

Performance and Emissions Characteristics of Unmodified Diesel Engine Running on Waste Plastic Fuel, Diesel, and n-Butanol Blends



Parvesh Kumar, Harveer Singh Pali, Vikash Kumar, Sidharth, and Shailesh Mani Pandey

Abstract The disposal of single waste plastic is becoming from worst to disaster due to its continuous increasing demand in the market. The majority of single-used plastic ends to landfill after its useful life that leads to several problems including air and water pollution. In the present research, the single-used plastic is converted into liquid fuel by the pyrolysis process. The waste plastic fuel (WPF) is mixed with petroleum diesel in equal volumetric proportion to test it on the engine. To enhance the combustion characteristics of the fuel, oxygenated fuel is added to the blend, and the performance and emissions characteristics of the unmodified engine are tested. The better properties of WPF compared to diesel fuels improve the brake thermal efficiency of the engine by 1% for all loading conditions. However, a slight increase in emissions such as CO and NO_x is observed. Further improvement in the BTE is observed by adding a small proportion of n-butanol.

Keywords WPF · n-Butanol · Performance · Emissions characteristics · Single-use plastic

P. Kumar (✉)

Mechanical Engineering Department, Vaagdevi College of Engineering, Warangal, India
e-mail: pkkhatkar12@gmail.com

H. S. Pali

Department of Mechanical Engineering, NIT Srinagar, Srinagar, India
e-mail: hspali@nitsri.ac.in

V. Kumar

Department of Mechanical Engineering, MANIT Bhopal, Bhopal, India

Sidharth

Department of Mechanical and Automation Engineering, Maharaja Agrasen Institute of Technology, Delhi, India

S. M. Pandey (✉)

Department of Mechanical Engineering, NIT Patna, Patna, India
e-mail: smp.me@nitp.ac.in

P. Kumar · H. S. Pali · Sidharth

CASRAE, Delhi Technological University, Delhi, India

1 Introduction

Plastic and its products start gaining popularity right from its invention because of their unmatched properties such as durability, lightweight, waterproof, higher load-carrying capacity. All these properties of plastic bring revolutionary changes to the packaging and food industries [1]. Further, plastic products are easy to mold; therefore, in recent years, the use of plastic is also increasing in the toy sector as well. As a result, the production of plastic and its products reached 335 million tons in 2016 [2] with an average increase of 10% annually from its commercialization [3]. As per the report, the per capita production of plastic waste in India is 4 kg and at 94th in the list which is headed by Australia and Singapore with per capita single-use plastic waste of 56 kg and 76 kg, respectively [4]. However, India is ranked third in overall single-use plastic waste production, whereas China is at the top followed by the USA. Furthermore, the production of plastic products is increasing continuously because of its high demand. But, plastic products have problems in their disposal technique after their useful life. The self-decay period of most of the plastic variants is around 500 years that makes it difficult to dispose of once used. As a result, only 9% of single-use plastic waste is recycled mechanically, 12% is cremated, and the rest ended with landfill and ocean fill [5]. The cremation, landfill, and ocean fill of single-use plastic waste lead to degradation of air and water quality that give birth to several airborne and waterborne diseases. Almost all varieties of plastic are a rich source of carbon and hydrogen with some traces of nitrogen, sulfur, and other compounds that make it a good source of energy [6]. Therefore, the conversion of single-use plastic waste into an energy-rich source helps to overcome environmental problems caused by plastic waste and provides a strategic alternative to the energy crisis. For this, pyrolysis is a more suitable and technically sound technique to convert single-use plastic waste to energy-rich end products like liquid fuel, syngas, and char. The end energy-rich products obtained after pyrolysis of plastic waste have very impressive properties, and all are user-friendly. The properties of liquid fuel obtained from pyrolysis are very comparable to petroleum diesel and are used in the unmodified diesel engine directly or as a blend with petroleum diesel. Also, the synthetic gas commonly known as syngas obtained is a rich mixture of methane, hydrogen, carbon monoxides, and carbon dioxide [7]. However, the properties of syngas are depended upon their composition. Further, the char obtained in the reactor after the pyrolysis process is richest in carbon content among all other products. The quality of end products obtained depends upon several factors including reactor type, reactor size, the catalyst used, heating process, heating rate, catalyst concentration, reacting environment, etc. Further, the quality of syngas obtained during gasification heavily depends upon the rate of steam or hot water supplied. Xue et al. [8] investigated the effect of operating temperature on the yield of liquid fuel obtained from high-density polyethylene in a continuous fluidized bed reactor. The authors took the temperature range between 525 and 675 °C and conclude that the maximum yield of 57.6 wt% can be obtained at 625 °C; however, further increase in temperature leads to the formation of light gases that decrease the yield of liquid fuel. Artetxe et al. [9] determine the effect of

