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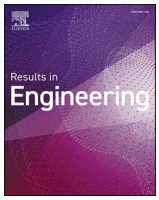

Sailing towards sustainability: Waste ship oil sludge as diesel alternative

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ABSTRACT

Waste ship-oil sludge (WSOS), a hazardous by-product of marine operations, was converted into sustainable liquid fuel through pyrolysis to reduce carbon footprint and support clean-energy transition in the maritime sector. The waste ship oil sludge has been converted into a sustainable liquid fuel at 550 °C and 600 °C (named as F1 & F2 respectively to indicate fuel 1 and fuel 2) with properties equivalent to that of diesel. The fuel derived from the pyrolysis of the waste ship oil sludge has been blended with 10 %, 20 %, 30 %, 50 %,& 100 % of diesel B10, B20, B30, B50 & B100 respectively. The F1 B100 blends reported 66.73 bar has the highest in-cylinder pressure and a maximum heat release of 34.05 J °CA^{-1}. The brake thermal efficiency decreased by 15 % for F1 B100 fuels in comparison with the diesel. A 20 % increase in fuel consumption was reported for F1 B100 sample. The F1 B100 fuel reported a reduced emission in comparison to commercial diesel fuel. The results indicated that the pyrolyzed WSOS has a greater potential to be used as a blend to diesel fuel to power an unmodified diesel engine as it exhibits comparable performance to that of diesel with lesser carbon footprint. The WSOS has been regarded as a hazardous material by the USEPA. Non availability of standards pertaining to ship oil sludge disposal results in unethical dumping the ship oil sludge in the oceans affecting the marine life. Previous studies on WSOS reports velarization through pyrolysis . the utilization of WSOS derived fuel has not been reported. This work is the first of its kind to descriptively cover the production of fuel-equivalent pyro-oil from WSOS and usage of the fuel derived in a diesel engine.

1. Introduction

Global freight transfer which includes ores, fossils and chemicals are handled through maritime transport [1,2]. As a safety precaution a merchant navy accompanies the freight ship thereby increasing the sea traffic. These carriers are fuelled by heavy fuel oil (HFO) obtained as the residual oil waste from petroleum refining industries [3]. HFOs are rich in carbon(85 %), hydrogen (11 %) and sulphur (4 %) [4,5]. Prior to ship fuelling, HFO is upgraded by mixing high-grade fuel like cutter stock [6]. Subsequently, the mixture is centrifuged and bottom oil- sludge is discarded. Apart from the bottom oil-sludge, the oil from machinery inside the ship also collected as oil sludge at the bilge. Owing to the strict regulations the oil sludge and waste oil from the carbo tanks cannot be discarded on shore. Presently, the oil sludge and waste oil from carbo tanks are collected together and termed as waste ship-oil sludge(WSOS) and discarded offshore [7]. The reports indicate that shipping agencies pay large amount to discard them offshore using permitted incinerators [3]. In spite of these strict rules, there is a high possibility of WSOS ending up in the sea due to improper handling, accidents and unlawful discharge [8,9].WSOS has tendency to form a coat over the flora and fauna found in the ocean thereby leading to the extinction this species [10].

Generally, organic wastes are treated using thermal or biochemical methods to produce value added products [11]. Global oily-sludge generation exceeds 60 million tonnes yr^{-1}, with maritime sources contributing approximately 0.2–0.4 million tonnes yr^{-1} [6,11]. Improper disposal of this waste continues to pose severe ecological threats. Similarly, easily biodegradable solid fraction is converted into biogas, bio hydrogen through dark fermentation and anaerobic digestion process [12].The drawback with biochemical pathways is that they are

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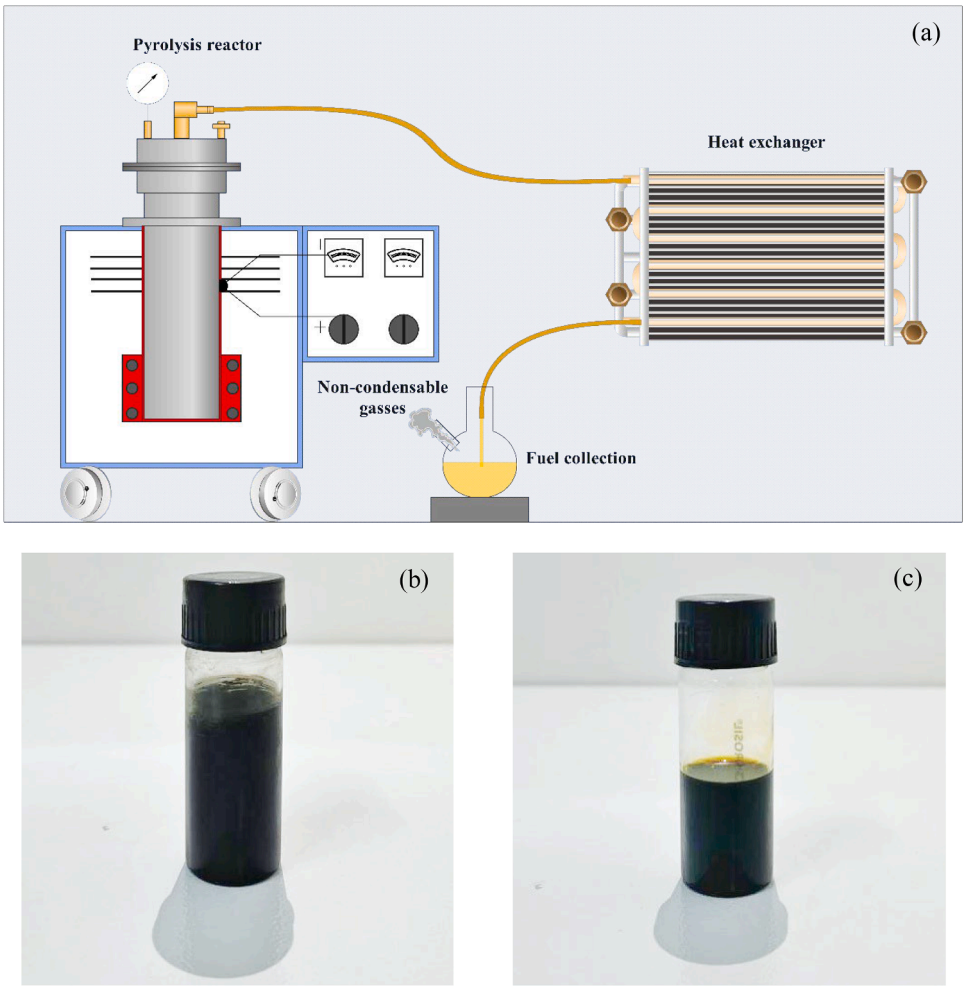

Fig. 1. (a) Layout of pyrolysis reactor (b) Raw WSOS and (c) Pyrolyzed WSOS.

Table 1
Observed properties of F1 and F2 fuels (adopted from [7]).

Observed fuel property	Units	F1	F2	ASTM standard for Grade 1 diesel
Calorific value	$MJ.L^{-1}$	37.330	38.456	37.71
Flash point	°C	52	110	>38
Kinematic viscosity @ 40 °C	$mm^2.s^{-1}$	9.11	12.63	1.3–2.4
Density @ 15 °C	$g.mL^{-1}$	0.861	0.877	0.840–0.875
Acid value	$mgKOH.g^{-1}$	0.37	0.32	0.8
Sulphur content	%	0.41	0.65	<0.5
Carbon residue	%	0.09	0.33	0.15–0.35
Copper strip corrosion @ 100 °C for 3 h	–	No.1	No.1	No.3
Cetane Index	–	51.03	47.43	40
Distillation 90 % recovery temperature	°C	310	260	282–338
Final Boiling point	°C	328	326	>350

inefficient to handle oil sludge. Conventional process such as solvent extraction centrifugation can be employed to handle oil sludge, but this process requires high capital cost or produce secondary sludge. Thermal and thermochemical methods can be employed to convert complex organic, oil sludges into wide range of product namely pyro-oil, biochar and pyro -gas. Recent studies have increasingly focused on leveraging machine learning and advanced statistical methods to enhance the accuracy of ship fuel consumption prediction and energy-related forecasting. For instance, Huber regression and Light Gradient Boosting Machines (LGBM) have been employed to model ship fuel usage, with Huber regression demonstrating superior accuracy and lower prediction error compared to LGBM and linear regression models [13]. Similarly, machine learning and time-series forecasting approaches have been applied to estimate energy consumption and carbon dioxide emissions in Vietnam, where ensemble methods such as Random Forest, XGBoost, and AdaBoost outperformed linear regression, and autoregressive models projected future trends in energy use and emissions [14]. In parallel, artificial neural networks (ANNs) have been highlighted as powerful tools for capturing complex, non-linear interactions affecting ship fuel consumption, offering significant improvements over traditional regression-based methods [15]. Together, these works underscore the growing role of artificial intelligence and machine learning in maritime energy optimization and emission reduction, providing a strong foundation for the present investigation.

