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REVIEW ARTICLE

Critical insights into the effects of plastic pyrolysis oil on emission and performance characteristics of CI engine

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Abstract

Pyrolysis is an encouraging solution considering the facts of energy demand and waste plastic management as it produces liquid fuel for compression ignition engine application. This study provides critical insights into the effects of waste plastic oil on the emission and performance characteristics of compression ignition engines. Though most of the studies have shown a negative influence, promising outcomes have been noticed in a few specific cases. A maximum of 71%, 80%, 76%, 71%, 21%, and 13% decrease in nitrogen oxide emission, carbon monoxide emission, unburnt hydrocarbon emission, smoke emission, exhaust gas temperature, and brake-specific fuel consumption, respectively, have been noticed with waste plastic oil or its blends at certain operating conditions. Nevertheless, the presence of long carbon chains, higher aromatic content, and non-homogeneous air-fuel mixture owing to the wide product distribution in plastic oil are the few reasons which affected the emission and performance characteristics of the engines. More rigorous investigations are needed to improve the quality of the fuel and to establish correlations between the fuel properties and pyrolysis parameters. In addition, the effects of incorporating exhaust gas recirculation, emulsification process, and use of additives with waste plastic oil need to be explored more for reducing the emissions with satisfactory engine performance, and in this regard, the use of bio-additives with waste plastic oil can provide a new direction to this research field. Further, studies on the economic feasibility and the impact of waste plastic oil on engine materials are also required.

Keywords CI engine · Emission characteristics · Performance characteristics · Pyrolysis · Waste plastic oil

Introduction

The usage of plastic is growing immensely due to its advantages over its counterparts (O'Brien and Thondhlana 2019). Some of the benefits are higher durability, cost-effectiveness, energy efficiency, lightweight, design flexibility, water-resistant nature, etc. (Derraik 2002). But the growing utilization of plastic has become the cause of enormous waste generation (O'Brien and Thondhlana 2019), and the effects are discernible through the land and marine ecological contamination (Adam et al. 2020). The measure of plastic that heaps up into the ocean yearly is roughly 4.8-12.7 million metric tons which is comparable to a truckload of plastic inflowing the oceans every minute (Jambeck et al. 2015). Thus, the disposal of plastic waste is the foremost obligation from an ecological outlook. With regard to the waste disposal, landfilling and incineration are the commonly followed practices. However, considering the fact of non-biodegradability nature of plastic, landfilling is not a reasonable choice, while incineration of waste plastic produces harmful and perilous contaminations (Kunwar et al. 2016). Besides, both the strategies finally end up with lost energy since plastics themselves can be considered a source of energy (Sharma et al. 2014). Aside from the difficulties of the disposal of plastic waste, another worldwide issue is the energy crisis due to the fossil fuel depletion which should be addressed simultaneously. Thinking about every one of these realities, the degradation of plastic through pyrolysis has gained a lot of consideration lately (Damodharan et al. 2018b; Zhang et al. 2020). Pyrolysis occurs in the absence of air, and it is a thermal degradation

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process. Pyrolysis of the waste plastics yields three products which are liquid, solid, and gas. The quality of the yields relies upon the types of plastic taken as the feedstock in the pyrolysis reactor, and it also depends upon the process parameters (Kalargaris et al. 2017a). In the context of pyrolysis of plastic, many studies have highlighted and established the suitability of pyrolysis process (through thermogravimetric analysis) for the treatment of waste plastics (Das and Tiwari 2017; Mumbach et al. 2019; Singh et al. 2020a; Hu et al. 2020; Patnaik et al. 2020; Saha et al. 2021). Ghodrat et al. (2019) reported that a 54% rate of return can be achieved through the pyrolysis of plastic waste. And pyrolysis of plastic is viewed as a promising way since it addresses the waste-recycling issue (Kalargaris et al. 2017c; Quesada et al. 2019), and simultaneously, it converts waste plastic into liquid fuel which can be utilized in internal combustion engine as well (Rinaldini et al. 2016; Erdogan 2020). In line with this, nowadays, substantial investigations have been focused on compression ignition (CI) engine as it is the prime mover in the transportation sector. However, CI engine emits life-threatening pollutants like oxides of nitrogen (NO_x), carbon monoxide (CO), unburnt hydrocarbon (HC), and smoke; the pollutants may cause adverse effects on human health and the environment (Prasad and Bella 2010). Many studies have shown evidence in this regard, and some of the adverse effects are respiratory problems, lung damage, cancer, ground-level ozone formation, acid rain, and reduced visibility (Sydbom et al. 2001; Lloyd and Cackette 2001; Lewtas 2007; Palash et al. 2014). Despite the fact of significant contribution to environmental pollution, CI engine is considered the backbone of the transportation sector because of its higher efficiency (Kalargaris et al. 2017a; Kalam et al. 2011), durability, reliability, and low operating cost (Reşitoğlu et al. 2014).

In recent years, the amount of investigation on the utilization of waste plastic oil (WPO) in CI engine has seen a sharp ascent (Ayodhya et al. 2018a; Ayodhya et al. 2018b; Budsaereechai et al. 2019; Praveenkumar et al. 2020; Rajamohan et al. 2020; Rajasekaran et al. 2020; Singh et al. 2019; Sundararajan and Ammal 2018). Many researchers have performed experiments for the extraction of fuel from individual types of plastic or mixed plastic (MP) through the pyrolysis process, and for the most pragmatic purpose, the extracted fuel was applied in CI engine to investigate the performance and emission characteristics. Adam et al. (2017) observed that with the application of WPO, NO_x emission of CI engine could be reduced by 19.3% to that of diesel fuel whereas, the variation of CO emission was also low compared with diesel. However, the lowest power curve was also noticed with the plastic fuel at all engine speeds due to lower calorific value (CV), kinematic viscosity, and density of WPO. Churkunti et al. (2016) also reported a lower level (w.r.t diesel) of NO_x emission with the application of waste plastic-derived fuel; additionally, a decrease in CO and HC emission was also observed in that study. It was also conveyed that at low blend concentration, waste plastic-derived fuel showed similar combustion performance w.r.t diesel; however, in the context of emission characteristics of CI engine, a substantial decrease in HC, CO, and NO_x emission was achieved. Similarly, 20.63% lower CO emission was also noticed with a blend of polythene-derived fuel and diesel (Güngör et al. 2014), but on the other hand, NO_x emission increased by 9.17%. In the same study, it was also mentioned that the properties of the waste polythene-derived fuel were similar to that of diesel, for which the variation in the performance characteristics of the CI engine was also marginal. Likewise, Mani et al. (2009) observed similar properties of waste plastic compared to pure diesel and the experimental results of the CI engine also showed stable performance, with brake thermal efficiency similar to that of diesel. Besides, smoke emission was reduced at all loads, but CO emission was higher compared to neat diesel whereas, the variation of HC emission was marginal. Similarly, stable performance of the CI engine was also reported by Vu et al. (2001) with an emulsion of WPO, with a substantial reduction (30%) of NO_x emission when compared with diesel. Sudrajad et al. (2011) observed a 9% lower brake-specific fuel consumption (BSFC) of CI engine with the application of WPO along with a significant reduction in NO_x and CO emission by 40% and 16%, respectively, in comparison with neat diesel.

From the literature, it has been observed that substantial achievements regarding the application of pyrolyzed WPO in CI engines have been reported in recent years. But there have been little or no critical reviews of these crucial reports in the literature. Moreover, as far as the authors know, no comprehensive literature is still existing, which compares the emission and performance characteristics of CI engine reported by different researchers with the application of WPO. Herein, a critical review of the findings related to performance and emission characteristics of CI engine with the application of WPO has been provided. Therefore, the objective of this study has been laid out as to outlay the effects of WPO on emission and performance characteristics of CI engine with critical insights.

Pyrolysis of plastic and properties of plastic oil

This section highlights the pyrolysis temperature, liquid yield, catalyst information, and the properties of plastic oil, specifically concerning the studies where CI engine was fueled with plastic oil. The results have been compiled and are shown in Table 1. A wide range of temperatures has been observed in the literature while treating different types of plastics through the pyrolysis process. Kalargaris et al. (2017a) performed pyrolysis of MP at 900°C whereas,

Table 1 Pyrolysis temperature, liquid yield, and properties of WPO

Sl. No.	Source of WPO	Pyrolysis temperature (°C)	Liquid yield (%)	Catalyst used	Properties								Reference
					Kinematic viscosity (mm^2/s)	Density (kg/m^3)	Cetane number	Flash point (°C)	Fire point (°C)	Pour point (°C)	Cloud point (°C)	Calorific value (MJ/kg)	
1	MP	300-900	-	-	2.52	790	51	42	45	-	-	43.34	Ananthakumar et al. 2016
2	MP	450-700	-	-	2.97	800.7	71.88	-	-	-	-	46.29	Churkunti et al. 2016
3	MP	300-400	75	-	-	798	51	42	45	-	-	45.22	Devaraj et al. 2015
4	MP	900	-	-	1.92	981.3	-	13	-	-	-	38.3	Kalargaris et al. 2017a
5	MP	700 900	- -	- -	2.90 1.92	927 981.3	- -	- -	- -	- -	- -	38.2 38.3	Kalargaris et al. 2017c
6	MP	900	-	-	1.92	981.3	-	13	-	-	-	38.3	Kalargaris et al. 2017d
7	MP	320-500	75-90	-	3.25	845	-	-	-	-	-		Kumar and Sankaranarayanan 2016
8	MP	350	-	-	4.57	780	44	72	-	15	-	42.9	Kumar et al. 2016
9	MP	400-550	-	-	2.21	792	-	30.2	-	9.7	14.3	41.46	Pal et al. 2019
10	MP	250-300	-	-	2.52	835	51	42	-	-	-	44.34	Ramesha et al. 2015
11	MP	300-450	-	Zeolite	2.3	800	-	-	-	-	-	42.6	Rinaldini et al. 2016
12	MP	320-500	-	-	2.12	835	50	41	49	-	-	43.39	Senthilkumar and Sankaranarayanan 2016
13	MP	300-400	-	Yes (name NM)	-	924.1	-	64	-	-	-	49.65	Sudrajad et al. 2011
14	MP	-	-	-	1.189	939	-	-	-	-	-	-	Vu et al. 2018
15	MP	500	-	-	2.9 ± 0.1	734 ± 2.4	49 ± 1	46 ± 1	47 ± 1	-3 ± 1	-27 ± 1	41.25 ± 6.4	Singh et al. 2019
16	MP	500	-	Zeolite-A	3.75	793	31	5	9	-	-	46	Das et al. 2020
17	PE	450	-	-	-	851.8	-	< 32	≤ 32	-3	-13	41.35	Cleetus et al. 2013
18	PE	414-480	-	Sodium aluminium silicate	2.34	788	43.75	< 100	-	18	-	45.47	Güngör et al. 2014
19	PE	350-400	70	Silica	-	854	44	62	70	-	-	42	Bharathy et al. 2019
20	LDPE	700	-	-	3	844	47.99	-	-	-	-	42.4	Kalargaris et al. 2017b
21	LDPE	500 ± 30	43	Zeolite	-	874.75	49.5	36.5	-	-	-	40.37	Singh et al. 2020b
22	LDPE	-	-	Binder with silica-alumina	0.82	784	46	6	-	-	-	42.9	Gopinath et al. 2020
23	LDPE	400-500	-	ZSM-5	2.75	832	48	45	-	-	-	38.68	Rajasekaran et al. 2020
24	LDPE + HDPE	350-425	-	-	2.4	837.5	62	43	-	-	2	46.2	Venkatesan et al. 2017
25	HDPE	350-400	80	Coal and silica	2.64	830	50	40	44	-	2	44.2	Kaimal and Vijayabalan 2016a

Table 1 (continued)