temperature and gas flow rate on the composition and product yield. Therefore, it can be concluded that the yield of the liquid fuel obtained during pyrolysis is dependent upon operating conditions and parameters; however, the quality of fuel obtained is nearly constant and very comparative to the petroleum diesel fuel. Conclusively, it can be said that the conversion of plastic waste into a liquid fuel contributes to the solution of air pollution and crude oil scarcity. However, long engine trials are not done with waste plastic fuel (WPF), so it is very difficult to project its effectiveness for the long run at present, but the experimental results obtained by the researchers are very positive and acceptable. Therefore, for the safer side, it is better to run the engine with the WPF and diesel blends. The blend varies according to the requirement and availability. To improve the combustion characteristics of the fuel, some oxygen rich additives such as biodiesel and higher alcohol can be used. The use of higher alcohols provide positive results while used with diesel fuel directly or in diesel–biodiesel blends. The higher alcohols such as butanol, octanol have better combustion properties such as cetane number, calorific value, pour point, and cloud point as compared to basic and lower carbon alcohol. All these properties are suitable for diesel engines this is the reason why higher carbon alcohols are gaining popularity over the lower carbon alcohols. The calorific value and cetane values of alcohols improve with an increase in carbon atoms, but the synthesis becomes difficult. Also, at present, only a limited type of alcohols is synthesized naturally, whereas most alcohols are synthesized through a chemical process. Therefore, it becomes important to select the right alcohol for the research. In the present work, the WPF and petroleum diesel are mixed in an equal volume percentage. The n-butanol is selected to improve the combustion characteristics of WPF and diesel blend. The composition of n-butanol in the blend is limited to 10% as a further increase in concentration decreases the calorific value of the blend. The tested fuels obtained are D-100, D-WPF, 95D-WPF05nB, 90D-WPF10nB, and 85D-WPF15nB. The prepared test fuels are tested on unmodified diesel engine to analyze the performance and emissions characteristics. The detailed nomenclature of the tested fuels is provided in the experimental section.

2 Experimental

2.1 *Materials and Preparations*

To prepare waste plastic fuel, the waste plastic products such as cold drinks and water bottles and food packaging papers are collected from the central canteen of the Vaagdevi College of Engineering, Warangal. The collected plastic waste is first cut into smaller pieces of 5–10 mm size. The cut pieces are thoroughly washed in the water and put into sunlight for drying. The initial process of preparation of the raw material takes 2–5 days depending on the availability of sunlight. It makes sure that all the moisture in the raw material is removed completely for a better

pyrolysis process. The chemicals such as catalysts and alcohols are purchased from an institutional local vendor. The catalyst bed is synthesized in the Department of Mechanical engineering of Vaagdevi College of Engineering, Warangal.

2.2 *Pyrolysis Setup*

To perform the pyrolysis process, one setup is developed in the Department of Mechanical Engineering of VCE, Warangal. The setup consists of one pyrolysis reactor attached with a thermocouple and pressure gauge for continuous monitoring of temperature and pressure. The reactor is heated with the help of a coil-based electric heater purchased from the local market. One setup for catalyst bed is also developed in the department only. This catalyst bed can carry catalysts and is easily installed over the reactor head. The gases generated are passed through the catalyst bed where they cracked into simple molecules. The gases released during the pyrolysis process are a mixture of condensable and non-condensable gases. Therefore, one condenser is installed to the outlet passage of the reactor in such a way that the pyrolysis gases will pass through the condenser after pass through the catalyst bed. To maintain the controlled temperature in the condenser, one chiller is attached to the condenser. The chiller cools the hot fluid coming out from the condenser. In most cases, the fluid used in the condenser is water so as in the present work. The condensable gases lose the heat in the condenser and are converted into liquid fuel that can be collected at the bottom of the condenser, whereas the uncondensed gases remain in gaseous form even after losing heat. One entry to the reactor is provided for the inert gas supply, so to eliminate any traces of the oxygen gas in the setup, nitrogen is passed through the complete setup before each pyrolysis trail. The power to the electric heater is supplied through temperature controller and transformer arrangement and designed in such a way that the power supply can be changed as per required temperature and heating rate. The thermocouple attached to the reactor is connected to a temperature controller and indicator to maintain the desired temperature during the pyrolysis process. The schematic diagram of the pyrolysis experiment setup is shown in Fig. 1.

