Exploring Recycled Plastic as a Sustainable Fuel Option for Diesel Engines

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Abstract – Pyrolysis, a thermochemical process in which organic materials are heated in the absence of oxygen, has emerged as an effective method for converting plastic waste into usable fuels in both gaseous and liquid forms. This paper reviews the potential of recycled plastics as an alternative fuel for diesel engines, with a focus on the performance, efficiency, and environmental implications of Waste Plastic Fuel (WPF) and its blended variants, including quaternary fuel mixtures with oxygenates. The study highlights that WPF exhibits fuel properties comparable to conventional diesel and can effectively power diesel engines. It further examines engine performance and emission characteristics across different fuel blends, demonstrating that the incorporation of oxygenates improves combustion efficiency and significantly reduces emissions of carbon dioxide, carbon monoxide, hydrocarbons, and nitrogen oxides. However, an increase in smoke emissions is observed, primarily due to incomplete combustion under certain conditions. Overall, the findings suggest that recycled plastic-derived fuels hold strong potential as a sustainable and eco-friendly alternative to conventional diesel, contributing to waste management and reduced environmental impact while supporting sustainable development goals.

Keywords – Waste Plastic Fuel (WPF), Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE).

I. INTRODUCTION

Pitches, polymers, and plastics have natural synthetic materials with long carbon molecule chains and high molecular weights. In [1], Sharuddin et al. concluded that 95% of the materials integrate thermal polymers like polyethylene terephthalate (PET), and polyvinyl chloride (PVC), both of which can be effectively recycled. Plastics represent complex polymers composed of carbon molecules, organic or inorganic constituents, oxygen, hydrogen, and nitrogen. Irrespective of its solid state, plastics may undergo a process of conversion into liquid state throughout its process of manufacturing, enabling it to be reshaped into different form, typically involving pressure and heat.

Over the last several decades, there has been a substantial surge in the occurrence of plastics in the environment, accompanied by a parallel escalation in the extensive use of plastic goods. Plastics have shown significant advancements in both security and durability throughout the course of time. As a result, these collections of 20 materials are now regarded as synonymous with materials that are resistant to various environmental limitations in the twenty-first century. Recently, there has been significant interest in the plastic trash pyrolysis, which involves the controlled heating or burning of materials in the absence of oxygen, as a method of managing solid waste. The production of plastics derived from fossil fuels has seen a significant surge. Starting at 2 million tons in 1950, it has escalated to over 454 billion tons in 2018. Projections as per current growth rates suggest that plastic output will double by 2025 and more than quadruple by 2050. In addition, further research conducted on global production of plastic in 2017 reveals that Asia has the distinction of being the foremost contributor to plastic manufacturing, accounting for 50.1% of the total output (with China contributing 29.4%, Japan contributing 3.9%, and the other Asian countries contributing 16.8%) [2].

Europe has the second highest percentage of plastic production at 18.5%, followed by the North America Free Trade Agreement (NAFTA) at 17.7%. The Middle East Africa region accounts for 7.1% of plastic production, while Latin America contributes 4%. The Commonwealth Independent State is the lowest producer, with an assumed proportion of 2.6%. According to Akan et al. [3], a total of 172 million metric tons of plastics and polymers were imported to Africa from 1990 to 2017. In Ghana, about 40 enterprises of manufacturing plastic are now generating over 26,000 metric tons of various plastic materials. Additionally, the country imports more than 10,000 tons of completed plastic goods annually [4]. Ghana annually imports around 2.58 million raw plastics metric tons, of which approximately 73% ultimately becomes garbage [5].

This article provides a rationale for using recycled plastic as a fuel source in diesel engines. The conducted study investigates the efficacy and environmental ramifications of using recycled plastic as an energy source. The experiment revealed that the characteristics of the liquid fuel derived from waste plastics closely resemble those of diesel fuel. Moreover, the engine may be effectively powered by pure pyrolysis oil derived from discarded plastics. Prior research has shown that pyrolysis oil has decreased emissions of exhaust pollutants and superior brake thermal efficiency (BTE) when compared to diesel combustion. The subsequent sections of the article are structured in the following manner: The second section reviews previous works related to the feasibility of using recycled plastic as a renewable fuel alternative for diesel engines. The third section presents the methodology employed in this research, identifying the method for data collection, conversion process, and experimental details. The fourth section presents a discussion of the results, which includes the performance characteristics, and emission characteristics. The final section presents a summary of the results in this article.

II. RELATED WORKS

According to Vighi et al. [6], the long-lasting disintegration of plastics has produced significant environmental issues for millennia, including the disposal of plastic trash in the environment. 15, 000 tons of various types of plastics are imported by Ghana annually, all of which are ultimately discarded as garbage since plastics are not biodegradable. Ghana generates about 12,710 tons of solid garbage on a daily basis. However, only around 10% of this trash is gathered and disposed appropriately off at designated facilities. Implementing effective solid waste management strategies in Ghana poses challenges; however, municipal authorities allocate around GH 6.7 million (US 3.45 million) per year for transportation and solid waste collection, and GH 550,000 per month for landfill and contractors.

According to Kumar, Panda, and Singh [7], most plastic garbage originates from municipal and industrial sources. The waste materials consist mostly of PET, Polypropylene (PP), High-Density Polyethylene (HDPE), and Low-Density Polyethylene (LDPE). The nation is facing significant environmental challenges due to the extensive accumulation of plastic garbage. These challenges include the negative impacts of floods and pollution on both the rivers and land, as well as the resulting economic and social repercussions. The conventional methods of manufacturing and utilizing plastic, followed by its indiscriminate disposal into the environment without prior reutilization and recycling to generate useful goods for society, undeniably resulted in this predicament. Adopting a “circular economy” concept is the most effective approach to create sustainable economic and environmental success in the long run. This concept advocates for the conversion of discarded plastic into practical items by upcycling, hence decreasing the quantity of plastic trash that contaminates the environment.

