Combustion, Performance, and Tail Pipe Emissions of Common Rail Diesel Engine Fueled With Waste Plastic Oil-Diesel Blends

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The demand for plastic is eternally growing in urban areas and producing enormous quantity of plastic waste. The management and disposal of plastic waste have become a major concern worldwide. The awareness of waste to energy retrieval is one of the promising modes used for the treatment of the waste plastic. The present investigation evaluates the prospective use of waste plastic oil (WPO) as an alternative fuel for diesel engine. Different blends (WPO0, WPO30, and WPO50) with diesel are prepared on a volume basis and the engine is operated. Experiments are conducted for various injection timings (9 deg, 12 deg, 15 deg, and 18 deg BTDC) and for different exhaust gas recirculation (EGR) rates (0%, 10%, 15%, and 20%) at 100 MPa injection pressure. Combustion, performance, and tail pipe emissions of common rail direct injection (CRDI) engine are studied. The NO_x, CO, and Soot emissions for waste plastic oil-diesel blends are found more than neat diesel. To reduce the NO_x, EGR is employed, which results in reduction of NO_x considerably, whereas other emissions, i.e., CO and Soot, get increased with increase in EGR rates. Soot for WPO-diesel blends is higher because of aromatic compounds present in plastic oils. Brake thermal efficiency (BTE) of blends is found to be higher compared to diesel. [DOI: 10.1115/1.4039965]

Keywords: waste plastic oil, CRDI, combustion, emission, exhaust gas recirculation

1 Introduction

Plastics are produced in ubiquitous quantities due to the great demand of their use in farming [1], housings [2], vehicles [3], packing materials [4], toys [5], electronics [6], and a variety of other applications (plastic card board, plastic books) [7]. The demand for plastics has increased by 5% every year since 1990 [8]. The surge in plastics usage increases the extent of plastic wastes being produced. Plastic waste can be categorized into two groups, i.e., municipal and industrial [9]. Industrial plastics are usually more homogeneous, whereas municipal plastics are more heterogeneous and contain extraneous materials [10,11]. The plastic waste disposal is a key environmental risk due to its nondegradability [12–14], its potential threat to aquatic and terrestrial animals [15], and its impact on environmental pollution [16]. The plastic footprint is considered more hazardous than carbon footprint [17,18].[2] Some of the solutions for plastic waste management are incineration. However, incineration contributes to pollution by producing dangerous and toxic emissions [19]. Apart from the challenge of plastic waste disposal, another worldwide concern is the energy crisis. The core energy sources for transportation are fossil fuels. Today, these fuels are being consumed at an unsustainably high percentage all over the globe [20]. The challenges of plastic waste management and energy demand can concurrently be addressed by the production of fuel from plastics. The fuels produced from plastics can have properties comparable to fossil fuels [21]. The absence of water content makes the fuel nonacidic and noncorrosive compared to other fuels [21–24]. Therefore, conversion of these plastic wastes to usable oil is increasing and important field of study that can possibly mitigate the energy crisis.

Investigation on the performance and emission characteristics of diesel engine fueled with WPO100 was carried out by Mani and Nagarajan [25]. They reported improvement in brake thermal efficiency (BTE) and decrease in NO_x, HC, and CO with increase in soot. Mani et al. [26] observed the effect of WPO-diesel blends and exhaust gas recirculation (EGR) on performance and emission of a diesel engine. They noticed that as blends and EGR rates increase, the BTE and NO_x decrease with penalty in CO, HC, and Soot. Study of combustion characteristics of a diesel engine using waste plastic oil and its blends was experimentally carried by Kaimal and Vijayabalan [27,28]. Heat release rate and peak pressure for blend are higher than neat diesel operations and marginally decrease in BTE. WPO-Diesel blends in combination with diethyl ether were studied by Devaraj et al. [29], and found the reduction in emission and improvement in performance with diethyl ether combination.

In the present investigation, plastic oil is used to find its suitability as alternative fuel in common rail direct injection (CRDI) system. The existing engine is operated without any modification for various operating parameters to get optimized performance with WPO-diesel blends. Literature on the optimization of injection timing and high injection pressure (CRDI) for WPO-diesel blends is not available; hence, this research work aims to optimize injection timing as a key parameter at an injection pressure of 100 MPa, which is five times higher than conventional injection pressure. In the present experimental study, two different WPO-diesel blends (WPO30 and WPO50) are considered. Performance and tailpipe emissions (NO_x, CO, and soot) at various injection timings (9 deg, 12 deg, 15 deg, and 18 deg) are measured for the WPO-diesel blends. Further, EGR technology is employed to overcome NO_x emission. Engine is operated for different EGR rates (0%, 10%, 15%, and 20%) for all injection timings and WPO-diesel blends. Such experimental studies are scant in open literature.

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[2]https://en.wikipedia.org/wiki/Great_Pacific_garbage_patch

Table 1 Properties of plastic oil

S. no.	Test parameters	Unit	Test method	WPO
1	Total acidity	mg KOH/g	ASTM D 664	1.36
2	Ash content	wt %	IS 1448 (P4) 2008	<0.01
3	Gross calorific value	kcal/kg	IS 1448 (P8) 2008	10,442
4	Sediment	%		2.53
5	Copper strip corrosion for 3 h at 100 °C		IS 1448 (P15) 2004	1B Passes
6	Flash point	°C	IS 1448 (P20) 2007	42
7	Kinematic viscosity (ν) at 40 °C	mm^2/s	ASTM D445	2.41
8	Density (ρ)	g/cc^3	IS 1448 (P32) 2008	905
9	Sulfur content	ppm	ASTM D 5185	355

2 Fuel Properties and Operating Range of Parameters

In the present research, the WPO is blended with the neat diesel to obtain different WPO-diesel blends. WPO0, WPO30, and WPO50 represents 0%, 30%, and 50% waste plastic oil in neat diesel by volume. Basic physical properties of the WPO employed in this investigation are provided by fuel supplier (powerol energy systems, Chennai, India), which are listed in Table 1 and range of experimental parameters considered for study are listed in Table 2.

Table 2 Range of engine operating parameters

Parameters	Range
Blend (% of WPO)	0, 30, and 50
Injection timings (CA BTDC)	9 deg, 12 deg, 15 deg, and 18 deg
EGR (%)	0, 10, 15, and 20