2.3 *Production of WPF*

First of all, the dried small pieces of plastic waste are put into the reactor. After that, to vanish any traces of the oxygen in the setup, the nitrogen gas is supplied at least for 10 min. All the valves are closed just after stopping the nitrogen supply. This process stops any combustion during the pyrolysis process. Now heating to the reactor is started with a rate of 10 °C/min. Only 80% of the reactor is filled with solid plastic waste pieces that become 30% after melting. The liquid plastic starts boiling after some time depending upon the variety of plastic waste used. Initially, the vapor

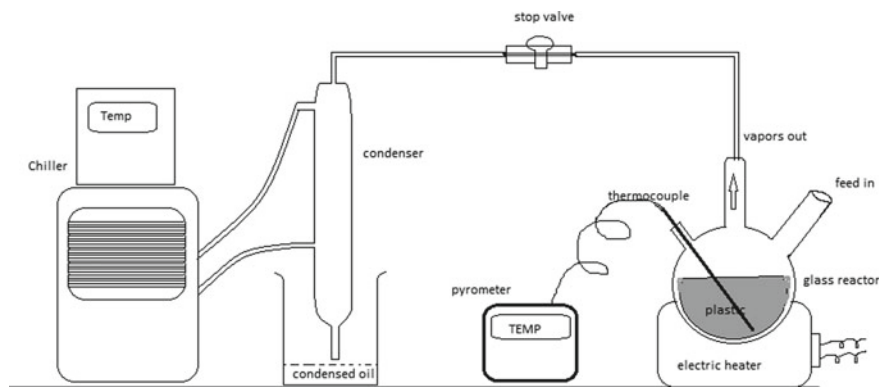


Fig. 1 Setup for pyrolysis and condensation

formed is rich in wax and uncondensed gases due to lower reaction temperature. Further, the continuous heating of the reactor increases the reaction temperature that improves the rate of conversion of the complex compound to the smaller and simpler compound. The reaction temperature maintained in the present research is 600–650 °C. The generated gases pass through the catalyst bed that further enhances the cracking rate of complex compounds. The simple compounds then pass through the series of the condenser where the condensable gases get condensed and converted into liquid, whereas the uncondensed gases leave the condenser in gaseous form only. The condensed liquid get collected from the bottom of the condenser for further analysis and usage, whereas the uncondensed gases which are very rich in carbon and hydrogen are collected in a cylinder and can be used for any heating purposes. Sometimes, the hybrid heaters are used that can use both electric powers when the supply of gaseous fuel is not available and gaseous fuels when it is available in enough quantity. The complete conversion of plastic waste into end products takes 4–10 h depending upon various factors. In the end, when no further release of gases is observed, it is a clear indication of completion of the pyrolysis process for that lot. The content of liquid fuel, gaseous fuel, and char obtained at the end of the pyrolysis process vary in the range of 40–70%, 20–50%, and 5–15%, respectively. In the present research, 58% of plastic waste is converted into liquid fuel, the char left in the reactor is 9 w/w% to solid plastic waste, and the remaining 33% is uncondensed gases.

