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Effect of Graphite Nanoadditives on the Behavior of a Diesel Engine Fueled with Pyrolysis Fuel Recovered from Used Plastics

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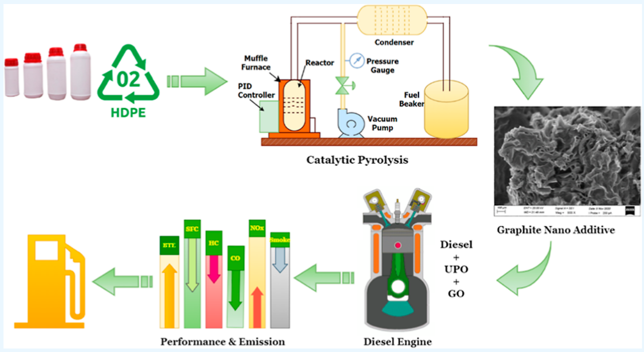
ABSTRACT: Plastic waste accumulation is a significant threat to the environment and humans. Pyrolysis is a promising method for recycling plastic waste since all of the yields are useful, reducing the associated environmental risks of plastic waste. Energy recovery from used plastic waste can help restore ecosystems by utilizing waste as fuel while addressing the environmental problem of plastic disposal. This study experimentally investigates the application of oil obtained by the pyrolysis of waste high-density polyethylene (HDPE) as a viable energy source for diesel engines, offering a unique solution to the issues of plastic waste and energy sustainability. The catalytic pyrolysis method was employed to convert used HDPE plastics into a fuel called used polymer pyrolysis oil (UPO). The UPO was blended at 20% and 40% on a volume basis with mineral diesel. The graphite nanoadditives of 50 and 100 ppm were doped to enhance the properties of the UPO20 blend. The results showed that UPO20n100 blends exhibited a 2.79% increase in brake thermal efficiency and an 11.6% reduction in specific fuel consumption compared to diesel. Utilizing the UPO20n100 blend as a diesel engine fuel resulted in reductions of hydrocarbon, carbon monoxide, and smoke emissions by 8.9%, 9.9%, and 8.9%, respectively, compared with diesel operation. These findings provide a pathway for reducing plastic pollution and reliance on fossil fuels, with significant implications for the development of sustainable energy solutions. Additionally, this study presents a novel application of graphite nanoadditives in fuel blends prepared from used plastics, highlighting their significant impact on enhancing engine efficiency and reducing emissions.



1. INTRODUCTION

In the current scenario, the requirement of energy is increasing due to the rise in population and the lavish lifestyle of human beings. The transportation sector is one of the largest energy consumers and relies heavily on fossil fuels.[1] Fossil fuel reserves are finite and are available in certain regions of the world. It is also anticipated that it will last only a few decades. The combustion of fossil fuels emits carbon dioxide (CO_2) and other greenhouse gases (GHGs), which are severely affecting the environment and human beings.[2] The transportation industry is responsible for around 25% of CO_2 and 15% of GHG emissions globally.[3] Global climate change and the negative impacts of higher carbon emissions have garnered significant attention throughout the world. Consequently, many efforts are being made to locally develop carbon neutral fuels to mitigate climate change and promote sustainable economic development.[4]

Polyethylene (PE) is the most extensively utilized material worldwide, accounting for around 36% of the overall plastic consumption.[5] Polypropylene (PP) has a market share of 20%, followed by poly(vinyl chloride) (PVC) with 13% and polyethylene terephthalate (PET) with 9%. These plastics are widely used in packaging, construction, textiles, and consumer goods. The versatility and affordability of PE make it widely used, but PP is preferred for its durability. PVC is commonly utilized in the construction and infrastructure sectors, whereas PET is extensively employed in the packaging of beverages and food products. Consumer preferences and environmental concerns may cause changes in global plastic consumption patterns.[6]

The excessive use of plastic made items has led to substantial environmental issues, particularly the accumulation of plastic waste in both landfills and natural ecosystems, because after a certain period of life, the plastic is thrown into the environment. Over the past five decades, plastic production

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has increased substantially, resulting in plastics constituting a considerable proportion of household garbage. Cigarette butts, straws, plastic bottles, tea cups, chocolate wrappers, etc., are the most common microplastics thrown into the open environment, and hence, waste accumulates. When this waste is dumped into landfills, methane and other GHG gases are released, which are equally harmful for the environment, wildlife, and humans.[7] Therefore, these alarming consequences caused by plastic waste are of grave concern in the scientific community. Researchers and policymakers are increasingly emphasizing sustainable alternatives and innovative recycling technologies to mitigate the adverse impacts of plastic waste. Effective management of plastic waste has become imperative due to the substantial environmental and health hazards associated with traditional disposal methods, such as landfilling and incineration. Recycling and reuse of plastic waste presents a promising approach to addressing these challenges.

Many researchers have proposed recycling of waste into fuel because it solves the problem of waste accumulation and also helps the economy.[8,9] One practical way to dispose of plastic waste is through the pyrolysis process, which also provides an alternative source of fossil fuel and helps lower the world's fuel consumption. Thermochemical recycling of plastic waste into useable fuel is known as plastic pyrolysis. This is accomplished by reducing long-chain polymers to their component parts in an oxygen-free environment. Thus, plastic pyrolysis has become an attractive and financially prudent way to recycle plastic waste. The method is advantageous because it permits the direct feeding of plastic garbage without prior processing and does away with the requirement for presorting.[10]

The yield of the pyrolysis of plastic waste is generally termed waste plastic oil (WPO), which has physical and chemical properties comparable to diesel. In previous studies, fuel produced from the pyrolysis of plastic waste was used in CI engines. An investigation was conducted to examine the effects of fuel derived from the pyrolysis of waste PET bottles (WPOB) on the diesel engine characteristics.[11] WPOB's combustion exhibited a slower rate compared to base fuel diesel, resulting in higher emissions of carbon monoxide (CO), unburnt hydrocarbon (HC), and smoke. Utilizing neat WPOB directly in diesel engines was not recommended due to the longer delay (ID) period and a subsequent rise in emissions. It was suggested that WPOB can be used with the blending of some other high-carbon fuels in order to reduce the reliance on diesel fuel. The engine trials of previous studies revealed that the use of WPO as a fuel gave inferior results compared to diesel. To enhance the properties of WPO, a study was carried out on the distillation of fuel produced from mixed plastic waste.[12] Raw WPO and distilled WPO were used as the CI engine fuel, and the results were compared with diesel. The results showed that distillate WPO had the highest brake thermal efficiency (BTE) among all of the fuels used in the study due to its high cetane index. The shorter ID helped to achieve a maximum rate of heat release (HRR) very close to the top dead center.

