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A circular economy approach to energy recovery from polymer waste with oxygenated additives as a sustainable fuel

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ABSTRACT

The generation of polymer wastes has become a continually growing environmental challenge for disposal and resource management. This research develops an innovative approach to environmental sustainability by recovering energy from polystyrene polymer waste through pyrolysis conversion to polymer waste oil blended with diesel fuel at 20 % and 40 % ratios. In consideration of further optimizing combustion efficiency and minimizing harmful emissions, the oxygenated additive diethyl ether is used at a concentration of 10 % and 20 % in fuel blends. This investigation discusses the performance and emission characteristics of these blends in a diesel engine based on the environmental impact. Recovery of plastic waste to usable fuel is a leading step in applying circular economy principles in handling plastic pollution. It offers the possibility of transforming waste into valuable resources where economic incentives are aligned with Sustainable Development Goals. The results show that PWO20DA20 has resulted in a notable SFC reduction of 16.7 %, and BTE increased by 1.27 % compared to diesel. PWO20DA20 blend significantly reduced hydrocarbon and carbon monoxide emissions by 15.71 % and 20.81 %, respectively. Response surface methodology resulted in 13.9 % PWO and 19.3 % DEE, is considered the best formulation, and resulted in lowering SFC to 0.2925 kg/kWh with minimal CO at 0.1762 % and HC at 61 ppm.

1. Introduction

Plastics have proved immensely important in contemporary life due to their portability, durability, energy efficiency, rapid manufacture, and design versatility. These are increasingly gaining significance in the industries and have been extensively used in several industries and homes. Plastic waste and recycling problems pose a significant environmental threat [1,2]. The large amounts of plastic waste generated by the plastics industry have already polluted many water bodies and land areas. Nearly one million species of aquatic animals die each year due to more than ten million tons of dumped plastics. Standard disposal methods for plastic waste include feedstock recycling, mechanical recycling, energy recovery, and incineration as municipal solid wastes. Prevention would start at the top while preparation for reuse follows, then recovery, recycling, and eventually landfilling as part of the European policy for the prevention and management of waste [3,4].

Plastic waste is converted into fuels or, preferably, into individual monomers, far more environmentally friendly waste management than simply piling it into landfills. Higher daily consumption of plastic materials extracted from petroleum may cause the eventual depletion of non-renewable fossil fuel resources. Direct use of crude oil production in manufacturing plastics amounts to about 4 % [5]. On the other hand, diesel engines have used fossil diesel fuel for more than a century. Among other uses, fossil fuel is used to transport people, farm crops, and manufacture products. Knowing that fossil fuels are of a finite supply, researchers and engineers have put great effort into finding alternative sources that can easily be reached instead of this fossil fuel [6]. As fuel

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Nomenclatures

BTE	Brake Thermal Efficiency
CO	Carbon Monoxide
DA	Diethyl Ether Additives
HC	Hydrocarbon
NOx	Nitrogen Oxides
SFC	Specific Fuel Consumption
PS	Polystyrene polymer
PWO	Polymer Waste Oil
PWO20	20 % polymer waste oil + 80 % diesel
PWO40	40 % polymer waste oil + 60 % diesel
PWO20DA10	20 % polymer waste oil + 80 % diesel + 10 % diethyl ether additive
PWO40DA10	40 % polymer waste oil + 50 % diesel + 10 % diethyl ether additive
PWO40DA20	40 % polymer waste oil + 40 % diesel + 20 % diethyl ether additive
PWO20DA20	20 % polymer waste oil + 60 % diesel + 20 % diethyl ether additive

costs continue to increase and environmental contamination grows, it is time to shift to a clean energy source. Since biodiesel is a cleaner and more effective alternative to regular diesel, its environment-friendly nature makes it a clean fuel source. It can reduce most contaminant and emission levels [7,8].

Low-cost plastics have recently been identified as an excellent feedstock for improving the fuel properties of biodiesel, thus offering a potential cure to the plastic pandemic. Used technologies are paramount in solving the Sustainable Development Goals (SDG) against plastic pollution's many environmental and societal challenges [9]. Polymer waste chemical recycling will be important in material cycles and transitioning to the circular economy model. Among the different available plastics recovery techniques, such as pyrolysis, gasification, and cracking, pyrolysis is best known for recovering helpful pollutants. It also presents a chance to recover the plastic monomer and thus the hope of breaking the worrying carbon loops created in plastic recycling [10,11].

Pyrolysis of polypropylene (PPO) and polystyrene (PSO) produces renewable fuels with optimized high liquid yields and minimal energy consumption. Fuel analysis showed that PPO had low density and high volatility, whereas PSO was aromatic and poor in ignition properties. Engine tests revealed blends of PPO show similar combustion behavior to diesel, and the addition of PSO increases particulate matter and emissions [12]. Research has looked into the effectiveness of Al2O3 nanoparticles as a blending additive for pyrolysis plastic oil ranging from P10 to P40 in engines under EGR conditions. P40 with 50 ppm Al2O3 resulted in a significant reduction of CO, and NOx was remarkably decreased with P30 + EGR. The highest brake thermal efficiency of 32 % and brake mean adequate pressure of 6.3 bar were determined for the P30 blend, with further improved performance characteristics than other blends [13].

The co-pyrolysis of Azadirachta indica seeds and waste LDPE using Al2O3 as a catalyst to produce liquid fuel blended with pure diesel was investigated. The maximum brake thermal efficiency obtained was 28.7 % for a 20 % blend that consumed an equal amount of fuel compared to diesel at 0.3 kg /kWh. Lower NOx and smoke emission levels were observed for 30 % blended fuel. Combustion characteristics like maximum in-cylinder pressure and heat release for 20 and 30 % blends were enhanced compared to diesel [14]. The pyrolysis process realized 78 % of the liquid yield, with a calorific value of 38.5 MJ/kg. The results showed a 6 % improvement in brake thermal efficiency and reductions of 4 % of hydrocarbons and 2 % of CO emissions compared to diesel. However, NOx emissions were not so advantageous [15]. For a diesel engine study, al2O3 nanoparticles are added to a diesel and waste plastic oil of 20 % blend with 10 and 20 ppm. WPO20 decreases engine performance besides increasing emission, while 20 nm nanoparticles increase brake thermal efficiency by 12.2 % and brake-specific fuel consumption by 11 %. Both nanoparticles have reduced emissions, but 20 nm is better in order of decrease in CO, HC, NO, and smoke opacity [16]. Table 1 displays that many researchers have enhanced the performance of waste plastic fuel with various oxygenated additives.

Diethyl ether (DEE) is a promising additive in biodiesel applications because of its higher cetane number and oxygen content, which produce improved combustion characteristics and lower emissions. Several studies have been conducted on the role of DEE as a potential enhancer for the performance of diesel engines running on biodiesel blends. Adding DEE to biodiesel blend with petroleum diesel increased the brake thermal efficiency and fuel consumption. Optimization of higher blends was found at 10 % DEE with 20 % biodiesel content, and this was considered to be the most effective blend under different engine loads and compression ratios [23]. Adding 5 % of DEE to a B20E blend has significantly enhanced the engine's fuel efficiency, especially with higher loads. Besides improved performance, the blend also emitted less NOx and PM. Positive impacts of adding DEE in biodiesel-diesel-ethanol blend on an environmentally friendly approach [24]. Similarly, the combustion of diesel-DEE-kerosene blends concluded that adding DEE increased the fuel's cetane number and oxygen contents and improved combustion efficiency. However, they also reported that at higher concentrations of DEE, the fuel consumption increased more, especially at full engine load, meaning that a balance in DEE concentrations is required to have optimal fuel economy and performance [25].

In the investigations of diesel-biodiesel-DEE blends, at a 5 % level of DEE blending, a tremendous improvement in the engine's performance was achieved, however slightly reducing fuel usage by 8 % and enhancing thermal efficiency by 6.8 %. With its exceptionally high cetane number, DEE contributed effectively to good combustion efficiency without drastically altering the combustive start instantly [26]. Adding DEE as an additive in biodiesel blends with waste plastic oil, particularly at higher percentages of 15 %, enhances thermal efficiency and reduces energy consumption. It also simultaneously lowers smoke and NOx emissions. These results highlight DEE's potential to improve both the functionality of biodiesel and its environmental sustainability. [27].

DEE in blends of plastic pyrolysis oil, with increases in BTE, carbon monoxide, and NOx decreases [28]. DEE in a dual-fuel engine with karanja methyl ester as biogas indicated an improvement of 2.3 % for BTE and a 5.8 % reduction in fuel consumption. However, the increased NOx was due to the oxygen present in the DEE [29]. Combustion of 4 % DEE with light fraction pyrolysis oil exhibited a 6 % reduction in BSFC, and NOx emissions decreased by 25 % compared to diesel fuel [30]. DEE blended with neem biodiesel and alumina nanoparticles showed a considerable increase in BTE and BSFC with a reduction in NOx emission by 17.5 % [31]. Collectively, these studies demonstrate the flexibility of DEE and its potential to enhance a range of biodiesel and alternative fuels, making it a valuable additive to strengthen performance and emission profiles in diesel engines.

Table 1
Literature with Oxygenated additive on waste plastic fuel.