The global energy demand surges by 2 % annually thereby increasing the fossil fuel demand [16]. Recently there was shift in the research towards energy generation using alternative fuels which have lesser carbon footprint. Usage of alternative fuel for energy generation helps the global fraternity reduce the emission and meet the sustainable developed goals (SDGS). However, WSOS is different from all other waste owing to their hazardous nature. The progressive technology like pyrolysis can be used for treating the WSOS. Pyrolysis has the potential to convert WSOS into diesel equivalent fuel. Diesel engines are significant in transportation sector and stationary power generation. The versatility of diesel engine allows use renewable fuel either in blend with

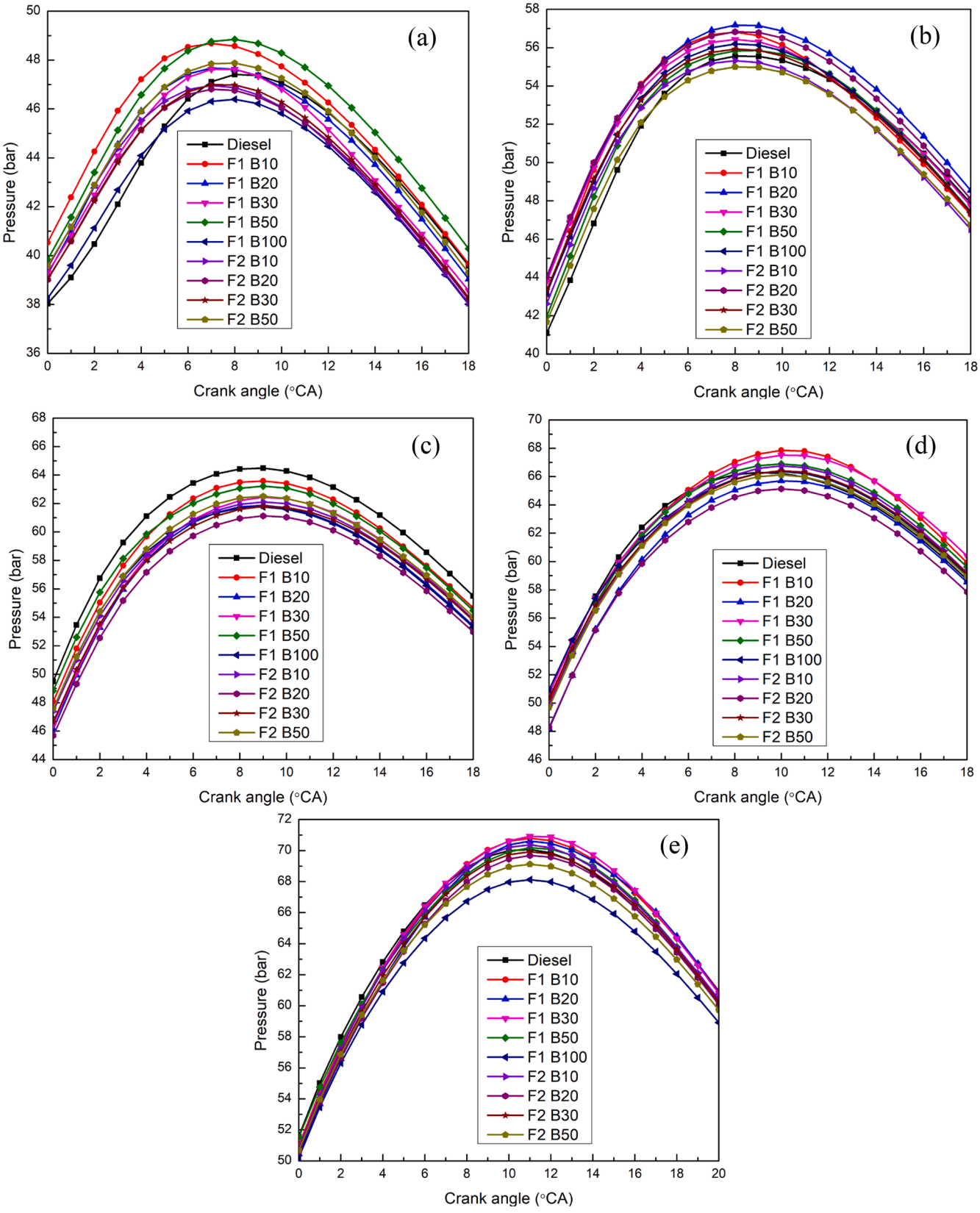

Fig. 2. Peak pressures reported at (a) no load; (b) 25 % load; (c) 50 % load; (d) 75 % load; and (e) full load.

Table 2
Peak combustion pressure at 8 degrees crank angle.

Samples	Maximum combustion pressure (bar)				
	No engine load	25 % engine load	50 % engine load	75 % engine load	Full engine load
Diesel fuel	47.41	55.56	64.42	66.13	68.92
F1 B10	48.57	56.81	63.49	67.04	69.13
F2 B10	46.87	55.32	61.95	66.11	68.84
F1 B20	47.62	57.17	61.77	65.05	68.71
F2 B20	46.76	56.83	60.95	64.55	67.98
F1 B30	47.62	56.43	62.21	66.72	69.09
F2 B30	46.98	55.93	61.60	65.79	68.35
F1 B50	48.84	55.83	63.08	66.38	68.48
F2 B50	47.87	54.99	62.39	65.60	67.66
F1 B100	46.39	56.19	61.68	65.82	66.73

diesel or as complete replacement to the diesel for reducing the emission and carbon footprint [17]. In line with this the present research aims to study the application of pyrolyzed WSOS in a single-cylinder unmodified diesel engine. A detailed literature review as conducted according to the authors knowledge; this work is the first of its kind to report usage of oil derived from WSOS in engine. In alignment with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water), the present study contributes to sustainable energy transition by transforming hazardous waste ship-oil sludge into a diesel-equivalent fuel. This approach not only addresses the pressing challenge of safe WSOS management but also reduces dependence on fossil-derived fuels, thereby lowering life-cycle greenhouse gas emissions. By demonstrating that pyrolyzed WSOS can partially or fully substitute conventional diesel in compression ignition engines without modification, this work advances pathways toward net-zero emission targets. The valorisation of WSOS into usable fuel not only prevents its unlawful disposal into marine ecosystems but also supports global decarbonization efforts by creating a circular economy solution for the shipping sector. Thus, this research establishes a direct nexus between waste mitigation, sustainable fuel innovation, and the broader international agenda of achieving carbon neutrality. The novelty lies in demonstrating the practical feasibility of upcycling WSOS into a usable fuel, thereby advancing sustainable energy and waste management practices.

2. Materials and methods

Waste ship-oil sludge was procured and stored under normal temperature and pressure conditions. The feedstock was characterized before being subjected to pyrolysis. The composition of the produced fuel was analysed before testing it in the engine.

2.1. Collection and characterization of waste ship-oil sludge

Residues of the HFO, sludge remains from oil tanks, bilge oil & water residues were procured from the port of Tuticorin (8.7563° N, 78.1791° E), India. These were mixed homogeneously and stored in dark containers and were labelled completely mixed WSOS. The physicochemical characterisation of the completely mixed WSOS was carried out according to ASTM standards and the fuel properties were analysed according to Indian Standard for testing petroleum and products. Detailed characterization techniques are mentioned in an earlier study [7]. WSOS-derived fuels were stored in sealed metal containers, handled using gloves, goggles, and respirators. Spill-containment trays and grounding were provided to mitigate static discharge. The inherent toxicity and flammability of pyro-oils warrant strict adherence to hazardous-material guidelines during storage and transport.

2.2. Pyrolysis reactor for pyrolysis of WSOS

The Pyrolysis WSOS was performed in 8.5-liter batch reactor fabricated using SS304 (Fig. 1). The reactor is heated using an insulated furnace which contains six electrical heating coils. The furnace has provision for providing temperature up to 1000 °C and different heating rates. The lid of reactor hosts pressure gauge and pressure release valve . The high-pressure cascade with metal reinforcement in between the re and lid ensure safety by avoiding leakages. The brass joint on top of the lid acts as the outlet pyro-gas which them pass through high temperature hose which connected to the heat exchanger. A control panel with specifically designed printed circuit board (PCB) was used to monitor the temperature, heating rate and holding time of pyrolysis process. Further description of the reactor can be found in an earlier study [7]. Comprehensive TGA, GC–MS, and CHNS results are reported in our earlier work [7], confirming high hydrocarbon content (C ≈ 84 %, H ≈ 10 %) suitable for pyro-oil formation. The pyrolysis experiments were conducted in a stainless-steel batch reactor (8.5 L) operated at atmospheric pressure. The feedstock loading was 3 kg per batch. The heating rate was maintained at 10 °C min^{-1}, with final temperatures of 550 °C (F1) and 600 °C (F2). Residence time at the target temperature was 60 min, and the system was cooled naturally to room temperature under an inert N_2 atmosphere at 200 mL min^{-1}. The condensed vapours were collected in a water-cooled condenser and weighed to estimate liquid yield. All experiments were repeated three times to ensure consistency. The average product distribution at 550 °C yielded 64 % liquid, 25 % gas, and 11 % char, whereas at 600 °C, the yields were 58 %, 33 %, and 9 %, respectively [7].

