

# Energy Recovery from Lemon Peel Waste and its Energy and Environmental Improvement with Economic Assessment

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## Research Article

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# Abstract

Waste-to-energy and its utilization in the commercial field have received wider attention in recent years. Lemon peel oil (LPO), a food waste by-product is used for this study to produce bioenergy, and a novel approach has been attempted to improve energy and environmental efficiency. The LPO was blended different percentages of water and 2-Ethylhexyl nitrate (EHN) and the energy, environmental and economic assessments were carried out. The outcomes show that LPO dominates the normal diesel in all aspects, except for NO<sub>x</sub> emission, and 10% of water in LPO (10WLPO) improves the overall performance. Meanwhile, this trend is reversed for 20% water in LPO (20WLPO) due to longer ignition delay period and low cetane numbers. EHN plays a vital role in fuel modification and EHN blended 20WLPO significantly improves the engine characteristics, and the engine behaviour is identical to 10WLPO. The cost-benefit analysis shows that 10WLPO fuel significantly reduces the running cost by 4.5% compared to neat diesel, and the cost is further reduced to 9.2% while the LPO is blended with 10% water.

## 1. Introduction

Fossil fuel consumption is increasing rapidly every year as demand is directly proportional to the total population growth. Billions of litres are consumed every year, leading to scarcity of diesel fuel in few decades [1]. Though the entire world is trying to move towards alternative power sources, diesel power is mandatory and should be existed for many decades, especially for heavy vehicles. The complete replacement for fossil fuel and its commercialization in a prescribed time limit is not worth considering [2]. Hence, alternative fuel sources need the present scenario to take off the diesel fuel crisis. Apart from that, the developed alternative diesel fuels should meet the stringent emissions regulation developed by the Board of National Emission Regulation Authorities (BNERA) to save the environment [3].

Biodiesel is preferred as a potential alternative source for existing diesel fuel as the biodiesel can be partially or fully replaced instead of diesel. Plenty of valuable studies have been conducted by many researchers in the domain of first-second-and third-generation biodiesels. The main sources for first-generation biodiesel are edible oils such as palm, soybean, corn, and rapeseed oils [4, 5]. Though these oils are renewable and environmentally friendly, oil production competes with food crops that lead to food-energy conflict. The non-edible oils are primary sources of second-generation biodiesels that have some potential benefits compared to first-generation biodiesels, such as effective land utilization and does not affect the environmental food chain. Jatropha, Karanja, Rubber seed, Pine, Eucalyptus, and Mahua oils are common second-generation biodiesels [6–8]. These biodiesels required sophisticated downstream processing techniques that lead to high production costs. The additional challenges in second-generation biodiesels are the water and land-use competition and uncertainty for long-term production [8]. Micro-algae are identified as third-generation biodiesel, which is having a distinctive yield compared to others. Though the micro-algae do not have any conflict in the environmental food chain, the algae biomass production is insufficient for commercialization, and the production cost is not economically viable [9].

Waste-to-energy is an interesting concept for biodiesel preparation as the raw materials are derived from organic and inorganic compounds. The engine researchers have made several attempts to derive biodiesel from the waste and developed some interesting products like waste plastic oil, waste cooking oil, waste food oil, lemon peel oil, etc. [6, 10, 11]. Out of these, lemon peel oil (LPO) recommends for this study as it has some unique characteristics such as low viscosity, low carbon chain length, high heating value, and innate oxygen content compared to other biodiesels [12, 13]. These properties promote a better mixing rate with air and improved atomization that results in complete combustion. Apart from that, the lemon peel is widely available throughout the world and will not lead to an additional cost for raw material [13].

Ashok et al. [13] have conducted a study using LPO in the diesel engine and reported that LPO could be replaced for diesel fuel. They have improved 12% in brake thermal efficiency (BTE) and 9% in brake specific fuel consumption (BSFC) for LPO compared to base diesel. They also pointed out that due to the complete combustion of LPO, the emission parameters such as hydrocarbon (HC), carbon monoxide (CO), and smoke are significantly reduced. In contrast, the oxides of nitrogen (NO<sub>x</sub>) emission are increased by 55% due to longer ignition delay period (IDP). The same authors reported in another study that 20% LPO in diesel fuel substantially reduces the BSFC and emissions level due to the enriched oxygen content [14]. The report concludes that 20% of LPO in diesel fuel can be used as a regular fuel for common rail diesel injection system engine at 600 bar injection pressure and 30% pilot injection rate. Velavan et al. [15] experimented with visualizing the in-cylinder combustion flame and evaluating the engine behaviour fuelled with LPO and gasoline. The experimental report stated that the presence of LPO in base fuel reduces the flame diffusion and increases the premixed combustion rate. The report also concludes that up to 10% LPO in base fuel significantly reduces emissions and improves engine performance. Aruna Kumari et al. [16] have examined the emission characteristics of LPO blended with base diesel and concluded that the presence of LPO (20%) in diesel fuel reduces the HC, CO, and smoke by 25%, 25.6% and 15.4%, respectively, whereas the NO<sub>x</sub> emission, is increased by 22%.

The above discussions related to the experimental results of LPO clearly show that the LPO is a suitable alternate for diesel fuel, and the overall engine performances are pretty good except for NO<sub>x</sub> emission. The NO<sub>x</sub> emission, which includes nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), and nitrous oxide (N<sub>2</sub>O), is of serious concern to the environment and human life. These emissions have been identified as ozone layer depletion, lung cancer, and eye irritation. Hence, the removal of tailpipe NO<sub>x</sub> emission from the diesel engine is essential for the present scenario. Selective catalytic reduction, selective non-catalytic reduction, and exhaust gases scrubbed with chemicals are represented as some post-processing NO<sub>x</sub> emission reduction techniques [17]. Water in base fuel, a pre-processing emission control technique, is a much interesting concept, as the NO<sub>x</sub> emissions can be regulated without any engine modification in water emulsion fuel. Additionally, water in base fuel significantly improves the engine performance and reduces the other emissions level [18].

Many researchers have conducted plenty of valuable research using water in base fuel (for both diesel and biodiesels) by many researchers and depicted interesting results. The experimental results of

Vellaiyan et al. show that 10% water in diesel fuel reduces the NO<sub>x</sub>, HC, CO, and smoke emissions by 32.5%, 9.9%, 12.8%, and 17.8%, respectively, at peak engine load conditions [4]. The same authors reported in another study that 10% water in diesel fuel improves the BSFC and BTE by 6.6% and 12%, respectively. They also pointed out that the IDP is continuously increasing with increased water concentration [19]. The possible causes for the improvements in engine behaviour are enhanced air-fuel mixing, micro-explosion phenomena, and high premixed combustion rate associated with water emulsion fuel [19, 20]. Many researchers report similar experimental results for the biodiesel water emulsion fuels such as soybean biodiesel, lemon peel oil, palmyra palm, waste cooking oil, and lemongrass oil. [12, 21, 22]. The collective results of the above experiments show that the water in base fuel is a suitable NO<sub>x</sub> emission control technique that can improve the performance and other emissions. Meanwhile, the improvement in engine behaviour can be derived for limited water concentration, and normally for the water concentration above 10%, the negative impacts are derived due to longer IDP associated with emulsion fuel [12, 21].

From the discussions related to low viscous LPO and water emulsion fuel, it is noted that the IDP has a vital role in engine performance. The IDP value should be reduced to improve the overall engine performances and obtain smooth operation. The IDP value is directly related to a cetane number, and an increase in the cetane number of the fuel is significantly reducing the IDP [23]. To improve the cetane number of the fuel, nano additives and other chemical agents are recommended by many researchers. Though the presence of the nanoparticles significantly improves the engine characteristics, the nanoparticle emissions to the atmosphere and the fuel cost are identified as major concerns [4, 19]. The cetane improver is a suitable option to improve the fuel properties. It contains carbon, nitrogen, and hydrogen as a major composition and can be blended with base fuel without any difficulty. From several cetane improvers, 2-Ethylhexyl nitrate (EHN) is preferred for this study as it is a commercial product that is readily available in the market at a low cost. The free radicals promoted by the EHN during the fuel combustion enhances the acceleration rate of the combustion process that can reduce the IDP [24, 25].

In light of the above deliberations, it is noted that the LPO can replace diesel fuel, and the water inclusion in LPO has a significant impact on engines' emissions and performance. To overcome the negative impact, i.e., the longer IDP associated with low viscous LPO and water emulsion fuels, a suitable cetane improver can be added to improve the fuel properties and enhance the cetane number. As far as the authors' knowledge is concerned, no efforts have been taken on the concept described above. This attempt will promote an efficient engine operation with a common environmental effect for high water concentrated emulsion fuels. Taking as an inventiveness, the current study has been carried out to examine the engine behaviour fuelled with 10% water in LPO (10WLPO), 20% water in LPO (20WLPO), and EHN blended 20WLPO (20WLPOE), and the assessments are compared with neat diesel (ND) and LPO. The cost analysis for various fuels is also carried out for the test fuels.

## **2. Materials And Methods**

### **2.1. Engine test setup**

A light-duty, single-cylinder, four-stroke and water-cooled agricultural purpose diesel engine was used to examine the fuel characteristics for this study. An eddy-current dynamometer (water-cooled) loading system was integrated into the engine output shaft to apply uniform load with minimum error in the engine setup. Air-flow and fuel-flow rates were measured using pressure transmitter and DP transmitter with measuring ranges of 0-250 mm and 0-500 mm, respectively. The air inlet and exhaust gas temperatures, cooling water, and lubrication oil temperatures were sensed by a K-type thermocouple with a measuring range of -260°C to 1260°C. Piezo sensor with a range of 0-350 bar pressure measurement was located in the engine cylinder head to measure the in-cylinder combustion pressure. A crank angle sensor with a resolution of 1 degree with a speed of 5500 rpm was used to measure the crank angle, and based on the in-cylinder pressure, the net heat release rate was estimated. The above-measured parameters signal was communicated to a computer through a high-speed data acquisition device (NI USB-6210, 16-bit, 250kS/s). Initially, the engine was run for 10 min in an ideal condition to attain constant temperature in the engine exhaust gas and lubrication oil. Once the steady-condition arrived with fluctuation of  $\pm 1^\circ\text{C}$  in temperatures, the engine combustion and performance parameters were recorded. To avoid error in the recorded values, the experiments were repeated at similar conditions about ten times, and an average value was considered for the assessment. The engine test setup and schematic layout are represented in Fig. 1.

The emission parameters such as CO, HC, and NO<sub>x</sub> were measured using a Non-Dispersive Infrared (NDI) AVL-444 digas analyzer on a dry basis. The tailpipe smoke emission was recorded using a filter type AVL-437 smoke meter. The exhaust gas from the engine tailpipe was allowed to pass over the moisture separator and filter element to ensure the zero presence of water and particulate inside the gas analyzer. The HC and NO<sub>x</sub> emissions were measured in terms of ppm, and CO and CO<sub>2</sub> were measured in volume percentage. The emission parameters were converted into kg/kW-hr for evaluation purposes. Like combustion and performance measurements, the emission parameters are also measured based on the average value of ten continuous executions at the same operating conditions. Table 1 representing the detailed specifications of the test engine and emission analyser.