Base Biodiesel	Additive	BTE	SFC	CO	HC	NOx	Author & Year
W10E10	Ethanol	▲	▼	▼	▼	▼	[17]
70PPO12E	Ethanol	▼	▼	▼	▼	▼	[18]
WPO20P05	Propanol	▲	▼	▼	▼	▼	[19]
W40H10	n-Hexanol	▼	▲	▼	▲	▼	[20]
50D50W	DEE, MEA	▲	▼	▼	▼	▼	[21]
W5DEE5	DEE	▲	▼	▼	▼	–	[22]

A circular economy seeks to minimize the environmental footprint of all its operations and is interested in reducing emissions through reusing, recycling, and regenerating; in other words, in a circular approach, unlike a linear method of 'produce and discard,' every waste material of plastics particularly polymers such as polystyrene can be repurposed as a source of materials, closing the loop in the production-consumption chain. This paper explores one of these closed loops by pyrolyzing waste plastics into polymer waste oil, which can be utilized as a diesel fuel blend. The model not only diverts landfill-bound plastic waste but also provides a renewable alternative to fossil-based diesel fuel, supporting a circular economy in which waste is reincorporated into the energy chain. This study focuses on energy recovery from polymer waste as a transportation fuel source to meet sustainable development goals (SDGs). The investigation aims to determine the emission and performance characteristics of polymer waste oil (PWO) recovered through the catalytic pyrolysis of waste polystyrene polymer in a single-cylinder diesel engine. Diethyl ether additives (DA) as oxygenated supplements with fuel recovered from waste polystyrene polymer have not been previously attempted in diesel engine applications. This study mixed blends of 20 % and 40 % polymer waste oil with 10 % and 20 % diethyl ether additives with conventional diesel fuel to enhance engine performance. Additionally, the influence of diethyl ether additives on the PWO blends was analyzed in terms of fuel consumption and emissions of CO and HC using response surface methodology.

2. Material and methods

2.1. Polystyrene polymer

Polystyrene is a polymer based on repeating styrene monomers, derived as by-products of the petrochemical industry. Each monomer comprises a phenyl group bonded to a carbon atom in a long hydrocarbon chain; that structure makes polystyrene extremely stable, with its desirable mechanical properties and resistance to environmental degradation providing further evidence of this. This resin is used in food packaging, containers, trays, and electronic devices, and these resins cover household appliances and toys, among other products protected by packaging. Polystyrene mainly has an environmental footprint due to the degradation period. Under natural conditions, polystyrene does not biodegrade; it takes hundreds of years before such materials degrade in landfills. Its durability is its biggest challenge: improperly disposed polystyrene finds its way into plastic pollution areas, especially marine ones. The general structure of polystyrene can be represented as **$[—CH_2—CH\ (C_6H_5)—]_n$**

Polystyrene has very low moisture 0.25 - 0.30 (wt%) and negotiable ash content, and the highly high volatile matter 99.50 - 99.63 (wt%), suggests that nearly the entire portion of this polymer is organic with minimal inorganic residue, placing it in a perfect category for pyrolysis or other kinds of thermo-chemical conversion techniques for fuel production. Pyrolysis is among the thermochemical decomposition methods that can effectively offer a solution for converting polystyrene polymer waste into valuable resources such as oil, fuel, and gas. Pyrolysis occurs in the complete or partial absence of oxygen to evade combustion and break long polymer chains into smaller hydrocarbons. The temperature typically ranges from 300 to 800 °C depending on the composition of the plastic waste, while the high temperature breaks the polymers down into three fractions: solid residues, gases, and liquids. The liquid fraction, or pyrolysis oil or bio-oil, contains a high concentration of hydrocarbons and is further treatable into fuels or any other chemical of value. This process has become imperative with the increase in global concern about accumulated plastic waste [10,32].

Catalytic pyrolysis, on the other hand, tends to enhance the depolymerization of the polymers and increase high-quality fuel products due to the efficiency added in converting waste plastic into usable energy resources [33,34]. The Polystyrene polymer's pyrolysis took place at the temperature of 350 °C with a reaction time of 50 mins. The pyrolysis does produce results of 75 % oil, 15 % wax and char, and 10 % gas. The approximate output of 1 kg of polystyrene would be 700 to 750 g of oil, 100 to 150 g of gas (containing methane, ethane, and ethylene), and 100 to 150 g of char; the remaining 5 % is wasted due to inefficiencies and mishandling. Pyrolysis oil may be utilized as a source of fuel; it exhibits combustion characteristics that are inefficient when compared with conventional diesel, hence doing further research into the improvement of fuel quality of pyrolysis oil [35,36].

According to FTIR analysis (Fig. 1), aromatic hydrocarbons that characterize pyrolyzed polystyrene dominated the analysis of polystyrene-derived fuel. These include toluene, ethylbenzene, and styrene derivatives, which confer a higher energy density than the aliphatic hydrocarbons in diesel. The diesel comprises long-chain alkanes with a small fraction of aromatic compounds; the polystyrene shows a narrow boiling point range due to its composition's simplicity, which could affect the combustion behavior. Comparing combustion characteristics of polystyrene-derived fuels and diesel, it is noted that polystyrene-derived fuels, with a higher aromatic character, usually exhibit a lower cetane number and tendency towards a delay in ignition, which means longer ignition delays and slower combustion phases. However, polystyrene-derived fuel may have energy density and calorific value comparable to or even higher, thereby being an economical energy source for controlled applications [37,38].

Chemical engineering of 800 °C and above processes in pyrolysis requires a notable quantity of heat, where an assumed energy input of approximately 4 to 5 MJ of energy is needed to convert 1 kg of plastic into fuel [39]. However, when products like oil, gas, and solid residues in pyrolysis are produced, the energy output is primarily limited by higher values, ranging from 25 to 45 MJ/kg. Roughly 40–45 MJ/kg of energy-dense fuel is produced from polystyrene, comparable to conventional diesel at 43 MJ/kg [3]. Studies indicate that pyrolysis systems can establish a positive energy balance since the energy from the fuel produced cannot be lower in value than the potential energy needed for its conversion. Providing sufficient heating is less costly than pyrolysis in converting polyethylene at 42.3 MJ/kg since the energy used here amounts to <3 % of the calorific value of the pyrolysis products. Similarly, pyrolysis of mixed plastics or polystyrene can yield 75 % oil, 10 % gas, and 15 % wax and char, showing high fuel recovery efficiency [35].

2.2. Diethyl ether additive

Diethyl ether (DEE), the simplest organic compound with formula $C_2H_5OC_2H_5$, has been considered as one of the additive options for diesel fuels (Table 2). The cetane number is relatively high at 125, and the

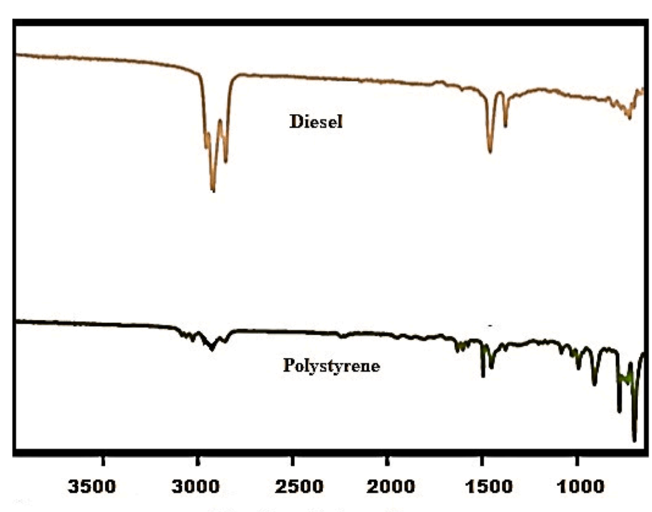

Fig. 1. FTIR of polystyrene and diesel.

Table 2
Performance of diethyl ether with biodiesel blends.

Biodiesel	DEE Additive Ratio	BTE	SFC	CO	HC	NOx	Author & Year
Jatropha biodiesel	10 %	Higher	Lower	Lower	Lower	Lower	[23]
Soybean Biodiesel + Ethanol	5 %	Higher	No change	Lower	Same as diesel	Lower	[24]
Diesel + Kerosene	5–25 %	Lower	Higher	Same as diesel	Higher	Higher	[25]
Diesel + Waste Cooking Oil	5 %	Higher	Lower	Lower	No change	Lower	[26]
Waste Plastic Oil	5–15 %	Higher	Lower	Lower	Higher	Lower	[27]
Pyrolysis oil	5–10 %	Higher	No change	Lower	Lower	Lower	[28]
Biogas + Karanja Biodiesel	4 %	Higher (+2.3 %)	Lower (−5.8 %)	Lower (−12 %)	Lower (−10.6 %)	Higher (+12.7 %)	[29]
Tire Pyrolysis Oil	4 %	Higher	Lower (−6 %)	Lower	Lower	Lower (−25 %)	[30]
Neem Oil Biodiesel	10 %	Higher (+7.2 %)	Lower (−6.7 %)	Lower	Lower	Lower (−17.5 %)	[31]

ignition properties are excellent. These days, intensive investigation and discussion are being conducted to enhance the performance and degrade the emission profile of diesel engines. DEE is a colorless, highly volatile liquid commonly used as a laboratory solvent and a starting fluid for gasoline engines. It offers significant improvements in combustion quality, cold start performance, and emissions reduction as a diesel additive. It has high volatility and low auto-ignition temperature of about 160 °C and is an excellent candidate to enhance the performance of a diesel engine. Specifically, DEE improves the atomization of fuels and enriches the fuel-air mixture, thus leading to almost complete combustion. In addition, it contains nearly 21 % oxygen by weight and minimizes PM and CO emissions due to its role as supplementary oxygen during combustion. Some of these attributes improve the combustion efficiency of diesel engines while confining the after-treatment system dependency for producing harmful pollutants.

At low concentrations, usually 5–15 %, DEE enhances the engine's cold-starting ability due to its high volatility and rapidity in igniting. This is especially useful in cold-climate areas, where most diesel engines are difficult to start. Research has found that DEE-diesel blends mean shorter ignition delays and smoother combustion processes and thus decrease the noise and vibrations generated by the engine [40,41]. In addition, the BTE values of diesel engines are improved by adding fuel economy through DEE. Indeed, one of the most essential advantages of applying DEE as a diesel additive is its capability to decrease harmful emissions. It was found that the PM and NO_x emissions were reduced due to complete combustion and the oxygenating effect of DEE in the diesel when DEE was added. It mainly works by improving the combustion of diesel fuel and increasing combustion completeness to the maximum extent possible with the minimal formation of soot and other dangerous products. In many studies, a 5–10 % addition of DEE to diesel decreased significant emissions by up to 10–30 %, making it cleaner than conventional diesel (Table 2).