Sl. No.	Source of WPO	Pyrolysis temperature (°C)	Liquid yield (%)	Catalyst used	Properties								Reference
					Kinematic viscosity (mm^2/s)	Density (kg/m^3)	Cetane number	Flash point (°C)	Fire point (°C)	Pour point (°C)	Cloud point (°C)	Calorific value (MJ/kg)	
26	HDPE	350-400	80	Coal and silica	2.64	830	50	40	44	-	-	44.2	Kaimal and Vijayabalan 2016b
27	HDPE	600-800	57-79.1	Bentonite	4.6	860	-	49	-	-	-	41.35	Sundararajan and Bhagavathi 2016
28	HDPE	450		Kaolin	2.1	790	66	-2	5	-1	12	40.17	Kumar et al. 2013
29	HDPE	376-420	75	-	5.86	917	48	142	159	-	-	42.89	Geo et al. 2018
30	HDPE	400-500	-	ZSM-5	3.11	835	45	94	-	-	-	37.13	Kulandaivel et al. 2020
31	PP	550		Kaolin	2.27	777.2	65	< -12	< -12	< -45	< -45	47.1	Panda et al. 2016
32	PP	500	-	Kaolin	2.27	777	51	-12	-12	-45	-45	47	Das et al. 2019
33	PP	700 900	- -	- -	2.7 1.5	812 839	34.1 -	- -	- -	- -	- -	40.8 40.8	Kalargaris et al. 2018
34	PP	350	90	ZSM-5	1.72	771.4	60	20	30	< -30	-	44.96	Mangesh et al. 2019
35	MSW	450-500	-	ZSM-5	2.16	813	51	38	-	-	-	40.35	Damodharan et al. 2016
36	MSW	450-500	-	ZSM-5	2.16	813	51	38	-	-	-	40.35	Damodharan et al. 2018a
37	MSW	450-500	-	ZSM-5	2.16	813	51	38	-	-	-	40.35	Damodharan et al. 2018b
38	MSW	350-400	80	Coal and silica	2.64	830	50	40	44	-	-	44.2	Kaimal and Vijayabalan 2015
39	MSW	350-400	80	Coal and silica	2.64	830	50	40	44	-	2	44.2	Kaimal and Vijayabalan 2017
40	NM	-	-	-	2.2	770	64.4	72	-	-	-	34.60	Adam et al. 2017
41	NM	300-400	75	Yes (name NM)	2.52	835.5 (at 30°C)	51	42	45	-	-	44.34	Mani et al. 2009
42	NM	300-400	75	Yes (name NM)	2.52	835.5 (at 30°C)	51	42	45	-	-	44.34	Mani and Nagarajan 2009
43	NM	300-400	75	Yes (name NM)	2.52	835.5 (at 30°C)	51	42	45	-	-	44.34	Mani et al. 2010
44	NM	300-400	60-80	Yes (name NM)	2.52	835.5 (at 30°C)	51	42	45	-	-7	44.34	Mani et al. 2011
45	NM	-	-	-	3.52	915	50	42	44	-	-	37.8	Ayodhya et al. 2018a
46	NM	-	-	-	3.52	915	50	42	44	-	-	37.8	Ayodhya et al. 2018b
47	NM	500	-	-	4.97	986	42	41	49	-	-	37.25	Rajamohan et al. 2020
48	NM	400-500	50	-	-	842.3	-	28	-	-	-	40.05	Daniel et al. 2015

NM not mentioned, - not available

Kalargaris et al. (2017c) performed the experiments at two different temperatures 700°C and 900°C. Ananthakumar et al. (2016) and Churkunti et al. (2016) also have taken MP as feedstock, and the pyrolysis was done at the temperature range 300-900°C and 450-700°C. MP was also pyrolyzed at mid- or low-temperature range like 250-500°C by many researchers for the usage in CI engine (Sudrajad et al. 2011; Mani et al. 2011; Kumar and Sankaranarayanan 2016; Ramesha et al. 2015; Devaraj et al. 2015). The liquid yield for MP varied between 80 and 90%. Almost all the studies related to MP were done without the catalyst. For municipal solid waste (MSW), the pyrolysis temperature range considered 450-500°C (Damodharan et al. 2016; Damodharan et al. 2018a; Damodharan et al. 2018b) and 350-400°C (Kaimal and Vijayabalan 2015; Kaimal and Vijayabalan 2017) (with 80% liquid yield). And the catalysts used for pyrolysis were either coal and silica (gave 80% yielding) or ZSM-5 (no information of yielding). In the context of polyethylene (PE), it has been seen that the pyrolysis temperature was in the range 414-480°C (Cleetus et al. 2013; Güngör et al. 2014); however, Kalargaris et al. (2017b) have done the pyrolysis of low-density polythene (LDPE) at high temperature (700°C), and similarly, Sundararajan and Bhagavathi (2016) have done the experiment with high-density polythene (HDPE) at the temperature range 600-800°C. Kumar et al. (2013) performed experiment with HDPE at 450°C with kaolin as a catalyst. Venkatesan et al. (2017) have taken a mixture of LDPE and HDPE and performed the pyrolysis process at 350-425°C without a catalyst. Likewise, other researchers (Singh et al. 2020b; Gopinath et al. 2020; Geo et al. 2018; Bharathy et al. 2019; Kulandaivel et al. 2020; Rajasekaran et al. 2020) also performed pyrolysis with PE-based plastics for liquid oil production and the yields ranged in between 57 and 79.1%. It is noteworthy to mention here that the information regarding liquid yield was very little in the literature, and regarding pyrolysis temperature, in the majority of the studies, the temperature was in the range of 350-450°C. And catalysts used (for PE) were ZSM, silica, bentonite, and binder with silica-alumina for deriving WPO. In the context of PP oil, the catalysts used were ZSM-5 and kaolin. Mangesh et al. (2019) found 90% yield with ZSM-5 while extracting WPO from PP. It has been seen that in only 50% of the studies, the authors used catalysts for plastic pyrolysis. It has been found in the literature that non-catalytic pyrolysis offers heavy hydrocarbons WPO while the use of catalyst further degrades it to lighter hydrocarbons (Singh et al. 2019) and the use of catalysts can reduce the activation energy thus speeds up the conversion (Sharuddin et al. 2016). Kinematic viscosity of WPO ranged between 1.18 and 5.86 mm^2/s; however, in the majority of the cases, the kinematic viscosity of WPO was similar to diesel. The density of plastic fuel varied in a wide range from 770 to 982 kg/m^3, and it has been observed that except few contradictions, the density of the plastic fuel was nearer to that of diesel (850 kg/m^3) when the pyrolysis temperature was in the range 350-450°C. In the context of cetane number, it has been seen that for the majority of the cases, the cetane number of plastic fuels was near 50 which is similar to diesel. The flash point of the plastic-derived fuel varied in the wide range from -12 to 100°C, and the majority of the studies have shown that the flash point of plastic fuels was lower than that of diesel. Likewise, in the case of fire point, it has been found that the fire point of plastic fuels was on the lower side compared to diesel. Very few studies have reported pour point and cloud point values of plastic fuels and the variations were in the range of -45 to 18°C and -45 to 14.3°C, respectively. However, Geo et al. (2018) reported very high values of flash point and fire point with HDPE oil. Regarding the CV of the fuel, the results were very promising because the value was as high as 49.65 MJ/kg, and the majority of the plastic fuels have shown CV more than 40 MJ/kg. Table 2 shows the results of elemental analysis of WPO derived from different sources of plastics, which indicates that WPO has high hydrocarbon content as the carbon content varied in the range of 79-88%, and hydrogen content varied in the range of 8-15%. The high hydrocarbon content ensures that the energy content in WPO is high (Singh et al. 2020a). On the other hand, nitrogen and sulphur content were very minimal in WPO which ensures the suitability of WPO for CI engine application (Sharuddin et al. 2017). In general, it has been observed that the properties of WPO are similar to that of diesel which makes WPO a potential fuel for CI engine application. However, the majority of the studies were focused on the characterization and engine application of WPOs which were derived at a single pyrolysis temperature or a single set of process parameters, but the effect of the process parameters on the quality of the WPOs in regard to their physical and chemical properties has been reported seldomly. One recent study reported by Singh et al. (2020a) addressed the effect of pyrolysis temperature on fuel properties, and after investigating at three different pyrolysis temperatures, it was concluded that the CV, viscosity, and density of WPO increases with the increase of pyrolysis temperature. It was also conveyed that with the increase in pyrolysis temperature the volatile evolution increases representing a higher presence of aromatics in WPO. However, such studies are too limited in the literature to draw a perfect correlation between fuel properties and pyrolysis parameters. Thus, future research focus should be towards correlating the effect of pyrolysis parameters with the properties of WPO which in turn can influence the emission and performance characteristics of the CI engine.

On the other side, it is a well-known fact that the pyrolysis of plastics provides a liquid hydrocarbon which is largely a mixture of diesel, petrol, and kerosene (Mani et al. 2009), whereas Jan et al. (2010) reported that the weightage of petrol and diesel-like fuel in HDPE-derived WPO is 50% each. Nevertheless, from a crude pyrolytic oil mixture, diesel-like

Table 2 Elemental analysis results of WPO

Sl. No.	Source of WPO	Carbon content (%)	Hydrogen content (%)	Nitrogen content (%)	Sulphur content (%)	Oxygen content (%)	References
1	MP	87.9	8.5	*820	0.155	3.3	Kalargaris et al. 2017a
2	MP	84.6-87.9	8.5-9.8	-	-	3.3-5.3	Kalargaris et al. 2017c
3	MP	86.57	13.8	*44	0.0014	0.05	Kalargaris et al. 2017d
4	MP	81.8	10.7	2.58	0.48	4.31	Kumar et al. 2016
5	MP	79.77	15.47	2.76	0.04	-	Singh et al. 2019
6	MP	85.5	13.36	0	0	0.84	Das et al. 2020
7	LDPE	85.8	12.8	< 0.1	-	1.4	Kalargaris et al. 2017b
8	LDPE + HDPE	83.6	-	-	0.046	-	Venkatesan et al. 2017
9	HDPE	84.56	14.01	-	-	0.22	Sundararajan and Bhagavathi 2016
10	HDPE	80.58	13.98	0.60	0.08	5.19	Kumar et al. 2013
11	HDPE	83.9	12.9	0.76	0.12	2.32	Kulandaivel et al. 2020
12	PP	86.4-86.8	12-12.9	< 0.1	-	0.7-1.2	Kalargaris et al. 2018
13	NM	82.49	-	-	0.03	-	Mani and Nagarajan 2009, Mani et al. 2009, 2010
14	NM	-	-	-	< 0.002	-	Mani et al. 2011
15	NM	79.64	12.35	-	0.15	7.85	Daniel et al. 2015

NM not mentioned, * measured in mg/kg

fuel can be separated through fractional distillation (Singh et al. 2020a) without alteration of fuel properties. In the study reported by Sharma et al. (2014), the distillation of WPO (extracted from HDPE) was done and it was found that the paraffinic, olefinic, and aromatic protons in WPO ranged from 94 to 96.8%, 2.6 to 5.4%, and 0.6 to 1%, respectively, and it was also conveyed that the obtained fuel can be an appropriate alternative to diesel; however, the study was not on the engine application. Geo et al. (2018) and Rajamohan et al. (2020) have performed distillation of WPO before applying it in the engine; however, no specific discussion was found in the context of distillation in those studies. Bharathy et al. (2019) segregated diesel-like fuel from the obtained WPO through distillation in the temperature range 255-280°C, and the measured properties of the fuel were also found to be similar to that of diesel. However, out of all the studies related to the application of WPO in CI engines, very few studies have stressed the importance of distillation, and in most of the studies, the distillation of pyrolytic WPO was not done and pyrolytic WPO was directly used in CI engine. Again, this is also subjected to additional costs invited and low yield.

Effect of WPO on emission characteristics of CI engine

The extenuation of harmful pollutants from engine exhaust which are responsible for ecological contamination is a serious issue that the world is confronting. These pollutants form noxious substances through physical, chemical, and biological reactions. Therefore, local and global bodies are forcing stringent guidelines for controlling engine emissions (Emission Booklet 2019). The pollutants from CI engine may have adverse effects on human health and may cause respiratory problems, acid rain, and the ground-level ozone layer, etc. (Palash et al. 2014). These pollutants may also cause visibility problems, lung infections, eye irritation, skin disease, and damage to agricultural production through smog formation (Ali et al. 2019).

The impacts of plastic fuels on the CI engine emission characteristics were investigated by different researchers. The percentage variations of respective emission parameters in comparison with diesel are represented graphically in Figs. 1, 2, 3 and 4 at different loading conditions (25%, 50%, 75%, and 100%). The subsequent section of the paper deals with the impacts of using WPO on the CI engine emission characteristics.

NO_x emission

Inside the cylinder, nitric oxide (NO) is primarily formed, with a minimal amount of nitrogen dioxide (NO_2). The oxidation of atmospheric nitrogen is the main reason behind the formation of NO, and secondly, it is formed due to the existence of fuel-bound nitrogen. NO is mainly formed in high-temperature zones; the higher combustion temperature leads to increased

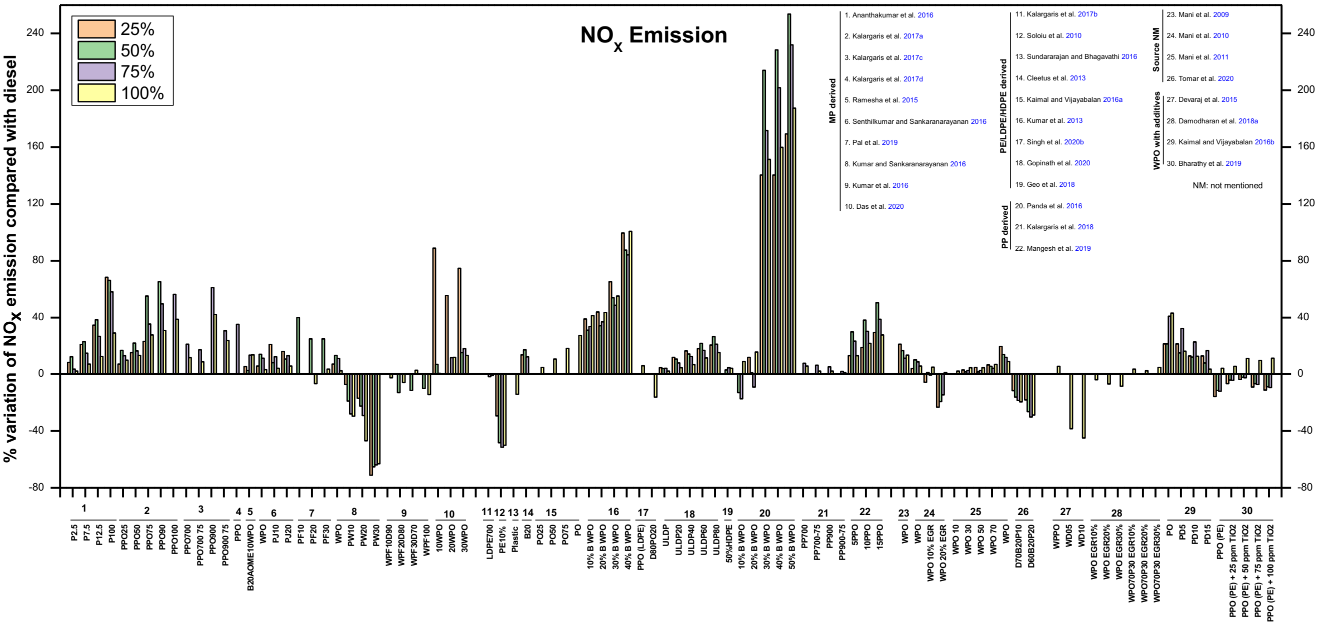

Fig. 1 NO_x emission at different loads using WPO

formation of NO (Heywood 1984). Although the estimation of NO alone is a decent approximation, but the estimation of NO_x is significant as NO quickly oxidizes into NO_2 (EMStec 2002).