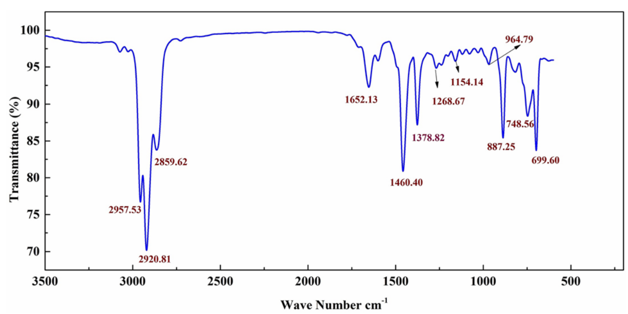
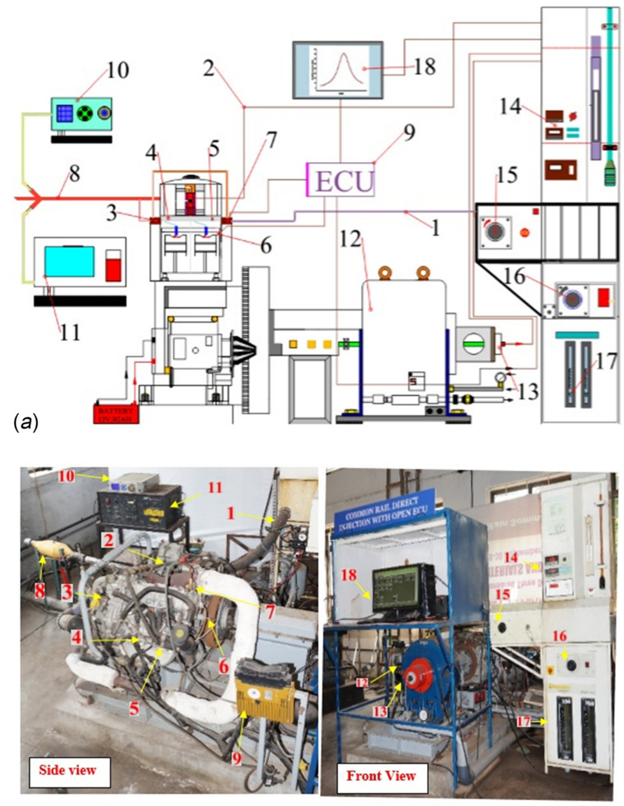


Fig. 1 Fourier transform infrared spectroscopy spectrum of waste plastic oil



1. Airline, 2. Fuel line, 3. EGR Valve, 4. Common Rail, 5. Pressure control valve, 6. Pressure transducer, 7. Vacuum pump, 8. Exhaust line, 9. ECU, 10. Gas analyzer, 11.Smoke meter, 12. Dynamometer, 13. Encoder, 14. Speed and load display unit, 15. Throttle control unit, 16. Load control unit, 17. Rota meters, 18. Computer display

(*b*)

Fig. 2 (*a*) Schematic diagram and (*b*) experimental facility

2.1 Fourier Transform Infrared Spectroscopy. The chemical structure of WPO is studied using Fourier transform infrared spectroscopy as shown in Fig. 1. This method categorizes the chemical bonds in a molecule by generating an infrared absorption spectrum results for several functional groups present in the waste plastic oil. It has absorption bands in the region of

Table 3 Fourier transform infrared spectroscopy analysis of waste plastic oil indicating functional groups

Functional group	Assignment	Wave number (cm^{-1})
$-CH_3$, branched alkane	Methyl C–H stretch	2957.5
CH_2, branched alkane	Methylene C–H stretch	2920.8 and 2859.6
C=C, alkene	Alkenyl C=C stretch	1652.1
C=C	Conjugated C=C	1650
CH_2, alkane	Methylene C–H bend	1460.4
$-CH_3$, alkane	Methyl C–H stretch	1378.8
C–C	Skeletal C–C vibrations	1268.6
C–O, alcohol	Tertiary alcohol, C–O stretch	1154.1
=C–H, alkene	Trans-C–H out-of-plane bend	964.7
C–H, alkene	Vinylidene C–H out-of-plane bend	887.2
CH_2	Methylene -$(CH_2)_n$—rocking	748.5
C–H	cis-C H out-of-plane bend	699.6

Table 4 Engine specifications

Make	Mahindra Maximmo
Number of cylinders	2
Piston	Re-entrant bowl
Bore (mm)	83
Stroke (mm)	84
Connecting rod length (mm)	141
Swept volume (cm^3)	909
Compression ratio	18.5
Maximum power	14.4 kW at 3600 rpm
Maximum torque	50 N·m at 2000 rpm
Injection type	Common rail
Number of nozzle holes (mm)	7
Spray-hole diameter (mm)	0.130
Cone angle	153
Injection pressure (MPa)	100
Injection timing	Variable (9–18 deg BTDC)

Table 5 Details of the engine instrumentation

Instrument	Functional use	Measuring technique
Saj test—eddy dynamometer	Load	Load cell
PCB piezotronics, pressure transducer	Pressure	Piezo-electric sensor
Piezo charge amplifier	A/D converter	Piezo-electric sensor
Angle encoder	Crank angle	Magnetic pickup type
AVL Di-gas 444 exhaust gas analyser	NO_x	Chemi-luminescence detector
	CO	Nondispersive infra-red
	HC emissions	Flame ionization detector
AVL 415SE	Soot	Opacity

Table 6 Operating range with percentage of uncertainties of instruments used during experiments

Instrument	Measured quantity	Range	Uncertainties (%)
Dynamometer	Load	0–50 kg	0.1
AVL Di-Gas 444 analyzer	NO_x	0–5000 ppm	0.1
	CO	0–10 vol %	0.1
Smoke opacimeter	Smoke opacity	0–100%	1.7
Speed measuring unit	Engine speed	0–9999 rpm	0.1
Pressure transducer	Cylinder pressure	0–345 bar	0.1
Crank angle encoder	Crank angle	0–360 deg	0.2