The preparation of the PWO20DA20 blend was done utilizing an ultrasonic emulsification technique. This was done to ensure a more homogenous mixture of polymer waste oil (PWO), diethyl ether (DEE), and diesel fuel. 20 % by volume of PWO was measured and added to a beaker, then 20 % DEE was added. The remaining 60 % diesel was slowly added while stirring with a magnetic stirrer to pre-mix the components. The pre-mixed solution was stirred by ultrasonication with a 750 W ultrasonic processor at a frequency of 20 kHz for 15 mins for proper mixing. The cavitation effects aided in disrupting such molecular aggregates and were instrumental in thoroughly mixing the components. The blend, PWO20DA20, was then stored in an air-tight container to avoid evaporation of DEE and contamination before its use in engine performance testing.

3. Experimental details

The engine study can be done with the help of a water-cooled single-cylinder direct injection diesel engine having an output of 4.4 kW. The test diesel engine operates at 1500 rpm with a 17:1 compression ratio. This investigation was conducted at an injection timing of 21 bTDC and an injection pressure of 210 bar. The test engine was connected to an eddy current dynamometer to provide manual engine loading from zero to maximum load in a step of 25 %. Exhaust pollution from the engine has been studied using an AVL di gas analyzer and its software. Fig. 2 shows the experimentation engine setup. The vital properties of polymer waste oil and diethyl ether additives were tabulated in Table 3.

Determination of the performance and characteristics of the engine involves a lot of uncertainty. This is not only the accuracy of the device being used to measure but may also include all possible errors resulting from the experimental conditions and how the engine is set up. Hence, there is a need to recognize and quantify that uncertainty so that the data derived experimentally is both factual and scientific. Table 4 lists the instruments used in this research along with their specifications. The engine was constantly subjected to three trials to observe the uncertainty in the investigations.

The pilot and subsequent test runs were performed in a standard diesel to develop steady-state conditions within the engine. With those stable conditions accrued, different blends were introduced to investigate the performance in terms of brake thermal efficiency (BTE), specific fuel consumption (SFC), and emissions, mainly focusing on carbon monoxide (CO) and hydrocarbon (HC). Polymer Waste Oil (PWO) testing fuel blends were prepared on a volume basis and blended with standard diesel fuel. PWO20 was blended with 20 % polymer waste oil with 80 % standard diesel. PWO40 comprises 40 % polymer waste oil and 60 % standard diesel. These mixtures were formed to observe the effect of increased polymer waste oil concentration on engine performance and emissions relative to pure diesel. Oxygenated additives in Diethyl Ether additives (DA) were added to enhance the combustion efficiency and emissions. For instance, PWO20DA10 was prepared by mixing 20 % polymer waste oil with 70 % standard diesel and 10 % diethyl ether. Similarly, PWO20DA20 contained 20 % diethyl ether, 20 % polymer waste oil, and 60 % diesel. Lastly, the higher concentration blend PWO40DA10 consisted of 40 % polymer waste oil, 50 % diesel,

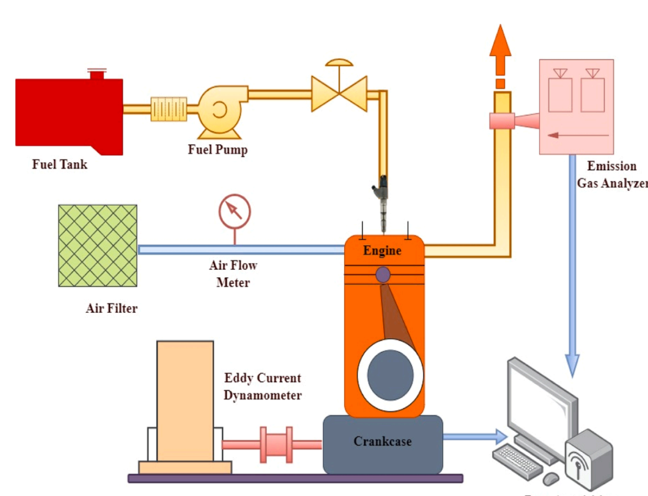

Fig. 2. Test engine layout.

Table 3
Properties of polymer waste and oxygenated additives.

Property	Units	Diesel	Polymer Waste Oil (PWO)	Diethyl Ether Additive (DA)
Lower Heating Value	kJ/kg	42,000–45,000	40,000–45,000	33,000
Density	kg/m³	820–870	850–900	713
Viscosity	mm²/sec	2–4.5	2–4	0.23
Carbon Content	%	85	80–85	64
Hydrogen Content	%	12–14	8–10	13.5
Oxygen Content	%	< 0.1	5–10	21
Cetane Number	–	40–55	45–55	125
Auto-Ignition Temperature	°C	250–300	250	160

Table 4
Engine testing instrument details.

Parameters	Range	Accuracy	Percentage of uncertainty	Instrument
Engine Load	–	+0.25 kg to −0.25 kg	± 0.50	Load cell
Engine Speed	0- 10,000 rpm	± 05 rpm	± 0.25	Digital tachometer
Fuel quantity	0–100 cm³	± 0.10 cm³	± 0.50	Burette Measurement
Hydro Carbon Emissions	0 to 10,000 ppm	± 05 ppm	± 0.25	AVL gas analyser, NDIR technique
Carbon Monoxide Emissions	0 to 15 %	± 0.25 %	± 0.25	AVL gas analyser, NDIR technique

and 10 % diethyl ether. In comparison, PWO40DA20 was formulated by adding 20 % diethyl ether into a blend of 40 % polymer waste oil and 40 % standard diesel. This study aims to ascertain these different blends' performance and emission characteristics in a single-cylinder diesel engine. The aim is to understand the effect of introducing polymer waste oil and diethyl ether on the engine's efficiency and emission. The present study is therefore pertinent as it affects the need for sustainable fuel alternatives with a thrust towards minimizing the environmental impact caused by carbon monoxide and hydrocarbon emissions.

4. Results and discussion

4.1. Study on brake thermal efficiency

Fig. 3 shows the variation of brake thermal efficiency of polymer waste oil performance with an oxygenated diethyl ether additive. In general, PWO20 and PWO40, biodiesel blends from polymer waste oil, show a drop in BTE across the board compared to standard diesel, with a higher reduction of 8.38 % for PWO40 at maximum load. PWO fuel has a higher content of aromatic compounds than diesel fuel, which can be the reason for its lower combustion rate since more energy will be required to break these chemical bonds only through thermal decomposition [39, 42]. However, adding an oxygenated additive, diethyl ether, PWO20DA20, demonstrated better incentive improvement in these blends, wherein BTE increased by 1.27 % relative to diesel and 8.72 % compared to PWO20 at full load. DA allows for a more complete combustion process and minimizes energy losses. Increasing to higher loads, even though DA presents some gains, the trend would be smaller with

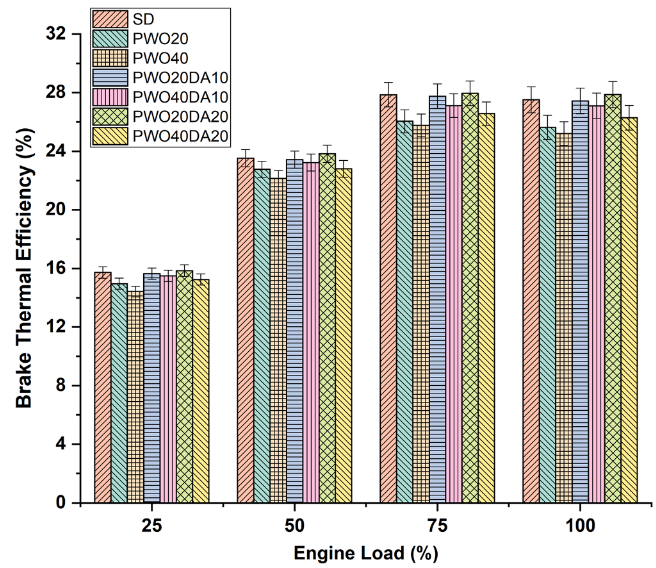

Fig. 3. Impact of Diethyl Ether on brake thermal efficiency.

the increase in demand from combustion efficiency. The presence of DA improves combustion efficiency due to the availability of additional oxygen that promotes full combustion; energy loss due to incomplete combustion is also reduced. This improvement is much more pronounced at lower loads as the oxygenated additive can compensate for combustion temperatures and support better fuel oxidation. Though additives improve the situation at high loads, their enhancement strengths are weakened as demand increases on combustion efficiency, underlining an important balance between fuel composition, oxygen levels, and load requirements [23,40].