Catalyst is a substance used to increase the rate of reaction during any chemical process.[13] To enhance the yield of the pyrolysis process, silica, alumina, magnesium oxide, zeolite, kaolin, etc., were used as catalysts for energy recovery from waste material.[14] The oil had a cetane number slightly lower than that of diesel and resulted in a longer ID and higher HRR during the premixed combustion phase. The pyrolysis process was performed in the temperature range of 350−450 °C, and the obtained oil underwent desulfurization and distillation to enhance its purity and refinement. The results showed that as compared to raw oil, the distilled products and their blend performed better in engine applications. Although the cetane number, sulfur content, acid value, and density were all reduced, the viscosity and density were increased.

The products of plastic oil pyrolysis include carbon chains, which have a carbon (C10−C25) concentration of about 70%, and their properties are similar to fossil fuel.[15] Based on the range of carbon atom densities found in the oil, WPO contains three different kinds of hydrocarbons. The lighter end of gasoline is represented by the C4−C11 range because hydrocarbons containing five to nine carbon atoms make up ordinary petrol. The bulk of diesel is composed of carbon atoms bound together through hydrogen bonds, which brings us to our second point. Last but not least, there is an abundance of C20 and increased carbon content in this variety. Although pyrolysis-derived fuels have great potential and can be used alone or in blends with other fuels, they exhibit some challenges. Pyrolysis oils generally have a higher viscosity, lower calorific value, moisture, and aromatic content, which affects the combustion process and results in a higher amount of smoke emission.[16] Hence, it is crucial to optimize the fuel qualities by blending some high-cetane fuels and using different additives in order to improve the performance and environmental advantages of these waste-derived fuels. The studies have been conducted utilizing innovative techniques, such as the incorporation of fuel additives and pretreatments, in order to optimize the performance of engine run on WPO and reduced exhaust emissions[17,18]

Doping nanomaterials with alternative fuels has been identified as one of the potential methods to enhance fuel properties.[19−21] Investigations on the use of graphite in alternative fuels have been carried out by a large number of researchers, and the findings have consistently proved that graphite possesses higher performance.[22] The use of graphite improved the efficiency of energy release by increasing the oxidation rates and facilitating a faster and more thorough combustion process. The combustion of fuels is enhanced by the increased number of contact sites provided by the high surface area due to the layered structure of graphite. Fuel molecules are more likely to collide with oxygen due to the larger interfacial area, leading to a more complete and faster oxidation process. Because of its hydrophilic properties, graphite is able to dissolve more easily in water-based solutions, leading to a more consistent distribution. Entire combustion process gets benefit from the enhanced catalytic and thermal conductivity effects of the uniformly dispersed graphite. Although graphite's electrical conductivity is lower than that of pure graphene, it is nevertheless present. This feature can improve the combustion efficiency of fuels by influencing electron transfer processes during oxidation, which, in turn, affects the combustion process.

An experiment was conducted to evaluate the performance of an electronic waste plastic oil (EWPO) in a diesel engine using nanofluids containing aluminum oxide and manganese oxide. Nanofluids enhanced BTE by 2.5% and decreased specific fuel consumption (SFC) by approximately 0.30 kg/kW h. When compared to EWPO20, the nanofluids exhibited a 1% increase in nitric oxide (NO_x) emissions and a decrease in CO and HC emissions.[23] In the study, different concentrations of cerium oxide (CeO_2) nanoparticles were added to a mixture of 80% diesel and 20% WPO fuel. The blend, which had 75 ppm

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of CeO_2 nanoparticles, gave 1.7% higher BTE and significantly lower emissions except for NO_x.[24] In another study, WPO-*n*-butanol-diesel blends with different fuel ratios in conjunction with hybrid nanoparticles containing alumina and TiO_2 at concentrations ranging from 20 to 60 ppm were used as an alternative fuel in a diesel engine.[25] With the help of multicriteria decision-making models, the best blend was identified and confirmed by the experimental results. It was noticed that HC, CO, and smoke emissions decreased and NO_x emissions increased. With the addition of 50 ppm TiO_2 to WPO, the BTE was observed to be 2.1% higher than that of pure WPO under full load conditions.[26] There was a considerable decrease in smoke, HC, and CO levels compared to those of the other fuel blends.

Different sizes of alumina oxide (Al_2O_3) nanoparticles with a concentration of 10−20 ppm were added to the WPO20 blend with the help of ultrasonic stabilization.[27] After the addition of Al_2O_3 to the blend, the BTE increased by 12.2% and the SFC increased by 11%. The CO, HC, NO, and smoke emissions were decreased by the addition of nanoparticles, irrespective of their size. Nanoadditives obtained from rice husk were blended with 20% mixtures of WPO at concentrations ranging from 25 to 100 ppm.[28] The BTE was increased by about 2.5% for the blend in which 75 ppm nanoadditives were added. When comparing its result to diesel at maximum power, HC, CO, and smoke opacity emissions were reduced by 15%, 7%, and 20%, respectively, while NO_x emissions increased by 14%. Graphite nanoparticles have demonstrated potential for improving the combustion properties of fuel blends.[29] Graphite nanoadditives have the ability to enhance engine performance and decrease emissions by improving fuel atomization, boosting thermal conductivity, and accelerating oxidation reactions.[30,31] Numerous studies suggest that fuel obtained by the pyrolysis of high-density polyethylene (HDPE) waste plastics can be used as an alternative energy source for diesel engine applications. Converting waste plastic into fuel has many advantages, such as reducing plastic waste accumulation and providing an alternative to fossil fuels. The pyrolysis of plastic waste could mitigate the environmental threat of both plastic pollution and fossil fuel consumption, thereby promoting sustainable environmental development. Table 1 provides an overview of the numerous nanoparticles that have been investigated in relation to WPO.

HDPE is characterized by its linear long-chain polymer structure, which exhibits a substantial degree of crystallinity and low branching, resulting in exceptional endurance attributes. HDPE exhibits exceptional resistance to alkalis, weak acids, and greases. HDPE is widely used in the manufacturing of oil containers, detergent containers, milk containers, toys, and other products due to its notable strong characteristics.[34] The global demand for HDPE in 2025 is estimated to be around 60 million tonnes, making it a significant contributor to plastic pollution. HDPE wastes possess exceptional potential as a feedstock for pyrolysis.[35]

Table 1. Overview of the Numerous Nanoparticles Doped with WPO

nanoparticles	additives ratio (ppm)	BTE	SFC	HC	CO	NO_x	references
Al_2O_3, MnO	25, 50, 75	▲	▼	▼	▼	▲	23
CeO_2	25, 50, 75,100	▲	▼	▼	▼	▲	24
Al_2O_3, TiO_2	20, 40, 60	▲	▼	▼	▼	▲	25
TiO_2	25, 50, 75, 100	▲		▼	▼		26
Al_2O_3	10, 20	▲	▼	▼	▼	▼	27
rice husk	25, 50, 75,100	▲	▼	▼	▼		28
ZnO	50, 100, 150	▲	▼	▼	▼	▲	32
TiO_2	50, 100, 150		▼	▼	▼		33