Table 1 provides a summary of past review publications that specifically examine Australian professional wrestling. These articles were published in international peer-reviewed journals. The search for “plastic waste” yielded a total of 16,464 publications in the research database, out of which 1171 were review articles. The articles were chosen from the Web of Science database by using the term “plastic waste”, coupled with the choices of “review article” and “Australia” in the Refine Research window of the database. **Table 1** demonstrates that the majority of prior review papers authored by Australian researchers focused on material substitution (the application of plastic waste as a replacement for new material), the manufacture of bioplastics to alleviate the effects of synthetic plastics, microplastics, and concerns connected to processing and treatment.

No prior research has been conducted on the topics of plastic use, sources of post-consumer waste (PW), the different forms of PW creation, or the present processing capacities within the PW recycling businesses and sectors that are exploring the use of PW as a secondary source of raw material. This underlines the study deficit in exploring the use of PW as a valuable resource for feeding supply chains, while also emphasizing measures to address the existing situation surrounding PW in Australia. The scholarly publications evaluated did not analyze the most up-to-date Australian data about the management and recycling of PW.

Table 1. Review Publications on Plastic Waste Already Published by Australian Academics.

Literature	Main research area	Focus	Major findings
Abdelbasir, Hassan, Kamel, and Nasr [8]	E-waste plastics	Possible strategies for recycling electronic waste plastics	Recognized the inadequacy of traditional recycling methods in handling challenging e-waste plastics and highlighted the potential for developing small-scale recycling solutions.
Ayeleru et al [9]	General management and generation	Challenges in sub-Saharan Africa	Urbanization was identified as a significant contributing element to the creation of particulate matter. Implementing proper collection and recycling methods would result in financial gains for local small and medium firms.
Onyena, Aniche, Ogbolu, Rakib, Uddin, and Walker [10]	Marine plastic	Environmental contamination and mitigation plan	The amount and biological impacts of nano plastics, which are at the sub-micrometer scale, remain uncertain and require more investigation.

Karan, Funk, Grabert, Oey, and Hankamer [11]	Bioplastics	Circular bioeconomy	The use of genetically modified organisms (GMOs) with biorefinery methods has been shown to be very beneficial in the advancement of the growing circular bioeconomy. When a comprehensive, long-term, and extensive infrastructure is established, bioplastics are regarded as a very efficient carbon sink.
Schmidt, Krauth, and Wagner [12]	Marine plastic	Plastic transportation and movement in aquatic ecosystems	Both field-based and laboratory-based investigations have shown the efficacy of remote sensing and numerical models as tools for quantifying the amount of marine plastic.
Xu, Ma, Pan, and Miao [13]	Microplastics	Factors, identification techniques, and environmental consequences of the accumulation of microplastics in aquatic ecosystems	Three primary concerns were identified: (1) Lab-based research should include the study of microplastics commonly present in the environment, (2) Conducting thorough fieldwork, and (3) Establishing standardized methodologies for collecting and identifying microplastics.
Dümichen, Eisentraut, Bannick, Barthel, Senz, and Braun [14]	Microplastics	Technique for identifying microplastics unique to polymers in terrestrial environments	The principal microplastics identified were PS, PP, and PE. The main methods used for identification were SEM (scanning electron microscopy), differential scanning calorimetry, visual examination, FTIR (Fourier-transform infrared spectroscopy), and Raman spectroscopy. Nevertheless, more advancements are needed for the refinement of sample and identification approaches.
Jin, Zhao, Zhu, Huang, Shi, and Yu [15]	New material development	Oil sorbents	The application of PP and polyethylene PE as oil absorbents has garnered significant interest. However, there is a need for more research to explore the factors that affect production yields and the quality of these sorbents.
Hopewell, Dvorak, and Kosior [16]	Recycling process	Global challenges and opportunities	The primary waste reduction and recycling solutions presented were the usage of biodegradable materials, energy recovery via fuel conversion, downcycling of waste materials, and product reuse.

According to Morgan and Kandiyoti [17], pyrolysis refers to the thermal breakdown of organic compounds by the application of heat. The term is derived from the Greek components' pyro, meaning "fire," and lysis, meaning "decomposition." Pyrolysis is the first chemical process that takes place during the combustion of many solid organic fuels, such as paper, cloth, wood, and some types of plastic. The Anhydrous Pyrolysis method may be used to generate a liquid fuel that closely resembles diesel, using plastic waste as the feedstock. Pyrolysis technology refers to a heat degradation process that occurs in the oxygen absence. The plastic trash undergoes treatment in a cylindrical reactor maintained at a temperature range of 300ºC – 350ºC. The plastic waste is fragmented with the use of a catalyst, and the resulting gases are compressed in a sequence of compressors to get a distillate with a reduced sulfur concentration.

According to Al–Salem, Lettieri, and Baeyens [18], this process occurs continually in order to transform waste plastics into a kind of fuel that can be used for power generation. The catalyst used in this system will effectively inhibit the synthesis of all dioxins and Furans (compounds containing a Benzene ring). Prior to release into the environment, all the gases generated by this process undergo treatment. The flue gas undergoes treatment using chemical/water treatment and scrubbers to achieve neutralization. Prior to combustion, the non-compressed gas undergoes water treatment. Due to the high temperature range of 300ºC - 350ºC and the absence of oxygen in the processing reactor, the majority of hazardous substances in plastics waste are incinerated. Nevertheless, the gas may be used in a dual fuel diesel-generator system to produce power. The waste plastics conversion into oil occurs according to the depicted procedure shown in **Fig 1**.

