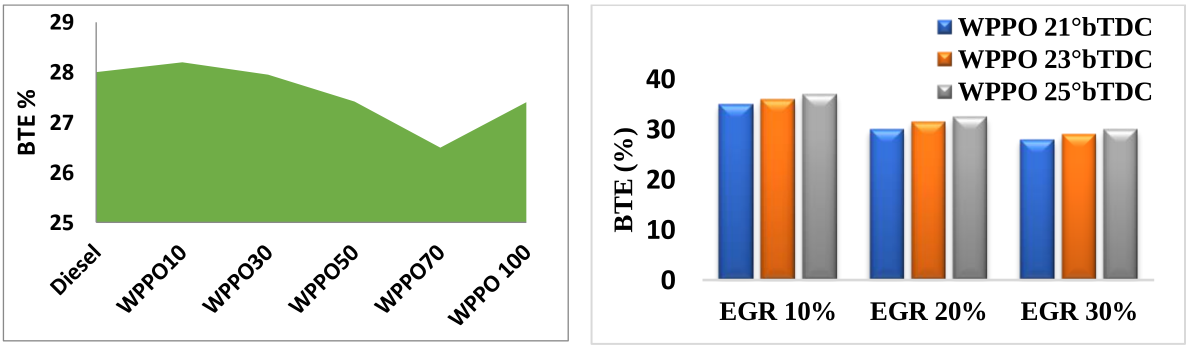
Performance characteristics of WPPO in CI engine when compared to fossil diesel.

Ref.	Engine Spes, Operating Conditions	Fuel Types and Blends	Engine Results	
			Performance	Exhaust Emissions
[86]	A4CRX46TI, CR:17:1, RP:68 kW, 1500 rpm, IP :240 bar	PP 100%, PP 75%	Lower BTE	Higher NOx, UBHC and CO, lower CO_2
[89]	A4CRX46TI, CR:17:1, RP:68 kW, Speed : 1500 rpm, IP :240 bar	LDPE 100%, EVA 100% EVA 75%	LDPE shows lower BTE, EVA shows longer ID, lower BTE	LDPE gave lower NOx, CO, and CO_2 . Higher UBHC. EVA shows higher NOx, and UBHC, lower CO and CO_2
[83]	Kirloskar TV1, WC, SC-4s, CR17.5:1, IP 200 bar, RP 3.5 kW, 1500 rpm	WPPO, WPPO15% WPPO 30%	Combustion efficiency improved with PO30 Lower BTE than diesel.	
[74]	Kirloskar TV1, WC, SC-4s, CR17.5:1, IP 200 bar, RP 3.5 kW, 1500 rpm	Co-Pyrolysis of PE & jute fibre Oil 15%, 30%	For each mix, the engine load increases EGT, BTE, ME, and BSFC drops.	NOx emissions increases, CO emissions decreased.
[76]	Eicher E483, Type: 4 cylinders, DI, CR17.5:1, Max. power 70 kW, Turbocharger	WPPO, WPPO 10%, WPPO 20%, WPPO 30%, WPPO 40%	EGT and BTE was higher and BSFC was lower for all blends than diesel	Higher emissions
[77]	Mahindra-Maximo (900 cc), 2C, 4S, RP18.4 kW at 3600 rpm, CR 18.5, WC	WPPO 30% with 10%, 20% and 30% EGR	Poor performance due to high viscosity and low HHV	HC, CO, and soot increased while NOx reduced with EGR rate
[78]	Engine type CI, SC, RP 3.7 kW at 1500 rpm, CR 16.5:1, WC	Plastic oil, BMEPs of 1.8, 3.8, 5.8, 7.8 and 10.8 bar.	BTE was nearly identical to diesel.	NOx emission was lower than diesel, other emissions increased.
[79]	Yanmar-L100V, SC, DI-CI engine, CRDI system	WPPO 5%, 10%, 20% and 100	WPPO and its blends gave similar results to diesel	NOx, HC, and CO were found to be lower, but PM was higher
[80]	Kirloskar TV1, WC, SC-4s, CR17.5:1, IP 200 bar, RP 3.5 kW, 1500 rpm	WPPO, 40%, 30%, and 20	BTE increases with n-Butanol %	NOx, HC, and smoke found lower at low concentrations, but NOx increased with increase in n-Butanol fraction
[90]	Kirloskar TV1, WC, SC-4s, CR17.5:1, IP 200 bar, RP 3.5 kW, 1500 rpm	WPPO 100% With EGR 10%, 20% and 30%	BTE unchanged	NOx decreased with increased EGR% and Inj. timing. HC, CO, and smoke were found lower at early inj. timing with 10% EGR
[91]	Kirloskar AV1, SC-4s, WC, RP 3.7 kW, CR16.5:1, IP 215 bar, 1500 rpm	WPPO with 5%, 10% DEE	BTE increased with 5% DEE	NOx and CO were reduced with 5% DEE
[82]	Kirloskar AV1, SC-4s, WC, RP 3.7 kW, CR16.5:1, IP 215 bar, 1500 rpm	WPPO 25%, 50% and 75%	BTE was lower for all blends	All blends had lower peak in-cylinder pressure, heat released rate, and ID. NOx decreased.
[92]	Comet VCT-10, TC-4s, CR17.5:1, RP 7.4 kW@1500 rpm	WPPO, Blend 10%, 20%,30% and 40%	BTE decreased	NOx decreased with increases the WPPO % but increased with engine load. HC, CO increased
[88]	Kirloskar TAF1, SC-4s, AC, CR17.5:1, RP 4.4kW @1500rpm	WPPO 100%	BTE decreased	NOx, HC, CO decreased. Smoke increased
[87]	Kirloskar TAF1, SC-4s, AC, CR17.5:1, RP 4.4kW @1500rpm	WPPO 100%	BTE close to diesel	NOx reduced with EGR %. HC, CO increased