The primary aim of this study is to evaluate the emission and performance characteristics of a fuel derived by the pyrolysis of HDPE plastic waste when it is used in a single-cylinder diesel engine. Catalytic pyrolysis method is employed to convert used plastics into a fuel, which is named as used polymer pyrolysis oil (UPO). Previous studies have investigated the addition of various nanoadditives to WPO and their effect on the behavior of diesel engines. Based on the previous studies, it can be concluded that the specific combination of graphite nanoparticles with HDPE-derived pyrolysis fuel has not been extensively studied. This gap highlights the need for a comprehensive understanding of how these nanoadditives can improve engine performance and emissions, particularly at different blend ratios and concentrations, to develop a viable alternative fuel that addresses both plastic waste management and energy crisis issues. Therefore, this study is formulated to use different blends of UPO with diesel. The 20% and 40% UPO are blended with diesel and denoted according to their percentages. To enhance the properties of the fuel and engine performance, graphite nanoadditives were incorporated into a 20% blend of UPO at concentrations of 50 and 100 ppm. The objective of this study is to investigate the novel application of graphite nanoparticles in pyrolysis fuel obtained from HDPE plastic waste to develop an efficient and ecofriendly substitute for traditional diesel fuel.

2. MATERIALS AND METHODS

PET plastic products such as water bottles, plastic carry bags, and plastic wrappers have a life span of less than a month in their utilization. Pyrolysis of plastic waste offers a practical option for managing plastic garbage while simultaneously providing an alternative supply of fossil fuel to reduce dependency on them. Pyrolysis is a heat-driven technique that enables the transformation of plastic waste into fuel. This process involves the decomposition of complex macromolecules into smaller, more intricate compounds in an environment devoid of oxygen.[36]

The pyrolysis of HDPE plastic waste was found to be mostly composed of different types of hydrocarbons. The chain consisting of carbon atoms ranging from C5 to C10 is categorized as gasoline, while the chain ranging from C12 to C15 is categorized as kerosene. Chains with more than 12 carbon atoms are classed as diesel oil, while chains ranging from C20 to C50 are classified as lubricating oils.[37] HDPE is a versatile and frequently utilized thermoplastic polymer because of its unique physical and chemical properties. HDPE's physical features include a density of 0.95 to 0.97 g/cm^3, resulting in a high strength-to-density ratio. This creates a lightweight, strong material with a tensile strength above 20 MPa. Linear hydrocarbon chains in its chemical structure provide its excellent impact resistance and mechanical stress resistance. HDPE is chemically inert and resistant to acids, bases, and solvents. Chemical stability and a melting point of 120−180 °C make injection molding and extrusion easy.

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HDPE is great for outdoor applications due to its moisture resistance, minimal water absorption (usually less than 0.01%), and UV resistance.[38]

Usually, the pyrolysis setup includes a pyrolysis reactor, a heating system, a controlling system, and a system for collecting the yields. Plastic waste is put into the reactor and heated to temperatures between 350 and 600 °C depending on the type of plastic. It is possible to make a fixed-bed reactor, which will allow efficient heat transfer and a long residence time. Vapors formed during the process are cooled with the help of condensation and cooling devices. The liquid yield obtained is called pyrolysis oil. Some noncondensable gases are left during the process which possess some amount of calorific value and can be used to run the pyrolysis system or some other useful work. The layout of experimental setup is shown in Figure 1.

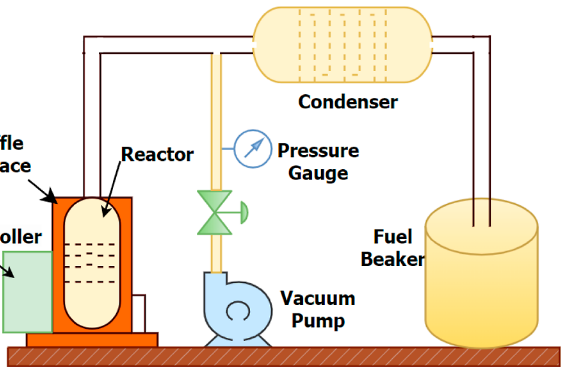

Figure 1. Schematic diagram of the pyrolysis reactor.

In this study, daily use products of HDPE waste, such as liquid detergent cans, cooking oil cans, and shampoo bottles, are collected and shattered for energy recovery. A muffle furnace, which can maintain a temperature up to 600 °C for long durations, was used to process the plastic waste. A constant temperature was achieved through the help of a digital controller and the thermocouple. Low pressure is necessary for the pyrolysis process. Zeolite was used as a catalyst to accelerate the pyrolysis process. In the temperature range of 400 to 500 °C, the HDPE reaction took around an hour. It took more energy to shatter molecules with shorter carbon chains compared with those with longer ones. The yield of the pyrolysis process was oil (60%), wax and char production (20%), and gas (15%). The last phase of pyrolysis, i.e., cooling of vapors formed, was facilitated by the installation of a vacuum pump.

The primary outcome of HDPE pyrolysis is a substance in the form of a liquid oil. The pyrolysis oil production in experimental setups might vary between 60% of the starting plastic mass. For every 1 kg of HDPE, there is an approximate yield of 600 g of pyrolysis oil. The gas component, comprising methane, ethane, ethylene, and other light hydrocarbons, generally accounts for approximately 20% of the initial mass. Therefore, the gas produced from 1 kg of HDPE would amount to around 150 g. The solid residue, known as char, refers to the carbonaceous material that remains after the volatile components have evaporated. Typically, this portion constitutes approximately 20% of the original mass. The estimated amount of char produced would be approximately 200 g. Out of the total, the remaining 5% corresponds to mass loss, namely, 50 g, which can be attributed to process inefficiencies as well as minor losses caused by errors in handling and measurement.

Figure 2 presents the results of the Fourier transform infrared (FT-IR) study of diesel and pyrolysis oils produced from waste polymer HDPE. The pyrolysis oil obtained from waste polymer HPDE exhibits the presence of stretching vibrations of hybridized carbon−hydrogen (C−H) molecules at a wavenumber just below 2800 cm^{-1}. In addition, carbon compounds with triple bonds can be identified at a wavenumber of 2200 cm^{-1}, while the stretching vibrations of hybridized carbon−carbon double bonds (C═H) can be observed below 1750 cm^{-1}. The primary diesel functional group demonstrates the elongation of hybridized carbon−hydrogen (C−H) molecules at a wavenumber somewhat lower than 3000 cm^{-1}. The absence of any further stretching in the functional group suggests the absence of hybridized C═H hydrocarbons.