2.3. Engine description

The present study uses a Kirloskar TV1, single-cylinder, four-stroke, water-cooled, direct injection open chamber diesel engine with a rated power of 5.2 kW at 1500 rpm, 17.5:1 compression ratio, 23° BTDC injection timing, and 6 L min^{-1} cooling-water flow at ambient temperature (27 ± 2 °C). The bore diameter of cylinder, length of the stroke was 87.5 mm and 110 mm respectively. A compression ratio 17.5 was reported of the operation of engine using pyrolysis oil. A 7.5 kW eddy current dynamometer measures torque and power output. The engine was coupled with sensors to measure combustion parameters . The exhaust concentration was measured using AVL Digas 444 gas analyser measured emissions . A K-type thermocouple monitors the exhaust gas temperature. The AVL 437 smoke meter was used to measure the smoke capacity. The brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) was measured by operating the engine at steady state condition. the different blends of the pyrolyzed oil were used for testing the engine performance and emission characteristics of the engine was tested at 25 %, 50 %, 75 % and 100 %. The pyrolyzed WSOS oils were blended with commercial diesel at proportions of 10 %, 20 %, 30 %, 50 %, and 100 % (denoted as B10, B20, B30, B50, and B100, respectively). The blending was carried out using a high-speed mechanical stirrer at 1500 rpm for 20 min to ensure uniform mixing and complete homogenisation. The stability of the blends was verified through visual observation and sedimentation checks for up to two weeks prior to engine testing, confirming no phase separation. The engine used was a Kirloskar TV1, single-cylinder, four-stroke, water-cooled, direct-injection diesel engine with a compression ratio of 17.5:1 and injection timing of 23° before TDC. The engine was coupled with an eddy-current dynamometer, and cooling water flow was maintained at 6 L/min with ambient room conditions (27 ± 2 °C, 60 ± 5 % RH). Performance parameters such as brake thermal efficiency and brake-specific fuel consumption were recorded, while emissions (CO, CO_2, HC, NO_x, and smoke opacity) were measured using AVL Digas 444 gas analyser and AVL 437 smoke meter. Safety precautions were taken by storing WSOS-derived fuels in sealed, labelled metal containers, handling them with appropriate PPE (gloves, goggles, respirators), and ensuring spill containment to

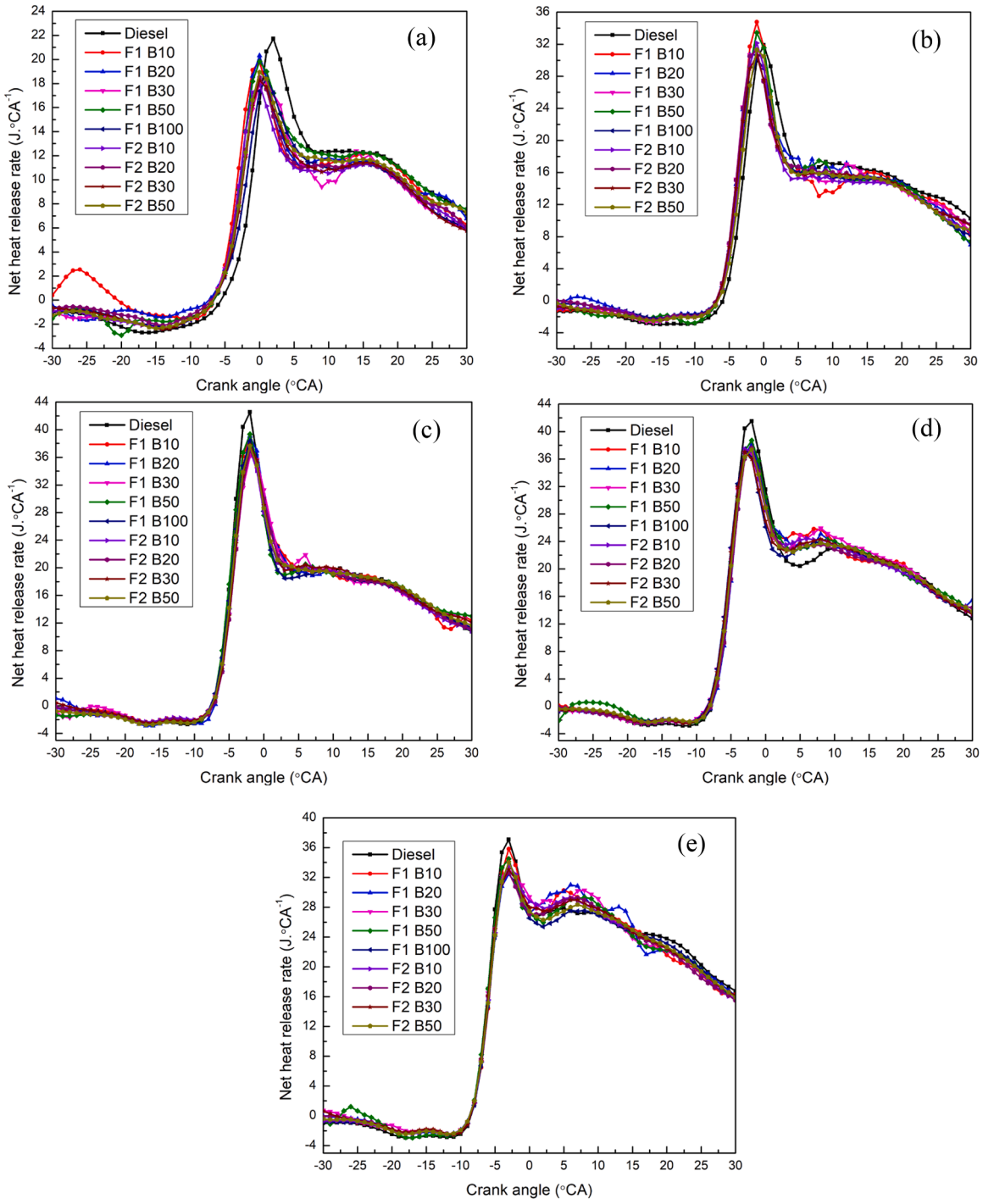

Fig. 3. Peak HRR at (a) no load; (b) 25 % load; (c) 50 % load; (d) 75 % load; and (e) full load.

minimise hazards associated with their toxic and flammable nature.

3. Results and discussions

3.1. Fuel properties of the pyrolyzed oil

The pyrolysis process produced diesel equivalent fuel at two temperatures ranges vis., 475 °C – 550 °C (reported henceforth as F1) and 550 °C – 650 °C (reported henceforth as F2). The properties of F2 were slightly inferior to F1 due to larger amounts of long chained carbon atoms. Table 1 reports the fuel property of F1, F2, and grade 1 diesel. It can be observed that F2 reported a higher calorific value of 38.456 MJ.L^{-1} followed by 37.330 MJ.L^{-1}. F1 also reported of calorific value 37.330 MJ.L^{-1} Which is almost equivalent to grade 1 diesel. However, the kinematic viscosity of F1 and F2 were 9.11 and 12.63 mm^2.s^{-1} respectively .These values are way higher compared to kinematic viscosity grade one diesel 1.3–2.4 mm^2.s^{-1}. The results indicated that F1 and F2 cannot be used as fuel in diesel engine directly. This challenge can be overcome by using this Fuel F1 and F2 blends with diesel.

Hence, both these fuels were blended with diesel and assessed in a diesel engine. The fuels were blended at 10 %, 20 %, 30 % and 50 % with diesel and labelled as B10, B20, B30, and B50 respectively. an attempt has been made for using the F1 fuel without blending with diesel B100. A 100 % replacement of the diesel by F1 fuel is labelled as B100.