Ananthakumar et al. (2016) have utilized MP-derived fuel for CI engine, four fuel samples were used which are P100, P12.5, P7.5, and P2.5 (refer to nomenclature for details of the fuel samples), and the experiments were performed at four loading conditions (25%, 50%, 75%, and 100%). From Fig. 1, it has been observed that all the tested fuel samples have higher (w.r.t diesel) NO_x emission at all loads. The variation of NO_x emission increased with the percentage of plastic fuel at all the loading conditions. Higher oxygen in the plastic fuel helped in complete combustion of the fuel which increased the heat released rate (HRR) and NO_x emission. Higher oxygen content enhances the cylinder temperature, which ultimately increases the NO_x (Panithasan et al. 2019). P100 has shown the highest increment amongst all the blends, and compared to diesel, it has shown 68.3%, 66.2%, 58.1%, and 29% higher NO_x emission. Devaraj et al. (2015) extracted fuel from MP,

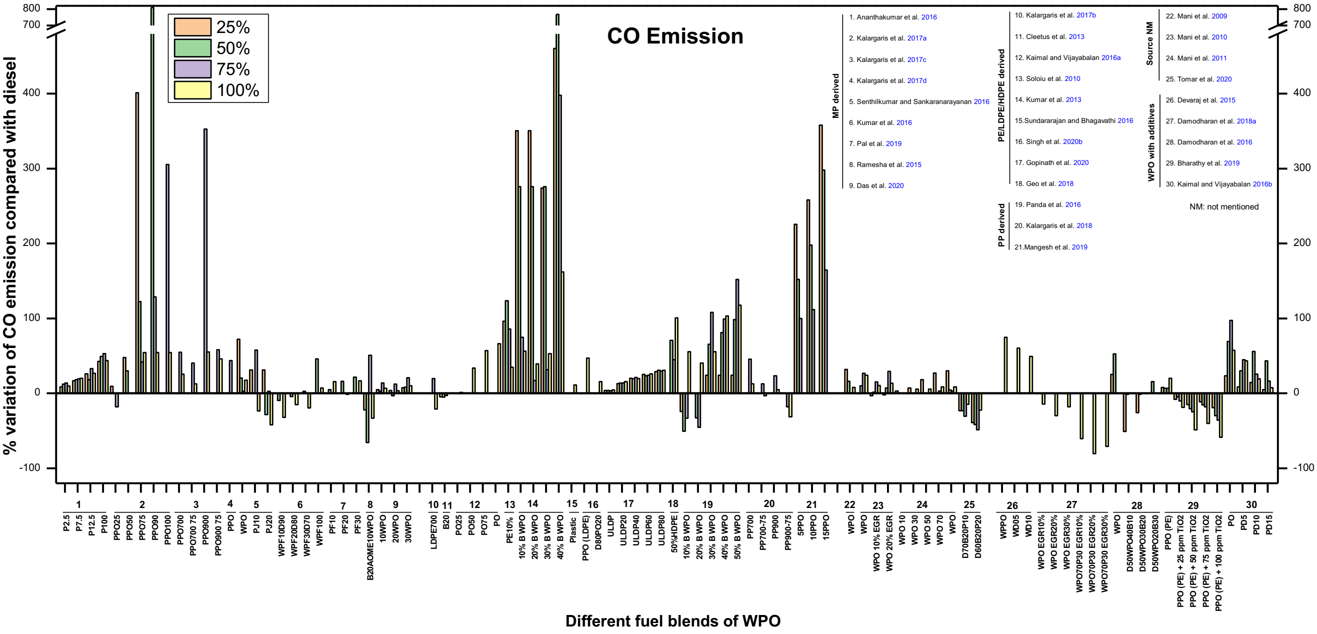

Fig. 2 CO emission at different loads using WPO

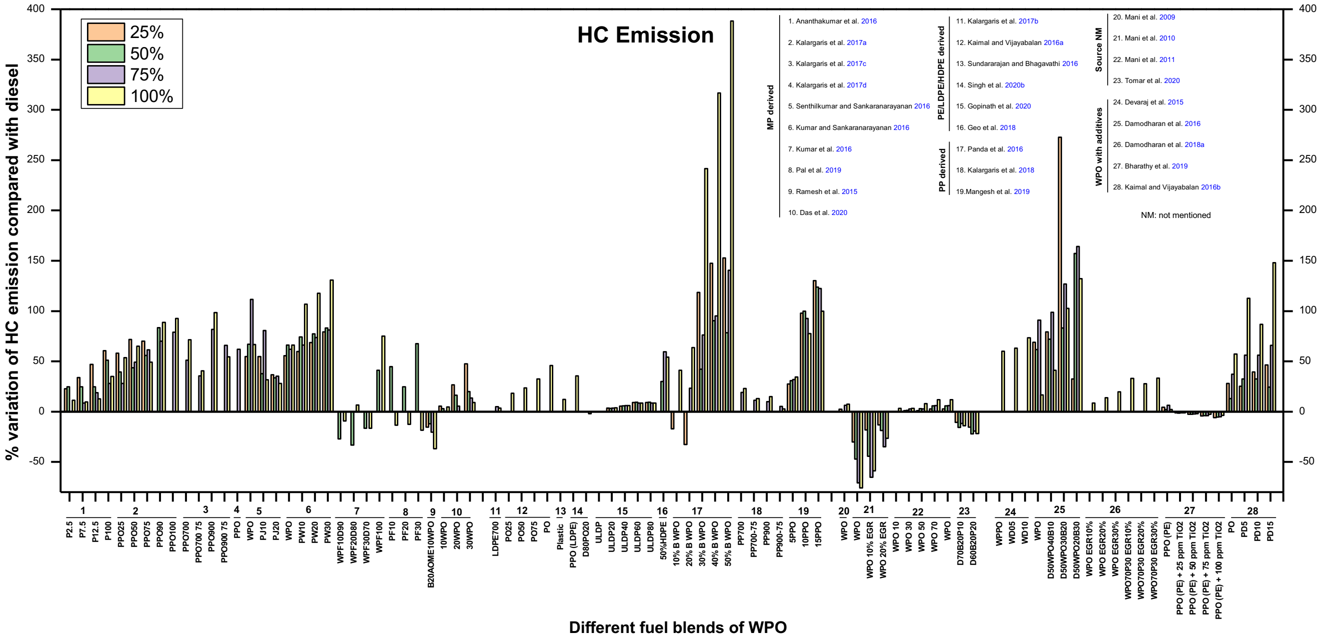

Fig. 3 HC emission at different loads using WPO

and three blends were prepared with or without application of diethyl ether (DEE), which are WPPO (neat plastic oil), WD05 (5% DEE with WPPO), and WD10 (10% DEE with WPPO). At full load, WPPO has a higher level of NO_x emission in comparison with diesel, whereas WD05 and WD10 reduced the NO_x level by approximately 38% and 45%, respectively (Fig. 1). The explanation behind the reduction in NO_x emission with the application of DEE is that the HRR in the diffusion-controlled stage decreased which thereby lowered down the NO_x level; higher cetane number and higher heat of evaporation of DEE are also other factors which helped in reducing the NO_x emission. However, no explanation was found in the study behind the increment in NO_x with the application of WPPO. A higher level of NO_x emission from MP-derived oil has been noticed in other literatures too, across the loading conditions (Kalargaris et al. 2017a; Kalargaris et al. 2017c; Kalargaris et al. 2017d; Ramesha et al. 2015; Senthilkumar and Sankaranarayanan 2016). And the majority of the studies attributed the fact of longer ignition delay (ID) with the application of MP-derived oil which leads

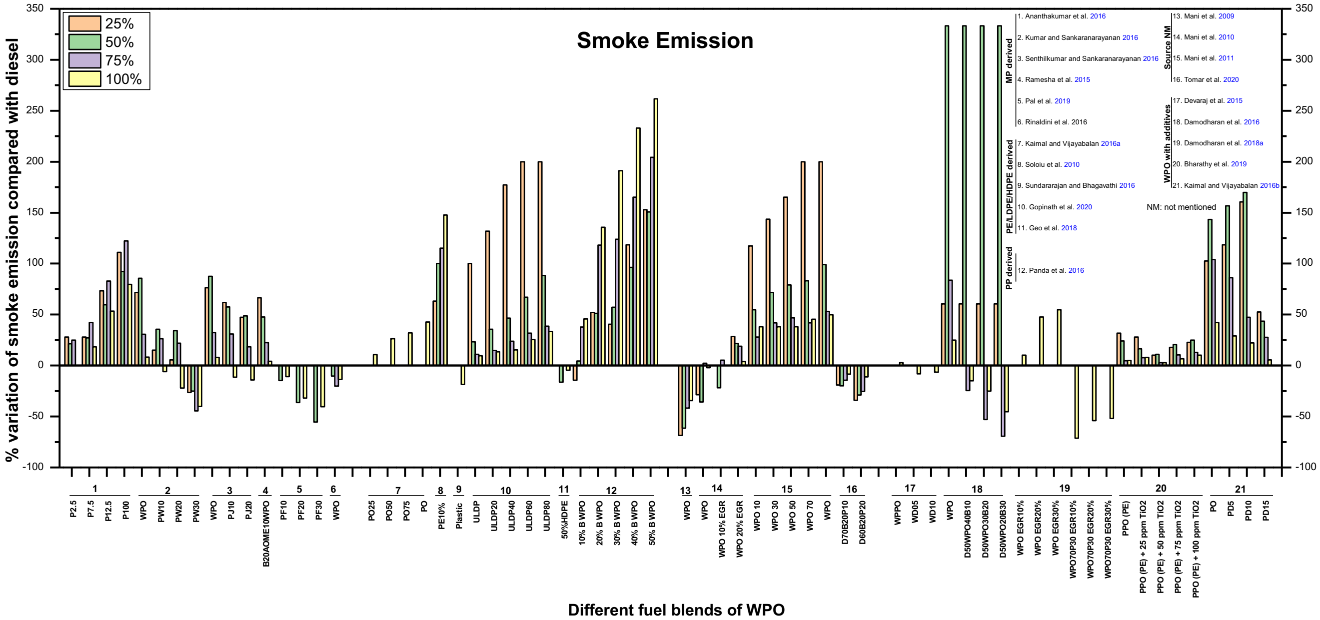

Fig. 4 Smoke emission at different loads using WPO

to higher premixed combustion duration thereby, higher HRR, and ultimately higher in-cylinder temperature. The other reason behind this increment in NO_x concentration may be the availability of nitrogen in the fuel which can contribute to the total NO_x through the fuel NO_x mechanism (Kalargaris et al. 2017a). However, it is important to state that majority of the total NO_x forms through thermal NO_x mechanism, in CI engine (Kalargaris et al. 2017b). Pal et al. (2019) investigated three blends of MP-derived oil taking three proportions of plastic fuel: 10%, 20%, and 30% (PF10, PF20, and PF30). It is noticed that at 50% load, NO_x concentration increased by 40%, 25%, and 25% for PF10, PF20, and PF30, respectively (w.r.t diesel). At full load, PF10 has shown very negligible variation, and PF30 has shown a higher level of NO_x emission, whereas PF20 has lowered down the NO_x level by approximately 6.5%. Kumar and Sankaranarayanan (2016) have performed experiments with emulsions of MP-derived oil (WPO). Water was added at three proportions (10%, 20%, and 30%), and the blends were abbreviated as PW10, PW20, and PW30. An increasing trend of NO_x emission, in comparison with diesel, was noticed with neat WPO as the emission level increased by 7%, 13%, 11%, and 2% at 25%, 50%, 75%, and 100% loads, respectively (Fig. 1). This increasing trend was due to the elevated combustion temperature and higher HRR. However, with the addition of water, NO_x emission decreased for all the blends, and the highest reduction was noticed for PW30 which offered approximately 71%, 65%, 64%, and 63% lower NO_x (w.r.t diesel) at 25%, 50%, 75%, and 100% loads, respectively. The reduction of NO_x emission with the emulsion blends is due to the latent heat of water which absorbs the heat during vaporization thereby and reduces the peak temperature (Jeevahan et al. 2017). Kumar et al. (2016) also found promising outcomes in regard to NO_x emission with the application of MP-derived oil and its blends. Almost all the test fuels have shown a decrease in NO_x, and the maximum reduction was noticed for neat plastic fuel at 100% loading condition which was approximately 14% (Fig. 1). Higher latent heat of vaporization and lower heating value of neat plastic fuel were attributed to this reduction. Similar explanations can also be found in other studies (Kidoguchi 2000; Loganathan et al. 2013).