4.2. Study on specific fuel consumption

Fig. 4 shows the effects of oxygenated additives on PWO in SFC under different load conditions. The results show that oxygenated additives have enhanced the fuel composition in the PWO beads. Unlike diesel, the notable SFC reductions ranged from 3.4 to 7.2 % for PWO20DA10 and 13.8 to 16.7 % for PWO20DA20. Aside from that, it achieved an impressive 20 to 25.2 % drop in SFC at all points after the load sweep compared to pure PWO20, where DA has a higher cetane rating and

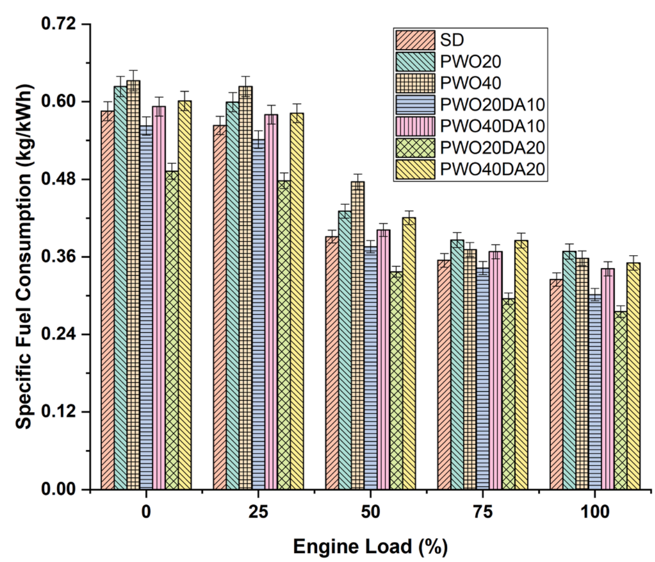

Fig. 4. Impact of diethyl ether on specific fuel consumption.

improves combustion efficiency. It was observed that adding DA will improve combustion due to improved fuel vaporization and spray atomization, thus providing reduced SFC [31]. However, when there were higher amounts of polymer fuel, such as in PWO40, the SFC started to rise by 21 %. This was because the higher viscosity and density of the polymer fuel made it harder to atomize. This feature indicates a critical problem with effective fuel atomization and combustion at higher polymer fuel concentrations [15]. However, the fuel economy improvement was only moderate when the DA concentration was lower, such as in PWO20DA10. However, increasing the DA concentration to PWO40DA20 led to a 16.7 % increase in the SFC at higher engine loads. This shows that lower concentrations of DA can improve combustion. Still, excess polymer content and higher levels of DA lead to poor fuel economy under certain conditions, especially under maximum loads. Balancing the fuel composition and oxygen content is crucial for optimal engine performance with minimal SFC, especially when using a polymer waste-based fuel blend [43].

4.3. Study on hydrocarbons emission

Fig. 5 shows the influence of oxygenated additives on PWO at HC emissions under different load conditions. The polymer waste oil blends, PWO20 and PWO40, significantly increase HC emissions across all load conditions. These PWO blends increased to 7.30–23.67 % of HC due to the accumulation of hydrocarbons unburnt in crevice volumes. PWO blends lead to some incomplete combustion and, therefore, yield more unburned hydrocarbons. This is probably all due to the fuel PWO having a lower cetane number and reduced auto-ignition capability, incomplete combustion, and its quenching effect. Unsaturated aromatic compounds also present in the polymer waste lead to higher rates of HC emission [35,44]. The incorporation of Diethyl ether, an oxygenated additive, typically reduces HC emissions compared with diesel. As can be observed from Fig. 4, the PWO20DA10 and PWO20DA20 blends resulted in significant reductions of hydrocarbon emissions in comparison with diesel by approximately 2.4–5.36 % and 8.96–15.71 %, respectively. This is because DA results in better combustion efficiency with supplementary oxygen introduced via further oxidation that fully oxidizes the fuel, thereby minimizing the emission of hydrocarbons—factors such as reduced vaporization, slower oxidation rates, and a fast fuel consumption rate. Because combustion favors complete combustion with additional oxygen from DA, it results in lower HC emissions [21].

4.4. Study on carbon monoxide emissions

Fig. 6 shows the influence of oxygenated additives on PWO at CO emissions under different load conditions. The polymer waste oil blends, PWO20 and PWO40, demonstrate a consistent increase in CO emissions across all loads. PWO blends show the most significant rise of CO from 13.46 % to 36.40 % when compared with base diesel. This increase suggests that these blends may lead to less complete combustion, producing more CO due to inadequate oxygen availability or suboptimal combustion temperatures. It is also due to higher fuel consumption and insufficient time for complete combustion to break the longer hydrocarbon chains present with PWO blends [45]. In contrast, the addition of diethyl ether, an oxygenated additive, to these biodiesel blends generally results in a substantial reduction in CO emissions; PWO20DA10 and PWO20DA20 reduced CO emissions by 8.7–9.6 % and 15.7–20.81 %, respectively, compared to diesel, while PWO20DA20 showed a significant reduction up to 36.4 % compared to PWO20. The equivalency ratio strongly influences CO generation, determining the balance between fuel and oxygen. Reduced CO emissions can be achieved with a lower equivalency ratio and higher in-cylinder temperatures. With its higher oxygen content, DA improves combustion efficiency by enhancing fuel-air mixing and spray atomization, reducing CO emissions [40].

4.5. Thermo physical and chemical impacts of PWO and diethyl ether additive

The combustion characteristics of polymer waste oil, PWO, derived from polystyrene, are quite different because of the relatively high viscosity and density. These properties adversely affect fuel atomization and air-fuel mixing during combustion. Thus, the physical properties with incomplete atomization and substantially longer ignition delays result in higher emissions of unburned hydrocarbons and carbon monoxide. The aromatic hydrocarbon-rich chemical composition of PWO further retards the combustion kinetics of the fuel because these compounds are more stable and difficult to oxidize. Furthermore, the calorific value of PWO is slightly lower than that of conventional diesel, which may lead to a decrease in the engine's power. The characteristics above make PWO less efficient as a single fuel, resulting in increased emissions and a decreased efficiency in burning [5,46]. Since it is a volatile oxygenated additive with very low viscosity, a low auto-ignition temperature, and a high cetane number of around 125, diethyl ether is an excellent combustion enhancer blended with diesel or polymer waste oils. Diethyl ether significantly improves fuel atomization, reduces

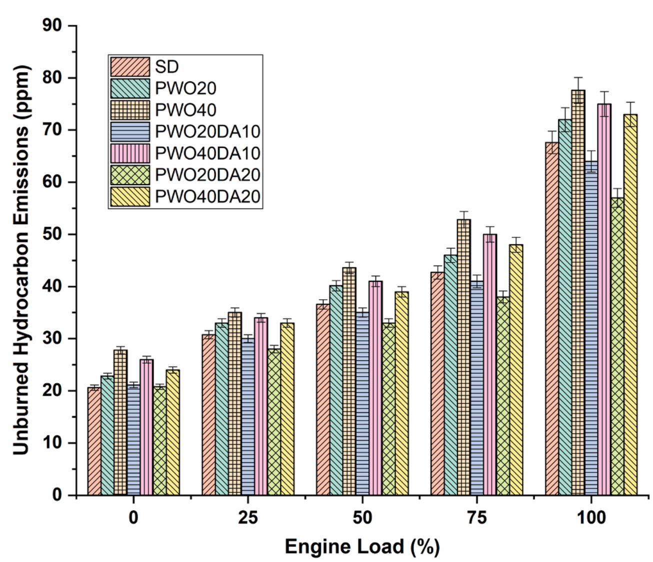

Fig. 5. Impact of diethyl ether on hydrocarbon emission.

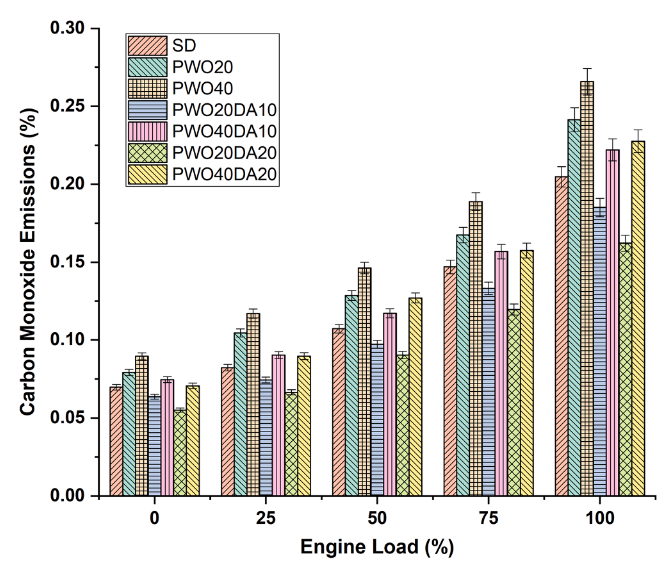

Fig. 6. Impact of diethyl ether on carbon monoxide emission.

ignition delay, and enhances air-fuel mixing, possibly leading to more complete combustion. Its high oxygen content supplies extra oxygen during combustion, enabling better oxidation of hydrocarbons and reduced CO and HC emissions. Adding diethyl ether to PWO significantly enhances combustion performance, overcoming some of the typical difficulties with PWO-related emissions. Combustion difficulties in PWO are compensated for by diethyl ether because of its low viscosity and high oxygen content, as it offsets the combustion kinetics typically related to the higher viscosity of PWO. Ignition delays are also shortened, and atomization is improved, thus contributing to quicker and better combustion of hydrocarbon fragments released from PWO. Diethyl ether also oxidizes the stable aromatic compounds in PWO, which helps increase the oxidation of unburned hydrocarbon, carbon monoxide, and soot emissions. The combination of PWO and diethyl ether balances the negative factors of polymer-derived fuels with an additive of diethyl ether, thus improving combustion, enhancing efficiency, clean combustion, and minimizing emissions [28].

4.6. Combustion mechanism of PWO and diethyl ether additive

The increase in Brake Thermal Efficiency (BTE) and reduction in Specific Fuel Consumption (SFC) in PWO20DA20 and similar mixtures can be ascribed mainly to the betterment of the combustion properties induced by diethyl ether (DEE). Thanks to its high cetane number (~125) and low auto-ignition temperature (~160 °C), DEE shortens the ignition delay and permits more efficient development of combustion. It stands for rapid flame propagation with improved energy conversion efficiency and reduced energy loss, consequent on delays in the combustion phases. The high oxygen content of DEE (~21 % by weight) ensures better mixing of the fuel and air, thus allowing for more complete combustion [26,43]. The oxygen enrichment minimizes the formation of unburned hydrocarbons (HC) and carbon monoxide (CO), typically demolished witnesses to incomplete combustion. This property becomes critical for higher load operating conditions regarding efficient atomization and complete oxidation, resulting in faster combustion reactions. DEE showed its benefits in reducing the viscosity, increasing the boiling point, and thus enhancing fuel atomization due to smaller droplets that further the air-fuel mixing. This helps alleviate the problems caused by the reduced viscosity and density of polymer waste oil, which causes zones whereby a rich fuel condition occurs and quenching during high engine loads, further avoiding incomplete combustion. Together, these factors ensure uniform in-cylinder pressure and smooth flame propagation.