This article provides valuable insights into the possible use of reused plastic as source in diesel engine. The essay highlights the efficiency and environmental impact of using waste plastic fuel (WPF) and fuel blends including quaternary compounds with the inclusion of oxygenates. The study investigates the performance characteristics of these fuels, like braking thermal efficiency, combustion efficiency, rate of consumption of fuel, exhaust emissions (smoke, carbon monoxide, nitrogen oxides, hydrocarbons, and carbon dioxide), and compares them to those of conventional diesel fuel. The results suggest that both WPF and quaternary blends operate similarly to diesel fuel, with modest improvements in brake thermal efficiency and exhaust pollutant management. This study contributes to the current knowledge by providing empirical evidence that supports the feasibility of using recycled plastic as a maintainable and eco-friendly substitute to traditional diesel fuels. This choice has the capacity to reduce emissions and promote sustainable transportation.

The data gathering process include the acquisition of primary data via laboratory experimentation, structured interviews, and collection of plastic garbage. The secondary sources of information were derived from journals and published papers, and books. The plastic garbage included a variety of items such as plastic bags, plastic bottles, food containers, water sachets, and other forms of plastic debris. The predominant plastic wastes are PS, PET, LDPE, HDPE, and PP. The garbage collected was subjected to a cleaning process using detergent and water to eliminate any foreign substances that may potentially contaminate the final product after pyrolysis.

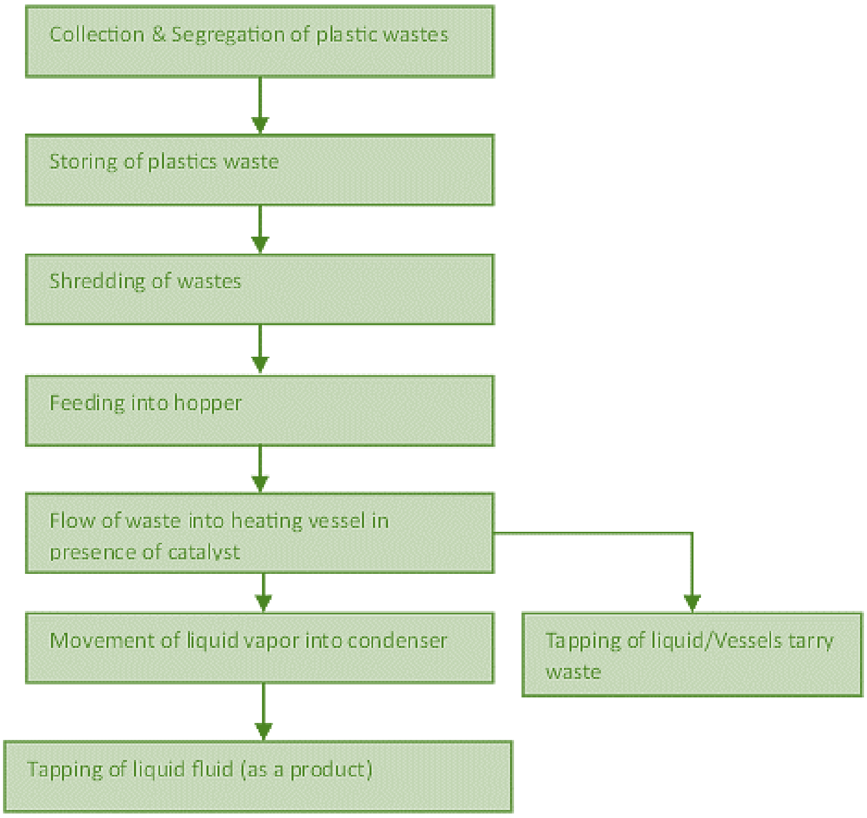

Fig 1. Plastics Waste Conversion into Liquid Fuel.

III. METHODOLOGY

Data Collection

Fig 2. Raw and Process Waste from Plastic.

The plastic granules were then dispersed and left to desiccate in direct sunlight. Subsequently, the accumulated plastic garbage was quantified, organized, and segregated into several categories based on the resin code. Subsequently, each variety of plastic is quantified by weight and its proportion is ascertained using the following procedure. The plastic components were further fragmented using a combination of cutlass and scissors. Following this, they were subjected to a three-day sun-drying procedure to eliminate any residual moisture, in preparation for subsequent processing (see **Fig 2**).

Conversion Process

Pyrolysis is the chemical breakdown of organic compounds by combustion in an O_2-free environment. This is a thermal degradation process where large hydrocarbon molecules (polymers) are broken down into monomers using high temperatures (450-800 oC) in the absence of oxygen and in a short time. The result is the production of volatile hydrocarbons and carbon residues, which can be condensed into non- compressible gaseous fuel and liquid fuel. Furthermore, scientists demonstrated that the characteristics of the liquid fuel derived from discarded plastics closely like those of the engine and diesel fuel can be effectively powered by pure pyrolysis oil obtained from waste plastics. Prior research has shown that pyrolysis oil had superior thermal efficiency of brake and greater levels of controlled exhaust pollutants, including carbon monoxide, hydrocarbon, and nitrogen oxides (NOx), compared to combustion of diesel [19]. The authors harnessed the energy from waste compounds and utilized it in solar energy applications. Not only is it ecologically benign, but it also offers a sustainable method for production of porous carbons for many users by transformation inexpensive waste polymers to valuable energy sources.

Experimental Details

This experiment used a single-cylinder, direct injection compression combustion engine with water cooling, operating on a four-stroke cycle. An eddy current dynamometer is loaded to the engine fitted with a load cell. The engine underwent testing at three distinct loads, namely 25%, 50%, and 75% of its maximum torque, while maintaining a constant speed of 1500 rpm. Lucrative diesel fuel was used as a reference point for collation throughout the engine run tests, alongside WPO. The rate of air flow to the engine was determined using an air box, while the flow rate for volumetric fuel was ascertained employing a timer and a burette. The analyzer of TESTO 350 was used to test NOx, while the TESTO 308 analyzer was used to assess the smoke index. **Table 2** presents the engine technical specifications.

Table 2. Diesel Engine Specifications.