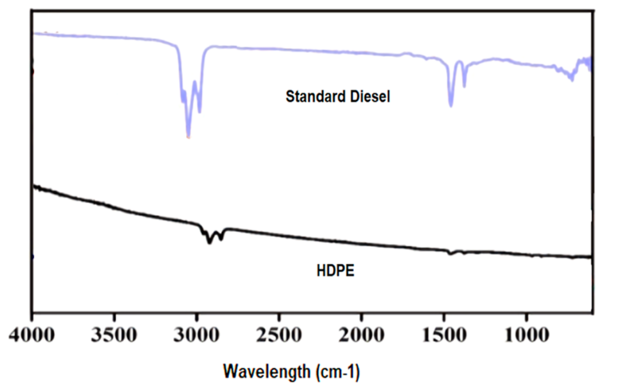

Figure 2. FT-IR analysis of diesel and HDPE oil.

The special characteristics of graphene oxide (GO) make it a promising material for improving the combustion efficiency and energy release during the oxidation of fuel. Inherent catalytic activity is bestowed upon GO by oxygen-containing functional groups on its surface, which expedite the degradation of complex hydrocarbons in fuels. The combustion oxidation processes are accelerated using this catalyst. The effective transfer of heat is possible due to GO's HDPE thermal conductivity and the rapid advancement of the combustion front.

A unique crumpled and wrinkled structure of graphite can be seen in Figure 3, which is the result of deformation that takes place throughout the process of exfoliation and restacking. As a result of this process, the morphology that is produced is similar to that of thin crumples. There is a clear indication that structures have been preserved in graphite due to the existence of wrinkling and crumpling, which are characteristics of graphite layers that are piled on top of each other in a multilayer pattern. Based on the findings of the experiment, it can be concluded that the presence of the oxygen functional group has effectively impeded the stacking of the graphite.[22]

In this study, used HDPE polymer oil (UPO) obtained from the catalytic pyrolysis process was blended with standard diesel at two ratios of 20% and 40% on a volume basis, and results were compared with diesel and UPO100. UPO20 was formed by blending 20% of oil obtained by the pyrolysis of HDPE with 80% standard diesel on a volume basis. The graphite

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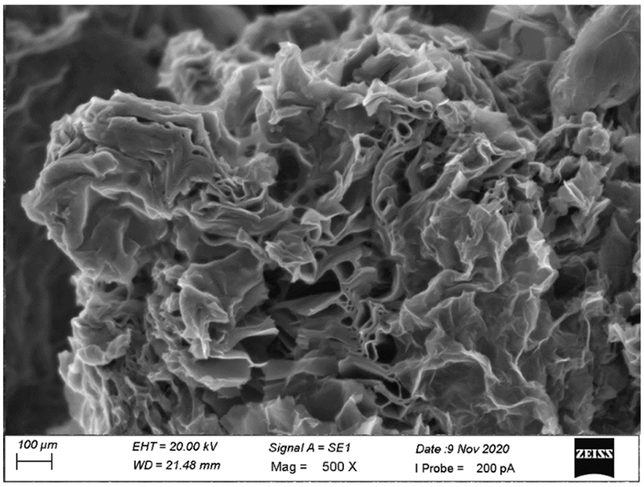

Figure 3. SEM of graphite.

nanoadditives of 50 and 100 ppm were added to enhance the properties of UPO20 blend. The fuel blends used in the study are UPO20, UPO40, UPO100, UPO20n50 (80% diesel + 20% UPO + 50 ppm of graphite), and UPO20n100 (80% diesel + 20% UPO + 100 ppm of graphite). Table 2 displays a comprehensive detail of the UPO and diesel properties.

In this investigation, ultrasonication was employed to create a thoroughly blended nano solution. In order to achieve stability in the mixture, the ultrasonication process was facilitated by the addition of sodium dodecyl sulfate surfactant. At first, a mixture of 20% UPO and 80% diesel was prepared by employing an ultrasonication bath for a duration of 60 min. An ultrasonication device operating at a frequency of 20 Hz was utilized for a duration of 30 min to further homogenize the blend. Subsequently, graphite nanoadditives with a concentration of 50 ppm (100 mg/L) and sodium dodecyl sulfate surfactant with a weight percentage of 0.5% were added to the UPO20 blend. The mixture was then continuously stirred at a temperature of 60 °C for a duration of 30 min to eliminate any remaining water molecules. This resulted in the formation of UPO20n50. Subsequently, the identical ultrasonication procedures were used to achieve a consistent dispersion of graphite nanoadditives of 100 ppm into UPO20 as well.

3. EXPERIMENTAL DETAILS

An examination of prepared fuels was carried out in a water-cooled single-cylinder direct injection system diesel engine with a maximum power output of 4.2 kW. The test engine was started using conventional diesel fuel and operated under stable test conditions. An eddy current dynamometer was used to apply the load on the diesel engine. The engine underwent gradual load increments using a dynamometer, starting from zero and advancing to the maximum load with each step being 25%. The test engine functions at a rotational velocity of 1500 rpm and possesses a compression ratio of 18:1 and an injection pressure of 210 bar. An AVL gas analyzer and smoke meter were employed for this investigation. Figure 4 illustrates the arrangement of the experiment engine setup.

There is a significant amount of uncertainty involved in determining engine characteristics. This uncertainty encompasses factors such as the accuracy of the measurement devices used, potential errors due to experimental conditions, and discrepancies in the engine setup. To ensure the factual and scientific accuracy of experimental data, it is essential to acknowledge and measure this uncertainty. Table 3 presents the instruments utilized for this research and their details. The engine undergoes continuous testing for five trials to observe the uncertainty in the investigations.

4. RESULTS AND DISCUSSION

An investigation was carried out to examine the efficiency and emission properties of fuel produced from pyrolysis of waste polymer when utilized in a diesel engine. The study was carried out on a diesel engine with a single cylinder, which was operated at four different loads that increased gradually from 0% to 100%. The evaluation of engine performance involves the performance and analysis of emitted exhaust gases, which consist of HC, NO_x, CO, and smoke.

4.1. Break Thermal Efficiency. Figure 5 presents the BTE of test fuels, indicating the efficiency with which the chemical energy of the fuel is converted into useful mechanical work. Comparing the BTE of the engine revealed that UPO has lower efficiency than diesel fuel when operating at a low load. The higher concentration of aromatic components in UPO slowed the slow combustion process.[39] Consequently, the BTE drops by 5%, 9.8%, and 11.8% for the 20%, 40%, and 100% UPO blends, respectively, compared to diesel at a maximum load. This phenomenon is attributed to the increased viscosity and decreased calorific value of UPO, which negatively impact ignition and combustion processes, thus reducing thermal efficiency.[36] The polymerization chains in plastic fuel require significant energy to break due to their high aromatic content.[40] The higher viscosity of UPO may cause issues with fuel injection and liquid fuel discharge quality, affecting fuel spray atomization and vaporization. These results can be anticipated due to incomplete combustion and lower heat energy compared to the base fuel.[41]