The shorter ignition delay period caused by DEE will not allow much time to set in and build up fuel-rich zones, lowering HC and CO emissions. In PWO20DA20, this mechanism contributed to a 15.71 % reduction in HC and a 20.81 % reduction in CO compared to conventional diesel. The improved combustion dynamics also yield an increase in BTE by 1.27 % over diesel and 8.72 % against PWO20, rendering this blend an energy-efficient alternative. As an oxygenated additive, DEE ensures a stable combustion process; this is remarkably imparted when the base fuel's cetane number is lowered, resulting in delayed ignition and compromising performance. According to researchers [21,47], the added oxygen from DEE balances ignition delays and allows for complete oxidation of hydrocarbons, while high volatility contributes to rapid and uniform propagation of flames, reducing the duration of combustion and quenching effects. These properties stabilize the flame, reduce knock potential, and augment energy conversion efficiency. Higher heat-release rates achieved due to DEE-enhanced combustion will ensure higher in-cylinder pressure, releasing more energy from fuel during combustion. The rapid ignition and reduced quenching zones enabled by DEE are claimed to lower HC and CO emissions while enhancing combustion efficiency overall [26]. Speeding up flame propagation will help reduce uneven heat distribution and enable homogeneous pressure build-up within the cylinder to enhance thermal management and combustion dynamics.

5. Sustainability study of diethyl ether with PWO

5.1. Influential study of SFC

The plots (Figs. 7 a, b) revealed that an increase in PWO alone led to the rise in SFC, and the introduction of DA decreased the SFC. For instance, when 5 % DA was added along with 5 % PWO, the outcome was a SFC value that was approximately 0.3 kg/kWh, a midrange value and, thus, depicted the positive role of DA in compensating for the higher values of SFC that PWO caused. As PWO percentages move down the lower end (0–10 %), SFC values go down sharply, meaning that a smaller percentage of polymer waste oil goes a long way to achieve better combustion efficiency. At 20 % PWO, the SFC remains high at 0.32 kg/kWh but below the maximum value. At 40 % PWO, SFC approaches its highest value, approximately 0.368 kg/kWh, indicating a drastic reduction in fuel efficiency at the high concentrations of the PWO. Typically, it contains longer hydrocarbon chains with lower volatiles; hence, using it in a high percentage may lead to incomplete combustion.

The minimum SFC contour plot should then indicate that a low-to-moderate level of PWO (5–10 %) along with a high level of DA (15–20 %) may be optimal for reducing the specific fuel consumption while exploiting the combustion-enhancing properties of DA. It can be noted from the curves that with the PWO increased to its maximum value of 40 %, SFC shows an increase of about 5 %. However, for DA, on the other hand, which enhances combustion with its higher volatility and oxygen content, there is a much steeper decline in SFC values at lower values of PWO. For instance, at a 5 % DA and 5 % PWO, the SFC is 0.3 kg/kWh, while with a 20 % DA and 0 % PWO, it goes down to about 0.275 kg/kWh. This indicates that an increased DA leads to more efficient combustion due to more oxygen availability, a consequent increase in nearly complete combustion, and a decrease in fuel consumption. The contour plot indicates that the lowest values for SFC occur if the level of DA is high, around 20 %, and PWO values are kept low. As the plots confirm, levels of DA higher than this, in the 15–20 % range, continually resulted in lower SFC values. The SFC is lowest at 20 % DA and 0 % PWO, at about 0.275 kg/kWh; this implies the enhancement of combustion due to DA, which causes higher ignition speed and efficiency and lower fuel consumption for equal power production.

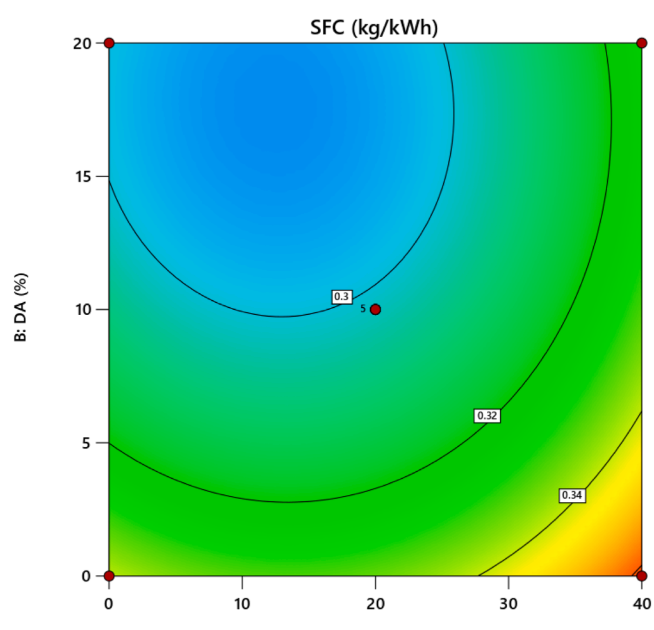

Fig. 7a. Influential study of SFC.

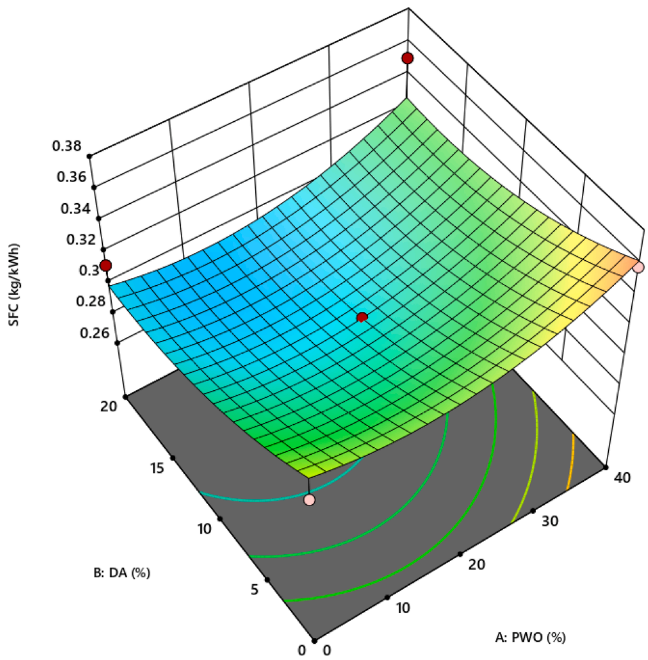

Fig. 7b. Influential study of SFC.

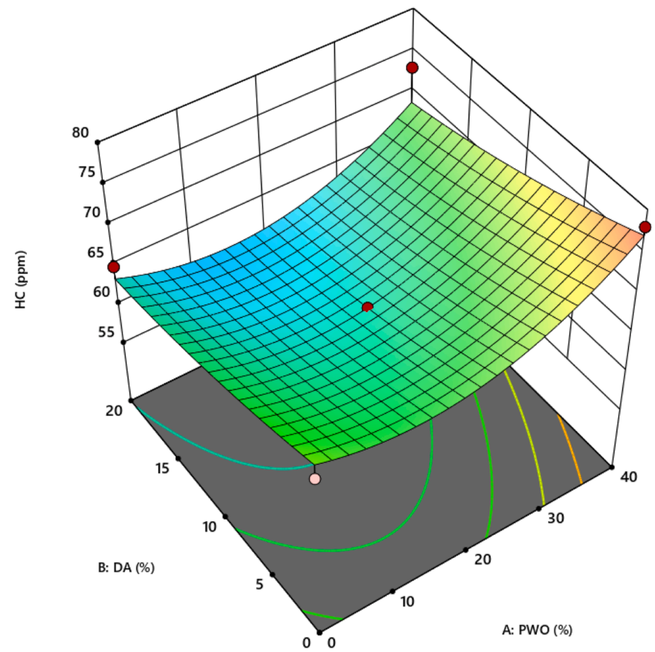

Fig. 8b. Influential study of HC.

5.2. *Influential study of HC emissions*

The oxygenation effect of DA contributes to lowering HC emissions with increased levels of DA. Oxygenated additives, such as diethyl ether, contribute to efficient combustion by reducing incomplete combustion, hence HC emissions. The concave topography, as shown in Fig. 8 a, b, features its lowest point and represents its best emission performance when DA is maximized at 20 % and PWO around 10–15 %. At 40 % PWO and 0 % DA, HC emission increases to about 75 ppm. This can only be attributed to the increased viscosity and reduced volatility of higher PWO blends, contributing to larger fuel droplet size, poor atomization, and incomplete combustion, increasing HC emissions. It is seen that lower values of DA coupled with higher PWO blends lead to increased emissions of HC, which indicates less efficient combustion. Higher PWO blend ratios mean higher fuel viscosity and poor spray characteristics, leading to incomplete combustion and higher HC emissions.

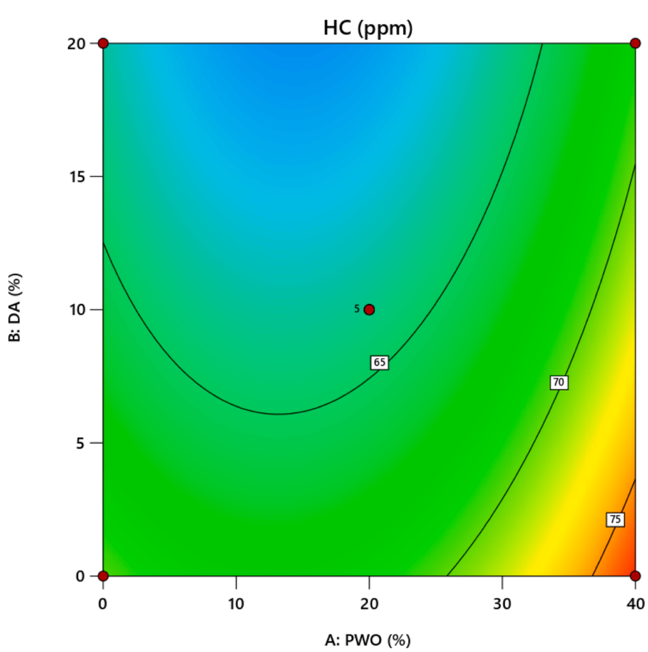

Fig. 8a. Influential study of HC.