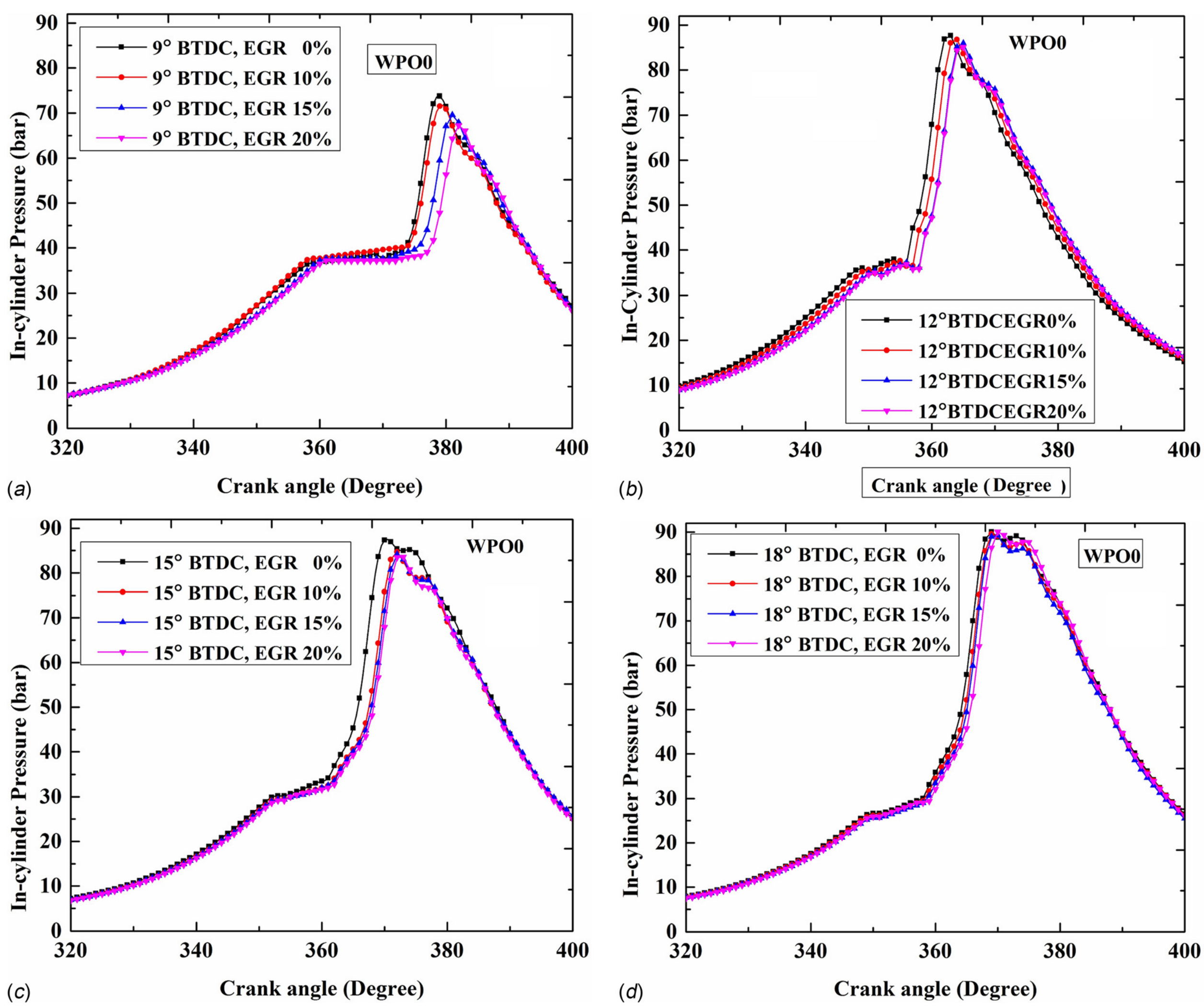


Fig. 3 In-cylinder pressure versus crank angle for WPO0 and various EGR rates at (*a*) 9 deg BTDC, (*b*) 12 deg BTDC, (*c*) 15 deg BTDC, and (*d*) 18 deg BTDC

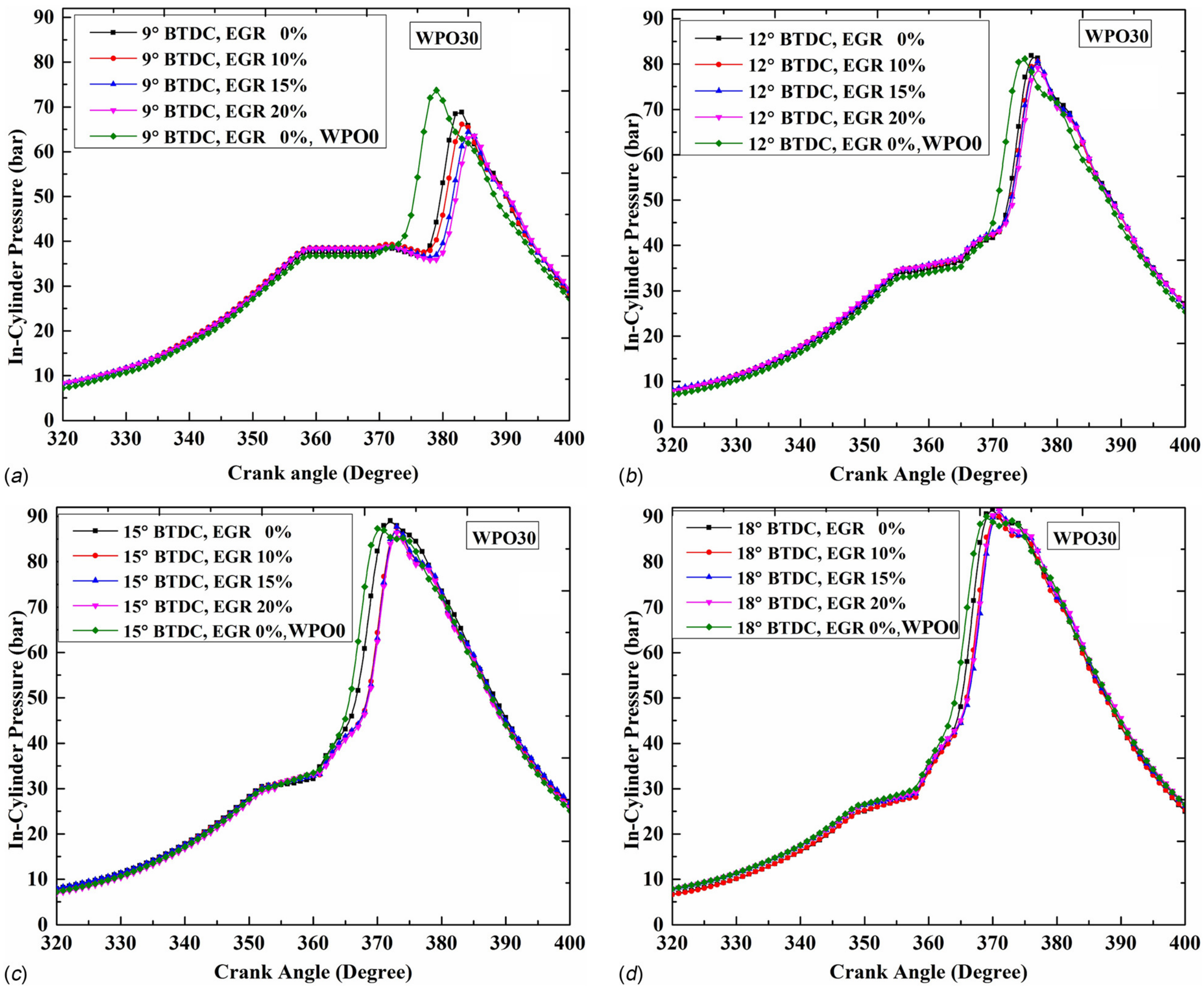


Fig. 4 In-cylinder pressure versus crank angle for WPO30 and various EGR rates at (*a*) 9 deg BTDC, (*b*) 12 deg BTDC, (*c*) 15 deg BTDC, and (*d*) 18 deg BTDC

4000–400 cm^{-1} with several peaks. The chemical bond will stretch, contract, and absorb infrared radiation in a precise wavelength range during the interaction of infrared light with the oil. Bruker series Fourier transform infrared spectroscopy was used to record the spectra. Table 3 shows the functional groups present in the WPO which were obtained by matching the peak wave numbers with standard data given by Coates [30].

3 Experimental Setup

Schematic diagram and photographic view of experimental facility are shown in Figs. 2(*a*) and 2(*b*). Twin cylinder, CRDI engine with open electronic control unit (ECU) developed by NIRA Control AB, is used to study the engine performance, emission, and combustion characteristics. The specifications of the engine are listed in Table 4. The fuel from the tank is supplied to the accumulator (common rail) by high pressure fuel pump at constant injection pressure of 100 MPa.