Conversely, a fuel charge with nanoparticles burns more efficiently than both diesel and UPO100. The BTE of UPO20n100 is 2.79% higher than that of diesel, primarily due to the presence of graphite, which increases the oxygen concentration. The catalytic activity of nanoparticles enhances the reaction kinetics and accelerates heat addition by increasing the surface-to-volume ratio. The engine performance of the nanoblend UPO20n100 was 16.6% higher compared to that of UPO100 because graphite nanoparticles improve fuel injection dispersion and promote fuel droplet

Table 2. Properties of UPO and Diesel

properties	units	diesel	UPO20	UPO40	UPO100
calorific valve	(kJ/kg)	44,750	42,236	41,200	40,200
kinematic viscosity	(cSt)	2.61	2.98	3.48	5.08
density at 15 °C	(kg/m^3)	838	803	792	799
flash point	(°C)	72	60	50	24
fire point	(°C)	82	70	60	34

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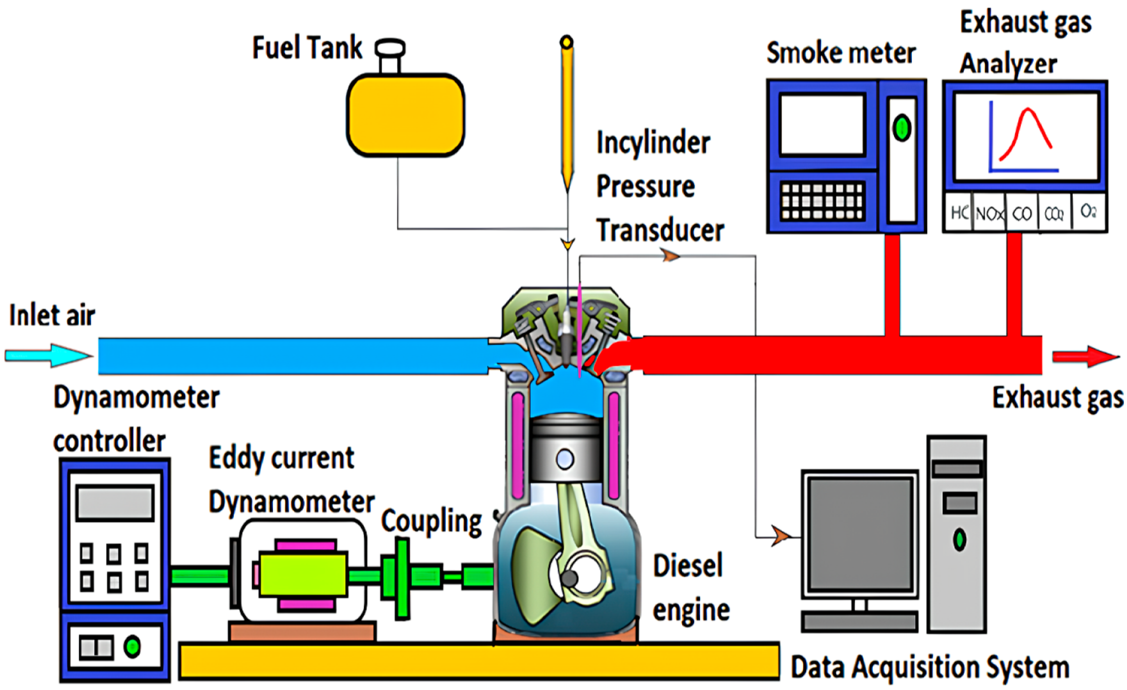

Figure 4. Schematic of the experimental engine setup.

Table 3. Uncertainty of the Instruments

parameter	Range	accuracy	uncertainty of data (%)	instrument utilized
engine load		+0.1 to −0.1 kg	±1	dynamometer
engine speed	0−10,000 rpm	±10 rpm	±0.50	digital tachometer
fuel quantity	0−50 cm^3	±0.1 cm^3	±1	buret measurement
hydro carbon	0 to 5000 ppm	±5 ppm	±0.50	AVL exhaust gas analyzer
CO emission	0 to 15%	±0.5%	±0.50	AVL exhaust gas analyzer
NO_x emission	0 to 5000 ppm	±10 ppm	±0.50	AVL exhaust gas analyzer
smoke	0−100%	±1%	±1	AVL smoke meter

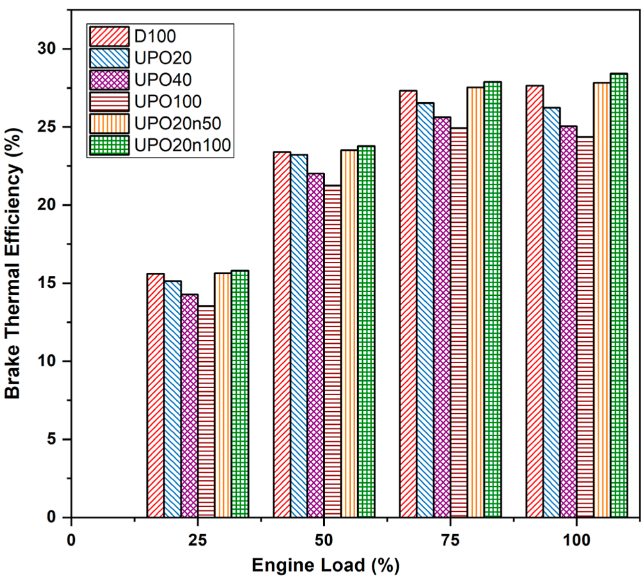

Figure 5. Break thermal efficiency vs engine load.

combustion. The enhanced fuel-air mixing, resulted in more effective combustion properties and improved thermal efficiency.[29]

4.2. Specific Fuel Consumption.

Figure 6 illustrates the SFC of UPO blends with diesel at various engine power levels. Under different load conditions, the fuel consumption of UPO20, UPO40, and UPO100 exceeded that of diesel by an

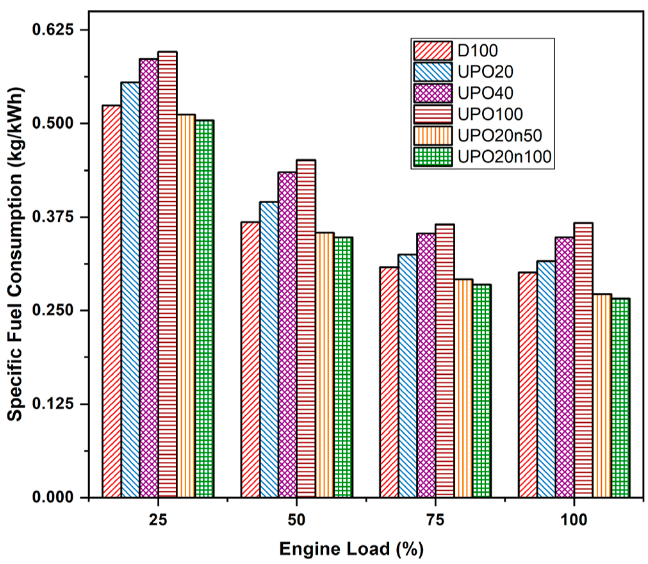

Figure 6. Specific fuel consumption vs engine load.