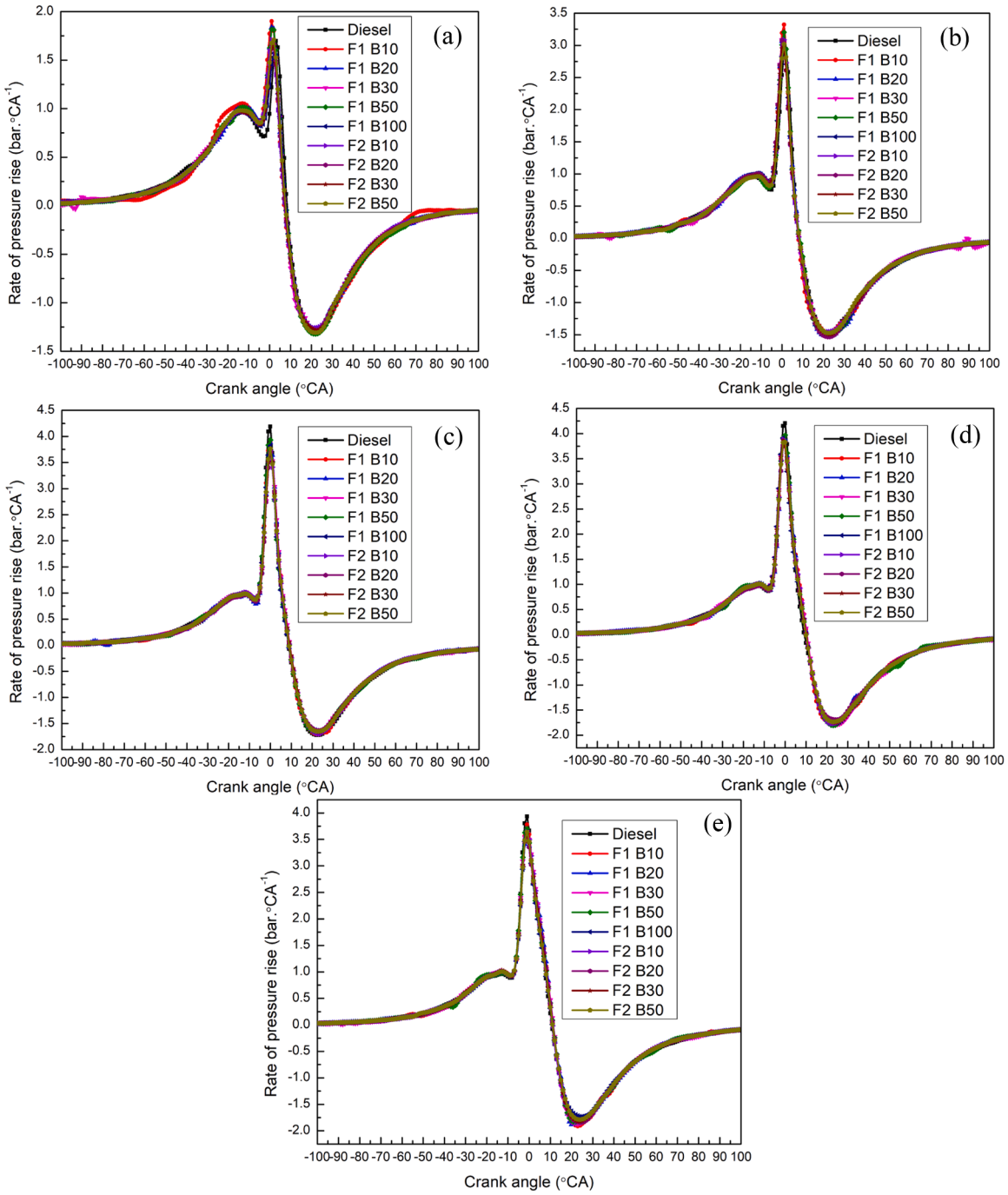

Fig. 4. ROPR variation with crank angle at (a) no load; (b) 25 % load; (c) 50 % load; (d) 75 % load; and (e) 100 % load.

3.2. Combustion parameters

In this section variation of pressure with crank angle, cumulative and maximum heat release rate, rate of pressure rise, combustion duration, and fuel fraction burned were discussed.

3.2.1. Relation between pressure and crank angle

The variation of in-cylinder pressure with crank angle is shown in Fig. 2. Diesel recorded a maximum pressure of 68.92 bar at full load, while F1–B10 achieved the highest blend pressure of 69.13 bar. F2 blends followed closely, and F1–B100 showed slightly lower pressures across all loads. This indicates that blends up to B30 exhibit combustion behaviour similar to diesel, while higher blends experience modest reductions due to delayed combustion. This can be due to the improved quality of the fuel entering the combustion chamber and thereby increasing the flame front propagation [18].

Table 2 represents the maximum combustion pressure of all the fuel studied.

3.2.2. Rate of heat release by WSOS derived fuel (HRR)

The heat release rate profiles in Fig. 3 demonstrate that diesel exhibited the highest HRR at all loads. F1 and F2 blends displayed slightly delayed and lower peaks, which can be attributed to higher viscosity and heavier fractions in the fuel. At higher loads, however, the HRR differences narrowed, suggesting improved combustion intensity. A higher O_2 concentration resulted in higher HRR for F1 and F2 fuel at

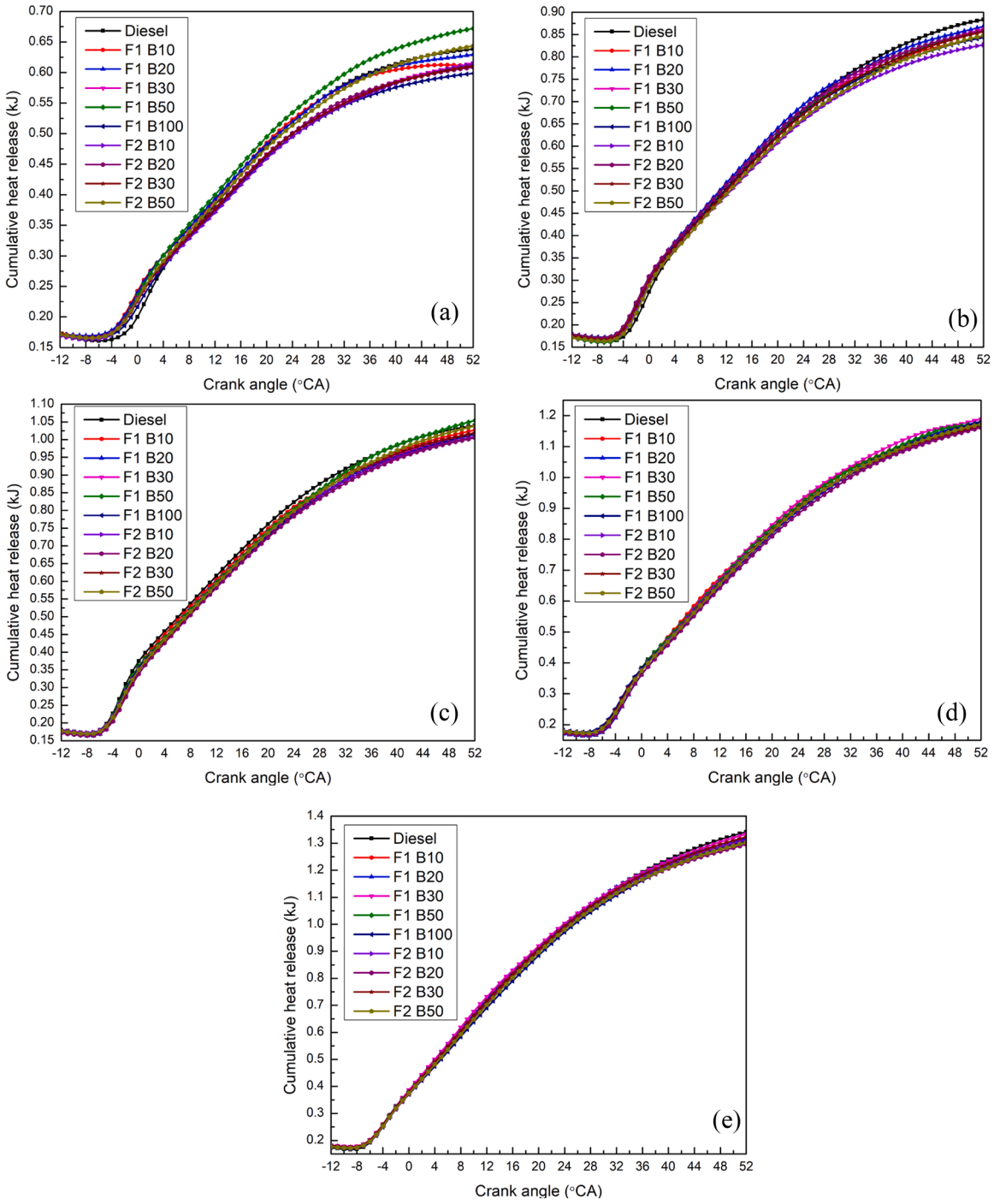

Fig. 5. Cumulative heat release with respect to crank angle at (a) 0 % engine load; (b) 25 % engine load; (c) 50 % engine load; (d) 75 % engine load; and (e) 100 % engine load.

increased engine loads. the faster and intensive combustion observed for higher HRR of F1 and F2 can be due to higher concentrations of petrol and diesel equivalent fractions (71 % and 75.5 % respectively) [7].

3.2.3. *Rate of pressure rise*

The ROPR is governed by HRR and fuel quality at the initial stage of combustion. The power stroke reports a positive rate when the air fuel mixture ignited resulting in increased in cylinder pressure. However, the exhaust and intake strokes reported a negative rate as the cylinder pressure reduces. Fig. 2 represents the variation in cylinder pressure for a range of maximum peak pressure around 8 −12 °CA. The ROPR of 0 −10 °CA (Fig. 4) exhibited similar trend of 8 - 12 °CA. The ROPR peaks reported steep decline during exhaust and intake strokes. As the engine load increases the ROPR peaks also increased (Fig. 4a-e). Ignition delay at higher load causes sudden combustion which can be aggravated to high ROPR at higher engine loads. The in-cylinder pressure is in line with the incremental and decremental trend of the ROPR (Fig. 2). The ROPR is akin and on par with diesel irrespective engine loading, indicating proper combustion.

3.2.4. *Cumulative heat release*

The maximum power produced by specific fuel in an engine is obtained by deducing the peak point of CHR curve. It can be observed from Fig. 5 (a-e). The power produced by the engine increases with increased

Table 3
Combustion duration of fuel blends at various engine loads.