Table 5
Combustion analysis of WPPO with respect to diesel fuel at full load.

Ref.	Engine	Types of fuel	ID	CD	Pmax	HRRmax	Explanation
[72]	Kirloskar TV1, SC, DI @1500 rpm, Water cooled	WPPO,10, 20, 30,40, 50% diesel blend	Shorter	longer	High	High	The peak pressure was delayed 50% blend gave higher peak cylinder pressure (67.87 bar), and HRR of 150J/°CA.
[87]	Kirloskar TAF1, SC, DI @1500 rpm, Air cooled	WPPO 100 with 10%, 20% EGR	longer	Shorter	H	H	WPPO gave higher in-cylinder pressure and HRR without EGR, they reduced with EGR%.
[88]	Kirloskar TAF1, SC, DI @1500 rpm, Air cooled	WPPO 100 With ret. Inj. Timing 14°CA	Shorter	longer	low	low	Retarded injection timing (14°CA) gave lower performance and combustion temperature
[85]	A4CRX46TI, Cyl-4, CR-17:1 @ 1500 rpm	WPPO100, 25,50, 75, 90% blend	Longer	Shorter	H	H	High Pmax and HRR due to combined effect of reduced CN and viscosity.
[93]	Kirloskar TV1, SC, DI @1500 rpm, Water cooled	WPPO 100% WPPO25% WPPO50% WPPO75%	Longer	Longer	H	H	Lower viscosity of WPPO improved fuel-air mixing rate, improved combustion efficiency
[90]	Kirloskar TV1, SC, DI @1500 rpm, Inj. Timing: 21,23,25°	WPPO100,with 10,20,30% EGR	Longer	Shorter	H $L_{\text{Ret. Inj. T}}$	H	ID increased with retarded injection and with EGR. Retarded injection reduced the peak combustion temp

Literature reported that the BTE increases with increasing fuel injection timing but reduced by varying EGR flow rates. Figure 4(b) shows the combined effect of EGR and injection timing (21°, 23°, and 25°CA bTDC) on diesel engine performance [90]. It was observed that injection timing of 25 °CA bTDC gave highest BTE. This is because delaying the injection timing allows time for better air/fuel mixing and hence improves combustion quality. In general, waste plastic oil operations with advanced fuel injection timing resulted in a greater BTE (Table 4) [90].



(a) [84] (b) [90]

Fig. 4. BTE of (a) WPPO-diesel blends (b) WPPO100 at various injection angles and EGR%.