Damodharan et al. (2018a) derived fuel from municipal solid plastic waste (MSW) for fuelling CI engine; the experiments were conducted at 100% load with the application of n-pentanol (30%) and exhaust gas recirculation (EGR). WPO has shown a reduction in NO_x emission with the application of EGR, and it has been observed that by employing 10%, 20%, and 30% EGR, the NO_x emission reduced by 3.9%, 6.8%, and 8.4%, respectively, w.r.t diesel (Fig. 1). As attributed by the authors, the oxygen concentration of the incoming air was diluted with EGR which increased the specific heat capacity of the working fluid, thereby reducing the flame temperature, and eventually, NO_x level reduced (Kulandaivel et al. 2020). However, all the blends containing n-pentanol (WPO70P30) have shown a higher level of NO_x emission which is due to the oxygenated n-pentanol that played a dominant role in increasing the combustion rate, as mentioned by the authors.

Kalargaris et al. (2017b) found a lower level of NO_x formation though marginally (approximately 1% and 2% lower at 100% and 75% loads, respectively), in comparison with diesel when the CI engine was fuelled with LDPE-extracted oil. Soloiu et al. (2010) have done experiments with 10% blend (PE10%) of LDPE-derived oil (rest is diesel), and the results revealed that PE10% has the potential of bringing down the NO_x emission by 29%, 48%, 51%, and 50% at 25%, 50%, 75%, and 100% load, respectively, w.r.t diesel. This was explained in regard to the less fuel burned in the premixed zone and lower peak cylinder temperature when the engine was run by LDPE fuel in comparison with neat diesel. Alike trend and explanation can also be found in the other study performing experiments with ULDP oil, and its blends (Gopinath et al. 2020). Similarly, Singh et al. (2020b) also found approximately 16% reduction (w.r.t diesel) in NO_x with 20% blend of LDPE oil. Sundararajan and Bhagavathi (2016) also found 15% (at full load) lower NO_x emission with HDPE-derived oil which was attributed to the fact of shorter ID which was again due to higher cetane-index (compared with diesel) of HDPE oil. Cleetus et al. (2013) have taken 20% of PE-derived oil and rest diesel (B20), for the application in CI engine, and it has been observed that B20 has 3.7%, 17.3%, and 12.4% higher NO_x than that of diesel, at 25%, 50%, and 75% loads. The increased NO_x emission was in agreement with the higher exhaust gas temperature (EGT) which was mentioned in the study. Al-Shemmeri and Oberweis (2011) also predicted a linear correlation between EGT and NO_x. It has been found in the literature that EGT is a good parameter for analysing exhaust emissions, especially NO_x (Fattah et al. 2014). In another literature, HDPE-derived fuel (PO) and its blends PO25, PO50, and PO75 have also shown increments in NO_x emission when compared to diesel (Kaimal and Vijayabalan 2016a). It has been seen that at full load, the percentage of increment in NO_x emissions was 4.7%, 10.8%, 18.2%, and 27.4% (approximately) for PO25, PO50, PO75, and PO, respectively, which means that the NO_x emission increased with the percentage of PO in the fuel blend. This increment is owing to the fact of increased premixed combustion, ID, and cylinder temperature with the application of PO, which increased the HRR in comparison with neat diesel. The presence of higher aromatic compounds in the PO might also increase the flame temperature which can result in high NO_x emission (Heywood 1984). Similarly, a marginal increment was noticed by Geo et al. (2018) with HDPE blend. Kaimal and Vijayabalan (2016b) also performed experiments with blends of HDPE-derived oil (PO) and DEE (5%, 10%, and 15%). In this case also a higher level of NO_x emissions has been noticed with the application of PO, compared to diesel. The NO_x emission increased by 21%, 21%, 41%, and 43% at 25%, 50%, 75%, and 100% loads with the application of PO. It has been mentioned by the authors that the higher delay period and CV of the fuel enhanced the peak temperature of the cylinder which resulted in increased NO_x for PO. However, when DEE was blended with PO, the emission level reduced (compared to PO) at all loading conditions and for all the blends. Higher latent heat of vaporization of DEE was attributed to this trend. During combustion, more heat is absorbed when the latent heat is higher which leads to decreased in-cylinder temperature and finally results in low NO_x emission (Kim et al. 2018; Mirhashemi and Sadrnia 2019). This is also in agreement with the fact of lower HRR and lower peak pressure (Sivalakshmi and Balusamy 2013). The lowest increment in NO_x (compared to diesel) emission was noticed for PD15 at 100% load; however, even with the application of DEE in PO, the overall NO_x level was higher than diesel at all operating conditions. Kumar et al. (2013) also observed that HDPE-based fuel blends 40%BWPO, 30% BWPO, 20%BWPO, and 10% BWPO (the numerical value signifies the percentage of plastic oil, rest is diesel) have higher NO_x emission when compared with diesel. It has been observed that the NO_x level increases with the higher percentage of WPO in the tested fuels. And 40%BWPO has shown approximately 99%, 87%, 84%, and 100% increment in NO_x emission at 25%, 50%, 75%, and 100% loads, w.r.t diesel. Better combustion owing to the existence of oxygenated hydrocarbons in plastic fuel might be the probable reason behind the increased NO_x formation, as specified by the authors.

A higher level of NO_x emission was noticed in other studies with the application of WPO (Mani et al. 2009; Mani et al. 2010; Mani et al. 2011) at all loading conditions. However, with the application of EGR, it has been seen that the NO_x emission reduced (except few contradictions) (Mani et al. 2010). In that study, it has been observed that the blend WPO20%EGR lowered down the NO_x level by 23%, 19%, and 14% at 25%, 50%, and 75% loads, respectively, compared with diesel. It is due to the rise in the total heat capacity of the working fluid by EGR, which lowers the elevated peak temperature. Similar attribution was also provided by Damodharan et al. (2018a) in their study when EGR was applied to run the CI engine with MSW-derived fuel. This explanation can also be supported by the attribution provided by Jorach (1997). In the study performed by Tomar et al. (2020), it was seen that the blends of biodiesel and WPO have overall lower NO_x than diesel which was attributed to the higher cetane number of the respective blends. However, it is hard to explain the exact impact of WPO on NO_x as biodiesel also could have contributed to this decrement.

Panda et al. (2016) found a very higher level of NO_x emission with the blends of PP-derived fuel (30%, 40%, and 50%). From Fig. 1 it is noticed that the increment in NO_x emission was as high as 253% (with 50% blend, at 50% load). A general tendency of higher emission with the increase of blend percentage of plastic oil has been noticed. A higher ID because of the presence of a longer carbon chain in plastic fuel was attributed to this trend. However, at a low blend percentage (10%BWPO), a lower level of NO_x emission was also noticed (17% low at 50% load) though the reason behind this trend was unexplained in the study. Similarly, Kalargaris et al. (2018); Mangesh et al. (2019) have also found higher NO_x with PP-derived oil. In these cases, the attributions include higher ID and lower equivalence ratio resulting in higher temperature, with PP oil. In addition, from mass fraction burned analysis, it was also noticed that the PP blends have a longer combustion period that can increase the residence time of the oil at higher temperatures (Kalargaris et al. 2018). And the higher residence time can also contribute to higher NO_x (Heywood 1984). Das et al. (2020) extracted WPO from medical plastic waste (MPW), and three blends (10WPO, 20WPO, and 30WPO) were prepared; in this case, also higher NO_x (due to prolonged ID) was noticed for the blends though in few cases marginal variations were seen.

CO emission

The higher formation of CO contamination is a sign of imperfect combustion (Kuzhiyil and Kong 2009). CO is a poisonous gas that is odourless and colourless. CO is the cause of many health issues like headache, nausea, cardiovascular, chronic fatigue, dizziness, muscle pain, joint pain, etc. Incomplete combustion is the reason behind CO formation. At lower temperatures and in a reduced oxygenated environment, the probability of CO formation is high (Khalife et al. 2017).

The investigation conducted by Ananthakumar et al. (2016) reveals that all the DEE and MP-derived oil blends: P100, P12.5, P7.5, and P2.5, have higher CO emission compared to neat diesel. A general tendency of higher CO emission was noticed with the higher proportion of plastic oil in the blend, and P100 has shown the highest increment in CO emission amongst all the blends. It can be seen from Fig. 2 that the CO emission level increased by 43%, 49%, 53%, and 43% (w.r.t diesel), at 25%, 50%, 75%, and 100% loads, respectively. However, the CO emission levels of DEE mixed blends were lower when compared with P100 and this is due to the oxidizing nature of DEE which helped in better combustion. Devaraj et al. (2015) have also observed higher CO emission with WPPO (extracted from MP), WPPO has shown 75% higher CO emission at full load, and this was attributed to lower in-cylinder temperature. With the application of DEE, the CO emission decreased slightly if compared with WPPO; this is because of the higher availability of oxygen with the application of DEE. But still, the level of CO emission for WD05 and WD10 were 60% and 49% higher, compared with diesel. A severe deterioration in CO emission has been observed with PPO (derived from MP) and its blends, in the study reported by Kalargaris et al. (2017a), particularly at low loads for higher blending ratios (≥75%). The lower cetane number of PPO is the reason behind this trend which was also understood from the lower peak pressure of the cylinder. However, at low blend ratios (<75%), a marginal variation in CO emission was noticed at all loading conditions, but the reason behind this was unexplained in the literature. Likewise, increased CO emission has been observed by Kalargaris et al. (2017c) and Kalargaris et al. (2017d), taking MP-extracted oil for experimentation, and similar attribution of lower cetane number and longer ID was given. The study performed by Senthilkumar and Sankaranarayanan (2016) also showed that MP-derived fuel has 72%, 21%, 3%, and 18% higher CO emission at 25%, 50%, 75%, and 100% loads, respectively (Fig. 2). However, when jatropha methyl ester was added with WPO, the CO level reduced slightly which might be because of excess oxygen in jatropha methyl ester. PJ10 has shown a 23% reduction at 100% load whereas, PJ20 has shown 28%, 3%, and 42% lower CO emission than that of diesel. In another literature (Kumar et al. 2016), MP-derived fuel has shown a mixed trend as WPF100 has higher CO emission across the loading condition, but the blends WPF10D80 and WPF20D90 have shown lower CO emission (4% and 15%; 9% and 32% at 50% and 100% loads, respectively, compared to diesel). Pal et al. (2019) also found higher CO emission with MP-extracted fuel blends; the main reasons behind this increment were less oxygen level, poor air-fuel mixing, and incomplete combustion. But an exceptional result was noticed for PF20 at full load where the CO emission decreased by 1% approximately. Ramesha et al. (2015) blended MP-derived fuel (10%) in B20 algal biodiesel; in this case, the CO emission was lower than diesel. The blend B20AOME10WPO has shown approximately 22%, 66%, and 33% lower CO emission w.r.t diesel, at 25%, 50%, and 100% loads, respectively. The algal biodiesel and plastic fuel have oxygen content which helped in complete combustion and that has resulted in the reduction of CO emission.

Damodharan et al. (2016) extracted fuel from MSW (plastic-based) which was blended with diesel and n-butanol. And it has been observed that at higher loads (75% and 100%); all the blends have almost the same level of CO emissions, whereas with the addition of n-butanol, the CO emission decreased by a maximum of 51% (for D50WPO40B10 at 25% load) which is due to the available oxygen that helped in better oxidation. Similarly, the blends of MSW-derived oil with the application of EGR and with or without the application of n-pentanol have shown a reduction in CO emission of CI engine (Damodharan et al. 2018a). The blends WPOEGR10%, WPOEGR20%, and WPOEGR30% have shown approximately 14%, 30%, and 18% reduction in CO emission, at full load, when compared with neat diesel (Fig. 2). This decrement further reduced to 60%, 80%, and 71% (for WPO70P30EGR10%, WPO70P30EGR20%, and WPO70P30EGR30%, respectively) when n-pentanol is used with WPO. The higher volatility is favourable to decline CO formation, and the oxygenated pentanol can make a significant influence to reduce the CO emissions (Chen et al. 2017).