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average of 5%, 14%, and 19%, respectively. The lower calorific value and higher viscosity of plastic fuel compared with pure diesel affect the atomization and vaporization of the fuel spray, resulting in incomplete combustion. Consequently, thermal efficiency decreased, and SFC increased.[42]

However, the blends UPO20n50 and UPO20n100 exhibited reductions in SFC by 9.6% and 11.6%, respectively, compared to diesel. This reduction is attributed to graphite nanoparticles, significantly improving the physical properties of the fuel. The catalytic activity of graphite nanoparticles enhanced combustion characteristics, increased the surface-to-volume ratio, and reduced fuel consumption.[43] Use of nanoparticles improved the fuel attributes associated with diesel by reducing both the physical delay and fuel evaporation time. The secondary atomization of oxide nanoparticles was improved, leading to accelerated fuel burning.[44] Notably, UPO20n100 recorded a 27.52% reduction in fuel consumption compared to that of UPO100. This phenomenon occurs because nanoparticles induce microexplosions, resulting in secondary atomization. This mechanism facilitates the evaporation of fuel droplets, increasing the quantity of fuel combusted during the premixed stage of the reaction, thereby expediting the ignition process and enhancing the output, which ultimately reduces SFC.[32]

4.3. Hydrocarbon Emissions. Figure 7 displays the UHC emissions of the test fuels at different engine loads. Incomplete

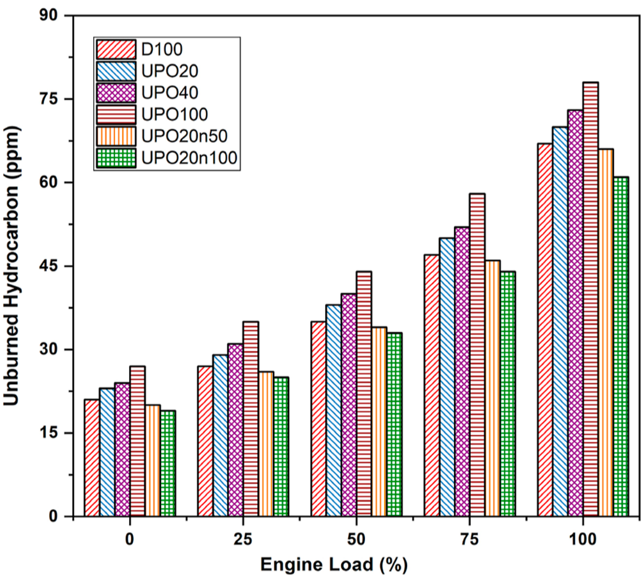

Figure 7. Unburned hydrocarbon emissions vs engine load.

combustion, resulting in unburned fuel in the combustion chamber, causes the UHC emissions produced by diesel engine.[45] The increased HC emissions in UPO blends, which are approximately 4.5%, 8.6%, and 16.4% higher than those of diesel, are primarily due to their longer IDs. This extended ID reduces the time available for complete combustion, leading to elevated HC emissions.[46] Inadequate combustion occurs mainly due to an excessive fuel mixture and fuel spray penetration during the ID phase. UPO blends are more likely to contact the cylinder wall during the spraying process because of their higher density and viscosity. The quenching action also contributes to increased HC emissions, stemming from UPO's low cetane number and reduced autoignition characteristics.[47]

Adding graphite nanoparticles to the fuel blend enhanced the combustion of carbon particles in the combustion chamber, especially at higher cylinder wall temperatures. When UPO20n50 and UPO20n100 nanoblended fuels were used, HC emissions decreased by approximately 1.5% and 9%, respectively, compared to diesel fuel. The increased oxygen content in graphite plays a crucial role in initiating the combustion of unsaturated hydrocarbons in the fuel, resulting in a more thorough and efficient burning process. This surplus oxygen facilitates the complete combustion process, reducing HC emissions.[48] The UPO20n100 blend recorded a 21.8% reduction in HC emissions compared to UPO100. This is due to incorporating nanoparticles into UPO blends, enhancing the uniformity of the fuel-air mixture and improved vaporization. The smaller size of nanoparticles promotes better fuel atomization, enhancing the interaction between reactants and ensuring complete combustion.[49]

4.4. Carbon Monoxide Emissions. The main source of CO emissions in diesel engines is incomplete fuel combustion, which occurs due to factors such as insufficient oxygen, an improper mixture ratio, and prolonged ignition delay.[50] Figure 8 illustrates the CO emission levels of test fuels across varying engine load.

The average CO emissions for UPO20, UPO40, and UPO100 blends were found to be approximately 6%, 11%, and 24% higher, respectively, compared to diesel fuel at various loads. The decreased energy output of UPO, resulting from its lower gross calorific value, may lead to incomplete combustion. Additionally, the prolonged ignition duration associated with UPO during engine operation contributes to elevated levels of CO emissions. The inadequate atomization of fuel blends, due to the higher viscosity of UPO blends, also directly results in higher CO emissions.[51] The inclusion of graphite nanoparticles in the fuel enhanced the oxidation rate of the fuel molecules in the combustion zone. UPO20n50 and UPO20n100 emitted approximately 4% and 9.9% less CO compared to diesel. Nanoparticle improves the atomization and vaporization of fuels, leading to better air−fuel mixing and a significant reduction in CO emissions. The presence of nanoparticles in the fuel facilitates quicker and more uniform fuel breakdown after injection.[52] As the surface contact areas of nanoparticles increased, their chemical reactivity and ignition properties are enhanced, which explains why UPO20n100 recorded a 29.7% reduction in CO emissions compared to UPO100. Furthermore, the presence of oxygen atoms in graphite enhanced heat transfer between the flame front and fuel molecules due to graphite's exceptional thermal conductivity. This results in more efficient combustion, where fuel molecules burn faster, thereby reducing the number of CO emissions.