Effect of additives on engine performance

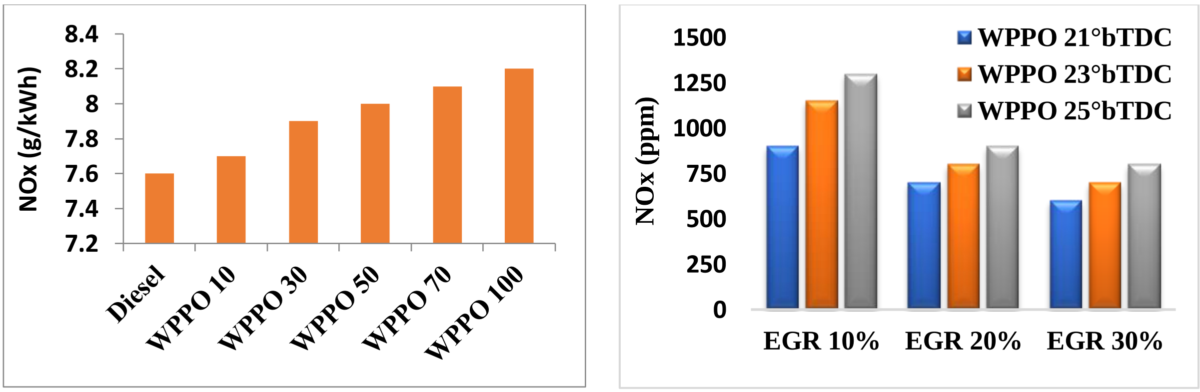
The BTE can be increased by adding oxygenated additives in WPPO. Diethyl ether (DEE) was studied as an additive in WPPO-diesel blends, such as WPPO 95% + DEE 5% and WPPO 90% + DEE 10% , and both blends gave a slight increment in BTE [94]. At full load, the BTE values for diesel, neat WPPO, WPPO95% + DEE5%, and WPPO90%+DEE10% were found to be 28 %, 27.75 %, 27.51 % and 29.12 % respectively. The addition of oxygenated aided DEE into WPPO improved the combustion efficiency and increased the BTE value [94]. The DEE additive helped to decrease the surface tension of fuel blends allowing for easier fuel atomization and better combustion [94]. Ternary blends made from n-butanol (BT), WPPO, and diesel have been investigated [80]. These blends were

D50%+WPPO40%+BT10%, D50%+WPPO30%+BT20%, and D50%+WCO20%+BT30%. Among all these blends, neat WPPO exhibited a higher BSFC than diesel at each engine load condition due to its lower calorific value [80]. The authors reported that neat WPPO gave lower BTE value; whereas blends with n-butanol gradually improved BTE. Increasing the amount of n-butanol (which has a low cetane number) in the blend lowers the density (Table 3), which results in better fuel atomization [80]. Furthermore, fuels blended with butanol lead to higher ID periods due to the H-abstraction by OH radicals present in n-butanol [95]. The high ID periods led to better air-fuel mixing and better engine performance.

Exhaust Gas Emission Characteristics

Oxides of nitrogen

Nitrogen oxides (NOx), form mainly at high temperatures during premixed combustion phase [96]. Air/fuel ratio, fuel atomization and vaporization with residence reaction time are the most critical parameters influences NO_x formation [97]. The NO_x emissions increased with an increased fraction of WPPO; this is due to higher number of oxygenated molecules in WPPO, which results in improved combustion (Table 4, Fig. 5(a)). It can be deduced from Fig. 5(b) that NO_x emissions increased with increasing injection timing, and reduced with increasing EGR %. The intake charge was diluted by the EGR, lowering in-cylinder temperature. The DEE addition in WPPO blends lowers CD by raising the CN, which resulted in lower NO_x [94].



(a) [84] **(b)** [90]

Fig. 5. NOx gas emission of WPPO and blends.

Hydrocarbon emission

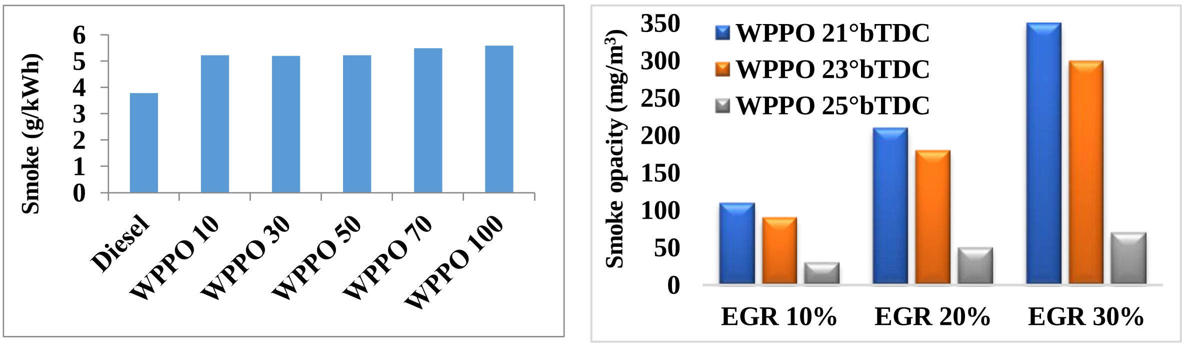
The primary sources of HC emission are low in-cylinder temperature and fuel impingement, which leads to incomplete combustion. The HC emission is also formed due to high viscosity and low volatility of the fuel. Large droplet formation is caused by high viscosity which leads to increased HC gas emissions [98–100]. The HC emission increases with the increase in WPPO content in the blend (Table 4) [84]. Hydrocarbon emission is also formed due to long-chain unsaturated hydrocarbons molecule, which is hard to break at lower in-cylinder temperatures during diffusion phase combustion. High aromatic contents present in WPPO is another factor for increased HC emissions. Advanced injection timing helped to reduce the HC emissions [98–100]. Higher EGR flow extends the diffusion combustion face, increasing the production of HC [90].