On the other hand, an increase in the DA concentration generally decreases HC emissions by enhancing fuel volatility and improving combustion efficiency. DA improves fuel ignition characteristics to give more complete combustion and lower emissions of HC. As the DA % increases to 20 %, it corresponds to a significant drop in HC emissions, with a minimum observed around 57 ppm. A moderate level of PWO of around 20 % gives a low DA, resulting in moderate HC levels of around 65 ppm. The HC emissions are at their minimum when PWO and DA are lower, especially under 10 %. This is because combustion has practically reached completion in that range. After all, fewer unburned hydrocarbons are emitted. Adding DA, a cetane improver, would further facilitate combustion efficiency by reducing the ignition delay and allowing complete combustion at moderate loads that reduce HC emissions. The functional concentration range for DA is in the middle portion, which is around 10 %, where HC emissions are kept low. HC emissions increase steeply at PWO higher than 20 %, and the increase in emissions to a maximum of about 40 % PWO indicates that higher concentrations of PWO correlate with less efficient combustion. Long-chain hydrocarbons in PWO would likely contribute to partial combustion, increasing the exhaust content of unburned hydrocarbons.

5.3. *Influential study of CO emissions*

The contour plot (Figs. 9 a,b) leads to an interaction between the levels of PWO and DA that influences the CO emissions. The CO percent lowers at low percentages of PWO that range within 0–10 %, while the concentrations of DA range at low percentages too, within 0–10 %, and the CO percentage remains relatively low, around 0.16 %. With increased DA concentration, the CO emission generally decreases because of improved combustion characteristics, such as better ignition and more complete fuel combustion. The surface is relatively low and flat for the parts with low percentages of PWO and DA. This is another way of saying that the lower percentages of these additives are very useful in minimizing CO emissions, possibly because the combustion of the fuel-air mixture is more effective. However, as the PWO increases beyond 20 % and the DA concentration above 10 %, the CO percent

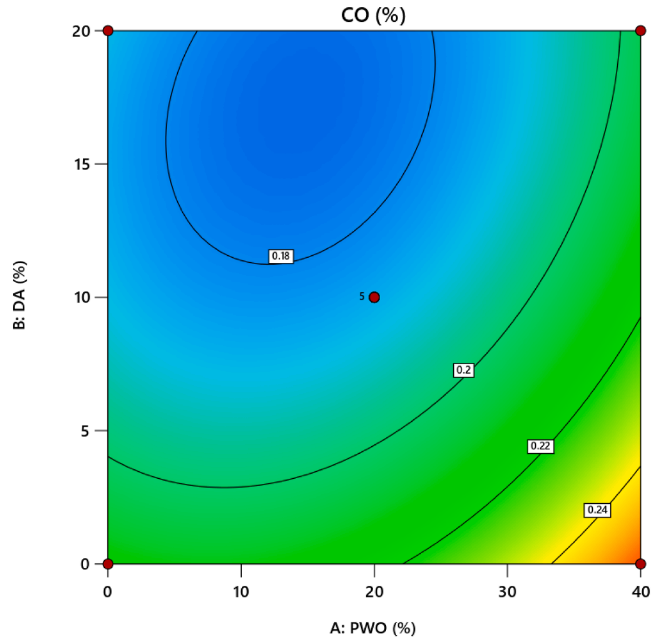

Fig. 9a. Influential study of CO.

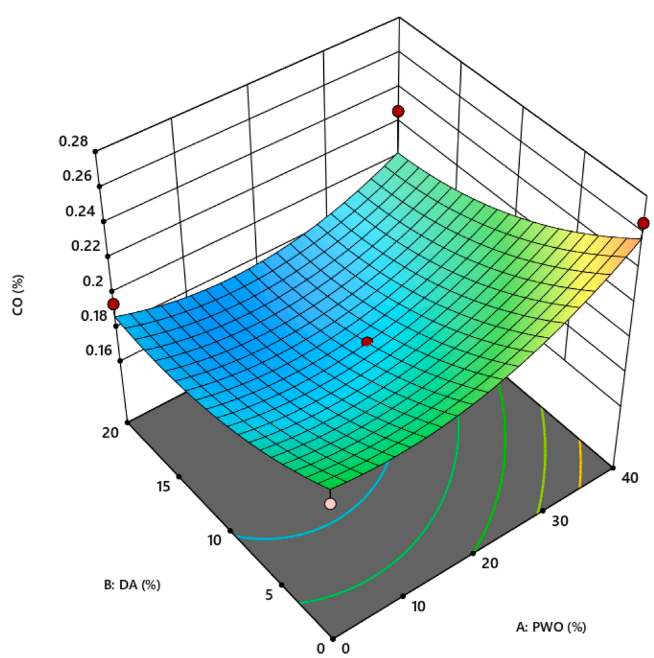

Fig. 9b. Influential study of CO.

levels increase slightly by about 0.18–0.2 %. It is in the upper right corner that the highest emissions take place (0.24–0.26 %). At higher percentages of PWO and DA, the surface tilts upwards at the top, with maximum CO emissions observed when PWO is 40 % and DA is 20 %. This suggests that while the oxygenated additive, DA, can enhance combustion at moderate levels, a higher level of both variables leads to a higher output of CO, possibly due to an imbalance of the fuel-to-air ratio. There, PWO and DA percentages are maximized, suggesting that beyond a point, increasing the concentrations of both PWO and DA could lead to higher CO emissions due to partial combustion or oxygen-related deficiency. This probably results from poor atomization and higher viscosity with higher PWO blends that lead to incomplete combustion and, thus, higher CO emissions.

5.4. Optimization of PWO and diethyl ether additive

Incorporating DA (Diethyl Ether Additive) and PWO (Polymer Waste Oil) into fuel blends holds enormous potential in ensuring the improvement of combustion performances. Diethyl Ether has high volatility, making it an oxygenated additive well known for having a low auto-ignition temperature and high vaporization and oxygen content, allowing the combustion process in diesel engines to be collectively improved. It is recycled material from plastic wastes and, therefore, faces challenges concerning combustion efficiency because it contains higher viscosity, lower volatility, and reduced oxygen content than conventional diesel fuels. However, its combustion characteristics can be markedly improved when blended with DA, as inferred from the optimization plots of Response Surface Methodology plots, as shown in Fig. 10. A highly enhances combustion through complete and effective oxidation of fuel. As evidenced in the SFC curve, an increase in the percentage of DA is seen to cause a drastic reduction in fuel consumption, mainly with moderate contents of PWO up to 20 %. The high volatility of DA facilitates good atomization of fuel, which ensures good air and fuel mixing within the combustion chamber, thus ensuring uniform combustion. No doubt, oxygen blending from DA balances the oxygen deficit with PWO, thereby minimizing incomplete products such as CO and HC. At higher levels of DA between 15 and 20 %, lower SFC values of about 0.3 kg/kWh reflect greater thermal efficiency in combustion, hence the reduced fuel requirement for the same energy output. PWO is less effective as it has a high viscosity, which may result in poor atomization, insufficient combustion, and higher pollutant emissions such as CO and HC. The plot for CO displays direct proportionality between increased PWO percentage and a rise in CO emission, primarily when PWO exceeds 20 %. This is mainly because PWO has no oxygen content needed for efficient combustion and suffers from incomplete combustion of large droplets. However, with a mixture of PWO blended with DA, the oxygenated character of DA and its low auto-ignition provide critical mechanisms for enhancing combustion from the PWO, allowing for CO emission to be lowered to <0.18 % and permitting better combustion even at modest levels of PWO, 10–20 %.

The interaction of DA and PWO alters the general pattern of the emission produced by the fuel blend. Typically, CO and HC emissions increase in the event of incomplete combustion. The HC plot shows that the hydrocarbon emissions are increased at a higher concentration of PWO above 30 % with a steep slope reaching nearly 70 ppm due to poorer combustion of heavier hydrocarbon molecules in the waste oil. However, moderate DA levels of about 10–15 % enhance combustion because such levels introduce supplementary oxygen into the oxidizer, which contributes significantly to the oxidative degradation of unburnt hydrocarbons. The contribution of DA towards lowering the ignition delay and enhancement vaporization tends to reduce the formation of both CO and HC emissions. The optimum blend of 10–20 % PWO and 10–15 % DA balances fuel economy with emission control. The desirability plot (Fig. 11) for this blend is centered at 0.829 maximum desirability, and the best of the blends proved to be the most favorable for clean combustion with very low emissions and efficient energy usage. This optimal mixture reduces specific fuel consumption to 0.3 kg/kWh while keeping carbon monoxide and hydrocarbon emissions below acceptable limits, such as at <0.18 % CO and about 61 ppm HC.