Kalargaris et al. (2017b) investigated with LDPE oil which has shown a reduction of approximately 21% in CO emission. This may be because of the shorter ID and high oxygen content in LDPE which resulted in decreased CO emissions in comparison to diesel operation. Likewise, Cleetus et al. (2013) have also observed 5%, 5%, and 3% lower CO emission (Fig. 2) with PE-derived oil at 25%, 50%, and 75% loads, respectively. However, the LDPE blend D80PO20 has shown 15% higher CO w.r.t diesel (Singh et al. 2020b), and the neat PPO (LDPE) has shown much higher CO. Similarly, ULDP and its blends have shown higher CO w.r.t diesel at all loads (Gopinath et al. 2020). This increment was linked with insufficient oxygen and higher aromatic content in the tested fuel which caused longer ID. The studies investigated by Kaimal and Vijayabalan (2016a); Kaimal and Vijayabalan (2016b), taking HDPE as the feedstock for fuel, have shown higher (compared to diesel) CO emission at all operating conditions. Soloiu et al. (2010) have also reported a similar trend of higher CO emission with PE10% as the blend has shown 96%, 123%, 86%, and 35% higher emission than that of diesel at 25%, 50%, 75%, and 100% loads, respectively. Similarly, Kumar et al. (2013); Geo et al. (2018) have observed a very high level of CO emission when the engine was run by HDPE oil (Fig. 2). Lack of oxygenated compounds in WPO, local rich regions, and poor mixture preparation may be few other reasons for increased CO emission (Mani et al. 2009). Sundararajan and Bhagavathi (2016) explained the cause of higher CO emission with HDPE oil in regard to the higher (w.r.t diesel) kinematic viscosity of the fuel. The higher kinematic viscosity may cause inferior vaporization and atomization of the fuel and as a consequence, incomplete combustion, which can ultimately increase the CO emission of the engine. However, the addition of TiO_2 diminished the CO level considerably (Bharathy et al. 2019) because TiO_2 donates oxygen for the oxidation of CO (Shaafi et al. 2015). The blend PPO (PE) + 100 ppm TiO_2 has shown 19%, 30%, 36%, and 59% reduction w.r.t diesel, at 25%, 50%, 75%, and 100%, respectively.

The investigation with WPO and its blends, by Mani et al. (2009) and Mani et al. (2011), also showed a higher level of CO emission than diesel. Mani et al. (2011) have observed that with the increase of WPO in the tested fuel, the CO level also increased. Reduced in-cylinder temperature, poor air-fuel mixture, and incomplete combustion were the reasons behind this variation. It has been also observed in the study that with the increase of load, CO emission decreased which is because of shorter ID at higher outputs; the available quantity of fuel during the delay period reduces; thus, the CO emissions were lower to that of low-load operation. A general tendency of higher CO has been also noticed with EGR when the engine was run by WPO (Mani et al. 2010). This was attributed to the fact that some oxygen available in the inlet charge might have been replaced with the EGR that caused incomplete combustion. However, from Fig. 2, it can be noticed that the blend D60B20P20, in the study of Tomar et al. (2020), has shown approximately 49% reduction in CO which might be linked with the higher oxygen content in the blend due to the presence of WPO.

Panda et al. (2016) have performed the investigation with PP oil; in this case, it has been observed that at a low percentage of PP in the PP-diesel blend, the CO emission level is lower than diesel. 10%BWPO has shown 24%, 50%, and 33% lower CO at 25%, 50%, and 75% loads, respectively, when compared to diesel (Fig. 2). And 20%BWPO has shown no variation in CO emission at 25% load, but 33% and 45% lower CO at 50% and 75% loads, in comparison with diesel. And the other blends: 50%BWPO, 40%BWPO, and 30%BWPO, have shown higher CO emission at all operating conditions; the highest level of CO emission was noticed for the blend 50%BWPO. Local rich regions and poor mixture preparation owing to the fact of wide product distribution of WPO might be the factor which contributed to higher CO emission. Similarly, the increasing trend of CO emission with PP oil was also seen in the study of Mangesh et al. (2019); however, a mixed trend was noticed by Kalargaris et al. (2018) in their research, and at 75% and 100% load, the blend PP900-75 has shown reductions of 18% and 30%, respectively. As suggested by the authors, this might be because of the combined effects of lower viscosity and higher oxygen levels, resulting in enhanced mixing of the air fuel. Das et al. (2020) also observed higher CO with MPW-derived WPO blends. The lean mixture and lack of oxygen were highlighted as the reasons behind higher CO.

HC emission

Better combustion of fuel diminishes the HC emission. Fuel composition and burning behaviour also play a part in HC formation (Datta and Mandal 2017). Incomplete combustion is the most important factor which leads to HC formation in the combustion chamber. HC is the portion of the fuel that could not contribute to the combustion process. So enhancement of the favourable circumstances for complete combustion can decrease HC emission (Ettefaghi et al. 2018).

From Fig. 3, it is observed that the MP-derived blends: P100, P12.5, P7.5, and P2.5, have shown increment in HC, at all loads, and the highest increment in HC emission was noticed for P100 as it has shown approximately 60%, 51%, 18%, and 35% higher HC in comparison with neat diesel (Ananthakumar et al. 2016). This is due to the formation of the local rich mixture and poor atomization which leads to incomplete combustion. Devaraj et al. (2015) have also observed 60% higher HC emission at 100% load, compared to diesel which was attributed to the higher fumigation rate of WPO. And it was also observed that even with the application of DEE, the HC emission was higher. It is noteworthy to mention here that DEE reduces combustion temperature as it has a higher heat of evaporation. Also, some amount of DEE may mix with air during the injection of fuel that may accumulate in the ring space between the cylinder and piston. Subsequently, the combustion flame might not effectively reach these spaces, resulting in increased HC emissions (Purushothaman and Nagarajan 2009). The study performed by Senthilkumar and Sankaranarayanan (2016) also showed that MP-derived fuel has 55%, 67%, 112%, and 67% higher HC at 25%, 50%, 75%, and 100% loads, respectively (Fig. 3). The reason behind increased HC in WPO may be the higher fumigation rate. The addition of jatropha methyl ester offered a slight decrement in HC emission level, though it was higher than diesel. Similarly, Kalargaris et al. (2017a); Kalargaris et al. (2017c); Kalargaris et al. (2017d) have also seen an increment in HC emission with MP-derived oil for all the blends at all operating conditions. A possible reason behind this higher HC emission can be that the WPO spray may have a higher chance to impinge in the cylinder wall due to its high density, low viscosity, and low cetane number which consequences in lengthier ID. On the other hand, it is also supposed that the higher aromatic content in the WPO may increase the HC emission (Murugan et al. 2008) however, the main reason is still unclear in the literature. All the emulsions of MP-derived oil have also shown higher HC emission at all loading conditions (Kumar and Sankaranarayanan 2016) which can be attributed to the fact of non-availability of oxygen and higher fumigation rate (Pradeep and Sharma 2005) and higher ID due to the presence of water in the blends which caused incomplete combustion. It is also observed from the study of Kumar et al. (2016) that WPF100 has higher HC than diesel at all operating conditions. But WPF10D90 and WPF30D70 have shown lower HC emission by 27% and 16% at 50% load and 9% and 17% at 100% loads, respectively, when compared with neat diesel. This might be because of the higher availability of oxygen which is in agreement with another study (Kannan and Anand 2011); however, on the contrary, a mixed trend in HC emission was noticed for WPF10D80, the reason of which is unexplained in the literature. In the experiments of Pal et al. (2019), the blends PF10, PF20, and PF30 have shown 45%, 25%, and 68% higher HC emission than that of diesel. This might be because of the bulk flame quenching and misfiring combustion of WPO due to the presence of aromatic compounds in it. However, at full load, the emission level reduced in comparison with diesel, as the blends have shown approximately 13%, 13%, and 19% lower HC emission. The blend of algal emulsion and MP-derived plastic oil

(B20AOME10WPO) has revealed promising result in regard to HC emission as it has shown approximately 15%, 12%, 20%, and 37% lower emission (Fig. 3) w.r.t diesel, at 25%, 50%, 75%, and 100% loads, respectively (Ramesha et al. 2015). This is because of the availability of oxygen in the algal biodiesel and plastic fuel that helped in complete combustion, resulting in the reduction of HC emission.

The MSW-derived oil (WPO) along with its blends with diesel and n-butanol: D50WPO40B10, D50WPO30B20, and D50WPO20B30, has shown substantial increment in HC emission. The highest increment was noticed for D50WPO30B20; at 25%, 50%, 75%, and 100% loads, the HC emission increased by 272%, 83%, 127%, and 103% w.r.t diesel (Damodharan et al. 2016). This upsurge in HC for WPO was due to the availability of unsaturated HC which were resilient throughout the combustion. On the other hand, n-butanol causes flame quenching due to its high heat of evaporation, resulting in increased HC emission. A similar increasing trend of HC emissions has been reported by Rakopoulos et al. (2010) while employing n-butanol with WPO, due to slower air-fuel mixing as a consequence of n-butanol's higher heat of evaporation. With the application of EGR, also the MSW-derived oil offered higher HC emission when compared with diesel (Damodharan et al. 2018a). Flame temperature reduces with EGR; consequently, more flame-quenching zones are formed thus, affecting the combustion (Babu and Anand 2017), and this favours HC formation. Even with the application of n-pentanol, the HC emission was higher than diesel. Pentanol has a longer ID and higher latent heat that leads to a larger cool-flame chemiluminescence area resulting in increased HC emission (Ma et al. 2017).

From Fig. 3, it is observed that PE-derived LDPE700 has offered a higher amount of HC than diesel; the emission level increased by approximately 5% and 4% at 75% and 100% loads, respectively (Kalargaris et al. 2017b). This is due to the fact of higher aromatics and aromatic bonds in the blend which require more energy to break (Murugan et al. 2008; Kaimal and Vijayabalan 2015). The study reported by Gopinath et al. (2020) shows that CI engine emits almost the same level (w.r.t diesel) of HC with neat ULDP, but a marginal increase in HC emission was noticed with the increase in the proportion of ULDP in the blend. Similarly, Singh et al. (2020b) also found higher HC with PPO (LDPE), but the blend D80PO20 has shown marginal reduction as compared with diesel, whereas Geo et al. (2018) have observed a substantial increase in the HC emission with HDPE blend (50%HDPE) w.r.t diesel at all loads. The studies reported by Kaimal and Vijayabalan (2016a); Kaimal and Vijayabalan (2016b) (with the application of DEE), taking HDPE as the feedstock for fuel extraction, have shown higher (compared to diesel) HC emission at all loads. The higher viscosity and density of plastic oil reduces the combustion-efficiency; besides, the low volatility of the tested fuels caused glitches in the preparation of the air-fuel mixture owing to the higher aromatic content in the plastic oil. Quenching of reactions (due to low temperature) might also be a possible reason, and inadequate fuel evaporation can also contribute to HC formation (Heywood 1984; Imtenan et al. 2015). On the other hand, with the use of DEE, the quenching of flame due to the high latent heat of vaporization of DEE and formation of the lean flame out region might be other possible reasons behind higher HC emission (Rakopoulos et al. 2013). Likewise, Sundararajan and Bhagavathi (2016) have also observed 12% lower (w.r.t diesel) HC emission with HDPE oil at full load (Fig. 3). The higher kinematic viscosity may lead to poor vaporization and atomization of the fuel resulting in incomplete combustion which can ultimately increase the HC emission of the engine, as suggested by the authors. Similarly, a drastic increase in HC emission has been noticed by Kumar et al. (2013) with the blends of HDPE-derived oil. As stated by the authors, there might be two reasons for this trend. First is less propagation of the fuel-spray into the combustion chamber for which gaseous hydrocarbons stay along the crevice volume and cylinder wall thus left unburned. And, the second is the availability of unsaturated HC in WPO that are not breakable during the combustion. These two explanations can be supported by the other studies investigated by Muralidharan et al. (2011) and Kidoguchi (2000). However, the addition of TiO_2 with PE-derived oil reduced HC emission at all loads as TiO_2 acts as a catalyst and offered oxygen for burning (Bharathy et al. 2019).

The investigation with WPO and its blends, by Mani et al. (2009) and Mani et al. (2011), also shown a higher level of HC emission than diesel. This is due to the less availability of oxygen (w.r.t diesel) and the higher fumigation rate. Additionally, the non-homogeneity of the air-fuel mixture might be another reason behind this trend. Because of the non-homogeneity nature, few local spots with lean and rich mixture would be available inside the combustion chamber (Çelıkten 2003). Due to the lack of oxygen in fuel-rich zones, few droplets might not react and incomplete combustion may occur (Ren et al. 2006; Walendziewski 2002). Higher cetane number and excess oxygen in WPO can reduce the HC emission which was seen in the study of Tomar et al. (2020), as the blend D60B20P20 has shown a noticeable decrease in this regard. With the application of EGR, it has been noticed that the tested fuels WPO20%EGR and WPO10%EGR have lower HC emissions compared to neat diesel (Mani et al. 2010). WPO10%EGR has offered 18%, 44%, 65%, and 59% lower HC, whereas for WPO20%EGR, the reduction in HC emission was 13%, 19%, 35%, and 27% (Fig. 3) at 25%, 50%, 75%, and 100% loads, respectively (w.r.t diesel). In the same study, even neat WPO has offered 30%, 47%, 71%, and 76% lesser HC at 25%, 50%, 75%, and 100% loads, respectively, to that of diesel operation. It is necessary to mention here that no explanation was found in the literature in this regard.

Panda et al. (2016) have also found a general tendency of higher HC with the application of PP oil and its blends (Fig. 3). The attribution behind this trend of higher HC emission (w.r.t diesel) is the same to the explanation provided by Kumar et al. (2013) in their studies. Similarly, Mangesh et al. (2019); Kalargaris et al. (2018) have also shown higher HC at all operating conditions with the application of PP oil. Some of the likely reasons behind this trend are lower cetane number, higher ID, and higher aromatic hydrocarbon content of the PP oil. Alike variation in HC was also noticed with MPW-derived blends (Das et al. 2020).