Common rail pressure is maintained by pressure control valve and required fuel supplied to injector is controlled by solenoid valve. Operating parameters of engine are controlled by an open ECU developed by NIRA Control AB. Pressure versus crank angle data are measured by using piezoelectric-based pressure transducer. The signal of cylinder pressure is acquired at every 1 deg crank angle for 100 cycles, and average value of 100 cycles is considered for combustion analysis. The pressure signal is fed into the NI USB-6210 DAQ, then to a data acquisition card linked to the computer. Exhaust gas recirculation is activated by ECU with vacuum pump, solenoid valve, and vacuum modulator. Input EGR set point value is set in ECU maps, which monitors the vacuum pump to maintain required vacuum and solenoid valve operates accordingly. Further engine tail pipe emissions are measured by exhaust gas analyzer (AVL 444) with diesel probe to measure the concentrations of HC, CO, NO, CO_2, and O_2. The details of the engine instrumentation and range are presented in Tables 5 and 6. Soot emission is measured by opacity meter (AVL 415SE). Experimentally, maximum torque is obtained at 2000 rpm for neat diesel and the same engine speed is considered for study. Further at 12 deg BTDC and at 80% load, highest BTE was observed in the case of neat diesel. Hence, these engine operating parameters are fixed for all experiments including blends.

3.1 Error Analysis. Assessment of uncertainties and error is necessary while conducting any experimental study. Uncertainties may appear because of numerous reasons like: environmental conditions, calibration, observation, instrument selection, and incorrect reading. Error analysis quantifies the accuracy of the experiments being performed. The uncertainties of dependent parameters like brake power and fuel consumption are computed by partial differentiation method using the uncertainty percentages of various instruments as shown in Table 6. The uncertainties for

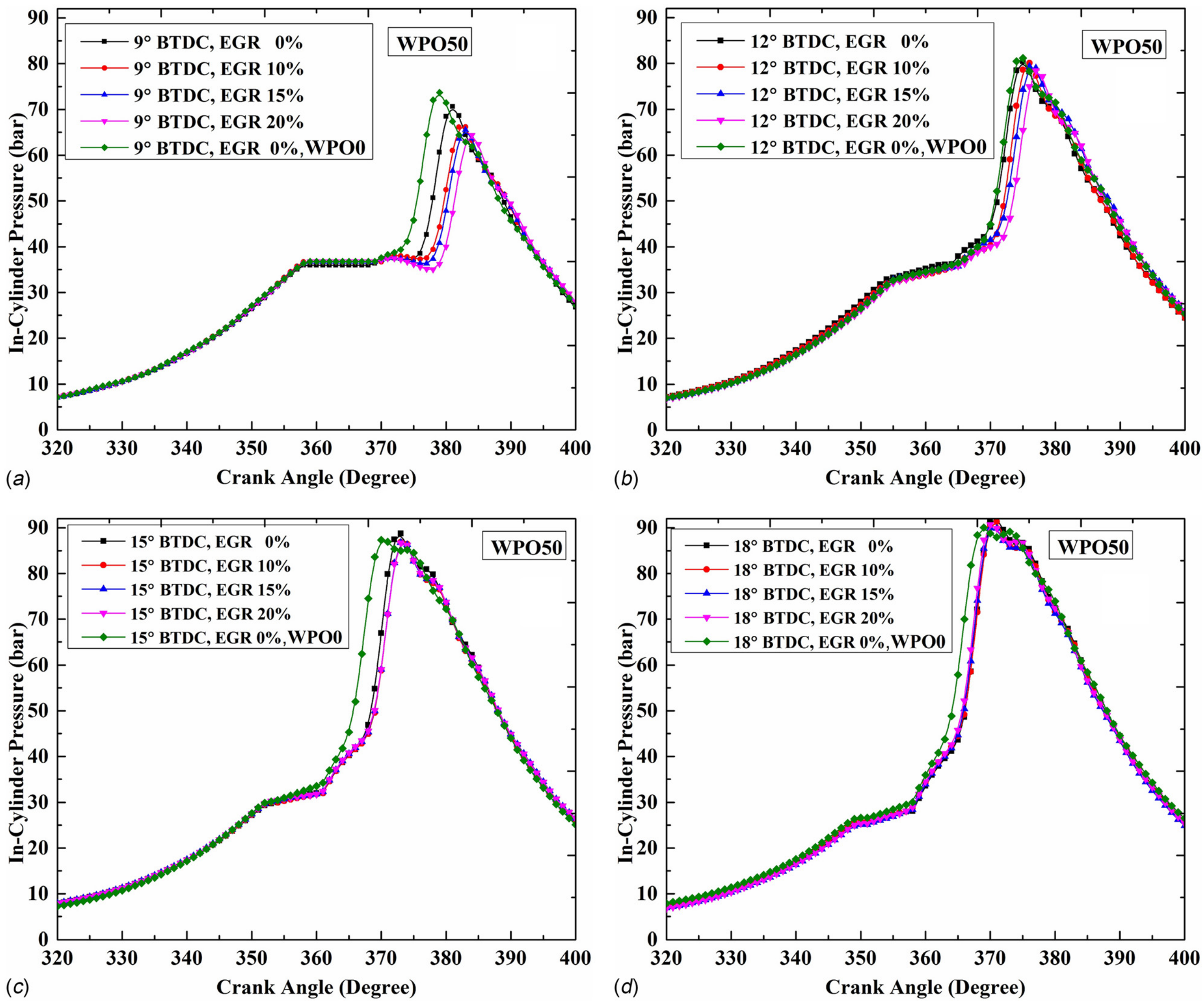


Fig. 5 In-cylinder pressure versus crank angle for WPO50 and various EGR rates at (*a*) 9 deg BTDC, (*b*) 12 deg BTDC, (*c*) 15 deg BTDC, and (*d*) 18 deg BTDC

independent parameters were found by calculating the mean, standard deviation, and standard error for the repeated set of 20 readings. The total uncertainty of the experimental investigation is $=\sqrt{\{(\text{uncertainty of CO})^2+(\text{uncertainty of NO})^2+(\text{uncertainty of soot})^2+(\text{uncertainty of load})^2+(\text{uncertainty of speed})^2+(\text{uncertainty of time})^2+(\text{uncertainty of brake power})^2+(\text{uncertainty of fuel consumption})^2+(\text{uncertainty of brake thermal efficiency})^2+(\text{uncertainty of cylinder pressure})^2+(\text{uncertainty of crank angle})^2+(\text{uncertainty of manometer})^2\}}$ $=\sqrt{\{(0.1)^2+(0.6)^2+(0.1)^2+(1.3)^2+(0.1)^2+(0.2)^2+(0.8)^2+(0.2)^2+(0.8)^2+(0.9)^2+(0.1)^2+(0.2)^2\}}=\pm 2.076\%$.

4 Results and Discussion

4.1 Variation of In-Cylinder Pressure Versus Crank Angle. Figures 3–5 show the variation of in-cylinder pressure with crank angle at various injection timings (9 deg, 12 deg, 15 deg, and 18 deg BTDC) for WPO0 (neat diesel), WPO30, and WPO50, respectively. Effect of various EGR rates (0%, 10%, 15%, and 20%) on in-cylinder pressure is presented. Results show that as injection timing advances, the in-cylinder peak pressure increases. It occurs because charge gets sufficient time to diffuse throughout the combustion chamber, thereby reducing the heterogeneity of the mixture. The low temperature combustion (EGR) results in marginally drop in in-cylinder pressure and more ignition delay as expected. Higher EGR rate results in larger ignition delay, which is reflected as less average area in pressure versus crank angle graphs resulting in the drop in performance of engine.