CO and CO_2 gas emission

The critical component to form CO gas emission is the air-fuel ratio [101,102]. The WPPO blends produced higher CO at full load than diesel fuel [84]. High BSFC at higher loads gave reduced in-cylinder temperatures; which led to incomplete combustion and hence higher CO formation (Table 4). The WPPO has a high concentration of oxygenated and aromatic chemicals, resulting in enhanced CO gas emissions [86,89]. The CO formation for WPPO decreased with advanced injection timing and rose with EGR % [90]. Compared to diesel fuel, WPPO showed lower CO_2 formation [84]. A decrease in CO_2 emission with WPPO blends are mostly due to lower in-cylinder temperatures, slowing down the CO oxidation rate [84].

Smoke emission

The smoke opacity refers to the soot particles emitted in exhaust gas [101,102]. Figure 6(a) shows the formation of smoke for WPPO at full load [84]. It is worth noting that WPPO-diesel blends produced more smoke than diesel fuel (Table 4, Fig. 6). The insufficient time to form a homogenous charge during combustion caused higher smoke emission. Higher smoke intensity may also be caused by lower combustion temperature, shorter combustion time, and quicker flame propagation [103]. Visible white smoke emission was reported at high loads due to a lack of adequate air and anomalous combustion . Smoke emission increased with the increases in EGR flow rate (10% to 30%) at all injection timings (Fig. 6(b)) [90]. Furthermore, it was observed that the smoke emission reduced with retarded fuel injection timing from 21°CA bTDC to 25°CA bTDC at all EGR rates [90]. The use of DEE as additive to WPPO improved the combustion process and reduced smoke formation [94]. Higher oxygen content and higher CN of DEE caused this.



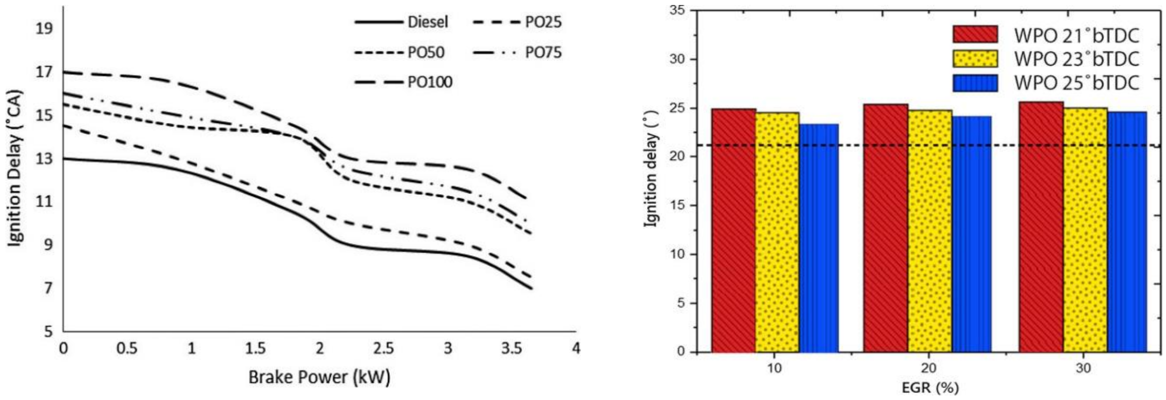
(a) [84]

(b) [90]

Fig. 6. Smoke emission of WPPO and blends.