2.4 Blend Preparation and Engine Setup

The properties of WPF obtained during the current trial are very much similar to the petroleum diesel fuel; therefore, the blend is prepared by taking both in equal percentage by volume, i.e., 50% of petroleum diesel and 50% of WPF. To enhance

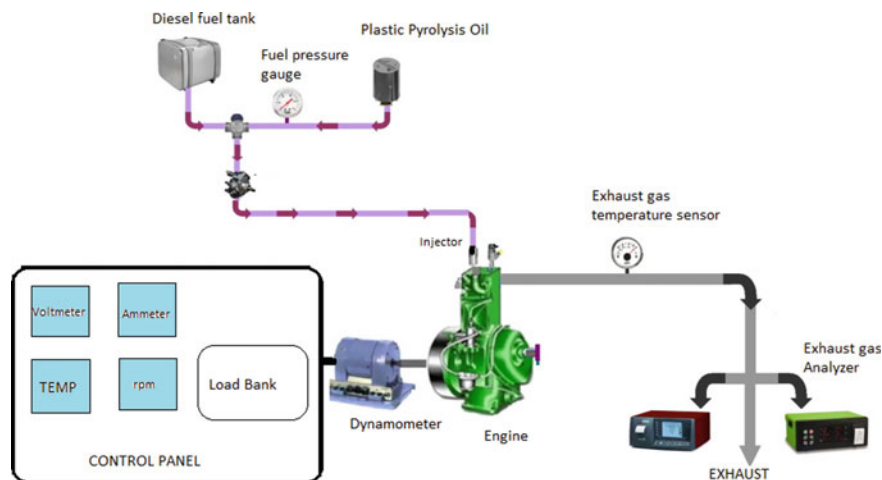


Fig. 2 Schematic diagram of the experimental test rig

the combustion characteristics of the fuel, isobutanol is mixed in the prepared blend in 5, 10, and 15% by volume. The physicochemical properties of all the tested fuels are measured as per the ASTM standard and presented in detail in the next section. The prepared blends are tested on the engine. The engine test rig used in the present research is the same (Kirloskar four-stroke, single-cylinder, vertical, air-cooled, manually cracked started, gravity fuel feeding system direct injection diesel engine coupled with an eddy current dynamometer) used in the last research. The schematic diagram of the test rig used in the present research is given in Fig. 2.

3 Results and Discussion

3.1 Physicochemical Properties

The physicochemical properties of all the tested fuels are measured as per ASTM standard, and the processes opt to measure the properties of all tested fuels are the same opt in our previous research [10]. The nomenclature and the results obtained for physicochemical properties of all the tested fuels are given in Tables 1 and 2, respectively.

Table 1 Nomenclature of all tested fuels

Notification	Nomenclature
D100	100% petroleum diesel
WPF	100% waste plastic fuel
D-WPF	50% petroleum diesel + 50% waste plastic fuel
nB	100% n-butanol
95D-WPF05nB	95% D-WPF + 05% n-butanol
90D-WPF10nB	90% D-WPF + 10% n-butanol
85D-WPF15nB	85% D-WPF + 15% n-butanol

Table 2 Physicochemical properties of all tested fuels

Property	Density	Viscosity	Calorific value	Cetane number	Flash point	Autoignition temperature
D100	823	2.6	43.3	45	53	230
WPF	816	2.8	45.2	51	42	195
D-WPF	820.5	2.7	44.65	50	43	202
nB	807	2.3	32.6	16	38	358
95D-WPF05nB	820	2.68	44.05	48	43	210
90D-WPF10nB	819	2.66	43.45	47	43	218
85D-WPF15nB	818	2.64	42.84	45	42	225

3.2 Performance Characteristics

The performance of all tested fuels is analyzed by testing them on an unmodified diesel engine. The parameters such as brake thermal efficiency (BTE), brake specific energy consumption (BSEC), and exhaust gas temperature (EGT) are analyzed in the current section. The effect of blending WPF with petroleum diesel is analyzed first, and after that, the effect of n-butanol on the performance of the blend is also analyzed. The results obtained are compared with the conventional petroleum diesel results, taking it as baseline data. The comparative study of all tested fuels with baseline data for BTE–BSEC and EGT is shown in Figs. 3 and 4, respectively.