Engine	Specifications
Dynamometer	Eddy current
Model	Kirloskar TV1
Rate output	3.5 kW at 1500 rpm
Engine type	Direct injection, 1 cylinder, Water cooled, 4 strokes
Swept volume	661 cc
Compression ratio	12:1-18:1
Bore x Stroke	87.5 x 110 mm

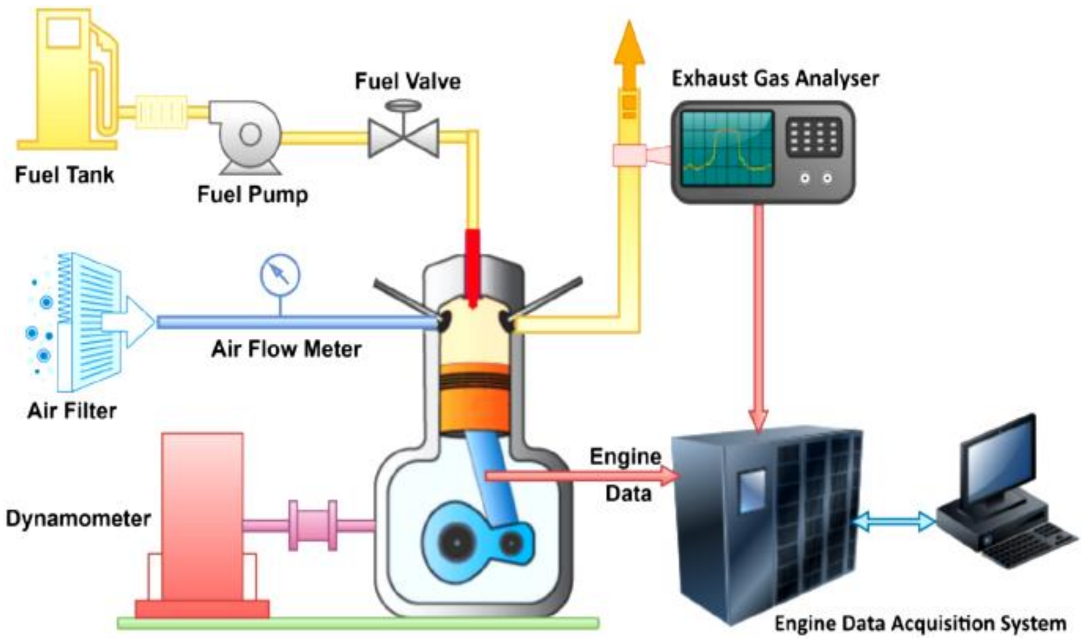

Fig 3. Representation of Engine Setup.

To perform the proper examination of the engine, a single cylinder and water cooled DIDE 4.2 kW power output may be used. The test engine was commenced using the technique of hand-cranking. An eddy current dynamometer was attached to the diesel engine in order to assess its efficiency. The power output dictates the intervals between zero and maximum load, which may be manually modified with a dynamometer. During standard testing circumstances, the test engine operated at a speed of 1500 rpm (revolutions per minute) and had a condensation ratio of 17:1. The experiment included setting the injection pressure to 210 bar and the timing to 21° bTDC (before top dead center). The engine's exhaust emissions were analyzed using a smoke meter and AVL gas analyzer. The engine's pollution levels and stability were assessed using the AVL program. **Fig 3** depicts the configuration of the experimental engine.

IV. RESULTS AND DISCUSSION

An investigation has been conducted to analyze the efficacy and environmental impact of using recycled plastic as a fuel source in diesel engine. The study included testing a diesel engine with fuel blends including 10% ethoxy ethyl acetate and 10% ethanol by volume, combined with varying proportions of 40%, 30%, and 20% of WPF. Diesel was used as the primary fuel source. The study was performed on a stock, unmodified single-cylinder diesel engine functioning under a 25% load of increment, covering the whole range from zero to one hundred percent of its maximum capacity. Research is being conducted on the emissions produced by engines, which consist of smoke, carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC).

Performance Characteristics

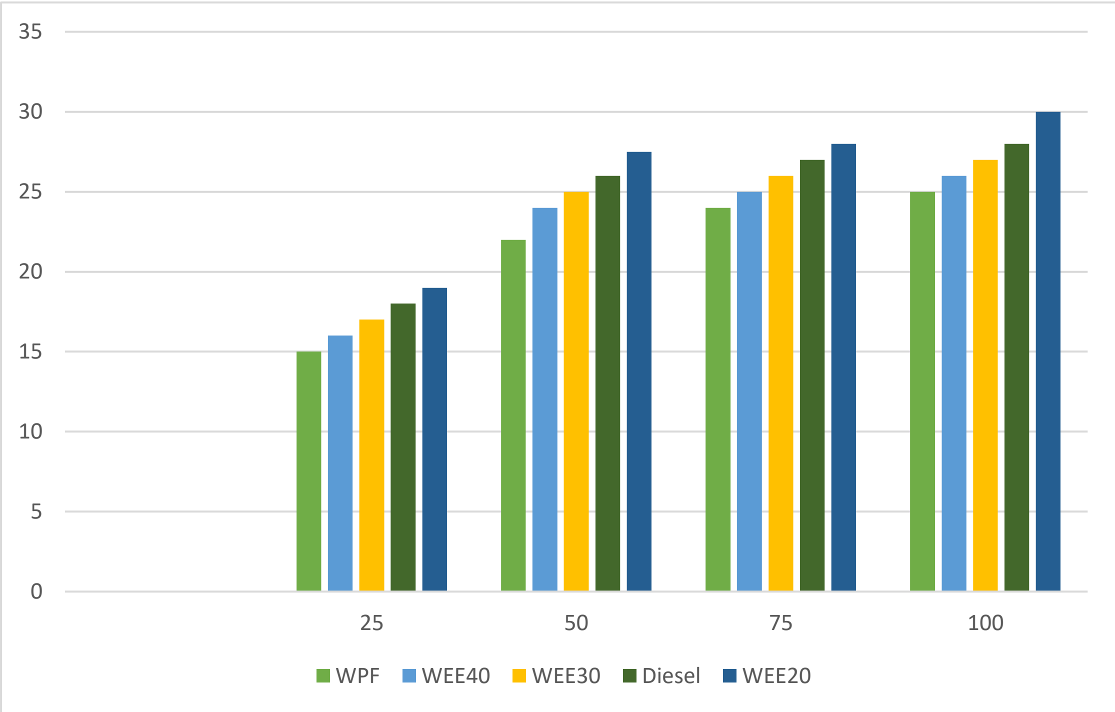

Fig 4. Analysis of BTE As a Function of Engine Loads.