5.5. Sustainability improvement of PWO

Carbon monoxide (CO) and hydrocarbons (HC) emissions from diesel engines are harmful not only to the environment but also to human health. CO can lead to problems in the body concerning carrying oxygen, resulting in severe health impacts like headaches, dizziness, and, in extreme cases, death. Hydrocarbons contribute to forming ground-level ozone, or smog; they damage plant life, reduce crop yields, and exacerbate respiratory illness, including asthma, in humans. Long-term exposure to HC has been linked to cancer and other significant health

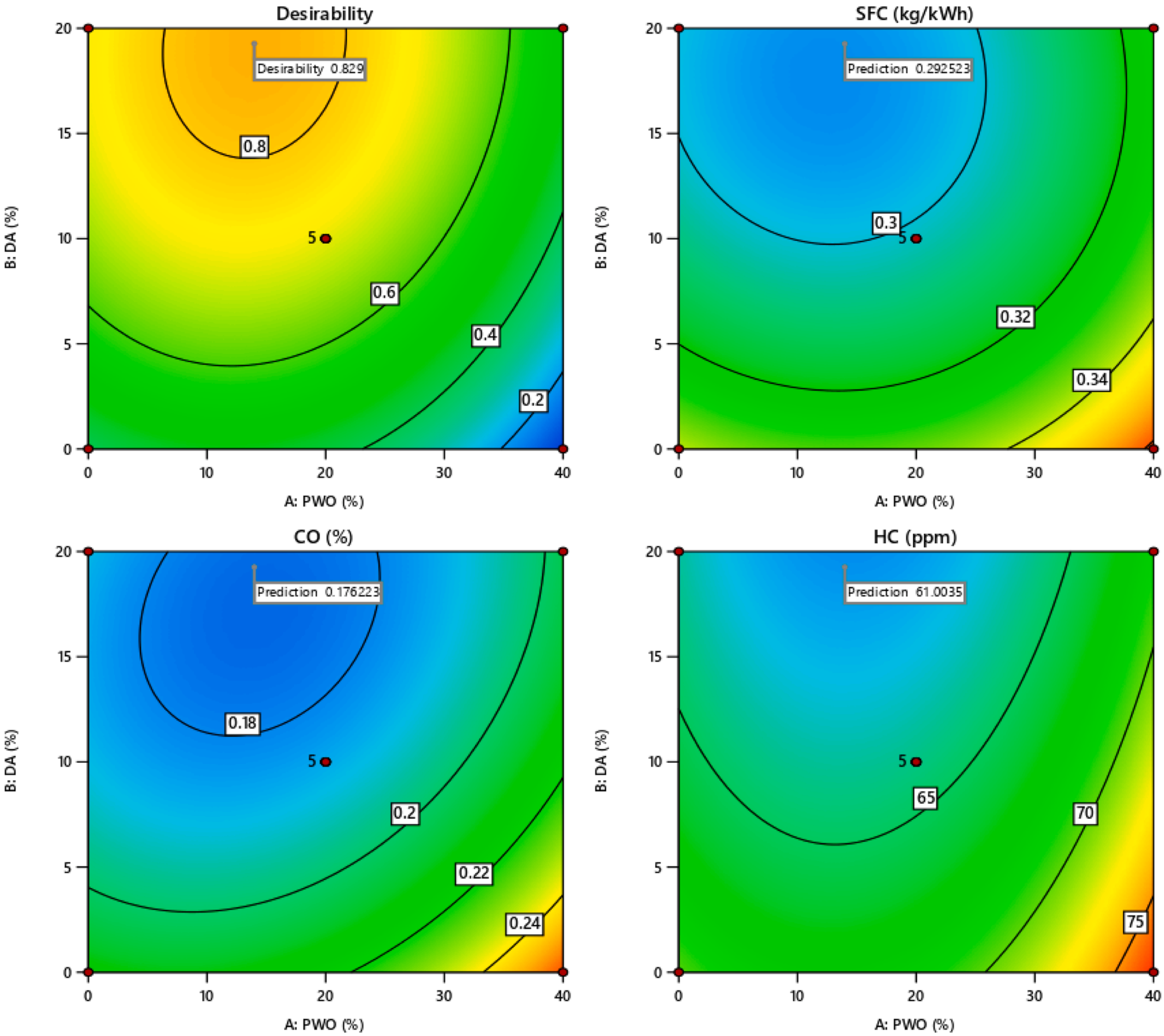

Fig. 10. Optimization contour plots.

effects [48]. This issue can be addressed by limiting the CO and HC emissions by fuel enhancement. The PWO and diethyl ether additive mixture presents a potential answer to the problems encountered in plastic waste that may be triggered through energy recovery and hazardous gases, such as hydrocarbons and carbon monoxide. Plastic waste, specifically polystyrene, is not biodegradable, making it a serious threat to the environment, with many tons of plastics remaining in landfills and oceans [49]. Converting this waste into PWO solves the issue of plastic pollution and, instead, renewable fuel sources. Introducing the DEE in a blend with PWO effectively solves both low viscosity and high cetane number with oxygen content, promoting more efficient fuel atomization and faster ignition, decreasing known ignition delay associated with PWO. This will provide for better and cleaner combustion, thus lowering the emissions of CO and HC. Moreover, DEE breaks down the stable aromatic compounds of PWO, minimizing the quantity of pollutants released into the environment. It also adds energy utilization while combining PWO and DEE, which helps improve the brake thermal efficiency of the engine. Such cleaner combustion means a smaller environmental footprint because, compared to traditional waste incineration, which typically has higher pollutant emissions, such blends may help in a circular economy by reducing fossil fuel dependence and providing a sustainable solution to waste management and energy production [27,50].

5.6. Circular economy and plastics recovery

The circular economy model is fast becoming a fundamental approach to plastic waste management, involving waste reduction and efficient reuse for minimum environmental impacts and savings in natural resources. The linear model, where products are found in a landfill once the lifecycle has been completed, does not preserve the value of products and materials, as they can only be reused, recycled, or regenerated. For plastic waste, especially non-biodegradable polymers such as polystyrene, this approach opens up new ways of converting waste into valuable resources rather than relegating them to landfills [51]. Plastic pyrolysis into fuel oil (PWO) is a practical circular economy solution that transforms plastic waste into energy sources for diesel engines when combined with oxygenated additives like diethyl ether (DEE). Apart from reducing environmental pollution, this acts as a supplement for developing a renewable fuel source and fosters a

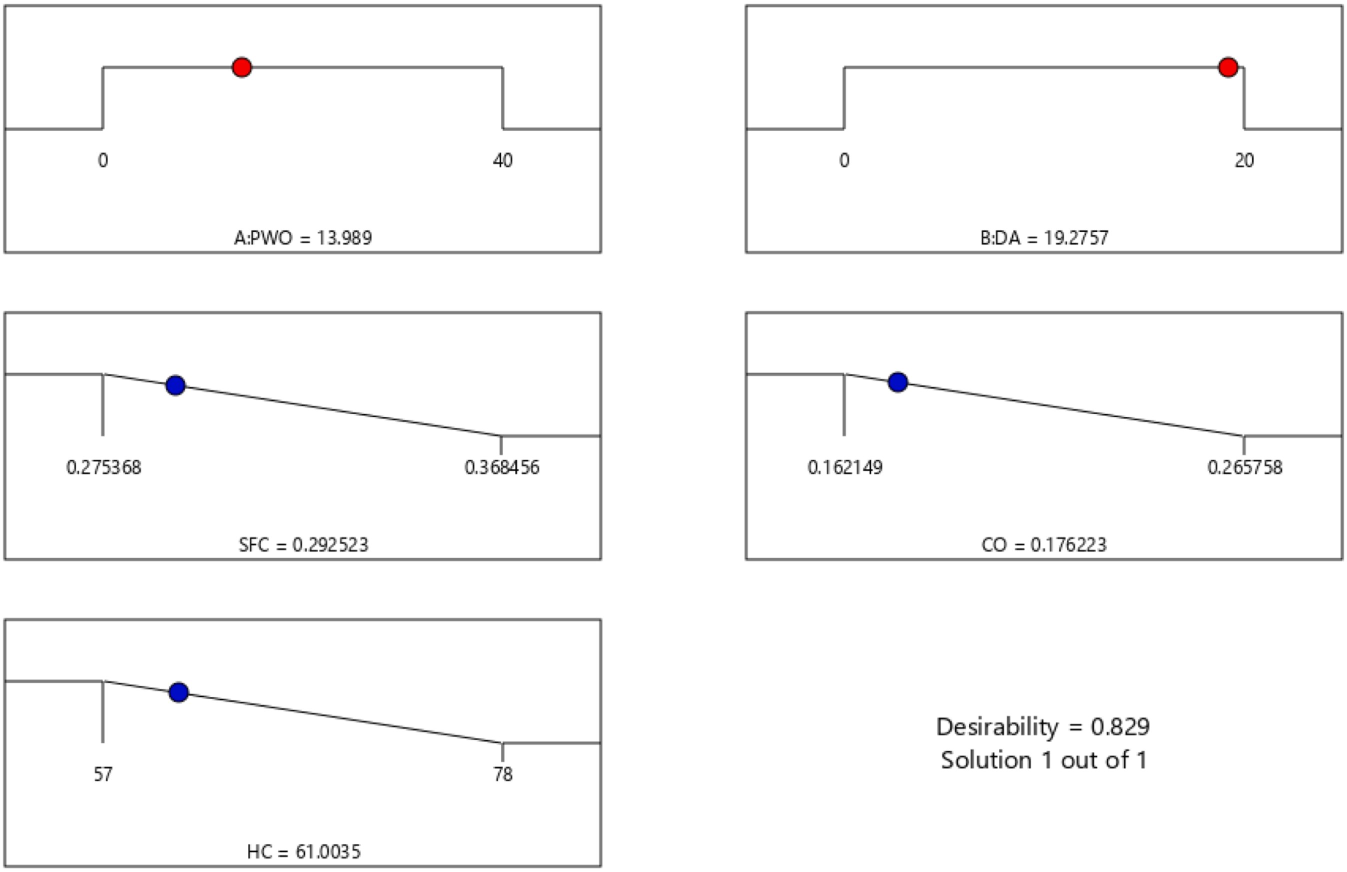

Fig. 11. Optimal parametric results of PWO and DA.

regenerative cycle of the material.

The energy recovery process through pyrolysis of polystyrene is the key to realizing the circular economy model for plastics. Pyrolysis is a thermal decomposition process in which plastic is converted into liquid hydrocarbons without oxygen, thus producing an oil that can be effectively blended with diesel fuel. The energy content of polymer waste oil (PWO) is comparable to conventional diesel, offering approximately 40–45 MJ/kg, near the 43 MJ/kg energy yield of diesel. This high energy recovery rate is one of the prominent advantages in alignment with circular economy principles: reintroducing waste as an efficient fuel source instead of mere virgin fossil fuels. Secondly, the general conversion efficiency of polystyrene-to-fuel in the pyrolysis process lies in the 70–75 % spectrum, thus ensuring that a significant part of plastic waste can be converted into energy, making the approach more economical and resource-friendly [52].