Combustion Characteristics

The WPPO was employed in a single-cylinder diesel engine to examine changes in ignition delay (ID) periods at various loads by using neat WPPO and its blends (25, 50 and 75 %) with diesel (Table 5) [88]. It was reported that the ID period was decreased with the increase in engine load (Fig. 7(a)). Due to high viscosity, the ID duration of neat WPPO was longer. Parameters such as injection timing, injection pressure, and EGR rate also effect the ID period [90]. Studies on the combustion characteristics of WPPO in a diesel engine utilizing various EGR flow rates (10, 20, and 30 %) and fuel injection time (21, 23, and 25 °CA bTDC) revealed that the ID period for neat WPPO with 10% and 20% EGR was longer than neat diesel (Fig. 7(b)) [90]. The EGR works as a heat absorber, lowering combustion temperatures and lengthening the ID period. Because of the low CN and high viscosity of WPPO, the atomization was poor; preventing adequate air-fuel mixing and hence lengthening the ID duration [90].



(a) [88]

(b) [90]

Fig. 7. ID of WPPO and blends as a function of : (a) brake power (b) EGR.

Damodharan et al [90] examined the combustion characteristics of WPPO by altering the EGR flow rate (10%, 20%, and 30%) and fuel injection timings (21, 23, and 25 °CA bTDC). Peak in-cylinder pressures and HRRs gradually decreased as the injection timing was delayed from 25-21 °CA bTDC. The WPPO had a higher combustion efficiency than diesel; therefore, WPPO-diesel blends gave higher maximum pressure (Pmax) than diesel in most circumstances (Table 5, Fig. A.7 in Appendix) [84]. Mani et al. [84] reported that ID increased HRR. The maximum HRR (80 J/°CA) for diesel was found at 2^{o}CA aTDC. The HRRmax varies when the concentration of WPPO changes in the blend (Table 5). The HRRmax were found to be 105, 108, 110, 114, and 119 J/°CA for 10%, 30%, 50%, 70%, and 100% WPPO respectively [84]. In the case of WPPO blends, higher F/A ratio resulted in higher HRR. At full load, Pmax for WPPO50% and diesel were found to be 67 and 62 bar at 4 and 1°CA aTDC respectively [85]. The Pmax was higher due to lower CN, longer ID, and higher viscosity of WPPO-diesel blends [104]. The HRR occurs mostly in the premixed combustion phase of WPPO blends; higher ID period allows for more fuel to burn, resulting in a greater HRR. The presence of WPPO in blends increased viscosity and lengthened the ID period, resulting in rapid expansion and higher in-cylinder pressure [105].

Recent Progress, Challenges and Opportunities

Catalytic pyrolysis of WPPO

Jha et al. [106] carried out the optimisation of catalytic pyrolysis of waste plastic using Taguchi technique of L9 orthogonal array. Three input parameters such as catalytic ratio, temperature and production time was used to assess the quality of the pyrolysis oil. They reported that the optimal conditions for producing 25g of oil from polypropylene waste plastic were found to be 10% catalyst, 36 minutes reaction time, and 465°C reaction temperature. They concluded that use of 25% catalysts could give better quality fuel for using in the automotive engines [106]. Pan et al. [107] studied numerical investigation of novel smouldering-driven reactor for pyrolysis of waste plastics. The reactor consists of two chambers – a smouldering chamber for production of heat by using char and a pyrolysis chamber using the heat from the smouldering chamber. They reported that plastics content, inlet air velocity and char concentrations influenced yield % and energy efficiency. They observed that pyrolysis process becomes shorter to about 1h when high concentration of char was used, and the air velocity was increased. This led to the decrease in the light liquid (C5–C15) and heavy liquid (>C15) yields and an increase in gas (C1–C4) yield [107].

Co-pyrolysis of waste plastics with other biomass could produce high quality oil. Co-pyrolysis of plastic trash and date seeds was examined by Inayat et al. [108]. They found that pyrolysis at 500 ^{o}C gave maximum liquid oil production of 59.16%. Pyrolysis at lower temperatures of 300 ^{o}C yielded more biochar (24.97%).They reported that oil yield increases with the increase of plastic waste content and pyrolysis temperature [108]. Wu et al. [109] studied the co-pyrolysis of corn stover and polypropylene plastics by using tube furnace reactor. They reported that composition ratio 1:3 (corn stover: polypropylene) gave highest yield of about 52.1%. The optimum temperature for the co-pyrolysis was obtained about 550 ^{o}C. Other studies carried out for co-pyrolysis of waste plastics with biomass [110,111]. Suriapparoa et al. [110], used HZSM-5 catalyst for catalytic co-pyrolysis of polypropylene and polystyrene plastics blended with rice straw and sugarcane bagasse using microwaves. They reported the increasing the catalyst content gave better quality oil [110]. The HHV, viscosity, density and flash point temperature values of the pyrolysis oil was found to be 43 MJ/kg, 1 cP, 850kg/m^3 and 70 ^{o}C respectively. Suriapparoa and Vinu [111] investigated the oil quality of the co-pyrolysis of mixed biomass (groundnut shell, bagasse, rice husk, Prosopis juliflora, mixed wood sawdust) and hydro-rich plastics (LDPE and Polyisoprene) in microwave. They reported that microwave assisted co-pyrolysis is a potential route to achieve hydrocarbon rich oil. They found that the HHV of co-pyrolysis oil was 38-42 MJ/kg as compared to 20-28 MJ/kg when only biomass was pyrolyzed [111].