The efficiency of brake thermal for Diesel at full load, WPF, and WPF quaternary fuel blends with oxygenate additions were 27.61%, 24.12%, 28.92%, 26.26%, and 25.45%, respectively, as shown in **Fig 4**. The efficiency of brake thermal exhibits a range of 17.84% to 28.92%, 16.81% to 26.26%, and 16.1% to 25.45% under varying loads, with the inclusion of oxygenates. The BTE (Brake Thermal Efficiency) of WEE20 was more than 20% more than that of WPF and about 4.74% higher than diesel when evaluated under maximum load conditions. When compared to fuel derived from waste plastic, the quaternary mixtures WEE40, WEE30, and WEE20 exhibited a 22%, 12%, and 8% enhancement in Brake Thermal Efficiency (BTE) values across various circumstances of loading. The use of WPF mixes led to an augmentation of BTE.

The combustion efficiency of waste plastic fuel improved with the summation of ethoxy ethyl acetate and ethanol. One potential reason for this might be because the additives include oxygen molecules, which increase the oxygen concentration and result in more effective combustion. A decrease in exhaust temperature results in less heat loss during combustion, perhaps leading to improved engine efficiency. Due to the abundant presence of plastic fuel aromatic compounds, a significant amount of energy is required to disrupt the polymerization chain of this fuel. Due to its higher viscosity, WPF exhibits worse thermal efficiency than the other fuels that were assessed. This viscosity may be responsible for fuel injection issues and subpar spray quality.

Every engine has a distinct fuel consumption rate that varies according to the engine's speed and workload. The most efficient operating conditions for a reciprocating engine are when there is unrestricted airflow and the engine is operating close to its maximum torque. The specific fuel consumption varies with various loading situations in proportion to the ternary mixtures, as shown in **Fig 5**. During WEE20, the use of diesel fuel results in a decrease in specific fuel consumption ranging from 3.16% to 7.77% across different load states. The fuel consumption shown a significant decrease compared to the WPF, varying from 14.1 percent to 23.8 percent across different load situations. Enhancing efficiency involves reducing fuel consumption while maintaining the same power output, particularly in highly oxygenated conditions. Furthermore, the fuel mixture calorific value has an important impact on output of the engine.

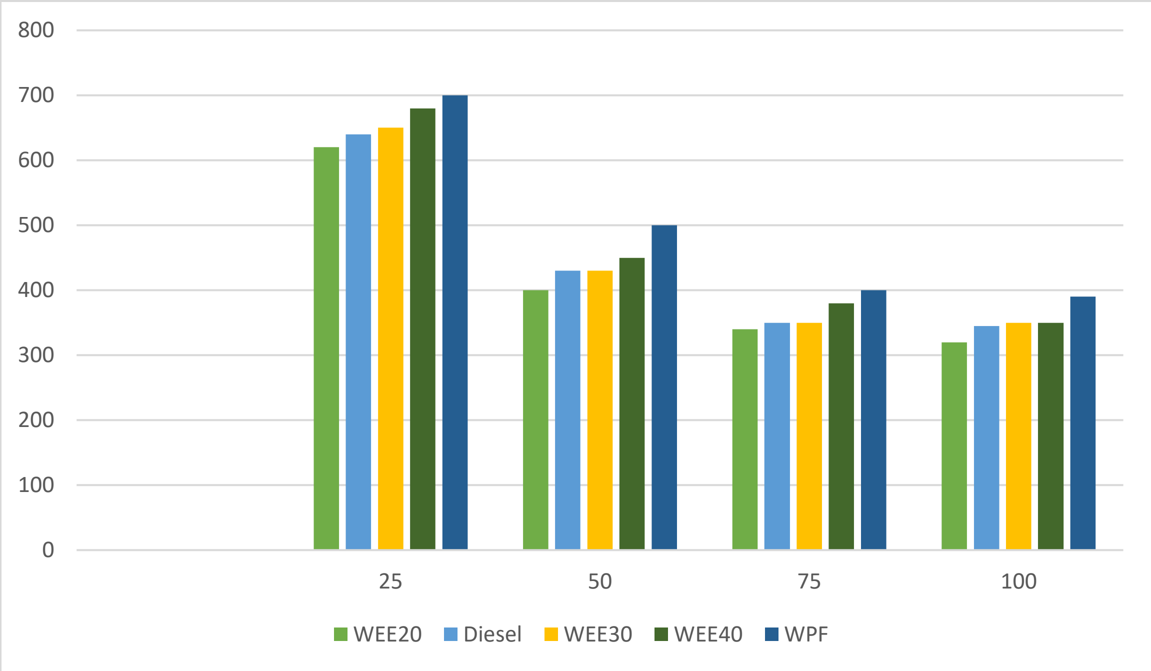

Fig 5. Analysis of Particular Fuel Usage at Various Engine Loads.