4.2 Effect of Various Waste Plastic Oil-Diesel Blends and Injection Timings on Nitrogen Oxide. Figures 6(*a*) and 6(*b*) show the illustration of the NO_x emissions for various injection timings at various EGR rates and different WPO-diesel blends. Oxides of nitrogen at tail pipe decrease with increase in EGR rates and increase with advance injection timing. Similar observation is found for all WPO-diesel blends (WPO30 and WPO50) considered in the study. The NO_x is greatly dependent on in-cylinder temperature, oxygen, and residence time for the reactions to take place. Compression ignition engines always run with lean fuel–air mixtures and emit higher amounts of NO_x. Figure 6(*c*) shows the NO_x emission for various WPO-diesel blends at 20% EGR. It is observed that NO_x is found to be less for diesel compared to the WPO-diesel blends and similar trends were observed by Mani et al. [26].

Waste plastic oil comprises certain oxygenated hydrocarbons, which stimulate combustion and thus the formation of NO_x in exhaust [31]. NO_x emission gets increased with advanced injection timing due to increased ignition delay because of more air and fuel mixture burns in premixed combustion. At 9 deg BTDC

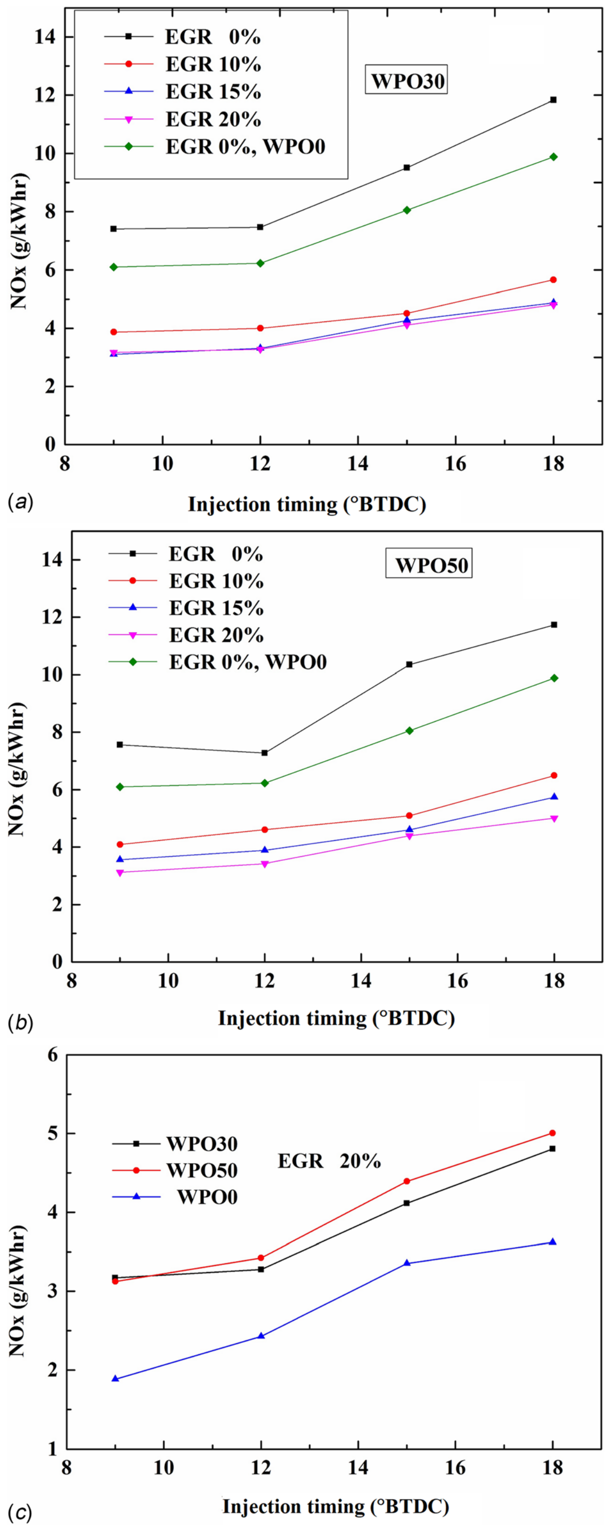


Fig. 6 Nitrogen oxide versus injection timing for (*a*) WPO30 at various EGR rates, (*b*) WPO50 at various EGR rates, and (*c*) EGR20 for various blends

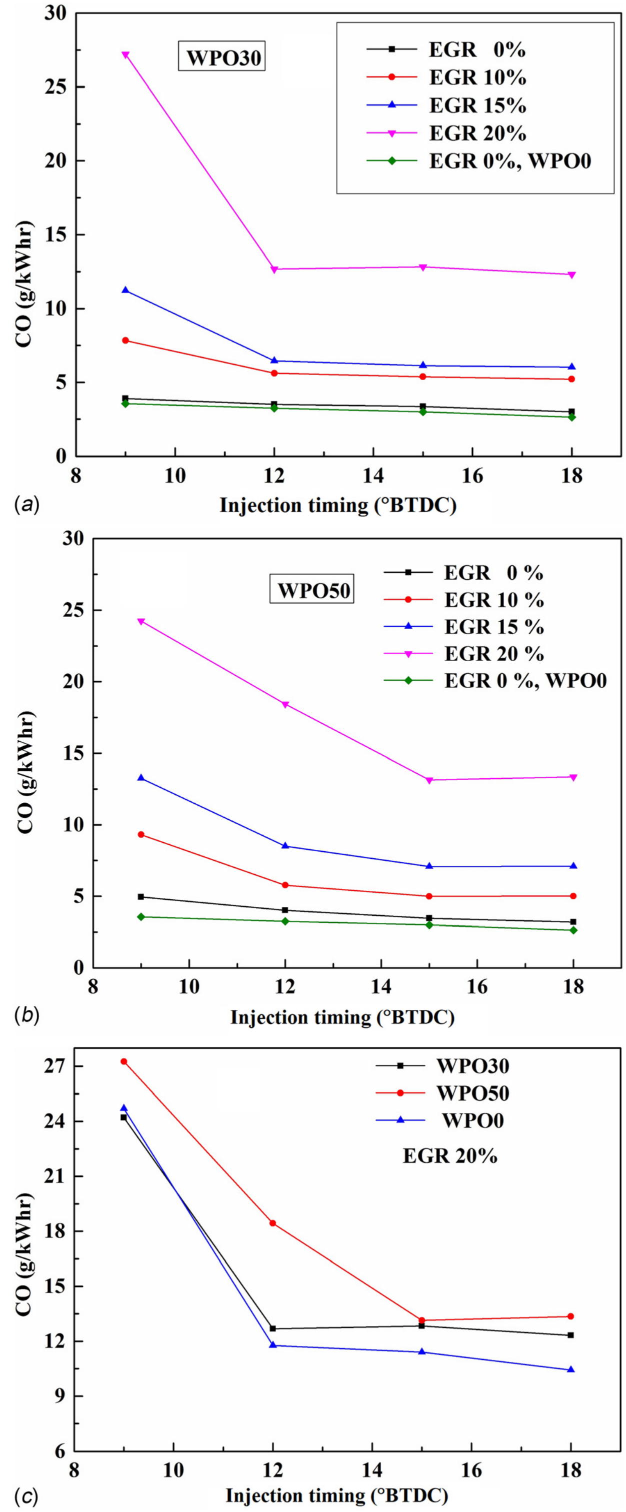


Fig. 7 Carbon monoxide versus injection timing for (*a*) WPO30 at various EGR rates, (*b*) WPO50 at various EGR rates, and (*c*) EGR20 for various blends