Smoke emission

Incomplete combustion is the source of higher smoke, and this is a perceptible indicator of the combustion process. Insufficient air-fuel mixing is the foremost cause of the formation of smoke. Smoke is formed if the local temperature is adequate for the decomposition of tested fuel and if the oxygen quantity is not sufficient to burn the carbon. Then again, smoke may also be generated if carbon is formed because of the rich localized mixture.

The investigation performed by Ananthakumar et al. (2016) discloses that MP-derived oil and its blends have higher smoke emissions at all loading conditions (Fig. 4). It is also seen that the smoke level increased with the percentage of WPO in the blend and P100 has shown approximately 111%, 92%, 122% and 80% higher (w.r.t diesel) smoke emission. In another study also, reported by Kumar and Sankaranarayanan (2016), MP-derived oil has shown higher smoke emission at all loading conditions; however, it has been noticed that with the addition of water in WPO, the smoke level decreased at all loading conditions. And for the blend PW30 (30% water), the smoke emission was even lower than that of diesel. PW30 has offered an approximate reduction of 26%, 25%, 45%, and 40% smoke (Fig. 4) in comparison with neat diesel which was attributed to the fact of non-availability of oxygen and higher fumigation rate. The micro-explosion phenomenon of the emulsified fuel substantially improves the evaporation of the fuel and enhances the air-fuel mixing; consequently, less smoke generates, and the lower smoke may also be due to the availability of premixed WPO inside the combustion zone with higher ID. Devaraj et al. (2015) have observed higher smoke emission with WPPO; however, with the addition of DEE, the smoke emission reduced, and it was lower than diesel-run operation. The smoke emission reduced by approximately 8% and 6% for WD05 and WD10, respectively, at 100% load. DEE, having higher oxygen content, depromotes the formation of smoke during the diffusion combustion phase. The study performed by Senthilkumar and Sankaranarayanan (2016) also showed that MP-derived fuel has 76%, 88%, 32%, and 8% higher smoke emission at 25%, 50%, 75%, and 100% loads, respectively (Fig. 4). This was attributed to the fact of heavier WPO molecules, along with longer combustion duration and longer ID, compared to diesel. However, when jatropha methyl ester was added with WPO, the smoke level reduced slightly which might be because of excess oxygen in jatropha methyl ester which can help in complete combustion. PJ10 and PJ20 have shown 12% and 14% reduction (compared to diesel) in smoke emission at 100% load. The blend of algal emulsion and MP-derived plastic oil (B20AOME10WPO) has also shown 67%, 48%, 23%, and 4% higher smoke at 25%, 50%, 75%, and 100% loads, respectively (Ramesha et al. 2015). This might be because of improper mixing (having higher viscosity) of air and fuel droplets and poor volatility. The fact of heavier molecules of biodiesel and plastic oil was also ascribed as the cause of higher smoke (Balusamy and Marappan 2007). However, a promising result has been reported by Pal et al. (2019) with the blends of MP-derived oil and diesel. Because PF10, PF20, and PF30 have shown 15%, 36%, and 55% lower smoke at 50% load and 11%, 32%, and 40% lower smoke at 100% load (w.r.t diesel), similarly, Rinaldini et al. (2016) also found 10%, 20%, and 14% reduction in smoke emission at 50%, 75%, and 100% loads, respectively, with the application of MP-derived WPO.

The MSW-derived oil (WPO) along with its blends with diesel and n-butanol: D50WPO40B10, D50WPO30B20, and D50WPO20B30, has shown substantial increment in smoke emission, at 25% and 50% loads (Damodharan et al. 2016). But at higher loads, n-butanol-added blends have shown a decrease in smoke which is due to the availability of oxygen in n-butanol (Rakopoulos et al. 2010). Besides, the low carbon content in n-butanol can also substitute WPO and higher carbon diesel, ultimately reducing smoke emission. Damodharan et al. (2018a) have also taken MSW-derived WPO for CI engine application (with the application of EGR and addition of n-pentanol), and it has been seen that with EGR (without n-pentanol), the smoke level was higher for all the blends. This is owing to the reduced availability of oxygen in air-fuel mixture with the application of EGR. But when n-pentanol was added, the smoke level reduced for all the blends. Maximum reduction was noticed for WPO70P30 EGR10% which was approximately 71% lower than that of diesel, at 100% load (Fig. 4). The addition of n-pentanol decreases the smoke substantially, as a single embedded oxygen atom present in pentanol is effective in reducing soot precursors, and also the lower percentage of WPO would lessen the aromatic content of the blend.

Kaimal and Vijayabalan (2016a) have found higher smoke emission with HDPE-derived WPO and its blends; at 100% loading condition, PO25, PO50, PO75, and PO have shown 11%, 26%, 32%, and 43% higher level of smoke when compared with neat diesel. This is in agreement with the fact that low volatility and high viscosity can result in worse spray characterization and mixture formation influencing the combustion efficiency. And it is also noticed that the smoke increased along with the proportion of WPO in the blend which can be explained in the context of higher aromatic content of WPO (Kidoguchi 2000). Similar attribution can be found in the study of Kaimal and Vijayabalan (2016b) who have also observed very high increment (compared to diesel) in smoke emission at all loading conditions when the engine was run with HDPE oil. Likewise, Soloiu et al. (2010) have also found a very high increment in smoke emission with PE-based fuel. However, Sundararajan and Bhagavathi (2016) have observed a reduction in smoke emission of the CI engine when fuelled with HDPE oil. It has been found that HDPE oil has 18% lower smoke (w.r.t diesel), at 100% load (Fig. 4). The decrease in smoke emission with HDPE oil could be possibly due to the presence of oxygenated moieties (alcohols) and the formation of the premixed combustion mixture before the combustion initiation. Early evaporation of HDPE blend can lead to homogeneous mixture inside the cylinder which can increase the HRR, and eventually, improved combustion can be achieved that can reduce the smoke level (Geo et al. 2018). The ULDP and its blends have shown higher smoke at all loads as compared against diesel; this was linked to the longer ID which is again due to the existence of rich fuel (Gopinath et al. 2020).

The investigation with WPO and its blends, by Mani et al. (2011), also showed higher smoke emission at all loads, compared with diesel. This is due to the lack of a homogeneous mixture inside the engine cylinder. Reduced combustion duration, lower combustion temperature, and rapid flame-propagation may also be the other reasons behind the higher smoke level (Agarwal 2007). Mani et al. (2010) employed EGR with WPO, but in this case, also, the smoke level was higher. The increased smoke level is because of the combustion instability due to the partial replacement of air by the exhaust gases (Wang et al. 2000). However, neat WPO in this study has shown 29%, 36%, and 2% reduction (Fig. 4) in smoke level in comparison with neat diesel, the reason for which was unexplained. Similarly, Mani et al. (2009) have also observed 68%, 61%, 42%, and 34% reduction in smoke emission at 25%, 50%, 75%, and 100% loads, respectively. The reason for the reduced smoke was explained in regard to the availability of homogeneous and premixed charge well before the initiation of combustion. The extended combustion duration, higher combustion temperature, and rapid flame propagation are the other possible reasons for lower smoke emission (Sayin et al. 2008).

Panda et al. (2016) have also found a general tendency of higher smoke emission with the application of PP oil and its blends. From Fig. 4, it is observed that the increment in smoke emission amplified with the proportion of PP oil in the tested fuel. This might be due to the lack of homogeneous charge in the engine cylinder, rapid flame propagation, and reduced combustion duration (Sayin et al. 2008). Likewise, the tendency of higher smoke was seen by Das et al. (2020) with MPW-based blends.

Summary of emission characteristics

Different investigators have carried out their studies with WPO, few researchers have performed experiments with MP or MSW-derived oil, whereas few of them investigated the potential of individual plastics either waste or virgin. They have performed the experiments by varying the load which is summarized and shown in graphical forms. Four different loads (25%, 50%, 75%, and 100%) have been taken into consideration in this review for different WPO blends reported in the literature. The summary of NO_x, CO, HC, and smoke emissions at various loading conditions are represented by Figs. 1, 2, 3, and 4, respectively. The percentage variation of respective emission parameters is made with respect to neat diesel. In comparison with diesel, the higher oxygen content and lower cetane index of MP-extracted WPO, increased premixed combustion and higher oxygen content of PE/LDPE/HDPE-extracted WPO, and presence of long carbon chain in PP-extracted WPO resulted in increased NO_x emission. The poor air-fuel mixing and incomplete combustion of MP-extracted WPO, the higher aromatic content and higher viscosity of PE/LDPE/HDPE-extracted WPO, and the fact of wide product distribution in PP-extracted WPO contributed to the higher CO emission. The higher density, low viscosity, and low cetane number of MP-extracted WPO, the higher aromatic content and higher density of PE/LDPE/HDPE-extracted WPO, and the higher ID of PP-derived WPO resulted in higher HC emission. The lower cetane index and longer combustion duration of MP-extracted WPO, the low volatility, high viscosity, and higher aromatic content of PE/LDPE/HDPE-extracted WPO, and lack of homogeneous-charge and rapid flame propagation for PP-derived WPO were the influencing factors that caused higher smoke emission. Apart from this, higher oxygen content in the additives increased the NO_x and reduced the CO and smoke in few cases, though the emission levels of CO and smoke were still higher than diesel-run operation for maximum fuel samples, and the higher latent heat of evaporation of the additives increased the HC emission. The above influencing factors of the corresponding emission characteristics (w.r.t diesel) are valid for the majority of the studies. However, reverse trends of each emission characteristic have been also noticed in a few studies. A substantial amount of reduction in NO_x emission has been observed with the addition of water (maximum 71% reduction with PW30) and application of the EGR technique (maximum 23% reduction with WPO20%EGR). Few blends of WPO, derived from MP, MSW, and PP, have also shown a substantial reduction in CO emission. A certain blend of PP-derived WPO has shown a maximum of 56% reduction in CO emission w.r.t neat diesel; similarly, application of EGR technique with WPO has also shown promising results in this context. In regard to HC and smoke emission also, some of the tested fuels derived from MP, PE, and PP have shown considerable reduction w.r.t diesel. The maximum reduction for HC emission was 76%, whereas for smoke emission, it was 71%. It is noteworthy to mention here that apart from the incorporation of the EGR technique or emulsification process, the application of additives like n-butanol, n-pentanol, DEE, and TiO_2 in WPO has also shown their potential in reducing the emission levels of CI engine in a few specific cases. The higher latent heat of evaporation of DEE contributed to lower NO_x; better oxidation of n-butanol and n-pentanol contributed to lower CO; similarly, oxygen offering catalytic nature of TiO_2 contributed to reducing the HC emission. In regard to the emission reduction, the effects of the application of bio-additives with WPO can be explored in the future. Because it has been found in the literature that bio-additives have the sound potential of reducing emissions (of CI engine) with satisfactory engine performance due to their better oxidation stability, higher latent heat of vaporization, higher combustion efficiency, and better air-fuel mixing (Pillai et al. 2017; Shah et al. 2018; Ettefaghi et al. 2018; Saha et al. 2020). However, to date, hardly any study has been reported in which bio-additives were applied with WPO for investigating the emission and performance characteristics of the CI engine. And, on the other side, in most of the studies, the emission parameters were found to be in the higher range with the application of WPO. Thus, looking at all the realities stated above and considering the fact of running CI engines with a fuel derived from waste plastic, it can be said that WPO has a wider opportunity in this field.

Effect of WPO on performance characteristics of CI engine

Different researchers have also explored the potential of WPO in terms of performances of CI engines, through their experimental studies. The performance parameters considered for this study are brake-specific fuel consumption (BSFC) and EGT. The percentage variations in the performance parameters w.r.t diesel are represented graphically (Figs. 5 and 6) at different loading conditions (25%, 50%, 75%, and 100%). WPO influences the performance parameters of the CI engine. The next section of the paper deals with the impacts of WPO on the performance characteristics of the CI engine.

BSFC

The consumption of fuel of an engine is usually expressed by BSFC. BSFC is one of the utmost significant parameters of the engine as it can be related directly to the current energy crisis era. BSFC is the ratio of fuel consumption per unit time and brake power. Lower BSFC is desirable as the engine would need lesser fuel to deliver the same power.

The investigation done by Ananthakumar et al. (2016) shows that MP-derived oil and its blends have higher BSFC at all the loads. It is also seen that the amount of BSFC increased with the amount of WPO in the blend, and P100 has shown approximately 11%, 23%, 28%, and 19% higher (w.r.t diesel) BSFC (Fig. 5). The higher BSFC can be ascribed to the higher viscosity of WPO which influences the vaporization and atomization. The conversion of chemical energy into thermal energy is lesser with the application of WPO; thus, more fuel is needed for the same power output. Devaraj et al. (2015) found 7% higher BSFC at 100% load, with WPO (MP-derived) which was due to low heating value, higher density, and higher bulk modulus of the tested fuel. The higher bulk modulus results in a higher discharge of fuel for the same displacement of the plunger in the injection pump thus leads to increased BSFC. However, the blend WD10 offered a negligible variation in BSFC w.r.t diesel. This is owing to the availability of excess oxygen and fast burning of DEE molecules leading to lower combustion temperature and resulting in improved combustion. The attributions of lower CV and henceforth higher bulk modulus were also highlighted by Senthilkumar and Sankaranarayanan (2016) investigating blends of MP-derived oil and jatropha methyl ester. Kalargaris et al. (2017a) also observed considerable increase in BSFC (compared to diesel) for all the WPO (MP-extracted) blends at all operating conditions, and the highest increment was observed for PPO100 (neat WPO) which is because of the aromatic compounds of PPO100 that needs higher energy to break down (Kaimal and Vijayabalan (2015). Another possible explanation might be the higher heat transfer loss of PPO at the higher combustion temperature, as mentioned by the authors. Similarly, in the study of Kumar et al. (2016), although a general tendency of higher BSFC was noticed with MP-extracted WPO and its blends, but WPF10D90 has shown an almost similar level of BSFC when compared with neat diesel (Fig. 5). However, no specific justification was found in the literature in this regard. In the study reported by Rinaldini et al. (2016), MP-derived oil has shown lower density for which the BSFC was found to be lower than diesel. From Fig. 5, it has been seen that the WPO has 9%, 6%, 7%, and 7% lower BSFC at different loads, compared to neat diesel. Higher CV and oxygen in the fuel can also contribute to this trend (Tomar et al. 2020).