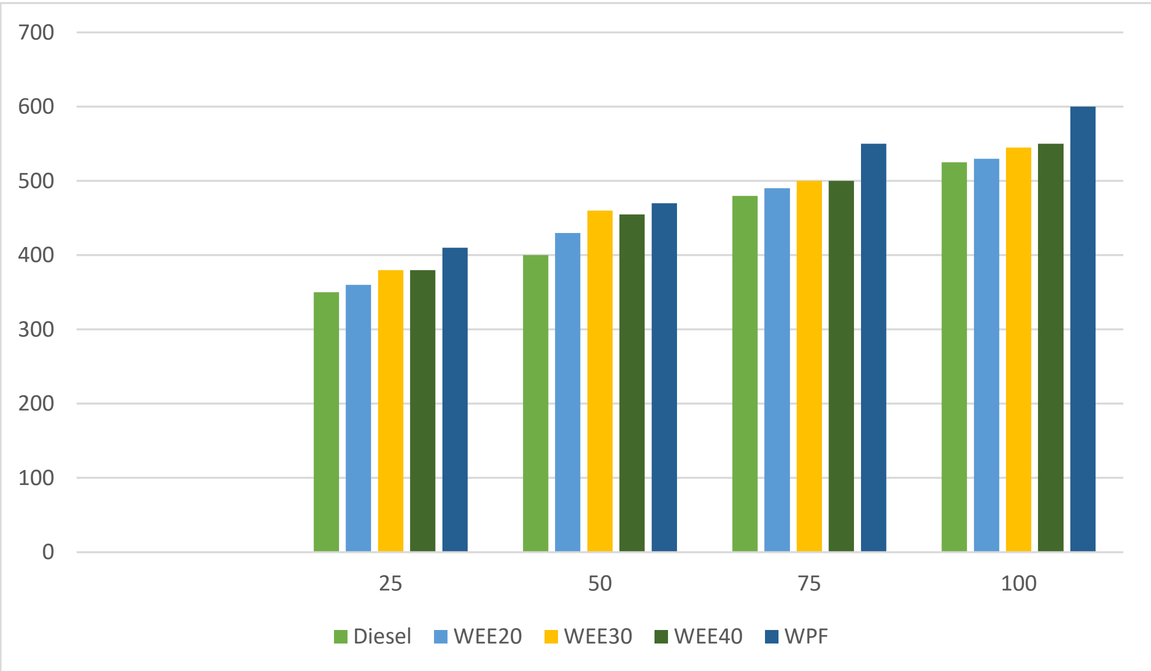

Fig 6. Fluctuation of Temperature of Exhaust Gas Based on Engine Loads.

The calorific value of waste plastic fuel is much lower than that of conventional diesel. It exerts an effect on the fuel spray formation, resulting in incomplete burning. Consequently, both the specific fuel consumption and thermal efficiency are adversely impacted. The quaternary blends WEE40, WEE30, and WEE20 yielded energy efficiencies of 322 g/kWhr, 312 g/kWhr, and 275 g/kWhr, at maximum load conditions. In comparison, the waste plastic fuel exhibited an energy efficiency of 361 g/kW-hr. The WPF fuel consumption and its blends is higher compared to that of diesel operation because of their lower calorific value and higher viscosity. Due to the reduced heating value of the blended additives, a greater quantity of fuel was required to provide an equivalent level of power. Additionally, the ignition delay was prolonged as a result of the combustion temperature, and the low cetane number was decreased due to the quenching impact of ethanol.

The heat generated in the ignition cycle of the engine chamber significantly affects the temperature of the exhaust gas in diesel engines. The Exhaust Gas Temperature (EGT) [20] provides a comprehensive assessment of performance, combustion heat, air-fuel ratio, and available levels of oxygen. The increase in load directly correlates with the rise in exhaust temperature due to the influence of combustion temperature on the EGT. Diesel exhibited consistently lower exhaust gas temperatures (EGT) than both WPF and quaternary mixtures across all load conditions, as shown in **Fig 6**. When compared to diesel, WEE20 exhibited a 5.3% elevation in EGT, whilst other blends showed a 9-10% surge. Because of its low volatility and high viscosity, incomplete combustion is more likely to occur with WPF, resulting in an increased EGT. The higher EGT is attributed to the occurrence of combustion in certain gases towards the end of the expansion stroke. Quaternary blends consistently exhibit elevated Exhaust Gas Temperature (EGT) due to their enhanced combustion efficiency and greater oxygen concentration across all load configurations.

Emission Characteristics

The majority of CO discharges result from combustion processes that either lack sufficient oxygen or fail to use oxygen effectively. Quaternary blends result in much lower CO_2 emissions in all aspects as compared to diesel. **Fig 7** demonstrates that all the combinations shown have a consistent decline in CO discharges from low to half load, followed by an escalation to full load.