injection timing, the NO_x emission gets reduced from 7.4 g/kWh to 3.17 g/kWh and 7.6 g/kWh to 3.12 g/kWh as EGR rate increases from 0% to 20% for WPOP30 and WPOP50, respectively.

4.3 Effect of Various Waste Plastic Oil-Diesel Blends and Injection Timings on Carbon Monoxide. Figures 7(*a*) and 7(*b*) show the illustration of the carbon monoxide emissions for various injection timings at different EGR rates and for different WPO-diesel blends. CO at tail pipe increases with increase in EGR rate and declines with increase in injection timing for all the cases of blends (WPO30 and WPO50). At 20% EGR rate, the CO emission gets reduced from 24.2 to 12.2 and 27.2 to 13.3 g/kWh as injection timing changes from 9 deg BTDC to 18 deg BTDC for WPOP30 and WPOP50, respectively. Figure 7(*c*) shows the CO emission for various WPO-diesel blends at 20% EGR. It is

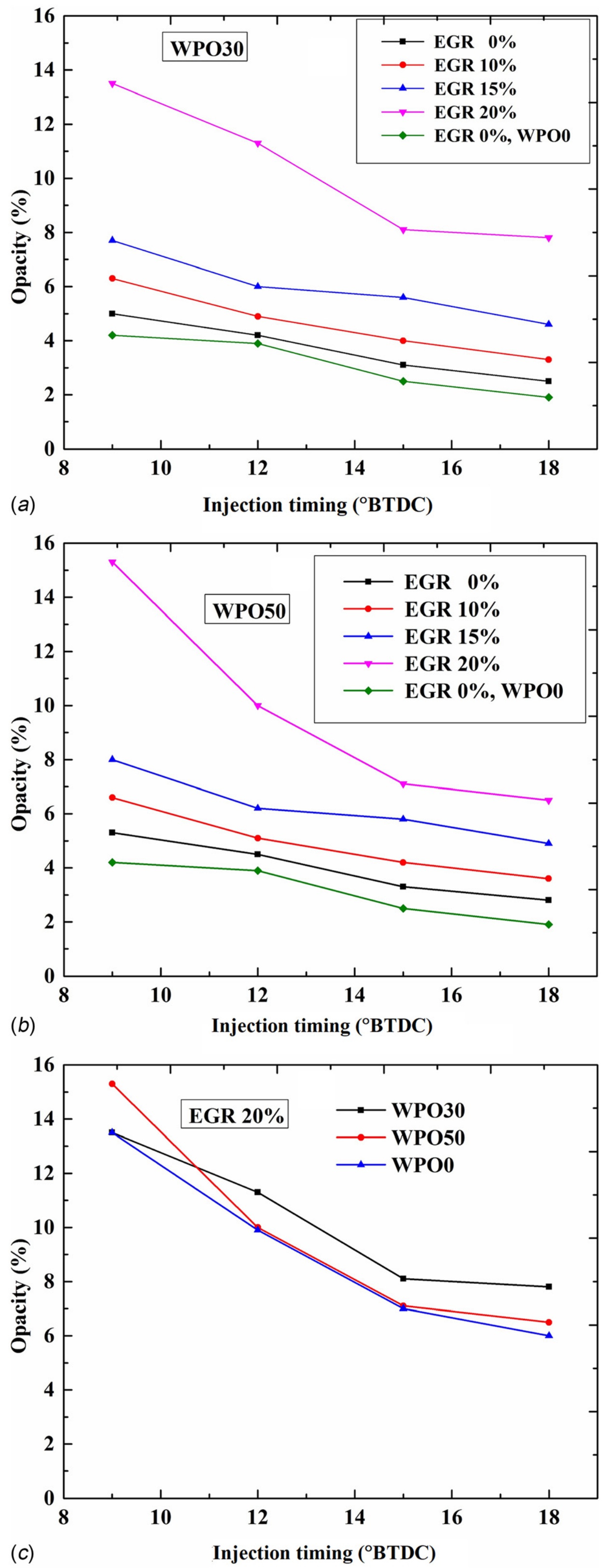


Fig. 8 Smoke opacity versus injection timing for (*a*) WPO30 at various EGR rates, (*b*) WPO50 at various EGR rates, and (*c*) EGR20 for various blends

observed that CO is found to be less for diesel compared to the WPO-diesel blends. Since calorific value of WPO is lesser than diesel, rich mixture of WPO is required to meet same engine load condition, which results in higher CO formation. In advance injection timing, the increase in cylinder temperature leads to early start of combustion due to increase in the chemical reaction speed and oxidation process between carbon and oxygen molecules in the combustion chamber region [32].

4.4 Effect of Various Waste Plastic Oil-Diesel Blends and Injection Timings on Smoke Emission. Figures 8(*a*) and 8(*b*) represent the smoke opacity emissions for various injection timings at different EGR rates and WPO-diesel blends. The exhaust smoke emission at tail pipe increases with increase in EGR rates and declines with advance injection timing for all blends (WPO30 and WPO50). Smoke number represents solid unburned hydrocarbon particles in exhaust emission in CI engine combustion. Formation of soot occurs in rich-fuel and moderate temperature zones. Advancing the injection timing decreases the formation of soot due to more homogeneous mixture [33]. Higher temperature promotes oxidation of the nucleated soot.

Retard injection results in inadequate time for soot oxidation (exhaust valve opens before the completion of soot oxidation) and augments smoke formation. At 20% EGR rate, the soot emission gets reduced from 13.7% to 9% and 15.5% to 8.8% smoke opacity as injection timing changes from 9 deg BTDC to 18 deg BTDC for WPOP30 and WPOP50, respectively. It is also observed that emitted smoke was less in the case of without EGR compared to EGR case. Also, smoke increases significantly with increase in EGR because of less oxygen [34]. Figure 8(*c*) shows the smoke opacity emission for various WPO-diesel blends at 20% EGR. It is observed that smoke opacity is found to be less for diesel compared to the WPO-diesel blends. Soot for WPO-diesel blends is higher because of aromatic compounds present in plastic oils [35].