The blending of WPF with petroleum diesel in equal proportion improves the properties such as calorific value and cetane number of the diesel fuel blend. However, other properties remain very comparable to petroleum diesel. Therefore, the prepared blend can be used in the unmodified diesel engine. After testing the blend, it is analyzed that the improved properties of the blend lead to better combustion, and as a result, the improvement in the BTE can be observed for D-WPF as compared to conventional diesel fuel. Further, adding n-butanol in the D-WPF blend provides free oxygen to the fuel that improves the combustion characteristics of fuel. Hence, improvement in the BTE of the engine can be observed with an increase in the content of n-butanol in the blend. However, the calorific value and cetane number of n-butanol

Fig. 3 Trends of BTE and BSEC for all test fuels

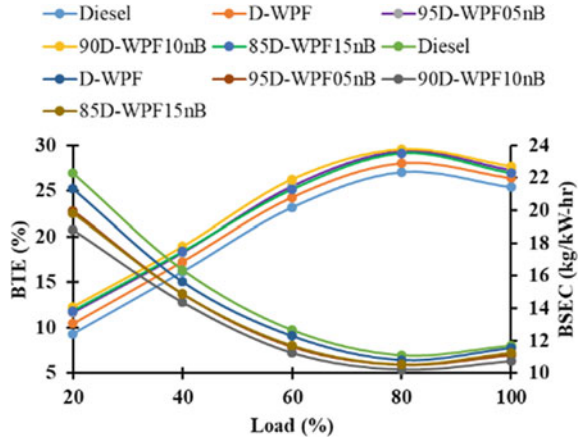
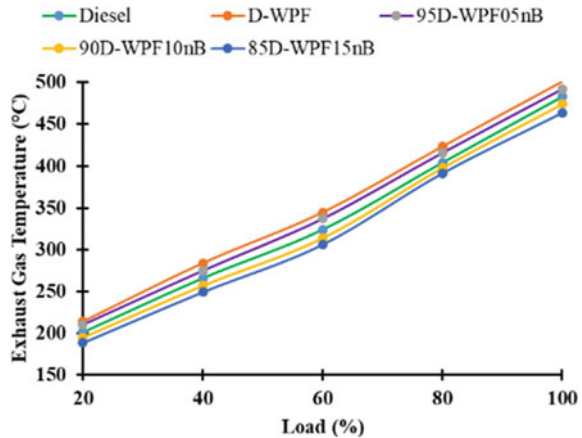


Fig. 4 Variation in EGT with respect to load



are less as compared to petroleum diesel and WPF; therefore, the adding of n-butanol in the blend beyond some limit put an adverse effect on the fuel properties. This can be observed with the 85D-WPF15nB blend result. The BTE of the engine increases with an increase in n-butanol content in the fuel up to 10%, and once the n-butanol content increase beyond 10%, the reduction in BTE of the engine is noticed. The BSEC is inversely proportional to the BTE; therefore, the trend followed by all the fuels in BSEC is opposite to the trend followed in BTE. However, the trends of EGT are slightly different from BTE and BSEC. The exhaust gas temperature for D-WPF is higher than conventional diesel fuel for all working loads. But, the addition of n-butanol provides some cooling effect to the fuel, and as a result, the increasing content of the n-butanol in the fuel decreases the EGT of the engine.

3.3 Emissions Characteristics

Emissions such as carbon monoxide (CO), unburnt hydrocarbons (HC), and oxides of nitrogen (NO_x) of unmodified diesel engines are analyzed in the present section for all the tested fuels. The comparative results of all the emissions for all tested fuels are given in Figs. 5, 6, and 7, respectively. It is observed that the CO emissions of the D-WPF fuel are slightly higher when compared with conventional diesel fuel. The higher CO emission might be due to a slightly higher density of blend while compared with petroleum diesel. However, the addition of n-butanol provides extra oxygen in the combustion chamber, and as a result, the CO emissions decrease with an increase in the composition of n-butanol in the fuel. However, a higher percentage of n-butanol further increases the CO emissions, and the reason is lower combustion temperature in the combustion chamber. On the other hand, the HC emissions of all the tested fuels are observed less compared to baseline data. This is due to the higher cetane number of D-WPF and oxygenated fuels. The HC emissions of oxygenated fuels are found lesser as compared to the blend and the diesel fuel. Similar to the CO emissions, the increase in the composition of n-butanol beyond 10% starts increasing the HC emissions, and the reason is the same as that of CO emissions. The oxides of nitrogen are dominant in diesel engines while compared to other internal combustion engines. The main reason for the formation of NO_x is higher temperature and pressure along with the availability of free oxygen in the combustion chamber. All the conditions are more favorable in diesel engines compared to gasoline engines. It is observed that NO_x emissions of D-WPF are higher than conventional diesel fuel because of higher combustion temperature. However, the addition of n-butanol reduces the energy content of the fuel and also provides a cooling effect in the combustion chamber before and during combustion. As a result, the NO_x emissions reduce with increasing the n-butanol content in the blend. Conclusively, the highest NO_x emissions of 17.21 g/kWh are observed for D-WPF, whereas the lowest NO_x emissions of 3.4 g/kWh are observed for 85D-WPF15nB at 20% load and 100% load, respectively.