Fuel Blends	Combustion duration (CA)				
	0 % engine load	25 % engine load	50 % engine load	75 % engine load	100 % engine load
Diesel fuel	32	38	38	41	43
F1 B10	74	40	42	47	49
F2 B10	41	39	42	44	49
F1 B20	32	39	44	46	45
F2 B20	32	40	41	44	47
F1 B30	37	46	40	43	49
F2 B30	33	44	41	44	50
F1 B50	41	47	49	41	49
F2 B50	42	41	48	43	48
F1 B100	32	38	44	47	55

engine load has the volume of fuel supplied to the cylinder increase with engine load. The power generation from the fuel blends of F1 and F2 was greater than that of diesel at 0 % and 25 % engine loads. However, it is worth noticing that the peak CHR of the F1 and F2 fuel blends and diesel converge to similar lines at higher engine loads (75 % and 100 %).

3.2.5. Combustion duration

Table 3 summarises combustion duration. Diesel recorded 43 °CA at full load, whereas F1–B100 showed a longer duration of 55 °CA. Blends up to B30 were within the diesel range, but higher blends displayed extended burn times. This demonstrates that WSOS fuels lengthen combustion but remain manageable within CI engine operation. The F1 B100 fuel blend reported the highest combustion duration of 38 %, 44 %, 47 %, 55 % for 25 %, 50 %, 75 % and 100 % engine load respectively. The higher combustion duration can be due to increase in engine delay with the higher fuel blends [19].

3.2.6. Mass fraction burned

The mass fraction burned results (Fig. 6) highlight that diesel exhibited faster initial combustion, while WSOS blends showed earlier start of combustion but longer completion times. At loads above 50 %, all blends converged toward diesel trends, indicating similar overall combustion efficiency despite differences in burn rate. The earlier start of combustion for fuel blends when compared to diesel also correlates well with the higher CD reported in Table 3.

3.3. Performance parameters

3.3.1. Brake thermal efficiency

Fig. 7 represents the brake thermal efficiency of fuel blends studied along with diesel fuel. F1 and F2 fuel blends reported BTE similar to that of diesel fuel at 25 % load. lower fuel blends F1 B10 and F2 B10 reported BTE in line with diesel fuel. On the other hand, the BTE of higher fuel blends reported BTE lower than lower diesel fuel. Higher kinematic viscosity of the fuel blends along with lower calorific value reduce the BTE [18]. A maximum of 30 % break thermal efficiency was reported by fuel blends at 50 % blending with diesel. The F1 B100 blend reported a BET of 28 % .The results indicated that F1 fuel blends reported 6 % lower efficiency in compared to diesel at 25 % engine load. The BET dropped further when engine load was increased. The efficiency observed at 50 % load was 18 % lower, at 75 %, the efficiency was 20 % lower than diesel and at 100 % load it was lower than diesel by 16 %.

3.3.2. Brake-specific fuel consumption

An increase in the engine efficiency always reports reduction in BSFC. Fig. 8 represents the BSFC of fuel blends and commercial diesel. It can be noted F1 B100 reported the highest BSFC as the engine loads increased as discussed earlier the fuel blends contained lower energy density and high kinematic viscosity that reduce the break thermal efficiency [20,21]. The F1 fuel uses 4 % more fuel than diesel at 25 % engine load, 19 % more at 50 % load, 23 % more at 75 % load, and 20 % more at full load.

3.3.3. Exhaust gas temperature

Fig. 9 indicates fuel blends reports EGT almost same with minor difference in values. This implies that the F1 and F2 blends are burned effectively, releasing energy in a manner akin to diesel combustion. Furthermore, it is evident that the usage of WSOS pyrolyzed oils in diesel engines can effectively be carried out without any alteration to the diesel engine. However, it is also possible that the exhaust emissions of WSOS might align with diesel. A careful investigation has to be carried out to identify the emission characteristics of the WSOS fuels.

A simplified energy balance was estimated by comparing the input fuel energy with the brake power output. The total energy input was calculated using the lower heating value (LHV) of each fuel and the measured fuel consumption rate. The useful output was obtained from the brake thermal efficiency (BTE) values. The energy utilisation efficiency (η_e) was determined using:

$$\eta_e = \frac{\text{BTE} \times \text{LHV}_f}{\text{LHV}_d} \times 100$$

where LHV_f and LHV_d represent the lower heating values of the WSOS blend and diesel, respectively. The estimated results showed that 65–70 % of the total input energy from WSOS blends (up to B30) was recovered as effective engine output, compared with 72 % for diesel. The marginal difference confirms that WSOS-derived fuels maintain comparable energy conversion efficiency under identical operating conditions.

3.4. Emission parameters

The cleanliness of fuel can be ascertained through excess gas analysis. Undesirable emission such as unbound hydrocarbon green gases NO_x, and smoke should be curbed to reduce the pollution. The above gases provide greater insight into the characteristics of the fuel while operating diesel engines. The emission and smoke capacity of F1 and F2 fuel blends has been reported and compared with diesel in this section.

3.4.1. Carbon monoxide emissions

Carbon monoxide (CO) poses severe threats to human as it causes lung and respiratory diseases upon ingestion. Globally, strict policies have been followed to root out the co Emission. emission from the engines is mainly due to improper air-fuel ratio inadequate oxygen supply and insufficient volume [22]. The lean mixture always emits lower or permitted level of carbon monoxide during combustion [19]. Fig. 10 represents the CO emission for the varies fuel blends studied along with diesel at various loads ranging between 0–100 %. It is evident that increases the engine load resulted in lower CO emission till 75 % engine load . The results indicate that F1 and F2 fuel blends reported lower emissions then diesel fuel. oxygen of F1 and F2 resulted in improving the efficiency thereby decreasing CO emissions. However, co-emission of fuel blends as well as diesel increased at 100 % engine load. Partial combustion due to the insufficient time for burning can be a reason CO emission 100 % load [23]. It can also be noted that F1 B100 fuel reported double the amount of CO emission in comparison with diesel fuel. Since, the oxygen concentration of F1 is more than diesel, and the cylinder pressure is also almost similar to that of diesel (Table 2).The higher CO value for F1 can be linked to insufficient time provided for combustion at 100 % engine load.

3.4.2. Carbon dioxide emissions

Stoichiometric combustion of fuels result in carbon dioxide emission then carbon monoxide emission. It is always desirable to have higher amount of carbon dioxide at it indicates good combustion. Fig. 11

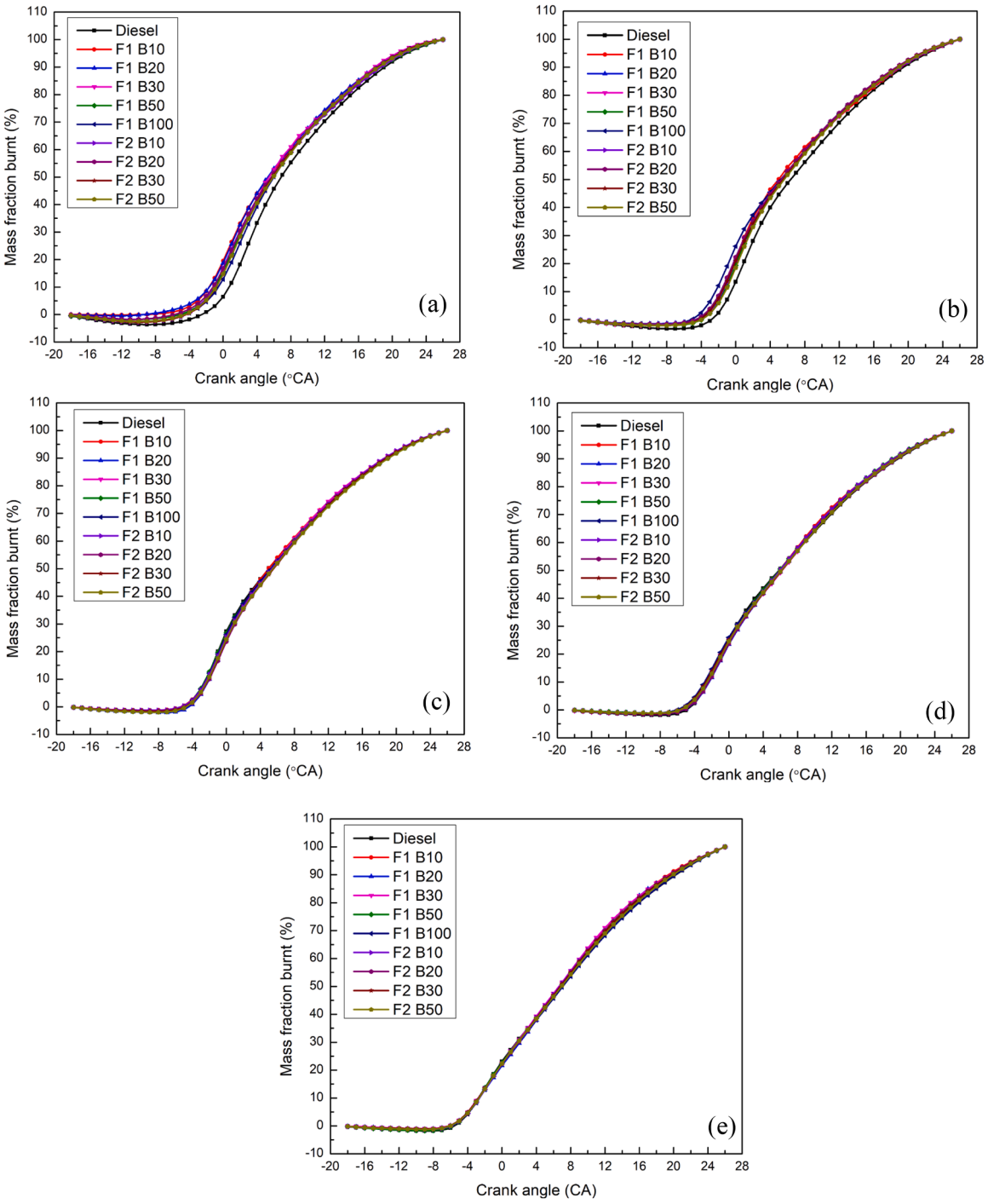

Fig. 6. Mass burnt fraction in the combustion chamber at (a) 0 % engine load; (b) 25 % engine load; (c) 50 % engine load; (d) 75 % engine load; and (e) 100 % engine load.