Use of additives in WPPO

Ravi et al. [112] investigated the effects of propanol (P), and di-tert-butyl peroxide (DTBP) as fuel additives in WPPO. Fuel properties were improved by blending diesel, WPPO, propanol, and DTBP : D70%+WPPO20%+P10%, and D60%+WPPO20%+P10%+DTBP10%. BSFC and BTE was found to be increased by about 11.96% and 8.78% respectively than diesel [112]. The CO and HC emissions were higher by 3.87% and 15.7% respectively. NOx and smoke emissions were decreased by 8.08% and 35.36%. Lower CN and higher latent heat of vaporisation gave lower NOx emission [112]. The diethyl carbonate (DEC) was used with WPPO [113]. They made D50% +WPPO45% + DEC5%, D50%+WPPO40%+DEC10%, and D50% +WPPO35% + DEC15% blends. The DEC additive helped to improve the BTE of the engine by 3.62%, 4.00% and 6.93% respectively than neat WPPO fuel. The BSFC decreased by 11.27%, 9.32% and 6.94% respectively than neat WPPO [113]. Higher premix combustion might have led to the constant volume combustion which allowed formation of lean mixtures, and hence lowered BSFC values when DEC was used. The NOx gas emissions of the blended fuel were reported to be 15.91%, 11.98% and 2.91% lower than diesel. CO emission was decreased by 20.72%, 30.63% and 41.44% respectively; and HC emission was decreased by 11.11%, 23.89% and 42.67%. Smoke was reduced by 4.10%, 6.30% and 11.50% respectively when DEC was used [113].

The effects of diethyl ether (DEE) and methoxy ethyl acetate (MEA) as WPPO additives was studied [114]. D50%+WPPO40%+MEA10% and D50%+WPPO40%+DEE10% blends were tested. The MEA10% blend gave 5.2% higher BTE than diesel at full load. The CO and HC emissions were found to be 15.8% and 22.4%, and 5.7% and 11.3% lower than diesel. Smoke for neat WPPO fuel was reported to be 12.4% higher than diesel. MEA blend gave 15.5% and 8.4% lower smoke than neat WPPO and DEE10% fuels. Higher oxygen content of MEA (40.8% oxygen) led to better A/F mixing and efficient combustion [114]. The NOx emissions were increased by 1.5 % for MEA and decreased by 5.3% for DEE additives. Higher oxygen % caused higher NOx emissions in MEA fuel [114]. Improvement in the engine performance and pollution was also observed by other researchers when MEA and DEE was used [115] [116].

Damodharan et al. [117] investigated the addition of alcohols as additives in WPPO. The optimal combination of alcohol-WPPO blend, EGR rate, and injection time for minimum NOx, smoke density, and BSFC was determined via response surface methodology (RSM) optimization. Three distinct blends were prepared: WPPO70% + P30% , WPPO 70% + H 30% , and WPPO 70% + O 30% . The n-pentanol blend gave optimum performance and emission results. Compared to neat WPPO fuel, at injection timing 21° CA bTDC and with 10% EGR; n-pentanol additive blend produced 74.2% lower smoke, 9.7% higher NOx, and 3.2% higher BSFC. On the other hand, when compared to diesel, 76.8% lower smoke, 32% higher NOx, and 17.8% higher BSFC was observed for same additive. They found that n-pentanol had the greatest pressure and HRR peaks, as well as the lowest ID and CD, followed by n-hexanol, n-octanol, and neat diesel [117]. The RSM technique was also used by Das et al. [118]. Optimum results were found at full load, compression ratio of 17, and WPPO10% + diesel 90% fuel blend [118]. Das et al. [119] examined the exergy analysis of WPPO when ethanol and graphene nanoparticle was used as additives. They reported that D80%+WPPO20% and D60%+WPPO20%+E20% blends gave lower exergetic efficiency than diesel fuel. They then added 100ppm graphene nanoparticle in the blend and found that exergetic efficiency of 80D20WPPO100G fuel mixture was increased by 22.2% at low load and 18.98% at full load. Addition of ethanol to WPPO increased the combustion efficiency of the engine [120]. The blend D70%+WPPO20%E10% consumed 3.5 to 7.5 % less fuel than diesel. The CO and HC emissions were reported to be 6.5 % and 6-13.5 % lower than diesel. Higher oxygen content and CN of these additives helped to enhance the combustion performance. Overall, MEA shows promise for WPPO use in the diesel engines.