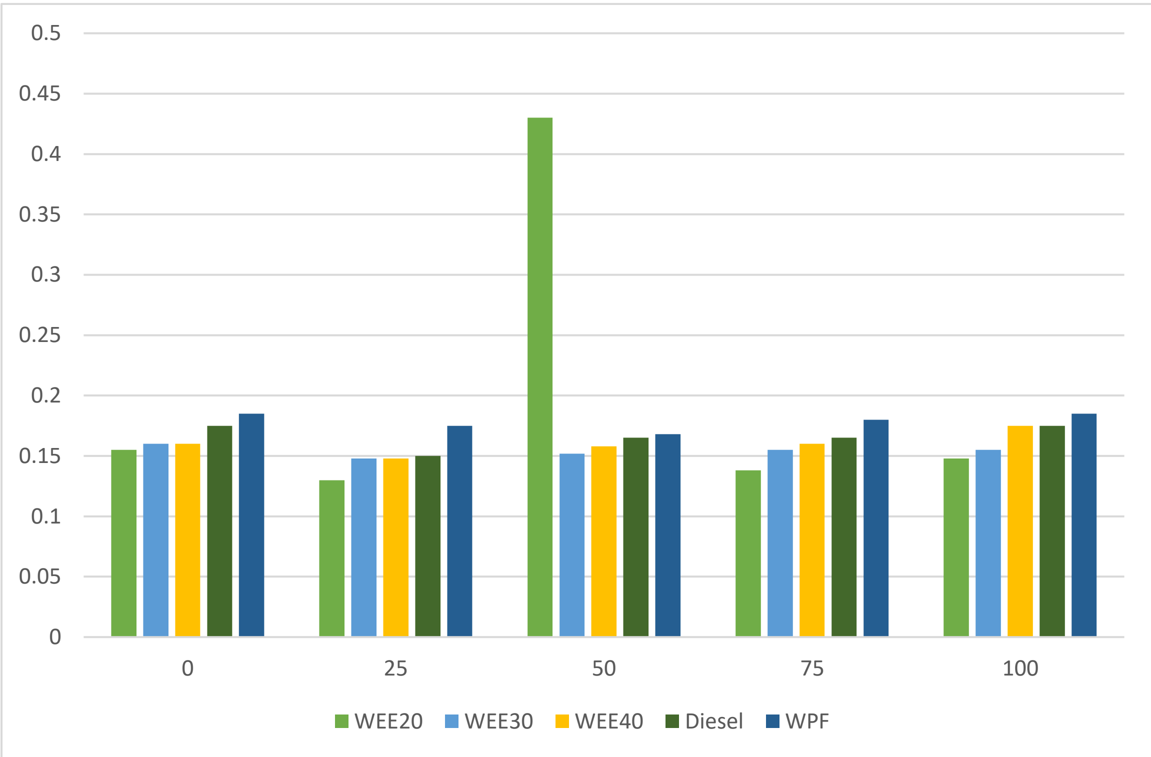

Fig 7. Fluctuations in CO Discharges Based on Engine Loads.

Under maximum load, the CO emissions of WEE20 should be reduced by 13.41% compared to diesel and approximately 20% compared to WPF. The WEE40, WEE30, and WEE20 quaternary blends decreased CO emissions by 3.73%, 6.21%, and 13.41% of diesel, as a result of loading. Quaternary blends provide in a reduction of carbon dioxide emissions by 9–23.6 percent as compared to WPF. An increased oxygen concentration in the quaternary blends enhances the fuel's combustion efficiency. The reduction of CO emissions is achieved by increasing the oxidation of fuel particles. The use of alcohols with low cetane values extends the duration of combustion ignition delay time. As previously mentioned37, most alcohols undertake H-abstraction from carbon sites by radicals of OH due to the influence of the OH group. Enhanced fuel-air mixing occurs due to the burning delay time, resulting in improved combustion and reduced carbon monoxide emissions. The waste plastic oil heightened viscosity leads to fuel mixes inefficient atomization, resulting in elevated CO discharges, as seen by the negative impact on these emissions.

The main cause of hydrocarbon emissions is mostly attributable to inadequate dispersion of air and fuel particles during the process of combustion, coupled with incomplete fuel combustion. When contrasting diesel fuel with blends of WEE40, WEE30, and WEE20, the emissions of hydrocarbon decrease by about 1.47% to 1.72%, 4.41% to 8.82%, and 11.76% to 16.39%, under varying load states (see **Fig 8**). The combustion chamber optimizes the combustion process by promoting the ideal blending of fuel and air, benefiting from the higher concentration of O_2 in the fuel mixtures. The fuel particles burned in the ignition chamber is more than that of diesel. The discharges of hydrocarbon of WEE20 demonstrated a decrease of around 16% in comparison to diesel, and a decrease of 21.5% in comparison to WPF at maximum load conditions. Idle conditions are defined by a low fuel injection pressure and low engine speed, creating a combustion environment that is somewhat fuel-rich in order to ensure stable combustion.

The main variables that contribute to the decrease in HC emissions when ethanol is mixed with diesel fuel are the decrease in areas with excessive fuel and the advanced atomization led by the injected fuel lower thickness, both of which are facilitated by the presence of oxygen. Mousavi and Dehaghani [21] identified that the heat capacity was 15.1% greater under higher load circumstances when contrasting diesel from plastic fuel. The persistent character of waste plastic is attributed to the availability of diluted aromatic chemicals, which therefore results in an elevation of HC emissions. The low cetane number of waste plastic oil (WPO) and its diminished auto-combustion properties result in an augmentation of the effect of quenching inside the leaner combination area of the cylinder. As a result, this results in an increased release of HCs.