Reducing emissions and pollutants is an essential element in the circular economy. The blends of PWO and DEE, particularly such formulations as PWO20DA20, significantly improved the performance of diesel engines. For example, the BTE and SFC are improved compared to conventional diesel fuel. As for the oxygenated properties of DEE, the combustion of DEE-based fuels enhances optimality. In this manner, emissions of hydrocarbons (HC) and carbon monoxide (CO) are reduced by 15.7 % and 20.8 %, respectively, thereby bettering air quality and health cost benefits of pollution. By reducing harmful emissions, this way of blending fuel realizes one of the basic tenets of a circular economy: resources must be recycled without harming the environment. Hence, a circular economy for plastics supports a broader environmental agenda by contributing to the saving of resources and reducing climate change through reduced virgin extraction of fossil fuels. For example, recycling plastic material into fuel saves virgin sources of fossil fuel extraction for use, conserving this natural resource while at the same time reducing their carbon footprint during fuel production and consumption [53]. Polymer waste oil in fuel blends reduces diesel engines' carbon intensity, lowering greenhouse gas emissions per kilometer traveled. Adoption in urban areas where diesel engines mainly contribute to air pollution can bring public health benefits through reducing exposure to pollutants.

6. Experimental constraints and future scope

6.1. Emission challenges

Plastic materials, such as polystyrene, break into liquid fuels, gases, and solid residues through thermal degradation in oxygen-free conditions around 350–500 °C, frequently using a catalyst like zeolites. Although pyrolysis avoids emissions derived from combustion, there will still be the production of CO2, CO, NOx, VOCs, and PM from the combustion of its products. Such emissions, if managed improperly, pose serious environmental and health hazards, aiding further in the unfolding of air pollution and climate change. High-temperature combustion processes are generally needed for efficiency, and this leads to an increase in the nitrogen oxide (NOx) formation levels since the in-cylinder temperatures are high and more oxygen is available in DEE-enriched blends.

Many advanced approaches along the line of emission control exist to handle this situation. EGR is a technology that lowers maximum combustion temperature by recycling exhaust gases, preventing NOx formation. Another style of additive that will reduce NOx to non-toxic gases, like nitrogen and water, using a catalyst, along with reducing agents like ammonia or urea, also exists. Another option is the catalytic converter and scrubbers, which will capture CO, VOC, and PM for cleaner exhaust. Adaptive combustion control strategies could also modify ignition timing and fuel injection parameters, thereby averting temperature spikes and the excessive formation of NOx. These ought to be joined together with adequate maintenance and monitoring as well. Future studies incorporating live monitoring of in-cylinder pressure and NOx determinations will account for further refinement in a combustion scenario that permits reasonably high thermal efficiency with generally low pollution output in PWO-DEE blends.

6.2. Feedstock handling and regulatory standards

Additives such as diethyl ether (DEE) increase combustion efficiency, lower emissions, and improve fuel properties but introduce safety and environmental concerns. DEE's volatility and flammability require stringent handling and storage procedures, such as explosion-proof containers and temperature-controlled environments. Furthermore, the need for safe and sustainable alternatives emerges along with DEE's lifecycle environmental impact. While the process is currently optimized for polystyrene as a feedstock due to its favorable pyrolysis characteristics, the blending of different plastics or the presence of contaminants results in inefficiencies within the process because of varying chemical and physical characteristics. Solutions like advanced sorting and decontamination techniques are proposed to expand feedstock compatibility, thus making even more diverse plastics useable without affecting fuel quality and yield.

Handling plastic waste and chemicals such as DEE is closely regulated for safety. DEE storage must comply with OSHA and NFPA regulations, with periodic safety audits and training for personnel to avert the risk of fire and explosion. There has to be careful disposal of residual by-products, like the char and non-recyclable residues. Char may find its usage as a soil additive, concrete modifier, or activated carbon, thus offering economic and environmental benefits in the long run. The non-recyclable residues would be subjected to an advanced treatment like gasification or incineration employing Emission Control Systems whereby energy generation would extract value from waste while minimizing environmental impact. These measures ensure compliance with regulations, reduce exposure risks and foster sustainable waste management in the overall plastic-to-fuel conversion system.

6.3. Scaling and economic viability

Scaling the plastic-to-fuel process to the industrial stage entails many logistical and infrastructural challenges, including ensuring a continuous supply of plastic waste and establishing large-scale processing facilities. To address feedstock supply challenges, strong partnerships among municipal waste management agencies and private recyclers must be formed. Decentralized collection centers near sources of waste should ensure reduced transportation costs and smooth supply lines. Significant investments should be made in high-throughput reactors, preprocessors, and emissions management systems, while a modular plant design permits scalability according to demand and feedstock availability. Additionally, incorporating renewable energy into plant operations will share economic and environmental benefits. Training programs designed to prepare the workforce should grant access to advanced technologies (like predictive maintenance systems) to ease large-scale operations and support plastic-to-fuel plants' long-term scalability and sustainability.

The capital and operating costs for plastic-to-fuel recovery plants are relatively high compared to conventional fuel systems. This infrastructure is especially required as there are pyrolysis reactors and emission control systems, which can add 20–30 % to the startup cost compared to a traditional refinery [42]. These costs can, however, be alleviated by government incentives, tax credits, and carbon credit schemes. Earnings generated from by-products such as char and syngas complement the revenue streams. Also, those modular plant designs and automated systems will enhance operational efficiencies to minimize energy consumption and upturn fuel yields. A feasibility study, including numerous costing details, revenue generation, market demand, and regional plastic waste availability, would ensure financial sustainability. A balance between weighing far-sighted profit and environmental benefit against the initial investments is fundamental to making it competitive.

6.4. Life cycle and real-world conditions

Laboratory formulations of PWO-DEE blends have shown promising achievements in BTE, SFC, and emissions; however, additional work is still required to establish foundations or references for comparison. Varying driving conditions strongly influence combustion dynamics, including transient engine speed, load cycles, and climate changes. For example, the volatile nature of DEE could be hindered by low ambient temperature conditions in its application, causing ignition delays and inefficient combustion during cold starts. Blending caused by urban stop-and-go traffic detrimentally promotes air-fuel stability. More testing should now be conducted to ascertain the conditions' performance conformity. Long-term field testing is thus critical to assess the effect on injectors, valves, and combustion chambers for engine durability over extended periods in practice.

PWO-DEE blends are less expensive across the lifecycle than traditional diesel. The relatively cheap feedstock of waste plastics allows for low production costs, while fuel consumption and operating expenditure are lowered through DEE's efficiency enhancements. Decreased emissions result in compliance with environmental regulations, hence avoiding carbon taxes and possibly bringing in subsidies. Compared with biodiesel, hydrogen, and electric vehicles, PWO-DEE blends are much cheaper and scalable. Further lifecycle analyses and tests in the field will finally verify the PWO-DEE's viability as a competitive, sustainable fuel alternative.

7. Conclusion

Recovering plastic waste into usable fuel is a pioneering step towards applying circular economy principles to address plastic pollution. It transforms waste into valuable resources, aligning economic incentives with the Sustainable Development Goals. The work shows that a polymer waste oil recovered from polystyrene waste using diethyl ether as an oxygenated additive is a promising way in which energy recovery from plastic waste can contribute toward environmental sustainability. It has been found that the PWO blended with diethyl ether as an oxygenated additive derived from polystyrene has shown promising results for enhancing fuel performance and reducing emissions in diesel engines. A high brake thermal efficiency of 1.27 % was recorded by the PWO20DA20 blend compared to diesel and 8.72 % higher than PWO20, indicating its better energy utilization. In addition, tremendous reductions in SFC are realized. PWO20DA10 reduces SFC by 3.4 % to 7.2 %, while PWO20DA20 achieves reductions of up to 13.8 % and 16.7 %. Emission analysis further reveals the environmental benefits with a remarkable decrease in HC emissions by 15.71 % and CO emissions by 20.81 % in PWO20DA20 concerning diesel. Desirability analysis identified the optimum mix of 13.9 % PWO and 19.3 % DEE, which achieved SFC as low as 0.2925 kg/kWh with HC emissions at 61 ppm and CO at a minimal 0.1762 %. These results prove to be efficiency and environmental compatibility.

This research aligns itself with circular economy principles, involving the valorization of plastic waste, a harmful product for the environment, into valuable fuel resources. This work brings forth the conversion of polystyrene waste into polymer waste oil and its enhancement with DEE. It successfully bridges the gap between waste management and sustainable energy production. This approach has gained popularity by providing a strategy to deal with plastic pollution while simultaneously prospects toward achieving Sustainable Development Goals (SDGs) as economic incentives with environmental returns exist. The methodology promotes a transition from waste to energy, allowing for resource recovery and a closer loop in material use. Further, applying such renewable fuel blends into diesel engines might significantly reduce the dependency on fossil fuels, reducing greenhouse gas emissions and enhancing environmental sustainability. This work provides significant social benefits due to the solution for two major global challenges on plastic waste management and energy sustainability. Solutions proposed reduce pollution levels, provide cleaner fuel alternatives, and enhance energy security, especially in diesel engine-dependent regions in transportation and industrial activities. Future innovations would further this cause to a cleaner and greener resource-efficient future. Future works should focus on incorporating nano-additives into blends of PWO and DEE to increase combustion performance and reduce emissions.

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Data availability

All data are available within the manuscript only.

CRediT authorship contribution statement

S. Baskar: Funding acquisition, Data curation. **Padmanabhan S:** Writing – review & editing, Writing – original draft, Conceptualization. **A. Raman:** Funding acquisition, Formal analysis. **Venkatesan M:** Supervision, Project administration. **Ganesan S:** Resources, Investigation. **K.M. Kumar:** Validation, Software. **Mahalingam S:** Visualization, Validation.

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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