Table 1  
Test Engine and Emission Analyser Specifications

<b>(a) Engine Specifications</b>		
Parameter	Specification	
Engine type	4-stroke, single cylinder, natural aspirated, variable compression ratio diesel engine	
Bore × Stroke (mm)	87.5 × 110	
Displacement volume (cc)	661.45	
Max. power	3.5 kW at 1500 rpm	
CR range	12-18	
Dynamometer	Eddy current dynamometer (max. load of 7.5 kW)	
<b>(b) Emission Analyser Specifications</b>		
Measured quality	Measuring range	Resolution
HC	0 to 20000 ppm vol	≤ 2000:1 ppm vol, > 2000:10 ppm vol
CO	0 to 10% vol	0.01% vol
NOx	0 to 5000 ppm vol	1 ppm vol
CO <sub>2</sub>	0 to 20% vol	0.1% vol

## 2.2. Uncertainty analysis

Uncertainty analysis had been carried out in this study to ensure the goodness of the experimental results. The values were taken 10 times (N) at a constant engine speed, and load for the measured parameters, and the mean value represented the best-estimated value. The uncertainty of measured parameters value was represented by the standard deviation of the mean (SDOM) and identified by using the following equation [26]:

$$SDOM = \frac{S}{\sqrt{N}}(1)$$

The derived parameters uncertainty values were identified by the root mean square method using the following equation [27]:

$$\Delta R = \sqrt{\left(\frac{\partial R}{\partial x_1} \cdot \Delta x_1\right)^2 + \left(\frac{\partial R}{\partial x_2} \cdot \Delta x_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \cdot \Delta x_n\right)^2} \quad (2)$$

Where R is the estimated quantity, and  $x_1, x_2, \dots, x_n$  are independent variables. Table 2 represents the uncertainty of different measured and derived parameters.

Table 2  
Uncertainty of Engine Parameters

Quantities	Resolution	Uncertainty percentage
Engine Torque	±1	±0.2
Dynamometer load cell (W)	±50 g	±0.2
Engine speed (N)	±10 rpm	±0.1
Pressure pickup (P)	±0.1 bar	±0.05
Brake power	-	±0.85
Brake specific fuel consumption	-	±0.9
Brake thermal efficiency	-	±0.9

## 2.3. LPO extraction

A normal steam distillation process was followed to extract the LPO from the raw material (waste lemon rinds). High-temperature steam was produced in the boiler and allowed to pass inside the distillation chamber, where the dry lemon rinds were kept. Due to the high steam temperature, the lemon oil was unmasked from the rinds and converted to fume. This homogeneous mixture of steam and lemon oil fumes entered inside the condensation flask, where the cooling process was carried out using normal cooling water. The condensed liquid was stored in the collecting tank, where the immiscible water was settled down at the bottom of the tank due to high density, and the low-density LPO was floated over the liquid water. The LPO was collected from the collecting tank, and the impurities were removed by heating and filtration process. The photographic view and schematic layout of LPO extraction using the thermal distillation process are represented in Fig. 2.

## 2.4. Emulsion fuel preparation

The extracted LPO was considered as a base fuel (continuous phase) for emulsion preparation, and 10% of double-distilled water (dispersed phase) in total volume was mixed with water along with 1% of sorbitan monolaurate surfactant (supplier: Sigma-Aldrich India;  $C_{18}H_{34}O_6$ ; Hydrophilic-lipophilic balance 8.6; density  $1.032 \text{ kg/m}^3$ ). During the emulsification process, the dispersed phase and surfactant were dispensed in the continuous phase at high speed of mechanical agitation, and the agitation process was continued for about 30 minutes. The emulsified fuel's impurities were removed using a normal filtration

process and named 10WLPO. A similar procedure was followed to make 20WLPO emulsion fuel comprised 20% water, 79% LPO, and 1% surfactant. The schematic layout of the emulsion fuel preparation setup is shown in Fig. 3, and the photographic view of sample fuels is shown in Fig. 4. The cetane improver (EHN - supplier: Sigma-Aldrich India;  $C_8H_{17}NO_3$ ; molecular weight 175.2 g/mol, density  $0.963 \text{ g/cm}^3$  and flash point  $76^\circ\text{C}$ ) was mixed with 20WLPO emulsion fuel in 2% of total volume and named as 20WLPOE.

## 3. Results And Discussion

### 3.1. Property test

The important physicochemical properties of test fuels are exposed in Table 3. The property tests were conducted using several experimental setups at different conditions based on ASTM norms. Five different test fuels have been chosen in the present work based on fuel source, water concentration, and EHN quantity. From the measured values, it is noted that the cetane index of LPO is much lower than ND, and an increase in water level in LPO further marginally reduces the cetane index value. However, this value is greatly improved due to the presence of EHN. The density of LPO is higher than ND, whereas the viscosity, heating value, and flash point are lower. The presence of water in LPO increases the viscosity, density, and flash point and reduces the heating value. A marginal variation in the fuel properties is noted for EHN blended emulsion fuel.

Table 3  
Properties of Test Fuels

Fuels	Cetane Index	Density at $15^\circ\text{C}$ ( $\text{kg/m}^3$ )	Flash point $^\circ\text{C}$	Heating value ( $\text{MJ/kg}$ )	Stability period (hrs)	Viscosity at $40^\circ\text{C}$ ( $\text{mm}^2/\text{s}$ )
ND	52	820	66	42.8	-	3.62
LPO	16	842	54	41.5	-	1.11
10WLPO	15	856	62	37.4	94	1.92
20WLPO	14	867	68	33.5	66	2.42
20WLPOE	18	869	69	33.7	78	2.48
ASTM method	D613	D1298	D93	D420	-	D445

### 3.2. Performance assessment

#### 3.2.1. Brake thermal efficiency

The graphical representation of BTE for different test fuels under different BP conditions is shown in Fig. 5. In X-axis, '0' represent the ND, and '100' represents the LPO, whereas '90' and '80' represent the 10% water and 20% in LPO, respectively. The term BTE is generally defined as the ratio between the power developed to input energy. It also explains how the fuel efficiently burns inside the cylinder at a combustion phase [12]. Usually, the results of BTE are elevated when BP gets increased, and the same trend has been derived during our assessment and represented in Fig. 5. The assessment also reported that the BTE of LPO fuel is increased by 8.3% compared to ND at the top load state. It is evident through the property table that the viscosity of LPO is much lower than diesel, which is resulted in a better air-fuel entrainment process and complete combustion.

The scrutiny of water emulsified LPO fuel performance shows that the BTE is increased by 5% for 10WLPO emulsion fuel than LPO, whereas 20WLPO emulsion fuel's BTE is decreased by 7.6%. At minimum water level, it is obvious that the latent heat evaporation of water particles is low, and this heat loss could be compensated by micro-explosion and secondary atomization. The relevant research work conducted by Vellaiyan and Amirthagadeswaran [12], Radhakrishnan et al. [20] also represented the higher BTE while supplying the water in base fuel. However, the high-water level in base fuel significantly increases the latent heat of vaporization and results in longer IPD. The accumulation of much fuel in the premixed combustion phase leads to abnormal combustion with less engine performance [18]. The emulsification of EHN in 20WLPO promotes the BTE to 34.2% at peak load state, which is 9.7% higher than 20WLPO. The rich oxygen content in LPO emulsion fuel and the combined effect with cetane improver enhance the atomization rate and improve the burning chamber's burning activity [28, 29].

### **3.2.2. Brake specific energy consumption**

The impact on brake specific energy consumption (BSEC) for different test fuels under different load states is represented in Fig. 6. The trend of BSEC for all the test fuels pursues a decrement pattern with the increment in BP due to efficient combustion at high engine torque. As reported in Fig. 6, LPO fuel gets 7.7% lower BSEC compared to ND at the top load state. It is evident that the viscosity value of LPO, which is better than ND, resulted in a better air-fuel mixing rate. Due to the enhanced air-fuel mixing and evaporation rate, the energy consumption to produce the same power for LPO is significantly reduced compared to ND [12]. The examination of water emulsified LPO fuels represents that the BSEC further improved for 10WLPO fuel. The additional power is acting on the piston surface due to the micro-explosion and secondary atomization. A drop of 4.8% in energy consumption is recorded with 10WLPO compared to ND at peak load state. The BSEC of 20WLPO is not par with LPO and 10WLPO due to the poor ignition quality and longer IDP associated with high water concentrated emulsion fuel. The combined effect of water and cetane improver in 20WLPOE reduces the energy consumption by 8.8% compared to 20WLPO. The presence of EHN increases the cetane number that ensures the advanced auto-ignition and results in efficient combustion [30].

### **3.2.3. Brake specific fuel consumption**

The BSFC of test fuels under various engine operating conditions is shown in Fig. 7. Similar to BSEC, BSFC also decreased with increases in BP for all the test fuels. The graph reported that LPO has a lower BSFC than ND; its heating value is still lesser than ND. Improved oxygen content in the LPO promotes efficient and complete combustion that results in low BSFC compared to ND [13], and a drop of 4.5% is recorded. The BSFC of emulsion fuels is higher than ND and LPO, and increases of 5.3% and 34% are noted for 10WLPO and 20WLPO compared to LPO at peak BP conditions. It is evident through emulsion fuels' heating value, which is much lower than LPO as the water is replaced for fuel. The micro-explosion and secondary atomization significantly improve the combustion characteristics of 10WLPO emulsion fuel, leading to a marginal variation in BSFC.

In contrast, this effect does not significantly impact high water concentrated emulsion fuel [18]. The collective positive attributes of 20WLPOE, such as oxygenated fuel, micro-explosion, and improved fuel properties, enrich the combustion phenomena and result in low BSFC compared to 20WLPO. The BSFC of 20WLPOE is 9.3% lower than 20WLPO emulsion fuel at high BP conditions. The combined assessment of BTE, BSFC, and BSEC is represented in Fig. 8. The figure shows that the presence of EHN in high water concentrated emulsion fuel pointedly improves the performance behaviour.

## **3.3. Emission assessment**

### **3.3.1. Hydrocarbon emission**

The primary source for HC emission in the engine exhaust is unburnt fuels which are the product of incomplete fuel burning. The HC emission pattern of test fuels under various load conditions is shown in Fig. 9. The HC emission for all the sample fuels is higher at low combustion temperature (low engine load). A decremental trend is noted for high combustion temperature at the high load state. Several studies agreed that the HC formation is higher at low engine torque. At high engine torque, the HC emission formation is reduced as the pressure and temperature within the cylinder is more at the high engine torque that could lead to complete combustion [7, 10]. The LPO combustion shows that the HC emission is significantly reduced compared to ND at all load conditions, and a drop of 38.6% in HC emission is noted for pure LPO. The relevant research works conducted by Vellaiyan and Amirthagadeswaran [12] and Ashok et al. [13, 14] also achieved better HC emission with LPO fuel, and the reasons for improvement are proper mixing of fuel droplets with air, exhaustive air entrainment, and formulation of higher lean zone regions. While considering LPOW emulsion fuels, the HC emission further gets diminished for 10WLPO on a par with ND and LPO. This may be a consequence of secondary atomization that leads to complete combustion [4]. An improvement in HC emission for 10WLPO compared to pure LPO is 18.6% at peak load conditions. Similar to performance characteristics, emission characteristics of 20WLPO are also in a negative trend due to poor ignition qualities of fuel such as low heating value and low cetane number. The cetane improver in high water concentrated emulsion fuel improves fuel qualities and reduces the HC formation in engine exhaust with efficient combustion. 20WLPOE emulsion fuel exhibits a drop of 6.3% in HC emission formation than emulsion fuel without cetane improver at high BP conditions.