4.5 Effect of Various Waste Plastic Oil-Diesel Blends and Injection Timings on Brake Thermal Efficiency. The effect of injection timing and EGR rates for various WPO-Diesel blends ratio on performance of CRDI engine is demonstrated in Figs. 9(*a*) and 9(*b*). Results show the increase of BTE with WPO-diesel; it occurs due to lower calorific value of waste plastic oil compare to diesel. The optimum BTE is observed at 9 deg and 12 deg BTDC for WPO30 and WPO50, respectively, as shown in Fig. 9(*c*). Further for advancing up to 18 deg BTDC, BTE is reducing. With EGR percentage, BTE is reduced due to insufficient oxygen in combustion process and more replacement of air by the exhaust gases. Higher EGR rate tends more decrease in the performance of engine.

5 Conclusion

In the present study, experimental investigations are carried out to determine the effects of WPO-diesel blends, EGR rates and injection timing on the performance, combustion and exhaust emission characteristics of CRDI engine. Based on obtained results, following conclusions are made:

- As injection timing advances, the in-cylinder peak pressure increases.
- The optimum BTE is observed as 9 deg and 12 deg BTDC for WPO30 and WPO50, respectively.
- At 9 deg BTDC injection timing, the NO_x emission gets reduced from 7.4 g/kWh to 3.17 g/kWh and 7.6 g/kWh to 3.12 g/kWh as EGR rate increases from 0% to 20% for WPOP30 and WPOP50, respectively.
- It is observed that NO_x is found to be less for diesel compared to the WPO-diesel blends.
- At 20% EGR rate, the CO emission gets reduced from 24.2 to 12.2 and 27.2 to 13.3 g/kWh as injection timing from 9 deg BTDC to 18 deg BTDC for WPOP30 and WPOP50, respectively.
- At 20% EGR rate, the soot emission gets reduced from 13.7% to 9% and 15.5% to 8.8% smoke opacity as injection

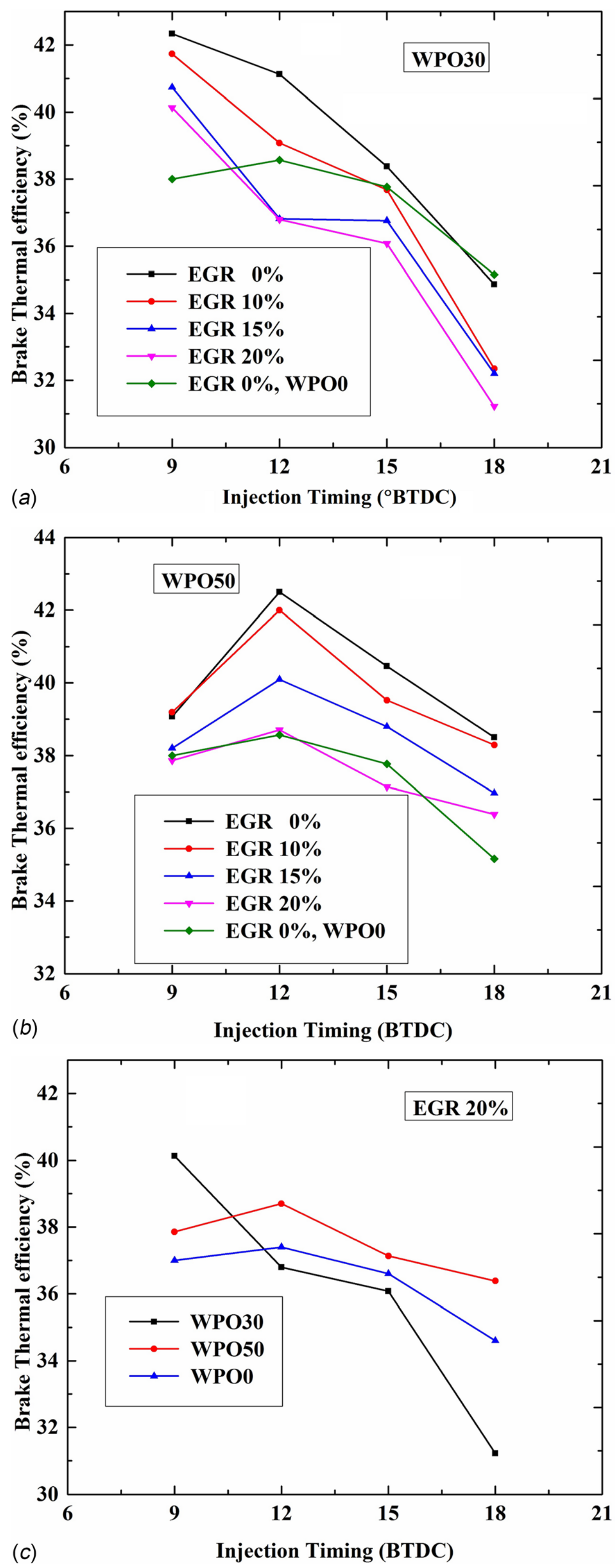


Fig. 9 Brake thermal efficiency versus injection timing for (*a*) WPO30 at various EGR rates, (*b*) WPO50 at various EGR rates, and (*c*) EGR20 for various blends

timing from 9 deg BTDC to 18 deg BTDC for WPOP30 and WPOP50, respectively.

- Waste plastic oil is better alternative to diesel engine fuel as it gives solution to multiple problems in concern to environment. Along with EGR and suitable after treatment techniques, all the emissions can be controlled simultaneously.

References

[1] Smit, J., and Nasr, J., 1992, "Urban Agriculture for Sustainable Cities: Using Wastes and Idle Land and Water Bodies as Resources," Environ. Urbanization, **4**(2), pp. 141–152.

[2] Riber, C., Petersen, C., and Christensen, T. H., 2009, "Chemical Composition of Material Fractions in Danish Household Waste," Waste Manage., **29**(4), pp. 1251–1257.

[3] Donahue, C. J., Exline, J. A., and Warner, C., 2003, "Chemical Recycling of Pop Bottles: The Synthesis of Dibenzyl Terephthalate From the Plastic Polyethylene Terephthalate," J. Chem. Educ., **80**(1), p. 79.

[4] Lange, J., and Wyser, Y., 2003, "Recent Innovations in Barrier Technologies for Plastic Packaging—A Review," Packag. Technol. Sci., **16**(4), pp. 149–158.

[5] Rastogi, S. C., 1998, "Gas Chromatographic Analysis of Phthalate Esters in Plastic Toys," Chromatographia, **47**(11–12), p. 724.

[6] Alston, S. M., Clark, A. D., Arnold, J. C., and Stein, B. K., 2011, "Environmental Impact of Pyrolysis of Mixed WEEE Plastics—Part 1: Experimental Pyrolysis Data," Environ. Sci. Technol., **45**(21), pp. 9380–9385.

[7] Pinto, F., Costa, P., Gulyurtlu, I., and Cabrita, I., 1999, "Pyrolysis of Plastic Wastes—1: Effect of Plastic Waste Composition on Product Yield," J. Anal. Appl. Pyrolysis, **51**(1–2), pp. 39–55.

[8] Lettieri, P., and Al-Salem, S. M., 2011, "Thermochemical Treatment of Plastic Solid Waste," *WASTE: A Handbook of Waste Management and Recycling*, Elsevier, Amsterdam, The Netherlands, pp. 233–242.