4 Conclusions

Some important conclusions drawn from the present research work are as follows:

- Most physicochemical properties of D-WPF are better or comparable to petroleum diesel. Therefore, WPF can be used as an energy source for conventional diesel engines.
- The addition of n-butanol improves the combustion characteristics of the fuel.
- The improvement of 1% of the BTE is observed for D-WPF compared to diesel fuel, and the BTE further increases by 1.3% with the addition of 10% n-butanol in the D-WPF.

Fig. 5 CO emissions trend for all the tested fuels

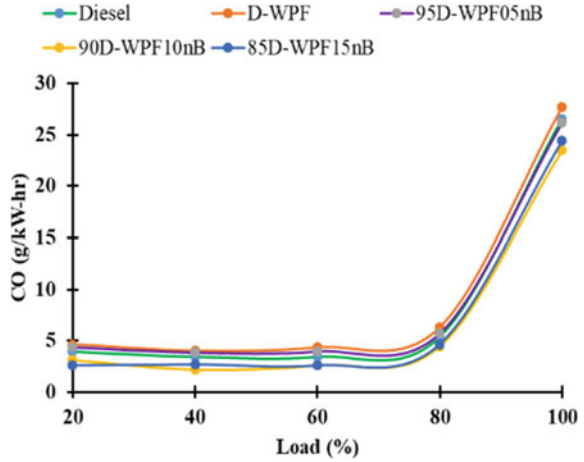
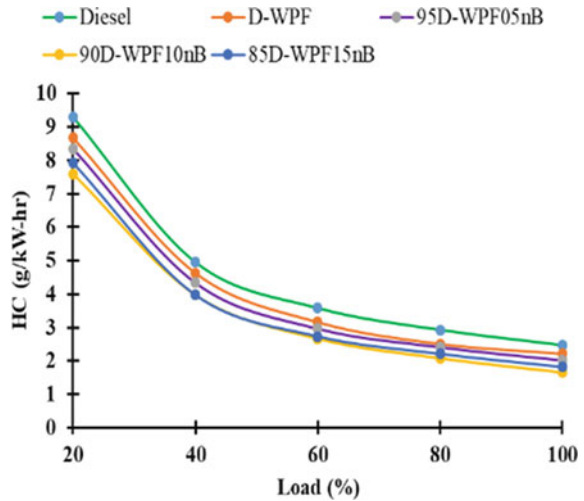
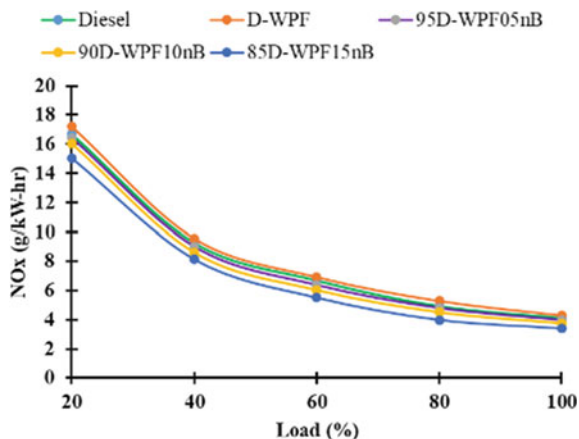


Fig. 6 HC emissions trend for all the tested fuels



- The EGT for D-WPF is decreased by 50 °C by adding 15% of n-butanol by volume.
- The emissions such as CO and NO_x are increased for the D-WPF compared to conventional diesel. However, with the addition of n-butanol, a reduction in all the emissions is observed.

Fig. 7 NO_x emissions trend for all the tested fuels



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