### 3.3.2. Carbon monoxide emission

Habitually, the formation of CO emission in IC engines depends on variable factors such as fuel quality, fuel-air composition, engine operational condition, air entrainment, and combustion quality [31, 32]. Fig. 10 enlightens the impact of water and EHN on CO formation under different BP conditions. The emission pattern of CO shows that an increase in BP decreases the CO formation due to better combustion at high engine torque for all sample fuels. At top load state, the CO formation for ND is noted as 3.64 kg/kW-hr, whereas LPO, 10WLPO, 20WLPO and 20WLPOE exhibits 2.27 kg/kW-hr, 1.52 kg/kW-hr, 2.29 kg/kW-hr and 1.91 kg/kW-hr, respectively. From the noted value, it is clear that 10WLPO emulsion fuel promotes a low magnitude of CO emissions followed by 20WLPOE. For ND, the low oxygen content compared to LPO leads to partial combustion, and the available oxygen is not sufficient to convert all the carbon particles in fuel to CO<sub>2</sub> [21]. Numerous researchers proved that oxygenated fuels promote a minimal amount of CO emission compared to ND [7, 8]. A significant drop in CO emission (about 37.6%) is arrived for LPO compared to ND, and 10WLPO further reduces the CO emission by 33.2% compared to plain LPO. Similar to HC emission, CO emission also increased for high water concentrated emulsion fuel due to incomplete combustion results of longer IDP. As stated in section 3.2.2, the combined effect of water and cetane improver in high water concentrated LPO significantly enhances the fuel quality and reduces the IDP, resulting in improved combustion and low CO emission formation.

### 3.3.3. Oxides of Nitrogen emission

The NO<sub>x</sub> formation during the combustion process is mainly due to the in-cylinder combustion temperature, directly proportional to the formation of nitrogen oxide [31]. Excessive oxygen in the fuel and low cetane index are also other possible causes for the high magnitude of NO<sub>x</sub> formation [12]. Numerous researchers supported this statement that the oxygenated fuels originate more amount of NO<sub>x</sub> emission in IC engine combustion [9, 10, 12].

Figure 11 represents the NO<sub>x</sub> emission behaviour of different test fuels under various operating conditions. As discussed above, the oxygenated LPO emits more NO<sub>x</sub> emission than ND, and an increase of 10.2% in NO<sub>x</sub> emission is noted compared to ND at peak BP conditions. To conquer the NO<sub>x</sub>-related issue in oxygenated fuel, water is added with fuel, and the peak combustion flame temperature is reduced in the present work. However, this emulsion technique is most suited to 10% water concentration, whereas the negative impact has arrived for 20% water. 10WLPO promotes a drop of 20.5% in NO<sub>x</sub> emission compared to plain LPO. Though the micro-explosion and secondary atomization of fuel droplets in emulsion fuel combustion enhance the engine performance, this positive effect is overshadowed for high water concentrated LPO emulsion fuel. The inclusion of water in low cetane indexed LPO further reduces the ignition quality of fuels and extends to longer IDP. At the top load state, the magnitude of 20WLPO emulsion fuel's NO<sub>x</sub> emission is 15.2% higher than 10WLPO. Besides, EHN in LPO emulsion fuel promotes the burning activity in the burning chamber during the combustion phase with low IDP. As a result, the fuel accretion during the premixed combustion phase is reduced, and sudden pressure and

temperature rises are avoided [33]. EHN added 20WLPO emulsion fuel reduces the NO<sub>x</sub> formation by 12.8% compared to plain fuel at peak BP conditions.

### **3.3.4. Smoke emission**

Generally, partial combustion of hydrocarbon and carbon particles leads to engine tailpipe smoke emission, and the smoke formation of test fuels during the assessment at various engine operating conditions is shown in Fig. 12. The graph shows that all the LPO-based sample fuels have lower smoke formation than ND. The surplus oxygen and nominal hydrogen-carbon ratio in LPO fuel promote complete combustion [13, 14]. Plenty of other studies also agreed that oxygenated fuels emit a minimal smoke emission due to efficient combustion [13, 16, 34]. An improvement of 15.9% in smoke emission is derived for LPO compared to ND at peak BP conditions. The combustion performance of fuel is directly related to smoke formation. As discussed in section 3.2., limited water quantity in LPO accelerates the combustion process and providing better performance results such as low BSEC and high BTE. Hence, the smoke formation of 10WLPO emulsion fuel is pointedly reduced to 11.9% at high BP compared to LPO.

Interestingly, the smoke formation is reduced for EHN assortment in high water LPO emulsion fuel. Due to improved fuel quality, a stoichiometric air-fuel ratio is derived at the initial stage of premixed combustion itself could decrease the smoke formation. Additionally, initiation of earlier combustion due to the presence of a cetane improver allows more time to oxidize the soot particles and results in low smoke formation [35]. A drop of 13.4% in smoke formation is noted for EHN assorted emulsion fuel at high BP condition compared to plain high water concentrated LPO emulsion fuel. In contrast, the smoke emission formation is increased by 12.7% for 20WLPO compared to 10WLPO emulsion fuel due to poor combustion quality.

## **3.4. Combustion parameters assessment**

### **3.4.1. In-cylinder pressure variation**

The pressure development inside the combustion chamber for test fuels under peak BP conditions is depicted in Fig. 13, along with an enlarged view at TDC. The in-cylinder pressure (ICP) assessment details the route to quantify the excellence of combustion and combustion duration inside the engine cylinder. This measurement also supports estimating whether the engine operation is smoothly or not [12, 20, 32]. The graphical representation noted that at peak load state, the maximum value of ICP is about 63.5 bar, 66.12 bar, 66.52 bar, 67.81 bar, and 65.58 bar for ND, LPO, 10WLPO, 20WLPO, and 20WLPOE, respectively. All the LPO-based fuels have a higher value of ICP compared to ND. As the viscosity and heating value of oxygenated is comparatively lower than that of ND, the vaporization rate of fuel and air-fuel mixing is significantly enhanced, resulting in better combustion [36].

Meanwhile, the poor ignition quality due to the lower cetane index of LPO leads to longer IDP, and more amount of combustible air-fuel mixtures are accumulated during the premixed combustion stage. The

explosion of this mixture creates a higher peak ICP, and similar observations are recorded by many researchers while using the low viscous fuels [13, 29]. While considering WLPO fuels, the peak in-cylinder pressure further marginally increased for 10WLPO, and a massive variation is noted for 20WLPO emulsion fuel. Though the heating value of 10WLPO emulsion is lower than LPO, the ICP is fairly increased as additional pressure is acting on the piston surface due to the micro-explosion.

The figure also represents that the combustion initiation of 10WLPO emulsion fuel is delayed compared to plain LPO due to the latent heat absorption of water particles. This effect is overshadowed by fine air-fuel mixing. Meanwhile, the high water concentrated LPO exhibits a high amount of pressure, and the peak value of ICP is far away from the engine TDC. Several studies agree that the high-water concentrated emulsion fuels promote high ICP, and the occurrence of peak value is away from TDC [12, 19]. The ICP is significantly reduced for EHN+LPO+water emulsion fuel, as the EHN presence improves the fuel quality and reduces the IDP. Apart from that, the incidence of peak ICP value moves towards TDC that will run the engine smoothly.

### **3.4.2. Net heat release rate**

The net heat release rate (NHR) of test fuels such as ND, LPO, 10WLPO, 20WLPO, and 20WLPOE at peak BP condition concerning crank angle (CA) is depicted in Fig. 14. The NHR value is calculated based on ICP, CA, specific heat ratio, and instantaneous cylinder volume as stated in Krieger and Borman's single-zone combustion model [37]. The maximum value of heat energy released during the combustion process for LPO is higher than ND due to longer IDP. Several reports pointed out that the low cetane indexed fuels promote poor combustion and exhibit the high value of NHR [13, 14]. Similar to ICP variation, the NHR variation also marginally increased for 10WLPO, and much variation is noted for 20WLPO emulsion fuel. The combined effect of water and EHN presence in high water concentrated emulsion fuel significantly improves the ignition properties and reduces the IDP that results in earlier-and-efficient combustion.

## **4. Economic Analysis**

The economic and cost-benefit analysis has been carried out based on the fuel consumption (kg/hr) for different fuels at different operating conditions to produce the unit power output. For assessment purposes, the cost of ND and LPO are assumed as 1USD/litre, whereas the actual cost is considered for EHN (2USD/litre). The cost analysis of test fuels is represented in Fig. 15. The cost analysis of LPO compared to ND represents that the LPO fuelled diesel engine running cost is significantly reduced (about 4.5%) at peak BP conditions. Interestingly, 10WLPO emulsion fuel running cost is further reduced by 4.9% than plain LPO due to efficient combustion. Like other assessment parameters, the running cost is also on the negative side for 20WLPO emulsion fuel. The running cost of the engine fuelled by 20WLPO is 12.8% higher than 10WLPO, and the possible reasons are well defined in section 3.2. Though the EHN cost is double the times of normal fuel, a small quantity in the base fuel significantly improves the performance behaviour and results in a low running cost compared to 20WLPO emulsion fuel. The

running cost of EHN blended emulsion fuel is 5.1% lesser than high water concentrated emulsion fuel, whereas this value is marginally high compared to 10WLPO emulsion fuel.

## 5. Conclusion

The present study details the energy, environmental and economic assessments of modified LPO blends, including different water and EHN volume percentages. The assessments are carried out in an unmodified single-cylinder diesel engine with different operating conditions and contrasted with pure LPO and ND. The followings are the conclusions for this assessment:

- The key physicochemical properties of LPO, such as viscosity, heating value, cetane index, and flash point, are lower than ND, whereas the density is significantly higher. The water emulsification in LPO marginally reduces the cetane index and heating value and increases the density, flash point and viscosity. Interestingly, the EHN presence in emulsion fuel encouragingly improves the physicochemical properties.
- The BTE of LPO is 8.3% higher than ND, whereas 10WLPO further increases the BTE by 5% compared to LPO due to efficient combustion. The poor ignition quality of 20WLPO emulsion fuel reduces the BTE by 7.6% compared to 10WLPO emulsion fuel. The combined effect of water and EHN significantly improves the combustion quality and increases the BTE by 9.7% compared to high water concentrated emulsion fuel. Similar improvements are recorded with BSEC for all the test fuels.
- The BSFC of LPO is 4.5% lower than ND. The water emulsification in LPO increases the BSFC, as an equal amount of water is replaced for LPO in the emulsion fuel. The addition of EHN in emulsion fuel significantly improves the BSFC as the cetane improver enhances the ignition characteristics. A drop of 9.3% in BSFC is noted for 20WLPOE compared to 20WLPO emulsion fuel.
- The oxygenated LPO reduces the HC and CO formation by 38.6% and 37.6%, respectively, compared to ND. These emissions are further reduced by 18.6% and 33.2% for 10WLPO emulsion fuel compared to plain LPO. Though the negative impact has arrived for 20WLPO, the combined effect of water and EHN enhances the combustion quality and reduces the HC and CO formation by 6.3% and 17% compared to 20WLPO, respectively.
- The NO<sub>x</sub> formation of low viscous LPO is 10.2% higher than ND, and 10% water in LPO reduces the NO<sub>x</sub> by 20.5% due to low combustion flame temperature. The longer IDP of 20WLPO emulsion fuel increases the NO<sub>x</sub> by 15.2%, whereas cetane improver reduces the IDP and results in a 12.8% drop in NO<sub>x</sub> formation. A similar trend is recorded for smoke emissions for all the test fuels.
- The peak value of ICP for low viscous LPO is higher than ND due to longer IDP. This value is further marginally increased for 10WLPO, whereas a significant increment is noted for 20WLPO emulsion fuel due to poor ignition quality. The cetane improver meaningfully reduces the IDP and initiates the combustion process well in advance. The peak value of ICP for 20WLPOE is lower than 20WLPO emulsion fuel, and the above similar trend is noted in NHR for all the test fuels.
- The economic analysis of test fuels indicates that the running cost of an LPO fueled diesel engine is 4.5% lower than ND, and the cost is further reduced to 9.2% while the LPO is blended with 10% water.