Damodharan et al. (2016) have seen higher BSFC of CI engine with the application of MSW-derived WPO and its blends with diesel and n-butanol. From Fig. 5, it can be noticed that the neat WPO has 12%, 15%, 6%, and 8% (at 25%, 50%, 75%, and 100% loads, respectively) higher BSFC than that of neat diesel, which is due to the low CV of WPO. With the addition of n-pentanol and decreased percentage of WPO in the blends, the BSFC has shown slight improvement

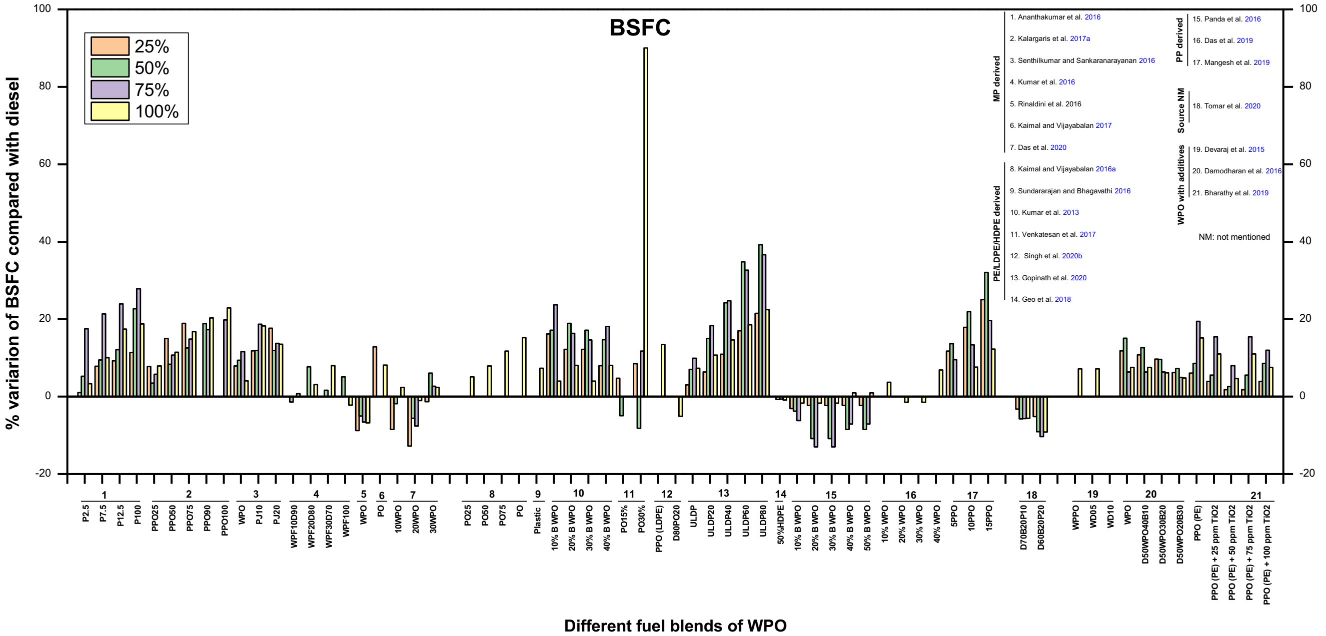

Fig. 5 BSFC at different loads using WPO

though the values of BSFC were higher than diesel. This can be attributed to the higher oxygenated conditions caused by the addition of n-butanol, requiring less fuel to be consumed to offer the same power. D50WPO20B30 has shown only 6%, 7%, 5%, and 5% higher BSFC compared to diesel, at 25%, 50%, 75%, and 100% loads, respectively. Kaimal and Vijayabalan (2017) have also observed higher BSFC with MSW-derived fuel, which has shown 13% and 8% higher (w.r.t) BSFC at 25% and 100% loads, respectively. However, at intermediate loading conditions, the BSFC has shown negligible variation, compared to diesel.

Kaimal and Vijayabalan (2016a) have run the CI engine with HDPE oil. It has been noticed that the blends PO25, PO50, PO75, and PO have 5%, 8%, 12%, and 15% higher BSFC at full load, in comparison with neat diesel (Fig. 5). BSFC rises with an increasing proportion of WPO in the tested fuels. This may be due to the higher density and viscosity of WPO, which affected the air-fuel mixing and combustion process. Sundararajan and Bhagavathi (2016) have also

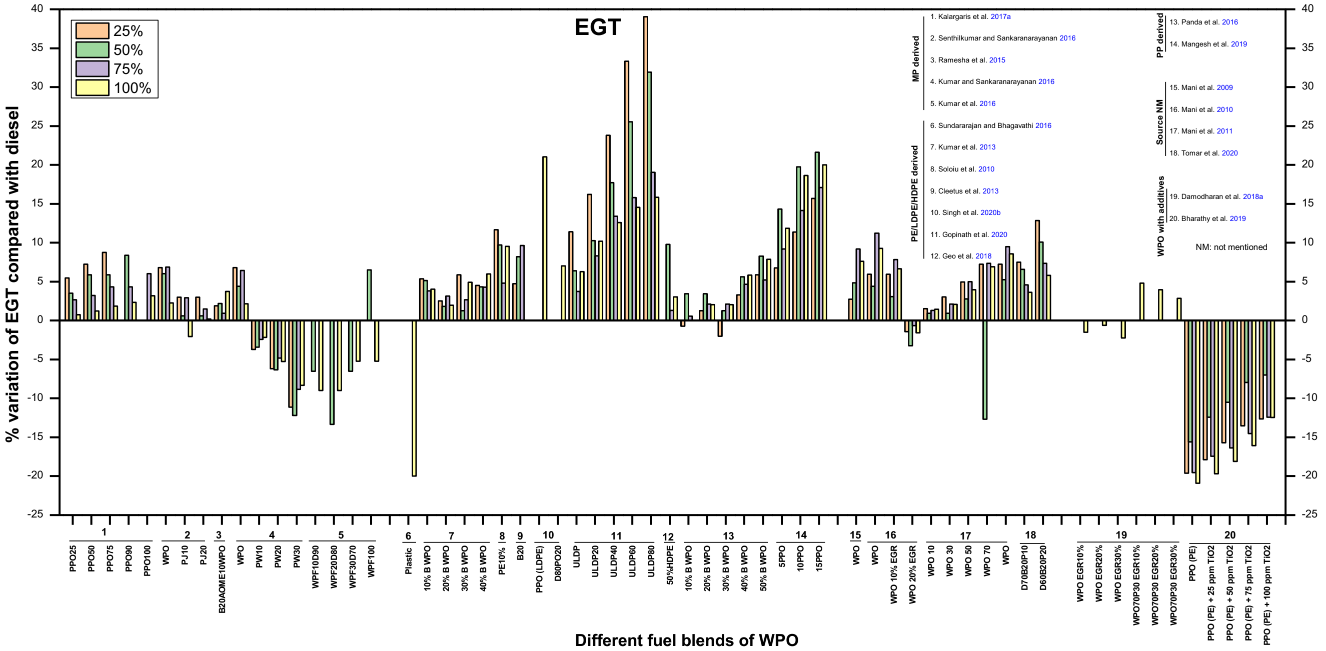

Fig. 6 EGT at different loads using WPO

observed approximately 7% higher (than diesel) BSFC with HDPE oil at peak load, and it was attributed to the low CV of HDPE oil which needs additional fuel for providing the same output. The lower heating value of HDPE can be explained by the presence of alkanes in lower proportions in comparison with diesel. Moreover, the higher cetane index of HDPE can also cause the burning of more fuel in the premixed phase, ultimately leading to increased BSFC. Similar attribution (of the lower heating value of HDPE) can also be found in the study reported by Kumar et al. (2013). In this study, also higher BSFC was noticed for all the blends of HDPE-derived oil and its blends. However, Geo et al. (2018) have found lower BSFC (marginally) with HDPE blend, w.r.t diesel. Higher HRR and CV were attributed to this trend. Venkatesan et al. (2017) have done the investigation with a mixture of LDPE and HDPE. The blend PO15% has shown negligible variation in BSFC at higher load, 5% reduction at 50% load, and 5% increment at 25% load (Fig. 5). Likewise, PO30% has also shown a mixed trend of variation in BSFC over the loading range. But no specific explanation in regard to this mixed trend was found in the literature. The blending of 20% LDPE oil with diesel showed approximately 5% lower BSFC w.r.t diesel (Singh et al. 2020b), but the reason behind this was also not attributed. Gopinath et al. (2020) attributed that higher volatility of ULDP reduced the volumetric efficiency for which the BSFC increased in their study. Bharathy et al. (2019) have observed that the addition of TiO_2 increased the BSFC of WPO which was linked to the lower CV of the PE-derived oil w.r.t diesel.

The investigation performed by Panda et al. (2016) with PP-derived oil has shown a promising outcome in the context of BSFC. From Fig. 5, it can be seen that almost all the tested fuels have shown a decrease in BSFC at all loads. A maximum reduction of approximately 13% was noticed for the blend 30%BWPO at 75% load (w.r.t diesel). This reduction in BSFC with PP oil was attributed to the higher CV of PP than that of neat diesel. However, Mangesh et al. (2019) have found higher BSFC with all the PP blends except 5PPO at one specific loading condition (full load), the reason of which was unexplained in the study. Similarly, Das et al. (2019) have noticed a mixed trend with PP oil. On the other hand, certain blends of MPW-derived blends have shown a decrease in BSFC at certain loads; higher CV of WPO was attributed to this reduction (Das et al. 2020).

EGT

EGT is an important indication of the HRR of the tested fuel. EGT also indicates combustion nature and the quantity of heat loss. Exhaust gas comes out from the engine after the useful power is achieved in the crankshaft, and exhaust gas contains high energy as it comes out at elevated temperatures.

Kalargaris et al. (2017a) observed higher EGT when compared to diesel, for all the WPO (MP-extracted) blends at all operating conditions, and this can be explained by the prolonged ID of WPO and its blends in comparison with diesel. Senthilkumar and Sankaranarayanan (2016) have also found 7%, 6%, 7%, and 2% higher EGT with WPO (MP-derived) w.r.t diesel (Fig. 6). By adding jatropha methyl ester also, the EGT was in the higher range. The blend B20AOME10WPO (MP-derived WPO) has shown a slighter increase in EGT when compared with diesel (Ramesha et al. 2015). The possible reason might be due to higher HRR and poor volatility that leads to late combustion which raises the EGT (Buyukkaya 2010). Likewise, Kumar and Sankaranarayanan (2016) have also observed higher EGT with MP-derived oil at all loading conditions. WPO has shown 7%, 4%, 6%, and 2% higher EGT than diesel at 25%, 50%, 75%, and 100% loads, respectively. However, with the addition of water, all the emulsion blends have shown a drop in EGT. And the uppermost reduction was noticed for PW30 with 11%, 12%, 9%, and 8% decrement in EGT (Fig. 6), at 25%, 50%, 75%, and 100% loads (w.r.t diesel). This is due to the lower HRR and due to the early evaporation of the water molecules available in WPO emulsions (Kim et al. 2002). This counters the working fluid's temperature in the combustion chamber. Kumar et al. (2016) also found lower EGT with MP-derived blends. WPF10D90, WPF20D80, and WPF30D70 have offered 7%, 13%, and 7% lower EGT at 50% load, whereas the reduction values are 9%, 9%, and 5% at 100% load. But the reason behind this trend was unexplained.

Damodharan et al. (2018a) have utilized MSW-derived WPO for CI engine application (with the application of EGR and addition of n-pentanol), and it has been seen that with EGR (without n-pentanol) EGT reduced marginally. This was attributed to the drop in the peak temperature of the cylinder. However, with the addition of n-pentanol, the EGT has been increased for all the blends which were due to the higher HRR and peak pressure of the blends with the application of n-pentanol.