indicates a higher volume of fuel burnt resulting in higher CO_2 concentrations in the exhaust. F1 and F2 fuel blend emitted lower CO_2 then that of diesel. It may be due to incomplete combustion of the pyrolyzed oil.

3.4.3. *Unburnt hydrocarbons*

Unburnt hydrocarbons (UHC) emissions are inversely linked to CO_2 emission. Following, similar trends at increased engine load. Fig. 12 indicated increase in unburnt hydrocarbon emission. It can also be noted diesel fuel and higher blends of F1 and F2 reported lower unburnt hydrocarbon emissions. The increased HC can be due to number of factors and not limited to chemical composition, higher kinematic viscosity improper fuel mixing and incomplete combustion [24]. The pyrolyzed oil contains higher hydrocarbons which is recalcitrant to combustion leading HC emission. F1 used as the sole fuel resulted in 81 %, and 28 %. However, the HC emissions of F1 was lower than diesel at higher engine loads indicating better combustion .

3.4.4. *Oxygen emissions*

Oxygen is the driving force of combustion inside the chamber. It is essential to maintain right amount of oxygen for a better engine efficiency and lower emission. Fig. 13 oxygen concentration decreases

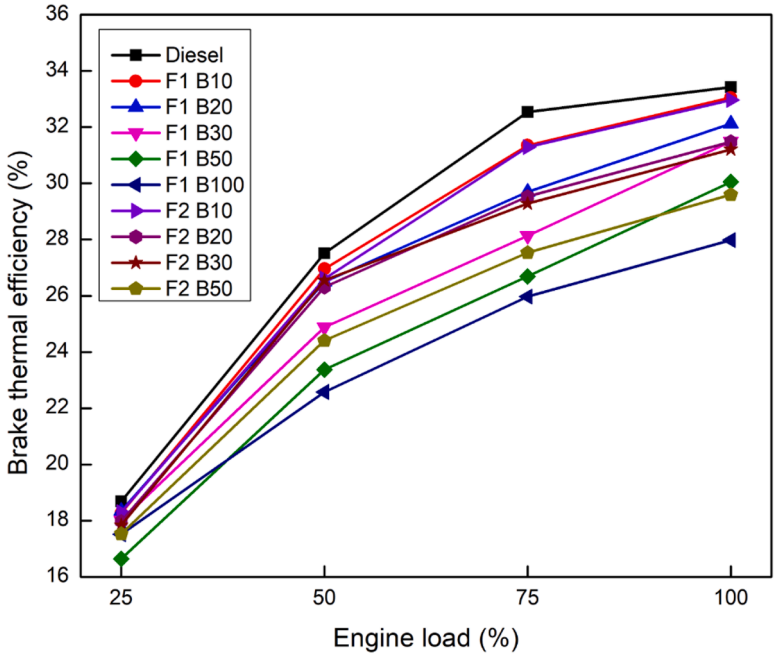

Fig. 7. Variation of brake thermal efficiency of the fuel blends at various engine loads.

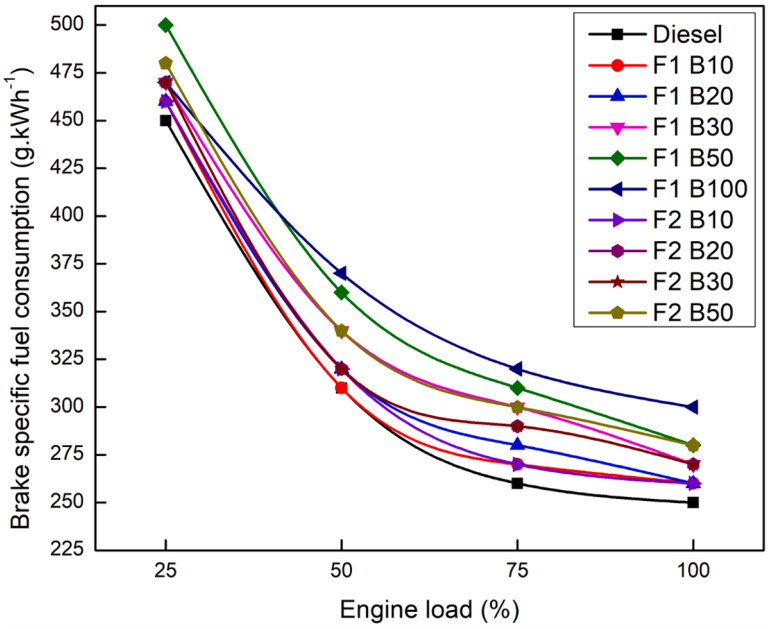

Fig. 8. Variation of BSFC at different engine loads.

because of with increase engine load. This can be due to utilization of oxygen by the increased volume of fuel at higher loads. This can be observed with higher amount of CO_2 in exhaust. The results indicate that F1 and F2 fuel blend reported higher oxygen emission than diesel fuel. The Insufficient fuel mixing is reduced combustion time can be reason for higher emissions of oxygen and UHC emission.

3.4.5. NO_x emissions

An increase in load requires more fuel supply resulting in higher combustion temperature. This increased temperature inside the chamber results in NO_x emission [28]. Fig. 14 indicates in NO_x emission from commercial diesel fuel is higher when compared with F1 and F2 fuel blends at all engine loads. The lower amount of NO_x in the emission refers to a proper combustion. However, the result from the present investigation presents an increased amount of HC, CO_2 concentration in the exhaust. The presence of lower amount nitrogenous compound in both F1 and F2 fuel blends could be a predominant factor NO_x reduction when compared with diesel.

3.4.6. Smoke opacity

The presence of micro-scope particles burned oil, and soup leads to exhaust smoke. It can observe that the smoke capacity of F1 and F2 fuel blends where substantially higher than diesel fuel (Fig. 15). It is quintessential from the outcome of the study that all other emission parameters of the F1 and F2 fuel blends were equal except smoke opacity. The increased smoke of F1 and F2 fuel blends can be attributed to

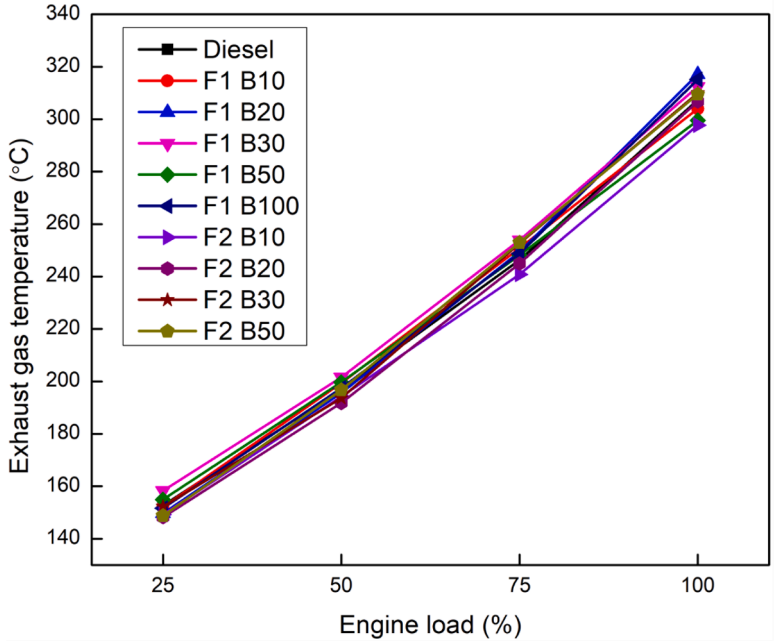

Fig. 9. Variation in exhaust gas temperatures with respect to engine loads.