For high water concentrated emulsion fuel, the engine running cost is 12.8% higher than 10WLPO emulsion fuel, and 2% EHN in emulsion fuel reduces the engine running cost by 5.1%.

Overall, it is concluded that the 10% water in LPO is an affordable technique to execute a better performance in an existing diesel engine with low emissions. The presence of EHN in emulsion fuel can further efficiently improve the usability of water.

## **Declarations**

### **Availability of data and materials**

Not applicable

### **Competing interests**

The author declare that he does not have any competing financial interests

### **Funding**

Not applicable

### **Authors' contributions**

Single Author

### **Acknowledgement**

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## Figures

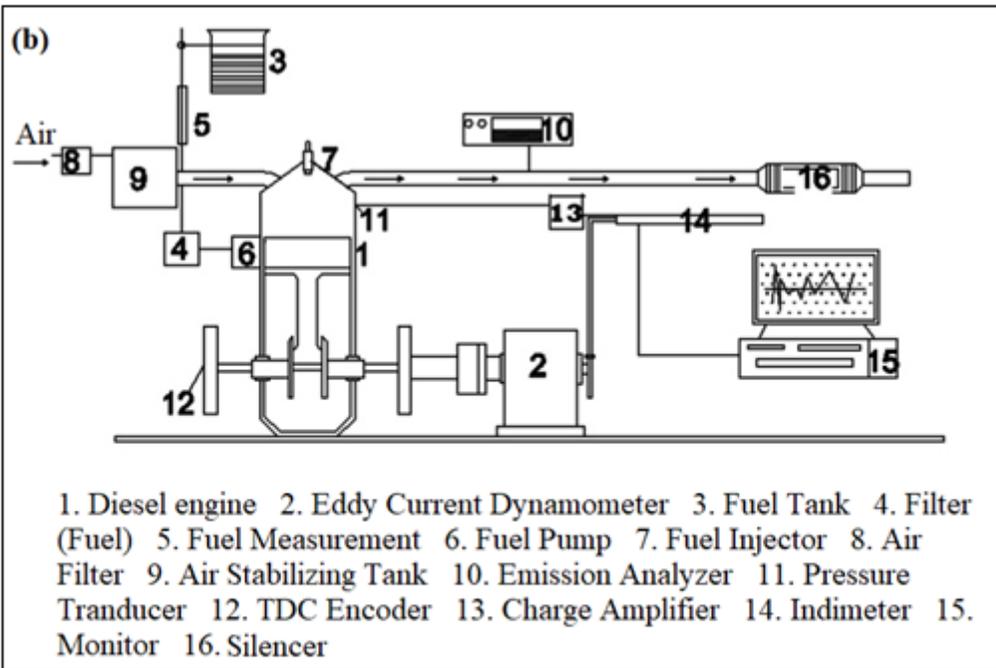


Figure 1

Engine Test Setup: (a) photographic view, (b) Schematic Layout

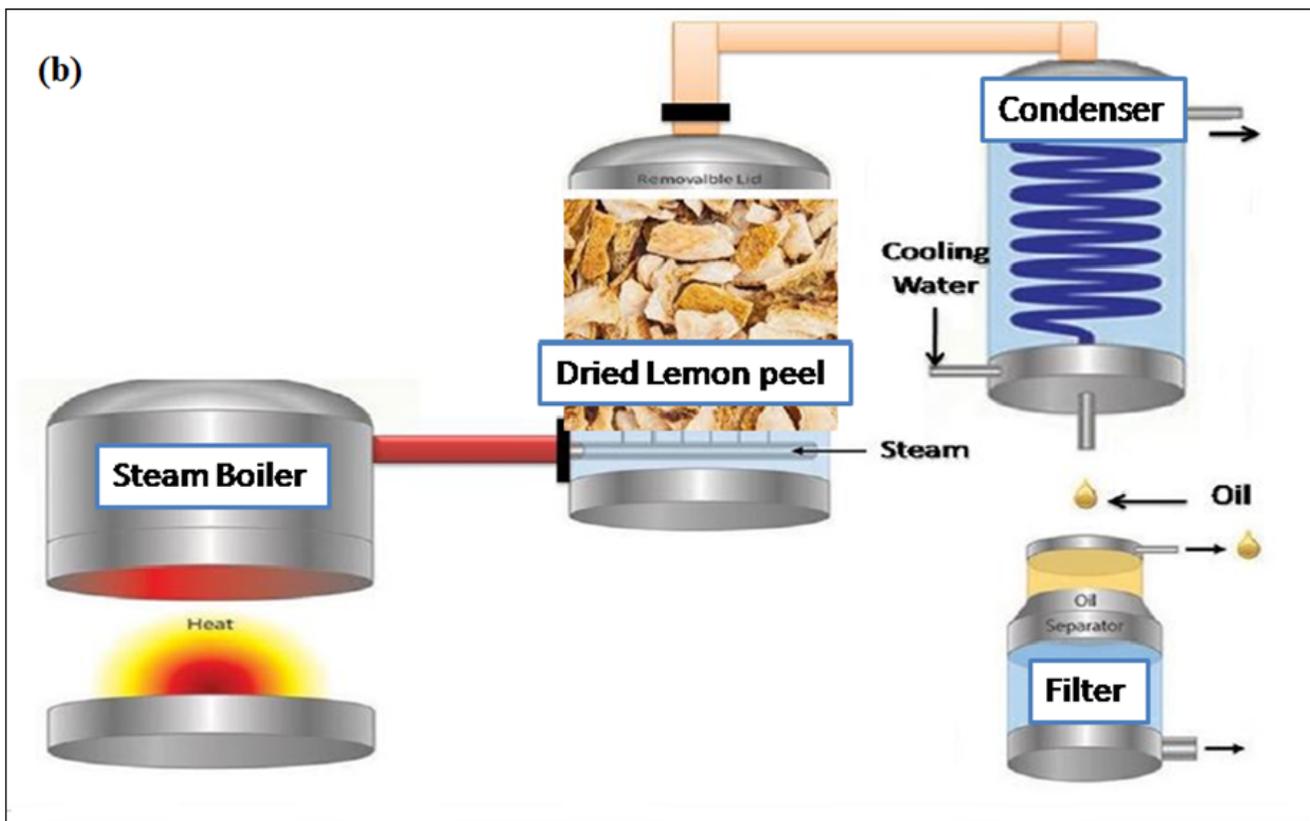


Figure 2

Thermal Distillation Process to extract LPO; (a) photographic view, (b) schematic layout

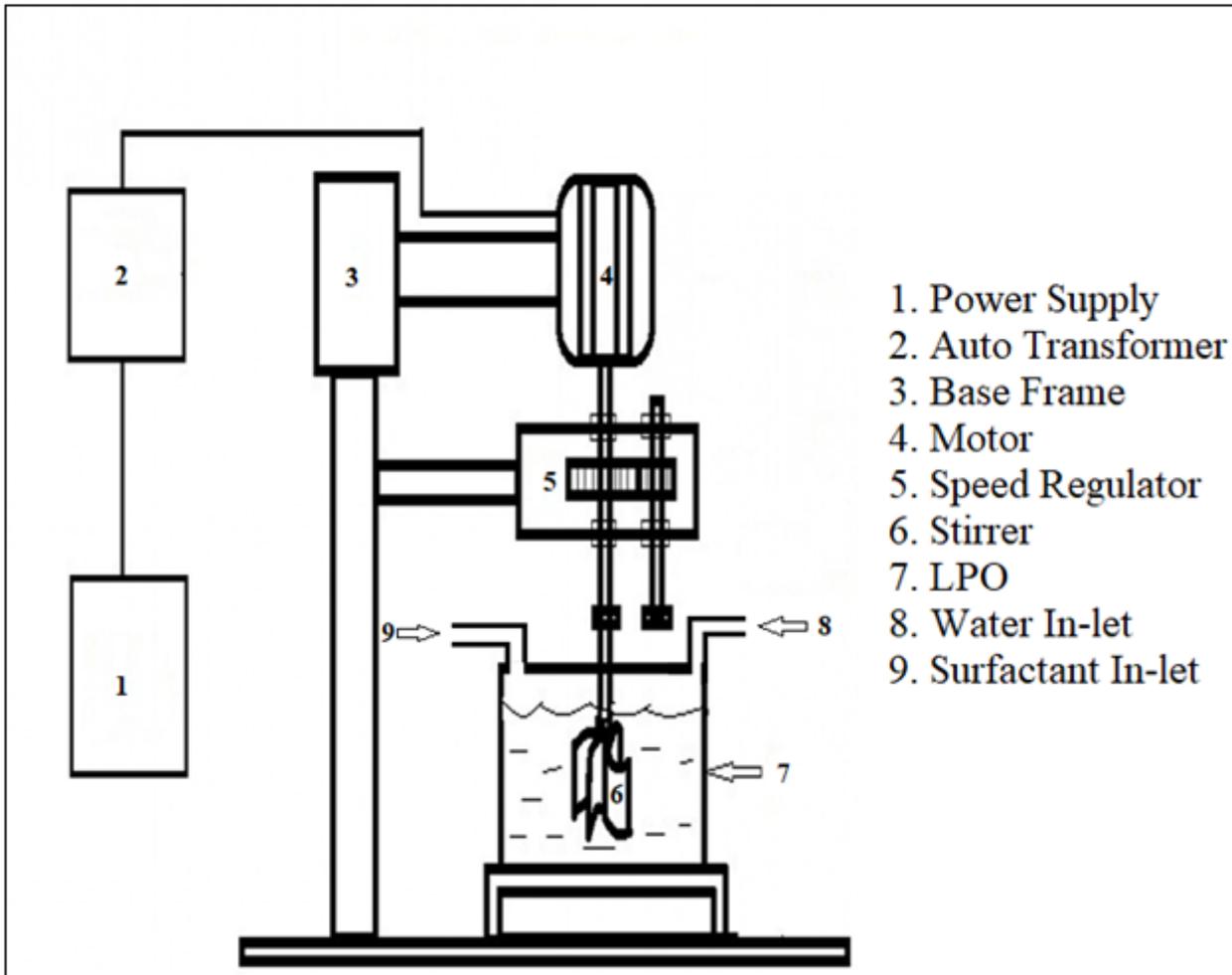
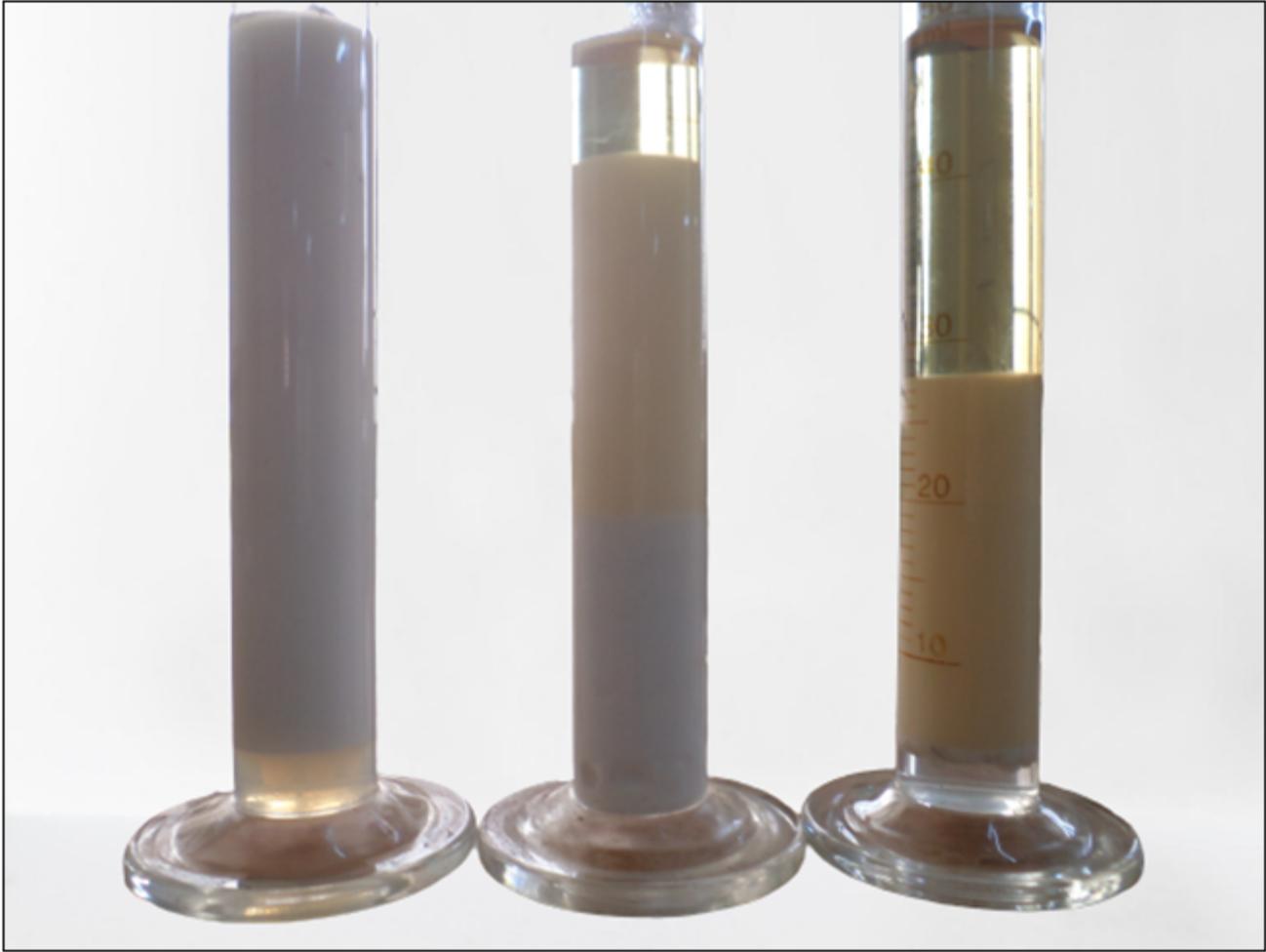