4.5. Nitrogen Oxide Emissions. Figure 9 depicts the correlation between engine power and NO_x emissions across all UPO fuel blends. Efficient combustion results in elevated temperatures and a heightened concentration of free oxygen atoms, which can interact with nitrogen to form NO_x.[53] The higher levels of NO_x found in UPO fuel can be attributed to the presence of oxygenated hydrocarbons in contrast to diesel fuel.[54]

Specifically, UPO20, UPO40, and UPO100 blends exhibited increases of 6.3%, 8.5%, and 17.7% in NO_x emissions, respectively, compared to base diesel fuel. The substantial generation of NO_x is due to the high temperature and pressure inside the cylinder when using UPO blends combined with the significant release of heat during the combustion process. This

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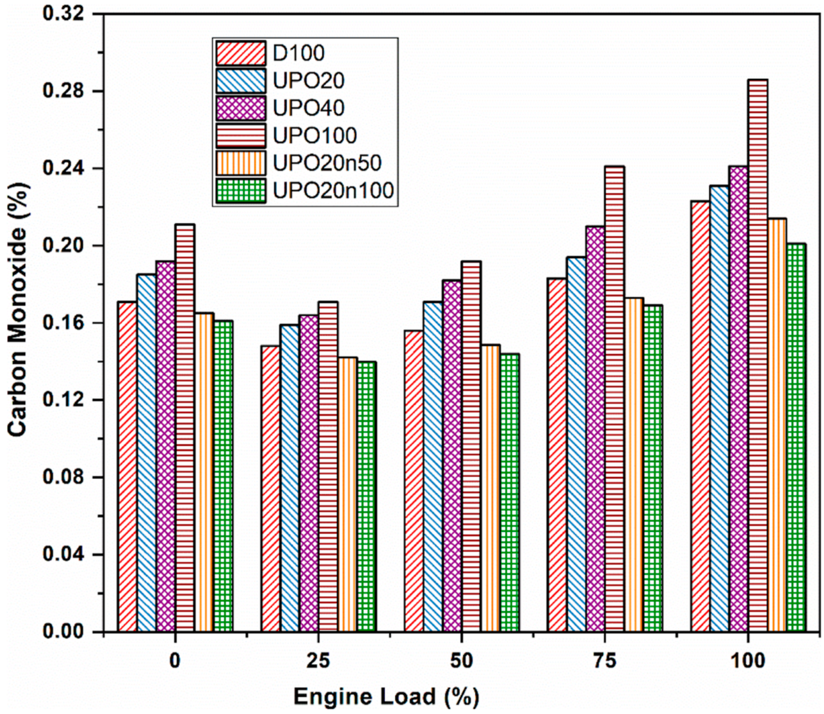

Figure 8. Carbon monoxide emissions vs engine load.

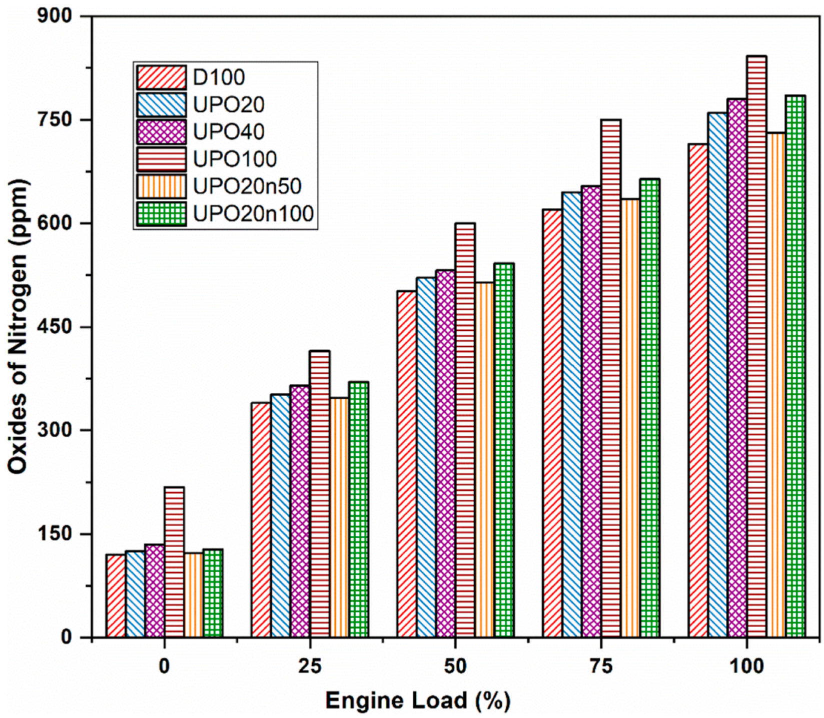

Figure 9. Nitrogen oxide emissions vs engine load.

behavior is also attributed to the increased aromatic content in UPO, leading to a higher adiabatic flame temperature.[55] The inclusion of graphite nanoparticles in the fuel enhanced the oxidation rate of fuel molecules in the reaction zone, resulting in a greater release of heat and, consequently, increased NO_x emissions. UPO20n50 and UPO20n100 emit approximately 2.2% and 9.8% more NO_x, respectively, compared to diesel, although this increase is less pronounced than in the UPO blends. Higher engine loads cause elevated cylinder and flame temperatures, which in turn result in higher NO_x emissions.[56] The generation of NO_x is influenced by the presence of oxygen, ignition timing, and the combustion chamber temperature.[57] UPO produces higher levels of NO_x emissions compared to diesel due to its physicochemical properties, which affect the cylinder temperature and alter the reaction kinetics of NO_x formation. The higher oxygen content in UPO blends leads to more complete combustion, resulting in higher combustion temperatures and increased NO_x emissions.[58]

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4.6. Smoke Emissions. Figure 10 depicts the smoke emissions of test fuels with respect to the engine load. The increased smoke in UPO mixtures is due to their higher viscosity and lower volatility. The presence of UPO emulsions significantly influences spray properties and composition, ultimately reducing combustion efficiency. Specifically, UPO20, UPO40, and UPO100 blends exhibited increased amounts of 6.7%, 14.5%, and 22.2% smoke emissions, respectively, compared to base diesel fuel. The greater quantity of aromatic components in UPO leads to improper fuel mixture formation and spray characteristics, resulting in incomplete combustion and significant smoke emissions.[59] UPO's heightened viscosity and reduced volatility further exacerbate these issues.[60] Graphite offers an advantage due to its superior thermal conductivity, which efficiently transfers heat to each molecule during combustion. This accelerates the oxidation of carbonaceous particles. UPO20n50 and UPO20n100 blends demonstrated smoke emission reductions of approximately 3% and 8.9%, respectively, compared to diesel fuel. The higher rate of combustion seen during the diffusion combustion phase, leading to decreased smoke production, can be attributed to the higher concentration of oxygen in graphite.[61]

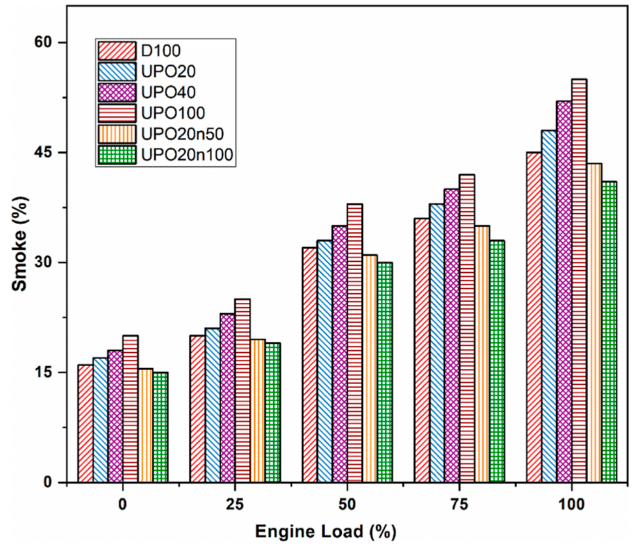

Figure 10. Smoke emissions vs engine load.