HDPE oil has shown a 20% reduction in EGT (Fig. 6) at rated load in comparison with diesel (Sundararajan and Bhagavathi 2016). This is in agreement with a higher brake thermal efficiency of the tested fuel which is because of the presence of oxygenated functional groups in HDPE oil. However, in another article, a higher EGT was observed with HDPE oil (Kumar et al. 2013), in which all the HDPE blends have shown increment in EGT across the loading conditions. The lower thermal efficiency might be the reason behind this increased EGT. With lower thermal efficiency, a lesser amount of energy input (fuel) is converted into useful work and increases the EGT (Nagarajan et al. 2002). Additionally, WPO usually contains constituents that have higher boiling points (w.r.t diesel); this results in higher EGT. Likewise, higher EGT was noticed with the blend 50%HDPE (Geo et al. 2018). A similar trend of higher EGT was observed by Soloiu et al. (2010); Singh et al. (2020b) when the CI engine was run by LDPE and its blends (Fig. 6). Gopinath et al. (2020) explained that better atomization (of ULDP and its blends) leads to premixed combustion which increases the EGT. Likewise, Cleetus et al. (2013) have also observed higher EGT with PE-based oil, the blend B20 has shown approximately 5%, 8%, and 10% higher EGT, compared to diesel. This higher EGT was attributed to higher ID which causes a sharp rise in the peak pressure resulting in higher EGT.

The investigation with WPO and its blends, by Mani et al. (2009); Mani et al. (2011); Tomar et al. (2020) also showed higher EGT almost at all the loads (w.r.t diesel). Higher EGT for WPO is due to the higher HRR. This might be also due to the oxygen availability in WPO that improves the combustion. The fuel spray becomes finer with WPO; thus, effective combustion takes place. With WPO, the diffusion combustion is more (having higher ID) than that of diesel-run operation, resulting in higher EGT. In the study reported by Mani et al. (2010), a reducing trend in EGT has been noticed when EGR (20%) was applied for WPO operation (Fig. 6). This was attributed to the fact of reduced peak temperature with the increase in the EGR rate. In the case of PP-derived oil, higher EGT was observed for all the tested fuels at all loads. Higher HRR is one of the reasons behind the increased EGT (Mangesh et al. 2019); this might be also because that some fractions of the fuel experience late combustion in the expansion stroke (Panda et al. 2016).

Summary of performance characteristics

Different researchers have carried out their experiments with WPO; few researchers have performed experiments with MP- or MSW-derived oil, whereas few of them investigated the potential of individual plastics either waste or virgin. They have performed the experiments by varying the load, which are summarized and shown in graphical forms. Four different loading conditions (25%, 50%, 75%, and 100%) have been taken into consideration in this review for different WPO blends reported in the literature. The variations of BSFC and EGT at various loading conditions are summarized and represented by Figs. 5 and 6, respectively. The percentage variation of the respective performance parameters is made w.r.t neat diesel. In comparison with diesel, the higher density and lower CV of MP-extracted WPO, the higher aromatic content and higher viscosity of PE/LDPE/HDPE-extracted WPO, and the lower CV of the WPO-additive blends increased the BSFC, whereas PP-extracted WPO offered a reduced BSFC due to its higher CV. The higher cetane index and higher HRR of MP-extracted WPO, the higher ID of PE/LDPE/HDPE-extracted WPO, and the late combustion nature of PP-extracted WPO and WPO-additive blends resulted in higher EGT. The above factors of the respective WPOs which influenced the corresponding performance characteristics (w.r.t diesel) are valid for the majority of the studies. However, reverse trends of each performance characteristic have been also noticed in a few studies. Few of the tested fuels derived from MP, PP, and PE have shown a decrease in BSFC when compared to that of diesel-run operation. A maximum of 13% (approximately) reduction in BSFC was observed with a certain blend of PP-derived WPO. A marginal reduction in EGT was also seen with few blends of PP, in comparison with diesel. The maximum reduction in EGT (of 21%) was noticed for PPO (PE), w.r.t diesel, and the emulsified WPO has also shown promising results in this context, and the blend PW30 has shown the highest 12% reduction in EGT. Likewise, few of the tested fuels, derived from MP, have also shown a marginal reduction in EGT with the application of the EGR technique. Besides, the use of TiO_2 additive has also shown encouraging outcomes in terms of the reduction of EGT for all the PE-TiO_2 blends, and a maximum of 20% reduction was noticed for a specific blend at particular loading condition. However, a very limited number of additives have been applied with WPO to date, which opens up a lot of opportunities for potential research in this area. Extensive investigations need to be carried out with different types of additives to achieve adequate engine performance with lower emissions. Additionally, more emphasis should be put on improving the quality of WPO by distillation to get more diesel-like yields that may result in alike (w.r.t diesel) engine performance.

Conclusions

This paper provides in-depth insights into the effects of pyrolyzed WPO on the emission and performance characteristics of the CI engine. Pyrolysis of plastic is a promising way since it addresses the waste-recycling issue, and simultaneously, it converts the waste plastic into liquid fuel which can be utilized in CI engines. And in general, the properties of WPO are closer to that of diesel. Graphical illustrations have been provided for showing the variations of emission and performance characteristics using WPO and its blends when compared with neat diesel. In-depth attributions have been also provided for each of the variations of the emission and performance parameters of the CI engine when run by WPO and its blends. In the majority of the studies, the emission and performance characteristics have shown a negative influence when the CI engine is fuelled with neat WPO or its blends. The higher density, higher oxygen content, and lower cetane index of MP-extracted WPO; higher viscosity and presence of higher aromatic content in PE/LDPE/HDPE-derived WPO; the presence of long carbon chains owing to the wide product distribution in PP extracted WPO; and higher oxygen content and higher latent heat of evaporation of the WPO-additive blends are the most influencing factors which affected the emission and performance characteristics of the CI engine, though, in a few specific cases, either neat WPO or its blends have shown very promising results in terms of both emission reduction and performance improvement. In this context, encouraging outcomes have been noticed with the use of emulsified WPO, and the application of the EGR technique has shown good consequences too. Besides, additives like DEE, n-pentanol, n-butanol, and TiO_2 have also shown good results in few specific cases. But a very limited number of investigations have been carried out with the application of EGR, emulsified WPO, and additives. Additionally, the effects of using bio-additives with WPO on engine emission and performance are yet to be explored which widens up the future scope of research. Besides, the majority of the studies were focused on the characterization and engine application of WPOs which were derived at a single pyrolysis temperature or a single set of process parameters, but the effect of the process parameters on the quality of the WPOs in regard to their physical and chemical properties has been reported seldomly. Thus, future research focus should be towards correlating the effects of pyrolysis parameters with the properties of WPO which in turn can influence the emission and performance characteristics of the CI engine. Additionally, more importance should be given to the distillation of pyrolytic WPO for further improvement of the quality of the fuel. Furthermore, rigorous investigations are also needed to comprehend the influence of WPO on the engine materials, and the assessment of economic viability is also required. So taking into account all these realities, a wider scope still exists for further research and development activities with WPO, for the application in the CI engine.

Nomenclature *BSFC,* Brake-specific fuel consumption; *CI,* Compression ignition; *CO,* Carbon monoxide; *CV,* Calorific value; *DEE,* Diethyl ether; *EGR,* Exhaust gas recirculation; *EGT,* Exhaust gas temperature; *HC,* Unburnt hydrocarbon; *HDPE,* High-density polyethylene; *HRR,* Heat release rate; *ID,* Ignition delay; *LDPE,* Low-density polyethylene; *MP,* Mixed plastic; *MPW,* Medical plastic waste; *MSW,* Municipal solid plastic waste; NO_x, Oxides of nitrogen; *PE,* Polyethylene; *WPO,* Waste plastic oil; TiO_2, Titanium oxide; *P2.5,* 2.5% MP-derived oil + 97.5% diesel; *P7.5,* 7.5% MP-derived oil + 92.5% diesel; *P12.5,* 12.5% MP-derived oil + 87.5% diesel; *P100,* 100% MP-derived oil; *B20,* 20% PE-derived oil + 80% diesel; *D50WPO40B10,* 50% diesel + 40% WPO derived from MSW+ 10% n-butanol; *D50WPO30B20,* 50% diesel + 30% WPO derived from MSW + 20% n-butanol; *D50WPO20B30,* 50% diesel + 20% WPO derived from MSW + 30% n-butanol; *WPOEGR10%,* 100% MSW-derived oil with EGR (10%); *WPOEGR20%,* 100% MSW-derived oil with EGR (20%); *WPOEGR30%,* 100% MSW-derived oil with EGR (30%); *WPO70P30 EGR10%,* 70% MSW-derived + 30% n-pentanol oil with EGR (10%); *WPO70P30 EGR20%,* 70% MSW-derived + 30% n-pentanol oil with EGR (20%); *WPO70P30 EGR30%,* 70% MSW-derived + 30% n-pentanol oil with EGR (30%); *WPPO,* 100% WPO derived from MP; *WD05,* 95% WPPO + 5% DEE; *WD10,* 90% WPPO + 10% DEE; *PO,* Plastic oil derived from HDPE; *PO25,* 25% PO + 75% diesel; *PO50,* 50% PO + 50% diesel; *PO75,* 75% PO + 25% diesel; *PD5,* 5% DEE + 95% PO; *PD10,* 10% DEE + 90% PO; *PD15,* 15% DEE + 85% PO; *PPO,* Plastic pyrolyzed oil from MP; *PPO25,* 25% PPO + 75% diesel; *PPO50,* 50% PPO + 50% diesel; *PPO75,* 75% PPO + 25% diesel; *PPO90,* 90% PPO + 10% diesel; *PPO100,* 100% PPO; *LDPE700,* LDPE-derived oil at 700°C; *PPO700,* Plastic pyrolyzed oil from MP (at 700°C); *PPO700-75,* 75% PPO700 + 25% diesel; *PPO900,* Plastic pyrolyzed oil from MP (at 900°C); *PPO900-75,* 75% PPO900 + 25% diesel; *PW10,* 10% water + 90% WPO derived from MP; *PW20,* 20% water + 80% WPO derived from MP; *PW30,* 30% water + 70% WPO derived from MP; *WPF10D90,* 10% WPO (from MP) + 90% diesel; *WPF20D80,* 20% WPO (from MP) + 80% diesel; *WPF30D70,* 30% WPO (from MP) + 70% diesel; *WPF100,* 100% WPO (from MP); *10%BWPO,* 10% WPO derived from HDPE + 90% diesel; *20%BWPO,* 20% WPO derived from HDPE + 80% diesel; *30%BWPO,* 30% WPO derived from HDPE + 70% diesel; *40%BWPO,* 40% WPO derived from HDPE + 60% diesel; *WPO10%EGR,* WPO with application of EGR (10%); *WPO20%EGR,* WPO with application of EGR (20%); *WPO10,* 10% WPO + 90% diesel; *WPO30,* 30% WPO + 70% diesel; *WPO50,* 50% WPO + 50% diesel; *WPO70,* 70% WPO + 30% diesel; *PF10,* 10% WPO (from MP) + 90% diesel; *PF20,* 20% WPO (from MP) + 80% diesel; *PF30,* 30% WPO (from MP) + 70% diesel; *10%BWPO,* 10% WPO derived from PP + 90% diesel; *20%BWPO,* 20% WPO derived from PP + 80% diesel; *30%BWPO,* 30% WPO derived from PP + 70% diesel; *40%BWPO,* 40% WPO derived from PP + 60% diesel; *50%BWPO,* 50% WPO derived from PP + 50% diesel; *B20AOME10WPO,* 10 % WPO (from MP) + 90 % B20 algae biodiesel; *PJ10,* 10% jatropha methyl ester + 90% WPO (from MP); *PJ20,* 20% jatropha methyl ester + 80% WPO (from MP); *PE10%,* 10% LDPE-derived oil + 90% diesel; *10WPO,* 10% WPO (from MPW) + 90% diesel; *20WPO,* 20% WPO (from MPW) + 80% diesel; *30WPO,* 30% WPO (from MPW) + 70% diesel; *PP700,* Plastic pyrolyzed oil from PP (at 700°C); *PP700-75,* 75% PP700 + 25% diesel; *PP900,* Plastic pyrolyzed oil from PP (at 900°C); *PP900-75,* 75% PP900 + 25% diesel; *PPO (LDPE),* Plastic pyrolytic oil derived from LDPE; *D80PO20,* 80% diesel + 20% PPO (LDPE); *D70B20P10,* 70% diesel + 20% biodiesel + 10% WPO; *D60B20P20,* 60% diesel + 20% biodiesel + 20% WPO; *ULDP,* Used low-density derived polyethylene; *ULDP20,* 80% diesel + 20% ULDP; *ULDP40,* 60% diesel + 40% ULDP; *ULDP60,* 60% diesel + 60% ULDP; *ULDP80,* 20% diesel + 80% ULDP; *5PPO,* 5% PP-derived oil + 95% diesel; *10PPO,* 10% PP-derived oil + 90% diesel; *15PPO,* 15% PP-derived oil + 85% diesel; *50%HDPE,* 50% HDPE oil + 50% diesel; *PPO (PE),* WPO derived from PE; *PPO (PE) + 25 ppm* TiO_2, 25 ppm added with PPO (PE); *PPO (PE) + 50 ppm* TiO_2, 50 ppm added with PPO (PE); *PPO (PE) + 75 ppm* TiO_2, 75 ppm added with PPO (PE); *PPO (PE) + 100 ppm* TiO_2, 100 ppm added with PPO (PE); *PO15%,* 85% diesel + 15% WPO derived from mixture of LDPE and HDPE; *PO30%,* 85% diesel + 30% WPO derived from mixture of LDPE and HDPE

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