Figure 3

Schematic Layout of Emulsion Fuel Preparation



**Figure 4**

Photographic View of Emulsion Fuels

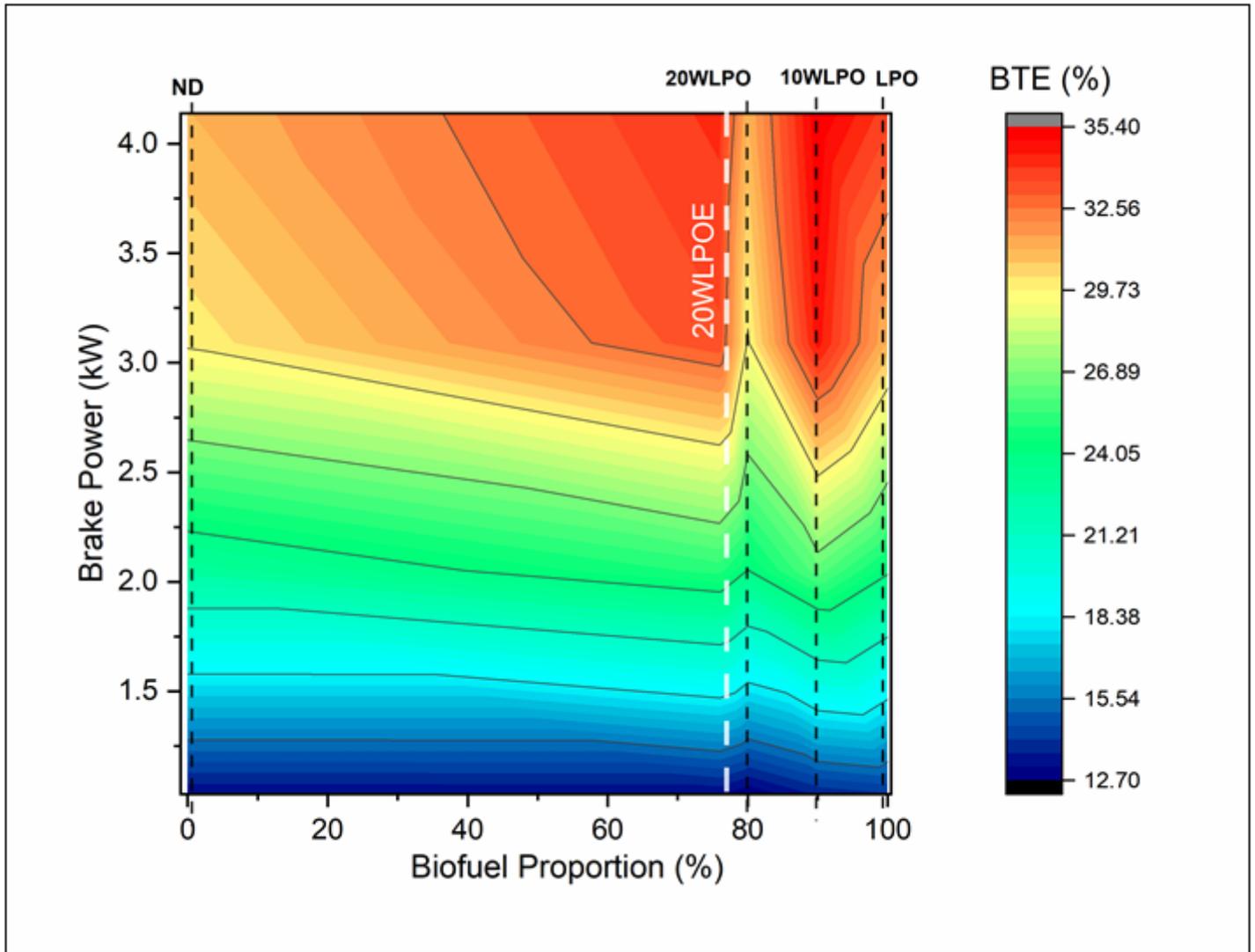


Figure 5

BTE of test fuels under different BP conditions