Plastic waste management challenges

The packaging sector alone consumes 96% of single-use plastic (Fig. A.1 – in Appendix), which creates environmental hazard [121]. About 60% of single-use plastic cannot be recycled, which is a significant challenge for industries and policymakers. Greenpeace reported that UK exports 40% (about 210,000 tons/year) of plastic waste to Turkey, they suggested that the UK government should address these ‘recycling issues’ in a sustainable manner [122]. In the UK, supermarkets are trying to reduce this single use plastic with various strategies, such as charging customers for plastic bags, substitutions of plastic bags with biodegradable bags, and use of bags-for-life strategy. These strategies have had a significant impact on the amount of household plastic garbage produced. Other important aspects to improve the plastic waste management is by instilling the essential behavioural and social institutional changes in people [123]. The creation of a suitable institutional structure, as well as policy-level directives, will aid in the essential transition. Through both personal behaviour and social structural changes occurring gradually and concurrently, essential integrated and sustainable plastic waste management can be established [123]. Strategies for achieving sustainable development (SD) and to mitigate the harmful impact of plastic waste on public health and the environment are given below:

i. Design of policies to address psychological and behavioural impediments, such as public suspicion of the sanitary of reused and recycled products; and raising public awareness on the related environmental hazards of single-use plastic [124] .

ii. The motivation to enlighten others about the importance of eliminating plastic usage must be strong. Using paper bags instead of plastic bags is encouraged as papers are more eco-sustainable than plastics [123].

iii. Since plastic bags (polyethylene) naturally break down after a lengthy period of time due to the bacterial action, More research is needed to develop a new bacteria which is able to break down plastics more rapidly and economically [125].

iv. Implementing efficient garbage collection and waste sorting strategies. Encouraging waste source separation through cash bonuses in taxes, as well as individual or community credit for their services, might assist industries in acquiring clean and homogeneous plastic streams.

Polymer recycling and degradation

Recycling of plastics has limitations because they can no longer be recycled once they have reached their end of its useful life [126]. An alternative to this is to create and use biodegradable polymers, where no recycling is required. One of the most effective methods for polymer degradation is biological treatment, which degrades the polymer in an environmentally safe manner, with no toxic by-products (Fig. A.2 – in Appendix). However, problem with polymers biodegradation is that their nature prevents them from breaking down into monomers. In reality, microbial enzyme systems are ineffective against synthetic polymers that cannot be hydrolysed [126]. To examine the potential of various microbes to degrade polymeric materials and detect their enzymatic-degradation system; more research on the biodegradation process and parameters are needed. The economic value of recycled plastics will rise as a result of the creation of a market for the commodity [127]. According to a life cycle assessment (LCA) study, fuels acquired by feedstock recycling of plastics emit much less CO_2 than fuels produced from primary fossil resources [128]. Pyrolysis can convert polymers into useful hydrocarbon compounds with a wide variety of carbon numbers, depending on the reactor and operating conditions [20]. Some limitations on recycling the plastic wastes are:

- During collection, processing, and further processing of recyclables, materials are lost since recycling materials does not ensure complete resource recovery from trash.
- Contamination of recyclables causing several issues, such as making material sorting extremely difficult and lowering product quality.
- When compared to landfilling, recycling initiatives are frequently more expensive.
- Recycling can pollute the environment, especially when waste products are sorted and not kept properly, they can leak into the soil, poisoning the land and groundwater. .

WPPO as a cleaner fuel

The WPPO could be used in engines either as blends or neat. The use of WPPO can also help to balance carbon footprints by reducing waste from the landfill sites. The properties of the WPPO are very close to gasoline and diesel. The WPPO produced from the PET, PE, PVC, and PP show high viscosity than diesel and gasoline. Whereas PS and mix plastic shows lover viscosity than fossil diesel fuel. The cetane number of WPPO lies between gasoline and diesel fuels, suitable for use in both SI and CI engines. Furthermore, WPPO is an oxygenated fuel (9-10% O_2) which gives better combustion efficiency than diesel. However, higher oxygen content may increase the acidity of the WPPO fuels and NOx gas emissions. The WPPO contain aromatic and toxic substances. This toxic content can release harmful gases. Hence, more R & D work is required to investigate the toxic gas emissions of the WPPO fuels. Long-time engine durability study with WPPO fuels is another challenge.