The UPO20n100 blend recorded a 25.4% reduction in smoke emissions compared to UPO100. The presence of fuel-bound oxygen in graphite, especially in areas with a high oxygen concentration, greatly influences combustion. The shorter ID and increased fuel consumption during combustion diffusion also contribute to reduced smoke emissions.[62] The addition of nanoparticles improves ignition capabilities, increases the surface-to-volume ratio, and enhances surface motion, all of which contribute to reduced smoke emissions.[63] The summary of the results of various parameters compared to diesel is shown in Figure 11.

4.7. Thermo-Physical and Chemical Effect of UPO and Graphite. Plastic waste-derived fuel, UPO100, exhibited greater viscosity, which influenced fuel atomization and spray patterns during combustion. This leads to inadequate atomization, incomplete combustion, and increased emissions. The density of UPO100 affects the fuel injection rate and the air-to-fuel ratio, thereby impacting combustion efficiency. The calorific value of plastic-sample-derived fuel blends determines the energy released during combustion; a lower calorific value reduces engine power output. The UPO20n100 optimum blend aims to balance these features to maximize energy release while reducing the SFC.[64] During combustion, HDPE undergoes thermal decomposition, breaking its long polymer chains into smaller hydrocarbon fragments such as alkanes, alkenes, and aromatic compounds. These fragments react with oxygen, forming carbon dioxide and releasing energy. Intermediate compounds, such as aldehydes, ketones, and alcohols, are produced in the early oxidation phases, influencing heat release and combustion efficiency. The combustion kinetics of polymer-derived fuels depend on the chemical structure of the hydrocarbon fragments; aromatic compounds and longer carbon chains typically exhibit lower

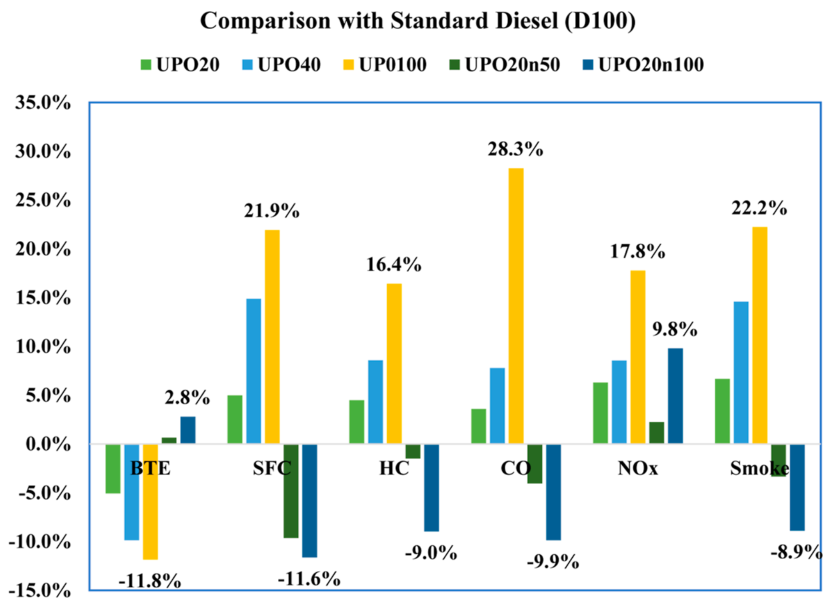

Figure 11. Summary of the results of UPO blends compared with diesel.

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reaction rates, potentially increasing the emissions of unburned hydrocarbons and carbon monoxide if not properly controlled. Diverse hydrocarbon structures can also affect ID, the time duration between fuel injection and combustion initiation. A prolonged ID leads to higher NOx emissions due to a rapid pressure increase.[65]

Graphite nanoadditives play a crucial role in modifying combustion chemistry by acting as catalysts that facilitate the oxidation of hydrocarbon fragments and intermediates, thereby enhancing combustion completeness and reducing HC and CO emissions. Nanoadditives increase the surface area available for combustion, promoting the adsorption of oxygen and fuel molecules and accelerating oxidation reactions. They help decompose stable aromatic compounds in polymer-derived fuels, improving combustion stability and reducing pollutants. Additionally, nanoadditives catalyze the oxidation of oxygenated intermediates, such as aldehydes and ketones, resulting in improved combustion efficiency and lower emissions of intermediates[41,43]

5. CONCLUSIONS

The energy demand in transportation, agriculture, and power generation sectors is increasing due to rapid urbanization and the lavish lifestyles of humans. The limited accessibility of fossil fuels and the implementation of emission standards in several countries have compelled scientists and automobile manufacturers to seek feasible alternatives to fossil fuels. The use of plastic is increasing due to its affordable price and versatile characteristics. Plastic products like water bottles, plastic carry bags, and plastic wrappers have a life span of less than 1 month in their utilization. Plastic pyrolysis is a thermochemical process through which plastic waste is broken down at high temperatures without air. This research demonstrates the feasibility and potential benefits of an alternative fuel for diesel engines derived through the catalytic pyrolysis of HDPE plastic. The study's innovative approach of incorporating graphite nanoadditives into the UPO blends showed significant improvements in engine performance and emissions. The results of the current study are summarized below:

- Compared to diesel, the BTE of UPO20n100 was 2.8% higher due to the oxygen content of graphite. The performance of the nanoblend UPO20n100 was 16.59% higher than that of UPO100.
- UPO20n50 and UPO20n100 exhibited a 9.6% and 11.6% decrease in SFC compared to diesel and a 27.5% decrease compared to UPO100.
- Emissions of HC in UPO20n100 nano fuel blends were reduced by approximately 9% compared to diesel fuel and by 21.8% compared to the base UPO.
- UPO20n50 and UPO20n100 showed reductions in CO emissions by 4% and 9.9% compared to diesel and by 29.7% compared to UPO100.
- The blends of UPO20n50 and UPO20n100 exhibit an increase in NO_x emissions of 2.2% and 9.8% compared to conventional diesel fuel.
- UPO20n50 and UPO20n100 resulted reductions in smoke emissions of around 3.3% and 8.9% compared to diesel fuel.
- The higher oxygen content in graphite nanoparticles promotes the reduction of emissions.

Efficiently converting plastic waste into a fuel source has the potential to dramatically reduce environmental pollution by mitigating land contamination and GHG emissions. This would contribute to creating an ecological footprint that minimizes carbon emissions. Future studies could expand this research to include different grades of plastic and their combinations. Additionally, synthesizing nanoadditives and studying their characteristics could further improve the fuel qualities. Parameter optimization can also be conducted to determine the optimal combination of the investigative factors.

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Notes

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