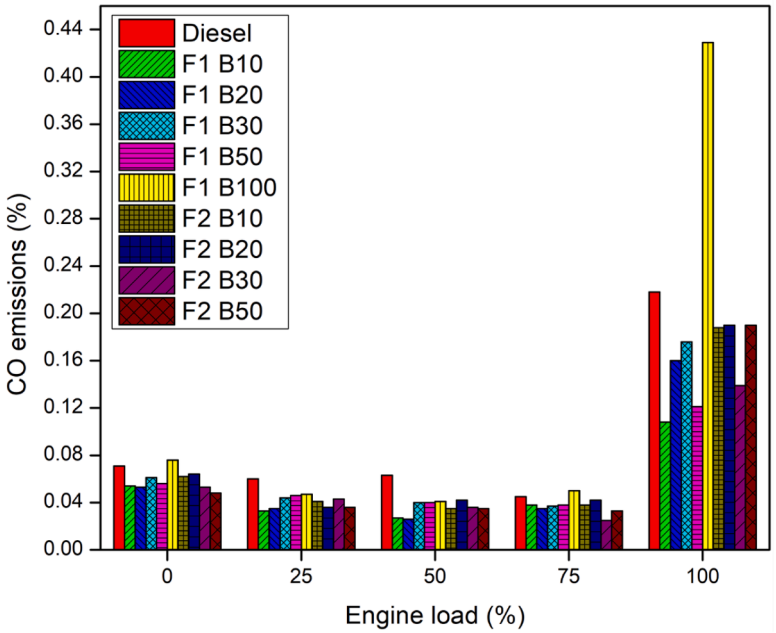

Fig. 10. CO emission from diesel, F1 and F2 blends at different engine loads.

heavier hydrocarbon and recalcitrant particular matter. Fig. 15 indicates that higher concentration WSOS reported higher smoke opacity. It is necessary to use a filter or proceeds to suitable treatment step to remove the particulate matter in fuel blend to reduce the smoke capacity.

3.5. Discussion

The performance of WSOS-derived fuels can be understood by relating feedstock characteristics, pyrolysis conditions, and subsequent engine behaviour. The proximate and ultimate analysis, TGA, and GC–MS data from our earlier work [7] revealed that WSOS is rich in long-chain hydrocarbons with minor oxygenated compounds and a small sulphur fraction. These characteristics favoured the formation of diesel-range hydrocarbons during pyrolysis but also contributed to high viscosity and instability in the raw product. The higher fixed carbon content in the feedstock promoted secondary cracking reactions at elevated temperatures, influencing both yield and quality of pyro-oil. The observed differences between F1 and F2 fuels are attributed to temperature-driven secondary cracking. At 550 °C, depolymerisation and volatilisation dominate, yielding mid-range hydrocarbons with higher stability. At 600 °C, intensified cracking generates lighter gaseous fractions and increases olefinic content, reducing viscosity but slightly affecting oxidation stability.

3.5.1. Influence of pyrolysis temperature and yield distribution

The yield data indicated that a temperature range of 550 °C produced

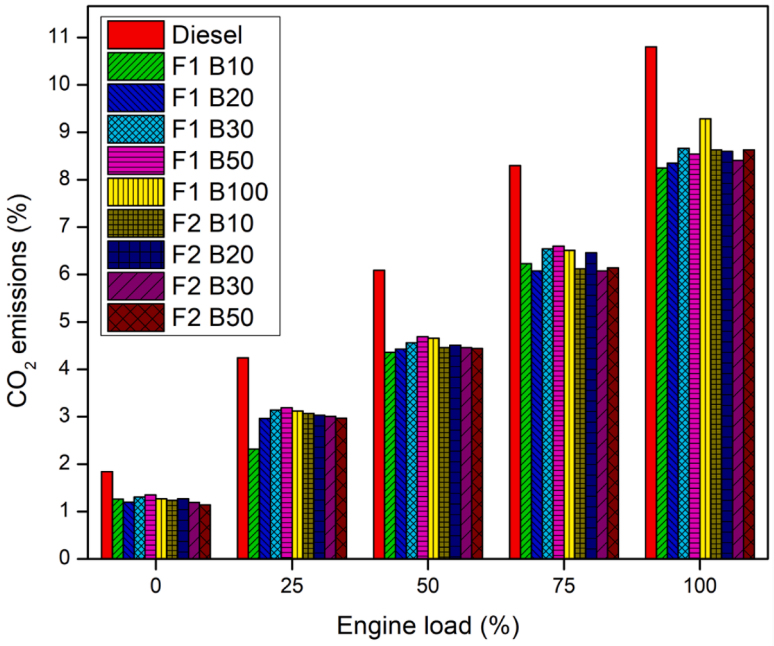

Fig. 11. CO2 emissions from diesel, F1 and F2 blends at different engine loads.

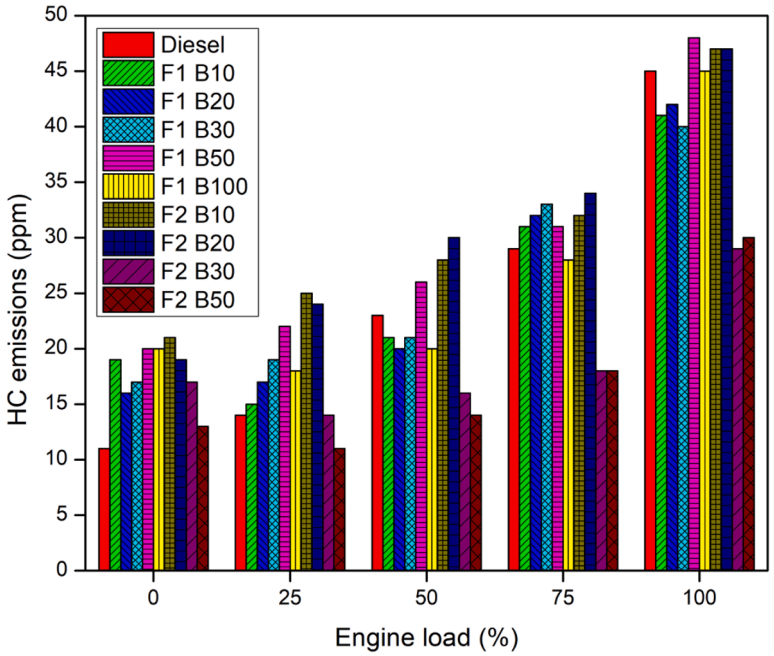

Fig. 12. Hydrocarbon emissions from diesel, F1 and F2 blends at different engine loads.

the highest liquid fraction, aligning with optimal devolatilization observed in similar studies [6,11]. Beyond 600 °C, secondary cracking increased gaseous production and reduced liquid yield, confirming that excessive temperature promotes chain scission into lighter hydrocarbons. The choice of two temperature regimes (F1 and F2) therefore allowed comparison between liquid recovery and product stability. F1, obtained at moderate temperature, yielded better viscosity and combustion behaviour, while F2, produced at higher temperature, contained more lighter fractions and exhibited slightly lower stability.

3.5.2. *Blending stability and fuel properties*

The WSOS pyro-oils demonstrated good miscibility with diesel up to 50 %, with no visible phase separation or sedimentation during stability tests. Their calorific values (37–38 MJ L^{-1}) were comparable to diesel, confirming the high energy potential of WSOS-derived oils. However, the higher kinematic viscosity (9–12 mm^2 s^{-1}) reduced atomisation quality, justifying the blending approach to ensure proper injection and combustion. These findings are consistent with previous works on waste oil pyrolysis [6,25], but the present study extends understanding by validating engine-level usability without modification.

3.5.3. *Combustion behaviour and performance evaluation*

The combustion profiles revealed that WSOS blends sustained pressure and HRR trends comparable to diesel up to B30. The slightly

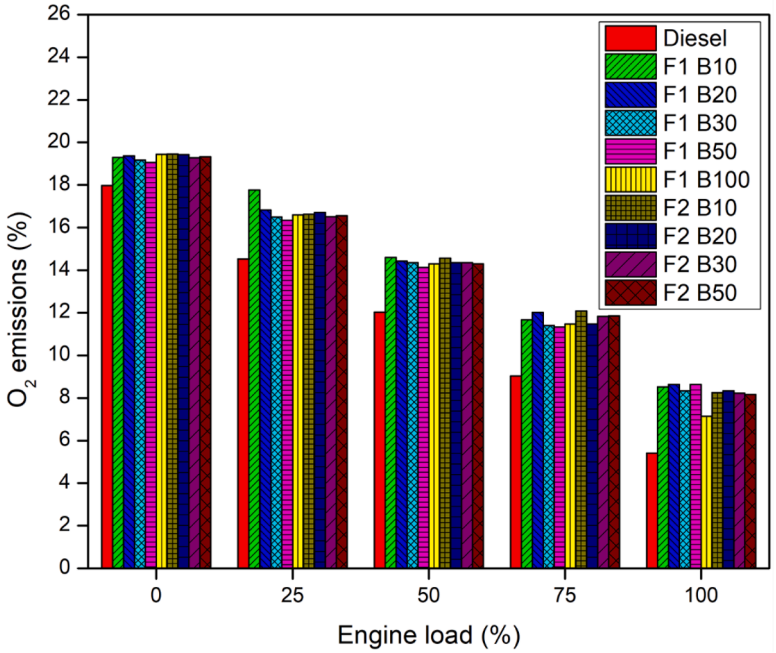

Fig. 13. Oxygen emissions from diesel, F1 and F2 blends at different engine loads.