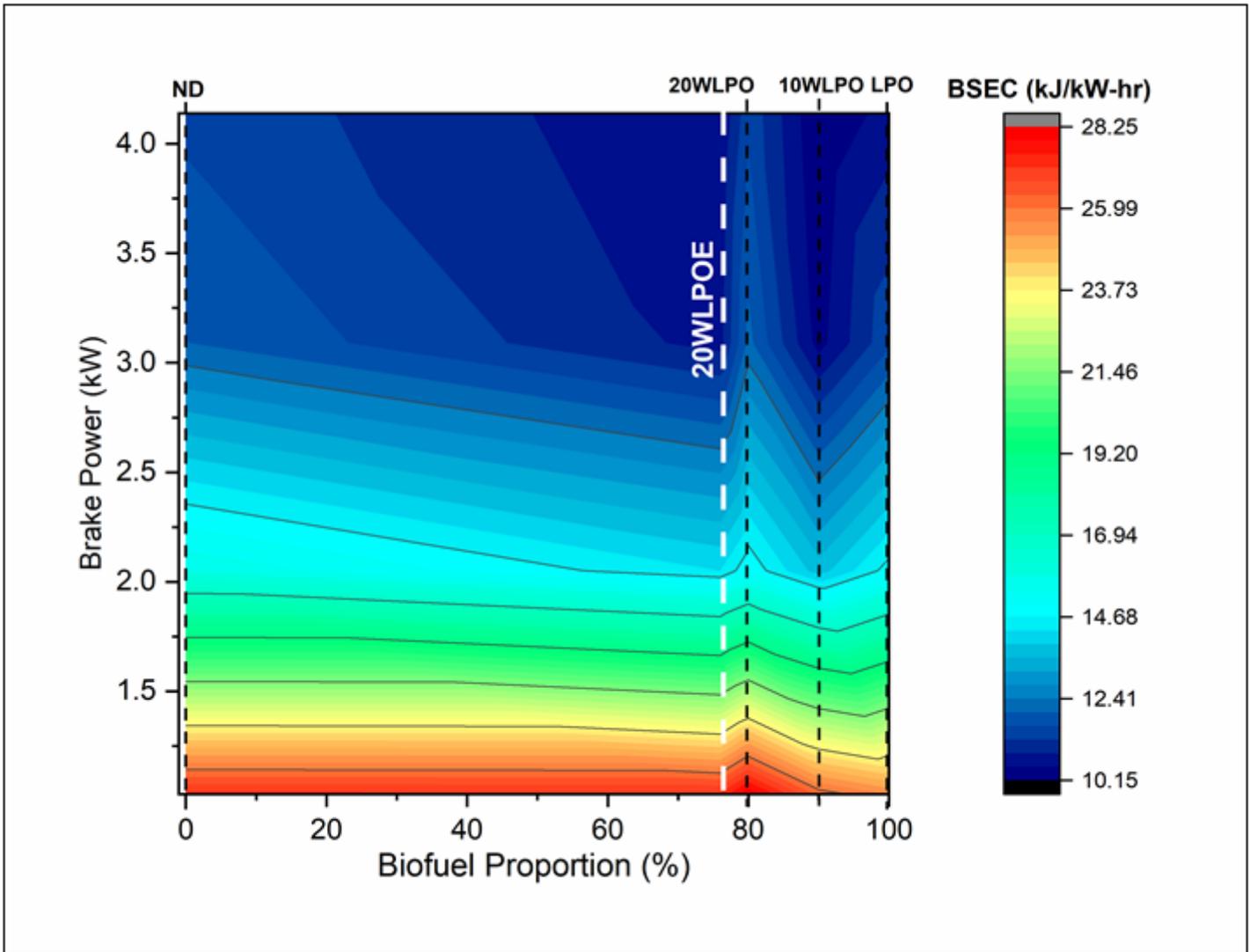


Figure 6

BSEC of test fuels under different BP conditions

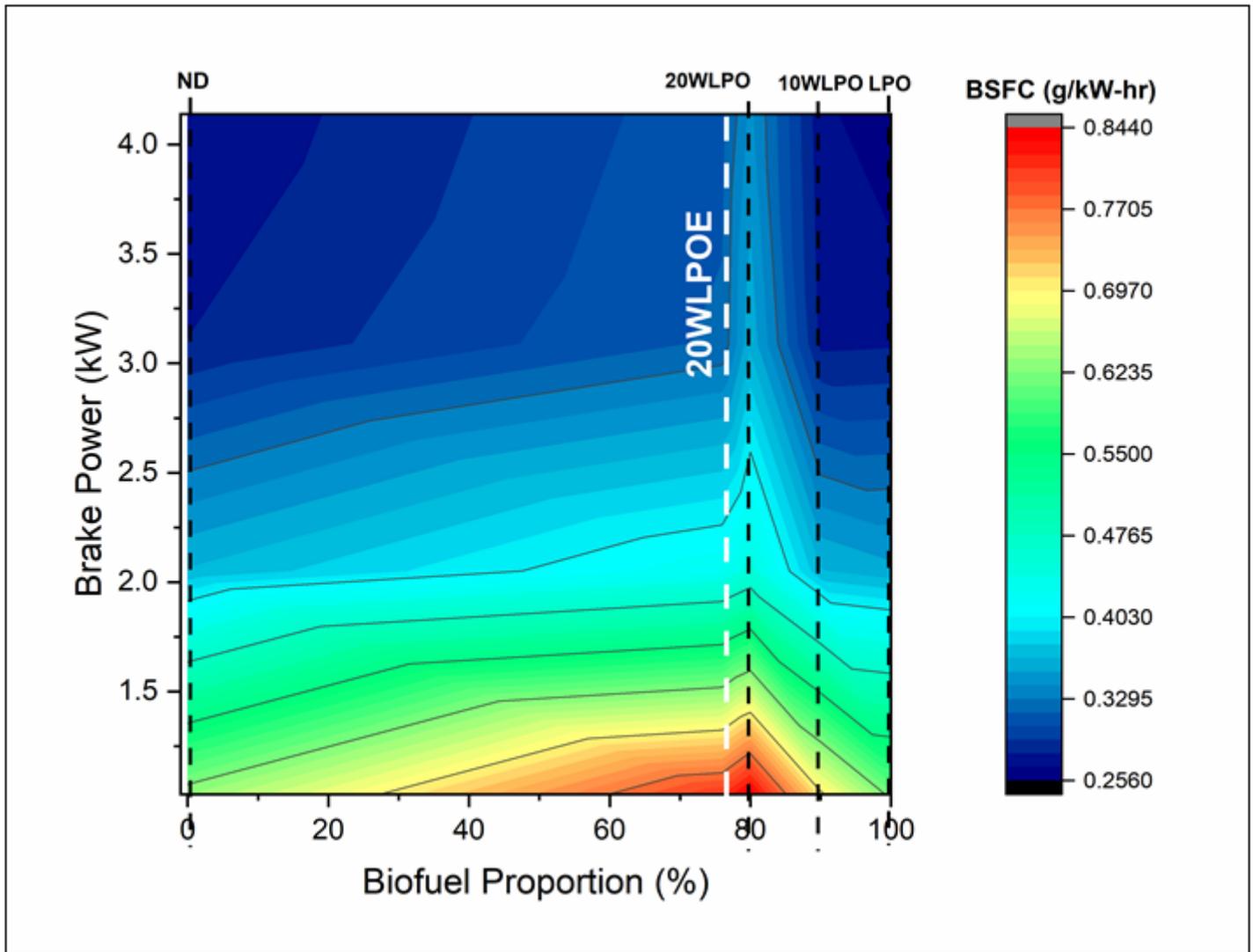
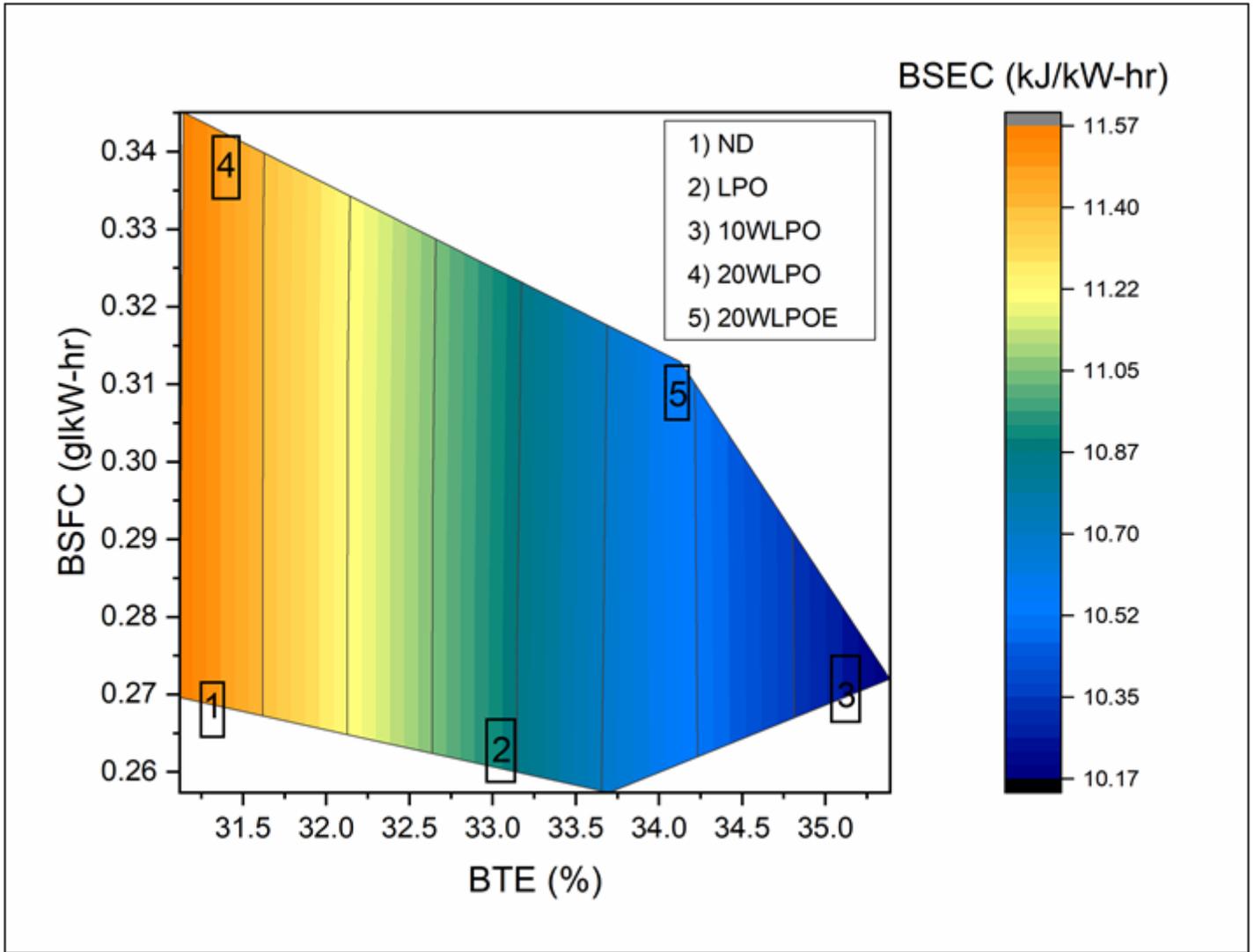