Strategies for WPPO utilization

To achieve lower NOx, EGR can be applied. While applying operating strategies, fuel injection position, fuel injection pressure would help to maintain the engine efficiency with lower emissions. Advanced low temperature combustion (LTC) and dual fuel combustion strategies introduced to achieve high thermal efficiency with simultaneous reduction in NOx, CO_2 and PM emissions can be adopted for WPPO uses in the diesel engines [129]. The WPPO is slightly corrosive, may damage engine components such as fuel pump, fuel line, fuel injector nozzle. As a result, material compatibility is one of the most critical issues which need to be addressed for long term uses of WPPO in engines.

Some of the effective strategies which could be applied for WPPO use are:

- ✓ ***Ceramic coating*** **-** Coatings on engine components are becoming more popular to preserve engine components while also boosting wear and corrosion resistance, reducing friction, and improving heat shielding. Engine components such as cylinder, piston, piston rings, inlet and outlet manifold could be coated for WPPO use.
- ✓ ***Suitable material*** – For WPPO use, fuel pump, fuel injector, fuel tanks and fuels supply pipes could be made using stainless steel or some other corrosion resistive materials.
- ✓ ***Blending*** – The WPPO can be blended both with the fossil diesel and fossil gasoline. Another option could be to blend WPPO with green biodiesel and use the biodiesel-WPPO blends in the CI engines. Use of WPPO as blends would reduce the risk of corrosion of engine components.
- ✓ ***Advanced combustion*** **-** The Reactivity Controlled Compression Ignition (RCCI) is a dual fuel concept, where a low reactivity fuel is introduced into the cylinder through the intake manifold and a high-reactivity fuel is fed directly into the combustion chamber [129] (Fig. A.8 – in Appendix). This strategy can improve engine efficiency and reduce emissions. The WPPO fuel could potentially be used using this RCCI concept.

Conclusions

The widespread use of plastic can be attributed to its low production costs, ease of availability and flexibility of applications. Landfilled waste plastics has become a significant problem for the Earth's ecosystems affecting both urban and marine environments. In this study, techniques related to the complete decomposition of waste plastic in the form of energy recovery has been reviewed. The current study focused on the types and quantity of plastic wastes, their effect on the environment and ecosystem, and plastic waste management in chemical recycling for energy recovery. It has been found that pyrolysis is the most promising technique, investigated by many researchers to produce liquid oil, gas, and char. The physical properties of WPPO are close to fossil diesel fuel. The viscosity of all types of WPPO is within international standard limits between 1.9-5 cSt. Higher heating values of WPPOs produced from HDPE, LDPE, PP, and PS were between 40 to 43 MJ/kg. The oil from PET and PVC have very low HHV. The CN of WPPO is reported to be higher than fossil diesel fuel.

Concerning engine performance characteristics with WPPO, researchers reported that the neat WPPO and its blends with diesel fuel gave better thermal efficiency than other oxygenated biofuels. However, neat WPPO (or blends) gave slightly lower thermal efficiency than diesel. However, addition of oxygenated additives such as DEE, DEC, DTBP, MEA, and various alcohols helps to achieve improved BTE and reduced pollution. The MEA found to be more effective additive for WPPO. Due to the optimum range of cetane and octane numbers, WPPO can potentially be used in SI engines, though few studies have been reported. The WPPO also provides better engine combustion performance, such as an earlier SoC, a shorter ID, and a shorter CD. The Pmax and HRRmax are both slightly low as compared to diesel. Smoke, CO, and CO_2 emissions were lower than diesel. The NO_x emission is higher than diesel, which can readily be controlled using the EGR and additives. Overall, the WPPO is found to be potential alternative to fossil diesel.

The future research scope include:

1) To improve the quality of the WPPO, advanced pyrolysis technology along with parametric study with novel catalyst is required. More R & D work on co-pyrolysis of waste plastics with biomass resources are an expanding area of future research topic.
2) Additives play an important role to control the engine out emissions. Use of various novel additives in WPPO is another important R & D scope.
3) More experimental studies in marine engines and automotive engines are required to consolidate current observations and assess engine hardware durability using WPPO.
4) Investigation of engine performance and emissions characteristics under various settings, including variable compression ratios, injection timings, and injection pressures.
5) Investigation of WPPO performance in HCCI, RCCI engines.
6) A comprehensive study on the life cycle energy and emission assessment of WPPO utilisation in engines is another important topic for further research.

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