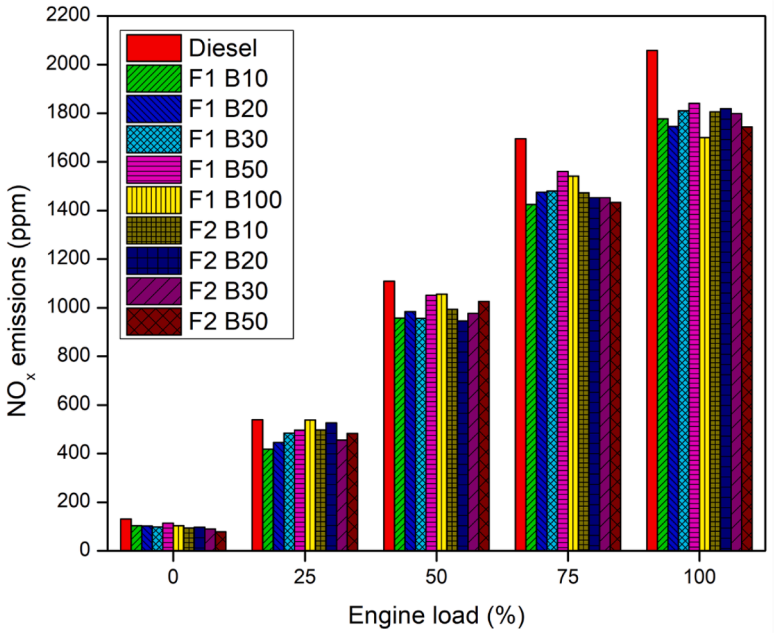

Fig. 14. NOx emissions from diesel, F1 and F2 blends at different engine loads.

delayed combustion in higher blends is associated with slower evaporation of viscous fractions. The observed BTE decline and BSFC increase with rising WSOS content are in agreement with studies on pyrolysis oils from similar feedstocks [20,21]. Nevertheless, the present results demonstrate that even at B30, efficiency remains within 5–7 % of diesel, confirming the practical feasibility of partial replacement. The comparable exhaust temperatures across fuels suggest that WSOS blends release energy effectively, supporting stable operation without knock or misfire.

3.5.4. Emission characteristics and environmental implications

Emission results showed notable advantages of WSOS fuels in reducing NO_x and CO_2, thereby contributing to lower greenhouse-gas emissions. The reduction in NO_x stems from lower peak combustion temperatures and minimal nitrogenous species in WSOS-derived fuels [16,22]. Increased CO and HC emissions at high substitution levels result from incomplete oxidation of heavy hydrocarbons, consistent with prior biodiesel–diesel blend reports [17,23]. The higher smoke opacity indicates a need for further fuel upgrading or use of particulate filters. From a sustainability standpoint, these results align with **SDG 7 (Clean Energy)** by providing a renewable diesel alternative, **SDG 12 (Responsible Production and Consumption)** by valorising hazardous waste, and **SDG 13 (Climate Action)** by potentially lowering lifecycle CO_2 emissions.

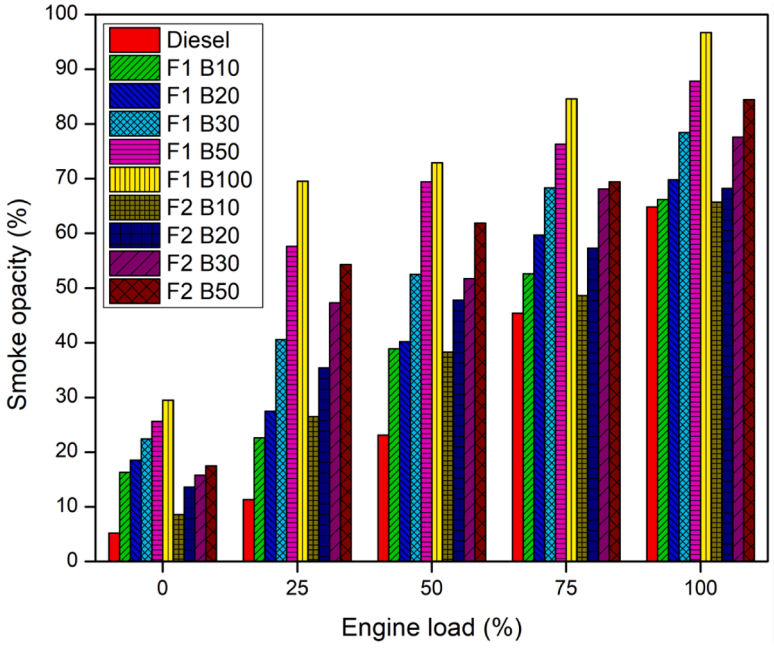

Fig. 15. Smoke opacity of exhaust for diesel, F1 and F2 fuel blends at various engine loads.

3.5.5. Limitations, scalability, and future perspectives

Although WSOS-derived pyro-oils demonstrated promising performance, some limitations remain. The scalability of the process requires attention to continuous reactor design, heat recovery, and control of emissions during pyrolysis. The presence of heavier hydrocarbons necessitates post-upgrading (hydrotreatment or fractional distillation) to enhance long-term storage stability and reduce particulate emissions. Handling WSOS feedstock and derived fuels requires proper safety protocols due to their toxic and flammable nature. Future research should focus on catalytic pyrolysis for quality improvement, life-cycle and techno-economic assessments for large-scale feasibility, and integration of emission-control technologies during engine operation.

3.5.6. Industrial and sustainability relevance

The present investigation confirms that WSOS can be upcycled into a high-energy liquid fuel suitable for diesel engines without modification at blending ratios up to 30 %. This not only addresses the environmental challenge of WSOS disposal but also offers a circular pathway for maritime waste utilisation. Adoption of such fuels could reduce the carbon footprint of the shipping sector and contribute to net-zero targets. Industrial application of this approach is feasible where port facilities or coastal refineries can establish decentralised pyrolysis units for converting WSOS into usable blends. The overall findings strengthen the linkage between waste valorisation, sustainable energy generation, and practical implementation of low-carbon maritime operations.

A simplified techno-economic assessment based on previous cost modelling [7] indicates that small-scale WSOS pyrolysis units (5 t day^{-1}) can operate profitably at a bio-oil selling price of €0.55 L^{-1}, assuming 65 % liquid yield and electricity recovery from non-condensable gases. Integration with port waste-management facilities can further reduce logistics cost, suggesting industrial viability of WSOS fuel blending as a supplementary energy source. The current WSOS pyro-oils can be used directly up to 30 % blend without upgrading. For higher substitution ratios, mild hydrotreatment or fractional distillation is recommended to enhance storage stability and reduce particulates. Commercial viability is achievable for decentralised port-based pyrolysis units using existing diesel infrastructure.

4. Conclusion

This study established the feasibility of converting waste ship oil sludge (WSOS) into a diesel-like fuel through non-catalytic pyrolysis and evaluating its performance in a compression ignition engine. The pyrolysis process conducted at 550 °C (F1) and 600 °C (F2) produced high-energy liquid fuels with yields of 64 % and 58 %, respectively, demonstrating effective recovery of hydrocarbons from hazardous marine waste. The resulting WSOS pyro-oils exhibited calorific values comparable to diesel and were successfully blended (B10–B100) without chemical modification, confirming their suitability for direct use as supplementary fuels. Combustion and performance analyses revealed that blends up to B30 maintained cylinder pressure, heat release rate, and brake thermal efficiency values close to diesel, with only marginal increases in brake-specific fuel consumption. Higher blends exhibited slower combustion and extended burn durations due to elevated viscosity and lower volatility. Emission results showed significant reductions in NO_x and CO_2 emissions but higher CO, HC, and smoke levels at elevated substitution ratios, suggesting that blending below 30 % offers the most favourable balance between performance and emissions. The findings highlight the dual advantage of WSOS utilisation in reducing environmental burden and producing renewable transportation fuel. From a sustainability perspective, the process directly supports SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Production and Consumption), and SDG 13 (Climate Action) by converting a hazardous waste into a low-carbon energy carrier. The simplified energy balance indicated comparable energy conversion efficiency between WSOS blends and conventional diesel, reinforcing the technical feasibility of WSOS-derived fuels in existing engine systems.

Despite these promising results, challenges remain in large-scale deployment. The high viscosity and aromatic content of WSOS oils necessitate further upgrading to improve long-term stability and reduce particulate emissions. Handling safety and feedstock variability also require attention for continuous operation. Future research should focus on catalytic pyrolysis to enhance fuel quality, long-term engine endurance testing, and comprehensive life-cycle and techno-economic assessments to validate industrial-scale implementation. Overall, this work demonstrates a sustainable route for valorising maritime oily waste into usable transport fuel, contributing to circular economy

initiatives and advancing low-carbon energy solutions for the shipping and port sectors.

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CRediT authorship contribution statement

G. Gowtham: Writing – original draft, Formal analysis, Data curation. **Gualbert Arkin:** Writing – original draft, Data curation. **K.B. Sasidhar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Santoshkumar Balasubramanian:** Writing – review & editing, Resources. **Murugavelh Somasundaram:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Elsa Antunes:** Writing – review & editing, Validation, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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