[9] Panda, A. K., Singh, R. K., and Mishra, D. K., 2010, "Thermolysis of Waste Plastics to Liquid Fuel: A Suitable Method for Plastic Waste Management and Manufacture of Value Added Products—A World Prospective," Renewable Sustainable Energy Rev., **14**(1), pp. 233–248.

[10] Buekens, A. G., and Huang, H., 1998, "Catalytic Plastics Cracking for Recovery of Gasoline-Range Hydrocarbons From Municipal Plastic Wastes," Resour. Conserv. Recycl., **23**(3), pp. 163–181.

[11] Zhou, C., Fang, W., Xu, W., Cao, A., and Wang, R., 2014, "Characteristics and the Recovery Potential of Plastic Wastes Obtained From Landfill Mining," J. Cleaner Prod., **80**, pp. 80–86.

[12] Scott, D. S., Czernik, S. R., Piskorz, J., and Radlein, D. S. A., 1990, "Fast Pyrolysis of Plastic Wastes," Energy Fuels, **4**(4), pp. 407–411.

[13] Sarker, M., Rashid, M. M., and Molla, M., 2011, "Waste Plastic Conversion Into Hydrocarbon Fuel Materials," J. Environ. Sci. Eng., **5**(5), pp. 1–8.

[14] Uçar, S., Karagöz, S., Yanik, J., Saglam, M., and Yuksel, M., 2005, "Copyrolysis of Scrap Tires With Waste Lubricant Oil," Fuel Process. Technol., **87**(1), pp. 53–58.

[15] Thompson, R. C., Swan, S. H., Moore, C. J., and Saal, F. S. V., 2009, "Our Plastic Age," Philos. Trans. R. Soc., B, **364**(1526), pp. 1973–1976.

[16] Yamamoto, T., Yasuhara, A., Shiraishi, H., and Nakasugi, O., 2001, "Bisphenol a in Hazardous Waste Landfill Leachates," Chemosphere, **42**(4), pp. 415–418.

[17] Boonniteewanich, J., Pitivut, S., Tongjoy, S., Lapnonkawow, S., and Suttiruengwong, S., 2014, "Evaluation of Carbon Footprint of Bioplastic Straw compared to Petroleum based Straw Products," Energy Procedia, **56**, pp. 518–524.

[18] Singh, P., and Sharma, V. P., 2016, "Integrated Plastic Waste Management: Environmental and Improved Health Approaches," Procedia Environ. Sci., **35**, pp. 692–700

[19] Aguado, J., Serrano, D. P., and Escola, J. M., 2008, "Fuels From Waste Plastics by Thermal and Catalytic Processes: A Review," Ind. Eng. Chem. Res., **47**(21), pp. 7982–7992.

[20] Shafiee, S., and Topal, E., 2009, "When Will Fossil Fuel Reserves Be Diminished?," Energy Policy, **37**(1), pp. 181–189.

[21] Sharma, B. K., Moser, B. R., Vermillion, K. E., Doll, K. M., and Rajagopalan, N., 2014, "Production, Characterization and Fuel Properties of Alternative Diesel Fuel From Pyrolysis of Waste Plastic Grocery Bags," Fuel Process. Technol., **122**, pp. 79–90.

[22] Miskolczi, N., Angyal, A., Bartha, L., and Valkai, I., 2009, "Fuels by Pyrolysis of Waste Plastics From Agricultural and Packaging Sectors in a Pilot Scale Reactor," Fuel Process. Technol., **90**(7–8), pp. 1032–1040.

[23] Mlsna, T., and Kunwar, B., 2013, "Upgrading Bio-Oil With a Combination of Synthesis Gas and Alcohol," 245th ACS National Meeting and Exposition, New Orleans, LA, Apr. 7–11.

[24] Elordi, G., Olazar, M., Lopez, G., Amutio, M., Artetxe, M., Aguado, R., and Bilbao, J., 2009, "Catalytic Pyrolysis of HDPE in Continuous Mode Over Zeolite Catalysts in a Conical Spouted Bed Reactor," J. Anal. Appl. Pyrolysis, **85**(1–2), pp. 345–351.

[25] Mani, M., and Nagarajan, G., 2009, "Influence of Injection Timing on Performance, Emission and Combustion Characteristics of a DI Diesel Engine Running on Waste Plastic Oil," Energy, **34**(10), pp. 1617–1623.

[26] Mani, M., Nagarajan, G., and Sampath, S., 2010, "An Experimental Investigation on a DI Diesel Engine Using Waste Plastic Oil With Exhaust Gas Recirculation," Fuel, **89**(8), pp. 1826–1832.

[27] Kaimal, V. K., and Vijayabalan, P., 2015, "A Detailed Study of Combustion Characteristics of a DI Diesel Engine Using Waste Plastic Oil and Its Blends," Energy Conversion Manage., **105**, pp. 951–956.

[28] Kaimal, V. K., and Vijayabalan, P., 2015, "A Detailed Investigation of the Combustion Characteristics of a DI Diesel Engine Fuelled With Plastic Oil and Rice Bran Methyl Ester," J. Energy Inst., **90**(2), pp. 324–330.

[29] Devaraj, J., Robinson, Y., and Ganapathi, P., 2015, "Experimental Investigation of Performance, Emission and Combustion Characteristics of Waste Plastic Pyrolysis Oil Blended With Diethyl Ether Used as Fuel for Diesel Engine," Energy, **85**, pp. 304–309.

[30] Coates, J., 2000, "Interpretation of Infrared Spectra, A Practical Approach," *Encyclopedia of Analytical Chemistry*, Willey, Hoboken, NJ.

[31] Kumar, S., Prakash, R., Murugan, S., and Singh, R. K., 2013, "Performance and Emission Analysis of Blends of Waste Plastic Oil Obtained by Catalytic Pyrolysis of Waste HDPE With Diesel in a CI Engine," Energy Convers. Manage., **74**, pp. 323–331.
[32] Hulwan, D. B., and Joshi, S. V., 2011, "Performance, Emission and Combustion Characteristic of a Multicylinder DI Diesel Engine Running on Diesel–Ethanol–Biodiesel Blends of High Ethanol Content," Appl. Energy, **88**(12), pp. 5042–5055.
[33] Damodharan, D., Sathiyagnanam, A. P., Rana, D., Kumar, B. R., and Saravanan, S., 2017, "Extraction and Characterization of Waste Plastic Oil (WPO) With the Effect of n-Butanol Addition on the Performance and Emissions of a DI Diesel Engine Fueled With WPO/Diesel Blends," Energy Convers. Manage., **131**, pp. 117–126.
[34] Ananthakumar, S., Jayabal, S., and Thirumal, P., 2017, "Investigation on Performance, Emission and Combustion Characteristics of Variable Compression Engine Fuelled With Diesel, Waste Plastics Oil Blends," J. Braz. Soc. Mech. Sci. Eng., **39**(1), pp. 19–28.
[35] Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M., Ismail, I. M. I., and Nizami, A. S., 2017, "Effect of Plastic Waste Types on Pyrolysis Liquid Oil," Int. Biodeterior. Biodegrad., **119**, pp. 239–252.