Figure 7

BSFC of test fuels under different BP conditions



**Figure 8**

Overall performance assessment of test fuels

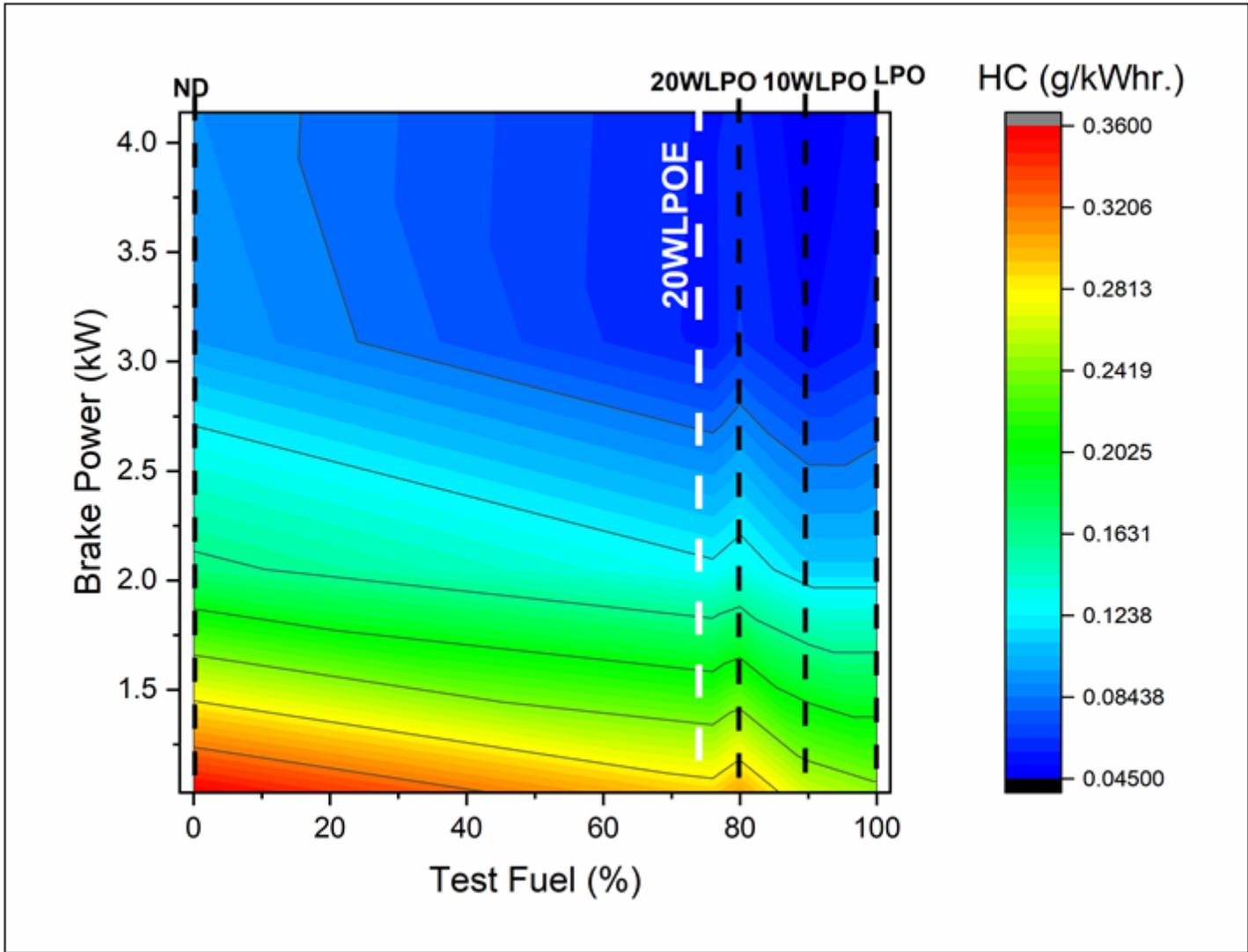


Figure 9

HC emission of test fuels under different BP conditions

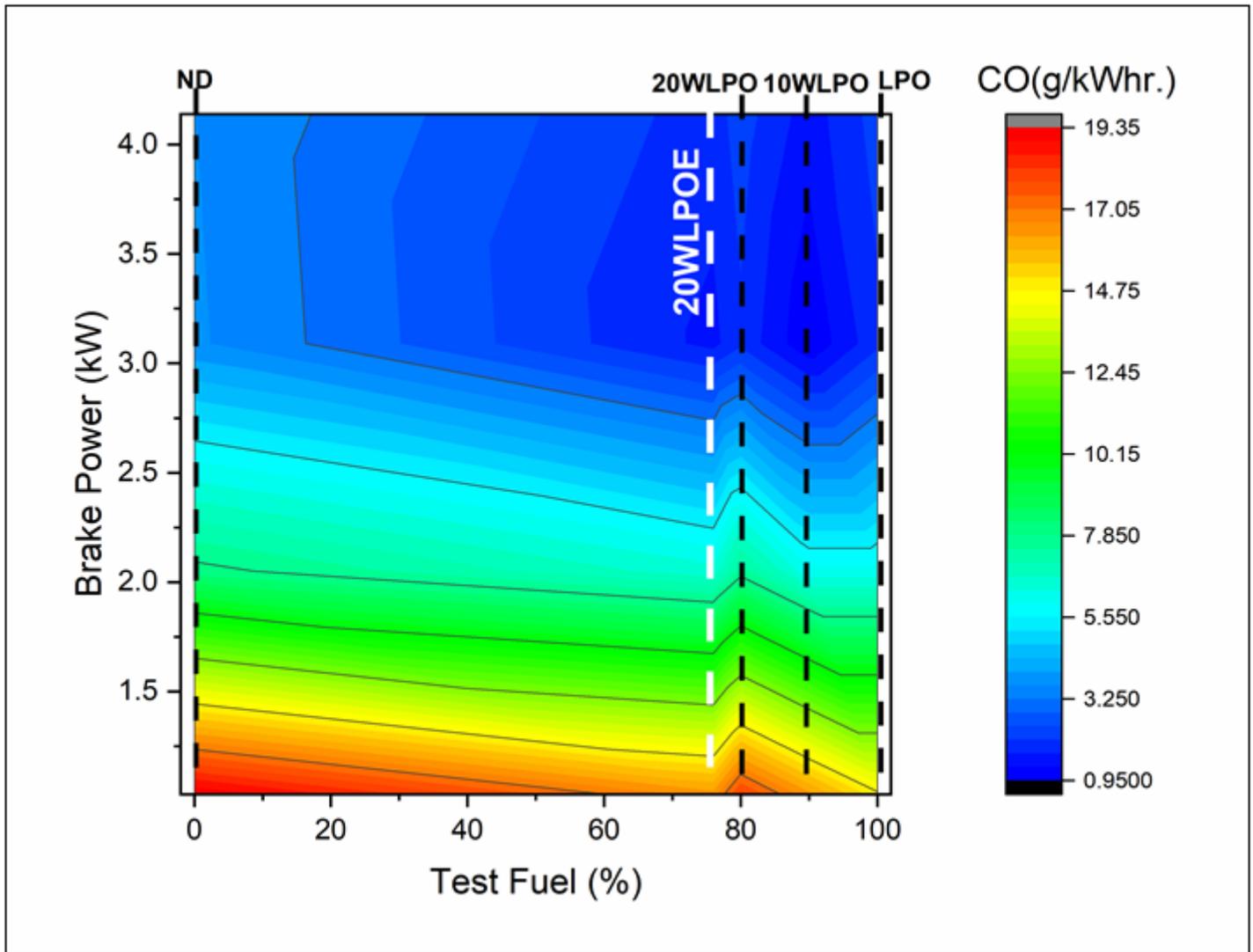


Figure 10

CO emission of test fuels under different BP conditions

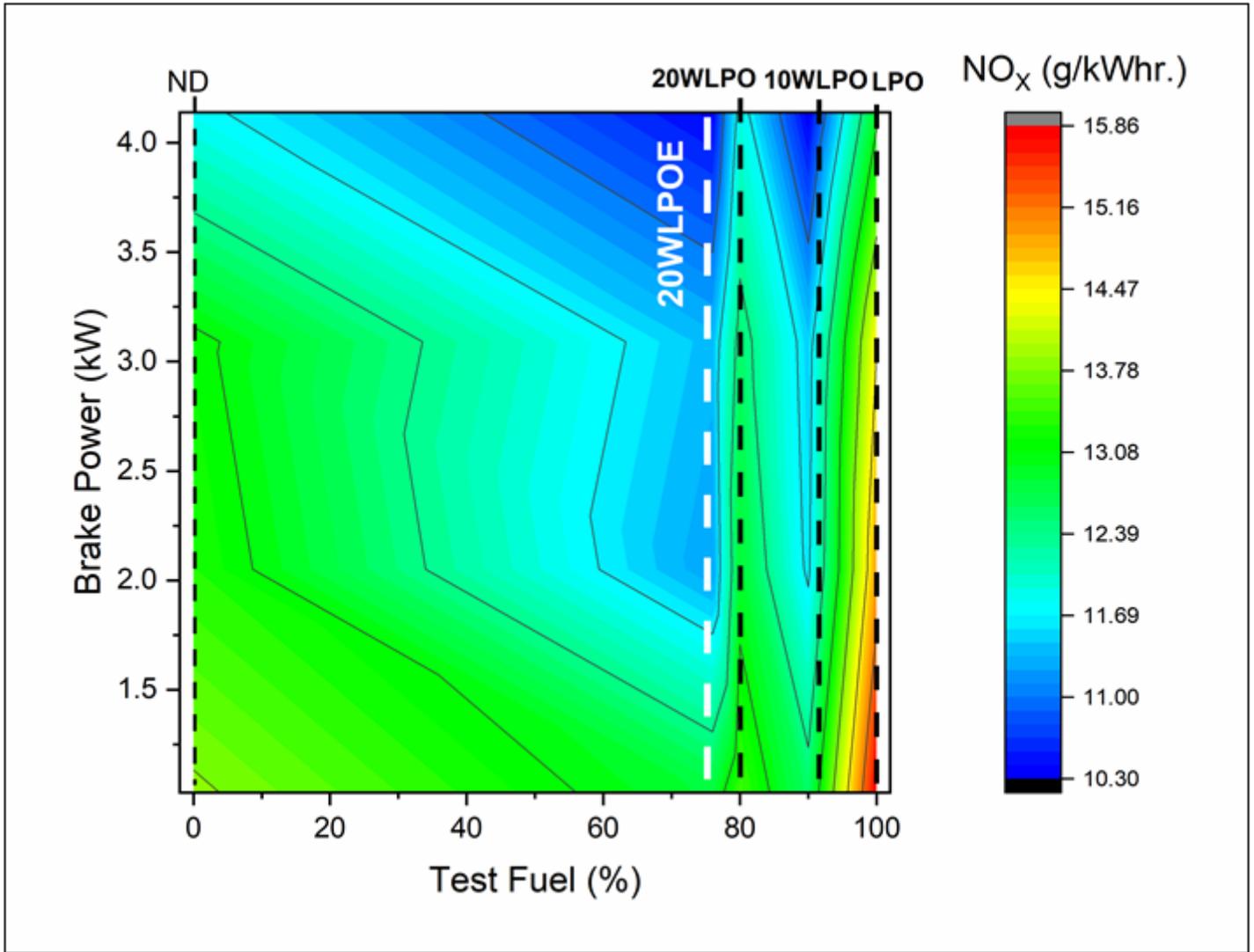


Figure 11

NO<sub>x</sub> emission of test fuels under different BP conditions

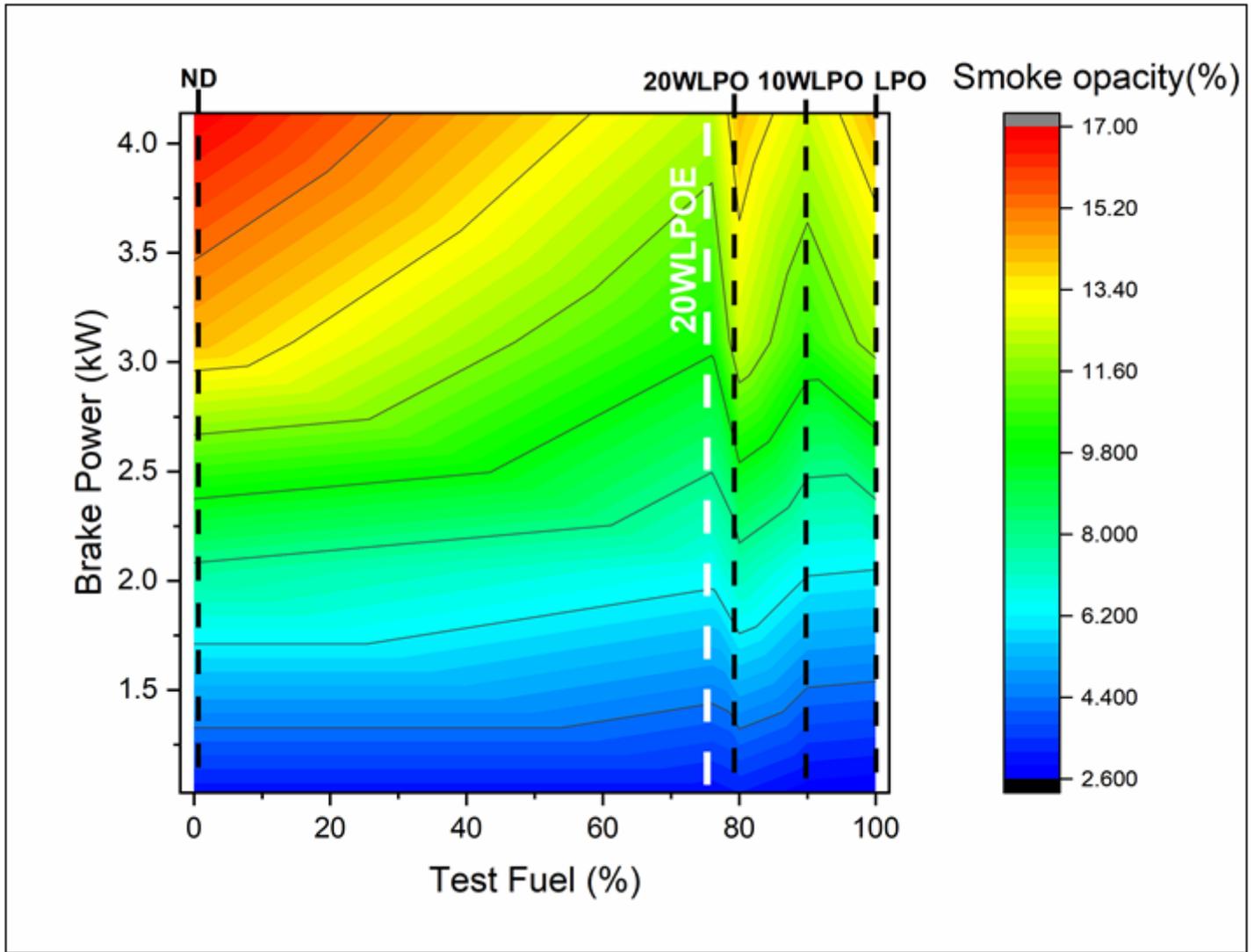


Figure 12

Smoke opacity of test fuels under different BP conditions

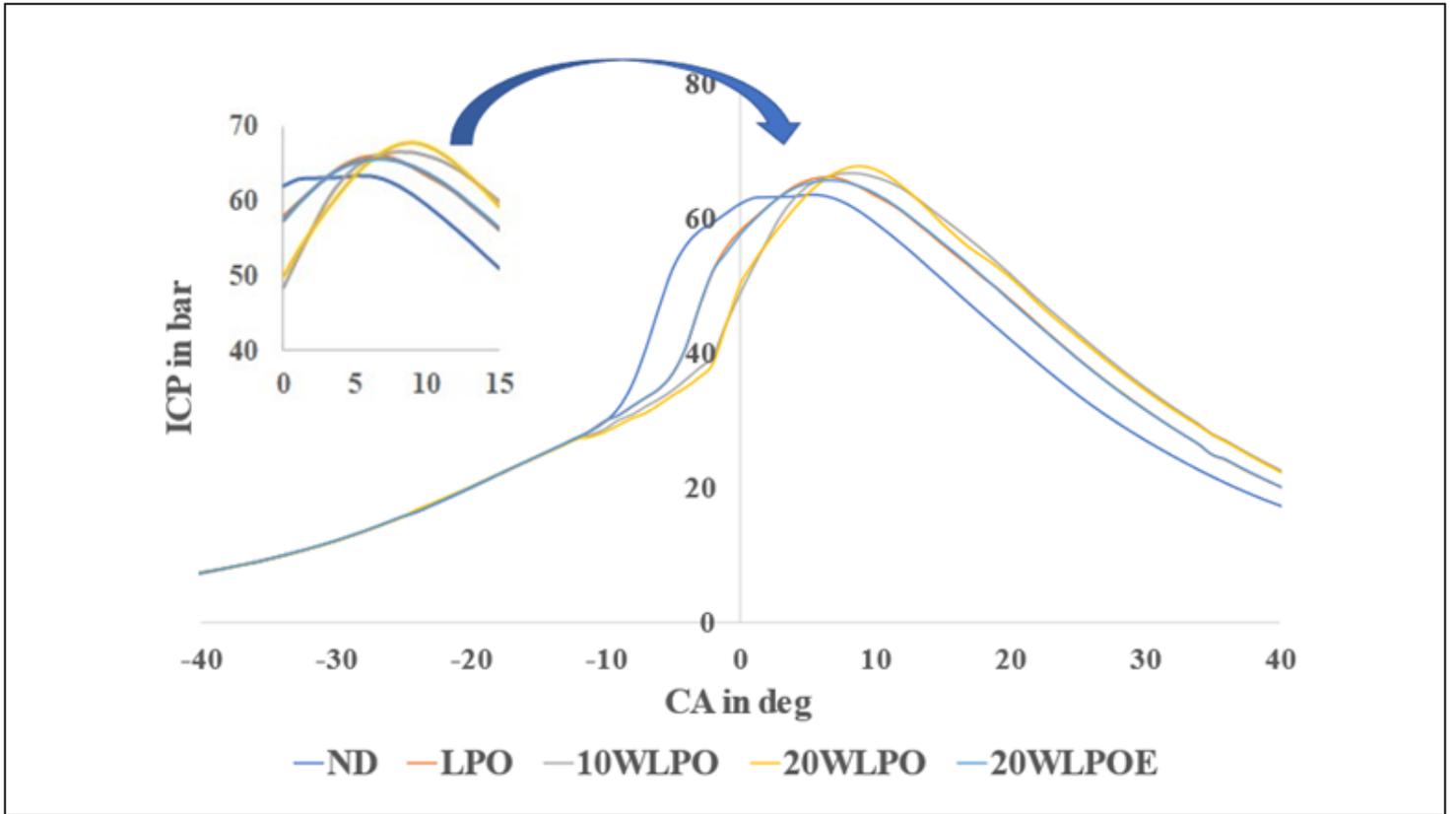


Figure 13

ICP assesment of test fuels at peak BP condition

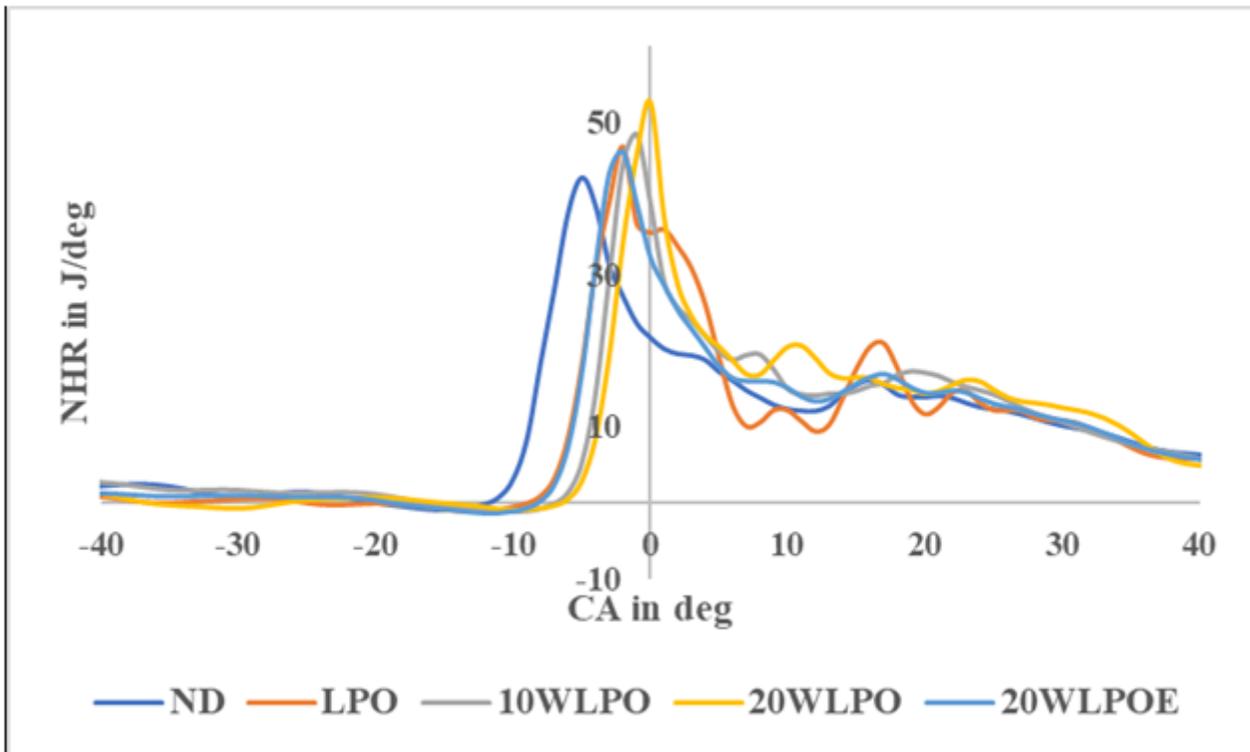


Figure 14

NHR assesment of test fuels at peak BP condition

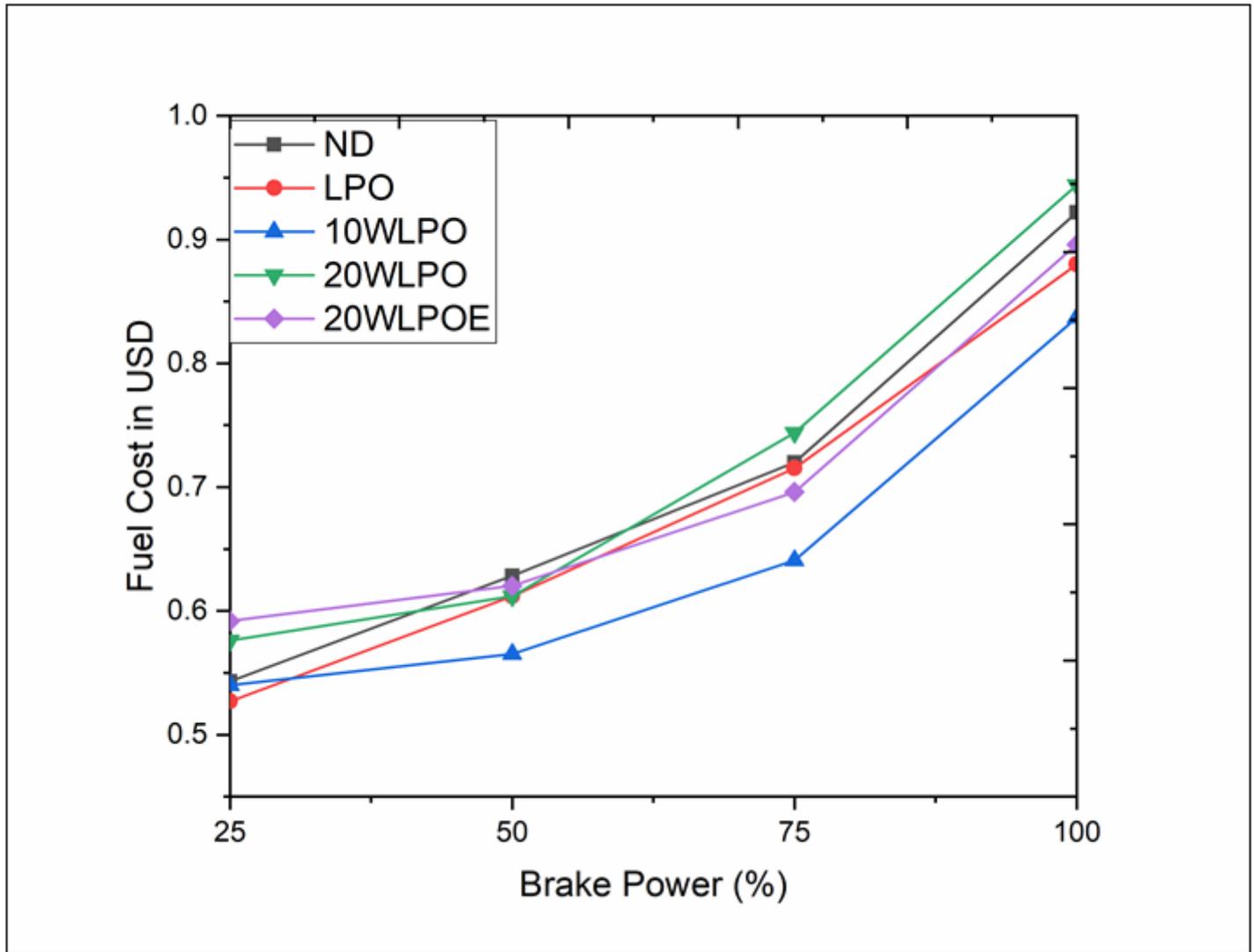


Figure 15

Cost-benefit analysis of test fuels under different BP conditions