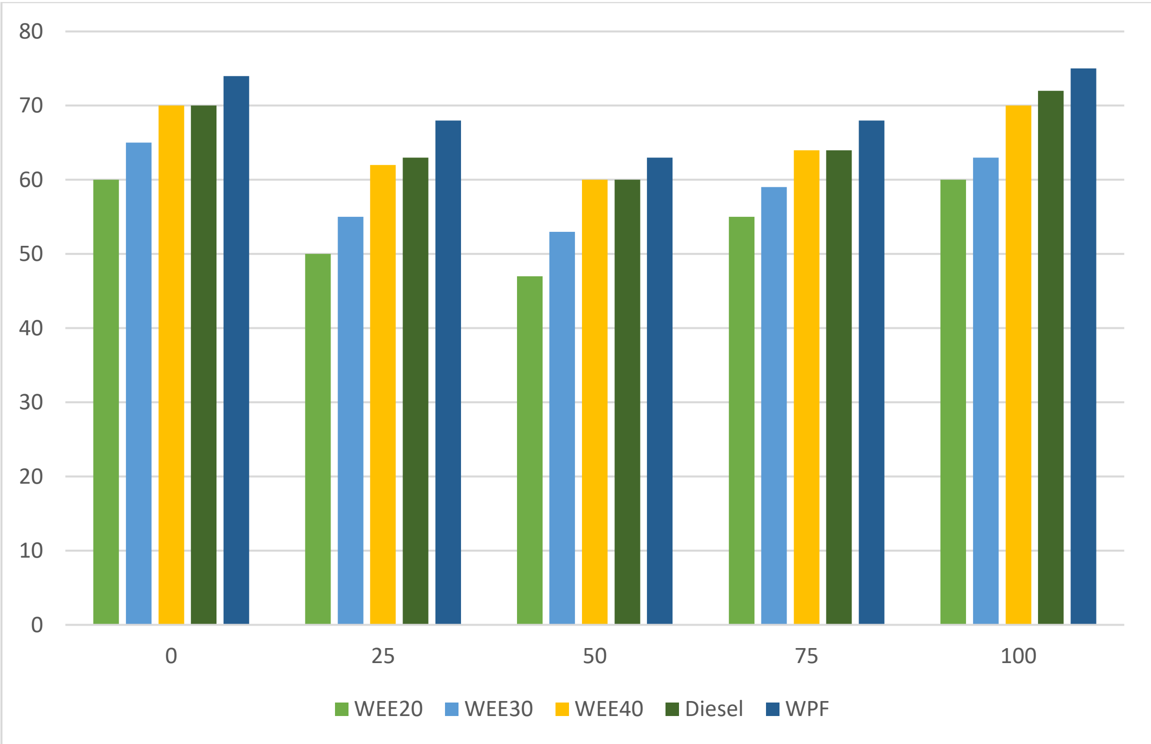

Fig 8. Fluctuation of HC Discharges Based on Engine Loads.

The main source of NOx emissions in diesel engines is the thermal mechanism, with a smaller contribution from the prompt technique. At higher temperatures, the thermal process leads to a rapid and exponential increase in NOx levels. The emissions of nitrogen oxides experienced a respective rise of 35.85%, 222.13%, and 12.06% when comparing quaternary blends WEE40, WEE30, and WEE20 to diesel fuel at various loadings (see **Fig 9**). The primary source of elevated NOx emissions in quaternary blends is the heightened combustion temperature resulting from the greater fuel mix. Combustion is completed because of high oxygen concentration in the fuel mixture. Consequently, the temperature of combustion increases, leading to a higher emission of NOx. The addition of oxygenates to diesel fuel increases its oxygen content. Consequently, the combustion chamber was operating with a fuel-air mixture that had a higher proportion of air than necessary. Oxygenated fuel supplies the supplementary O_2 needed for nitrogen oxidation. The emissions of nitrogen oxides (NOx) in oxygenated gasoline are elevated as a result.

According to Adam et al. [22] discovered that plastic fuel resulted in NOx emissions that were 25% more than diesel fuel when the engine was operating at maximum capacity. In their research, the levels of NOx emissions for all fuels examined are increasing. The presence of an excessive amount of oxygen has the greatest influence on the production of emissions of NOx inside the cylinder. Chains of nitrogen undergo degradation and disintegration in conditions of elevated temperatures. Subsequently, bonds of nitrogen engage with the O_2 molecules confined inside the cylinder's monatomic arrangement. The discharges resulting from the combustion of waste plastic fuel were determined to be 12 to 50% higher than those emitted by diesel fuel. WPF has a higher quantity of carbon compounds, which reduces the amount of excess air available, hence causing an increase in temperatures and resulting in elevated levels of NOx.

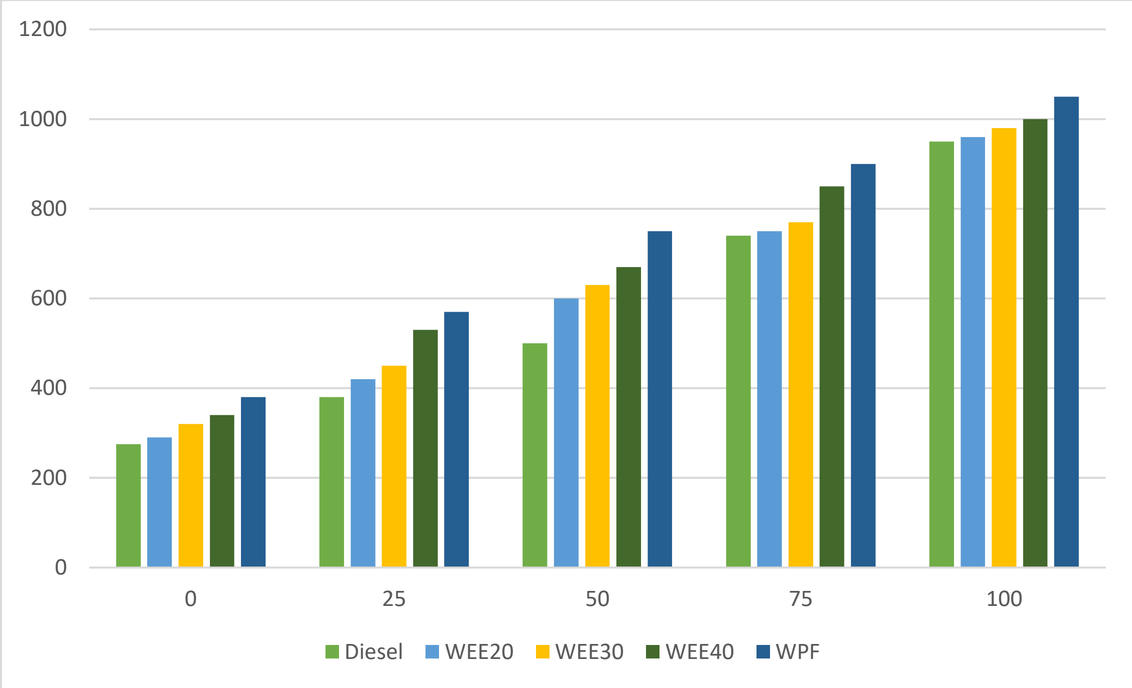

Fig 9. Fluctuation in NOX Discharges Based on Engine Loads.

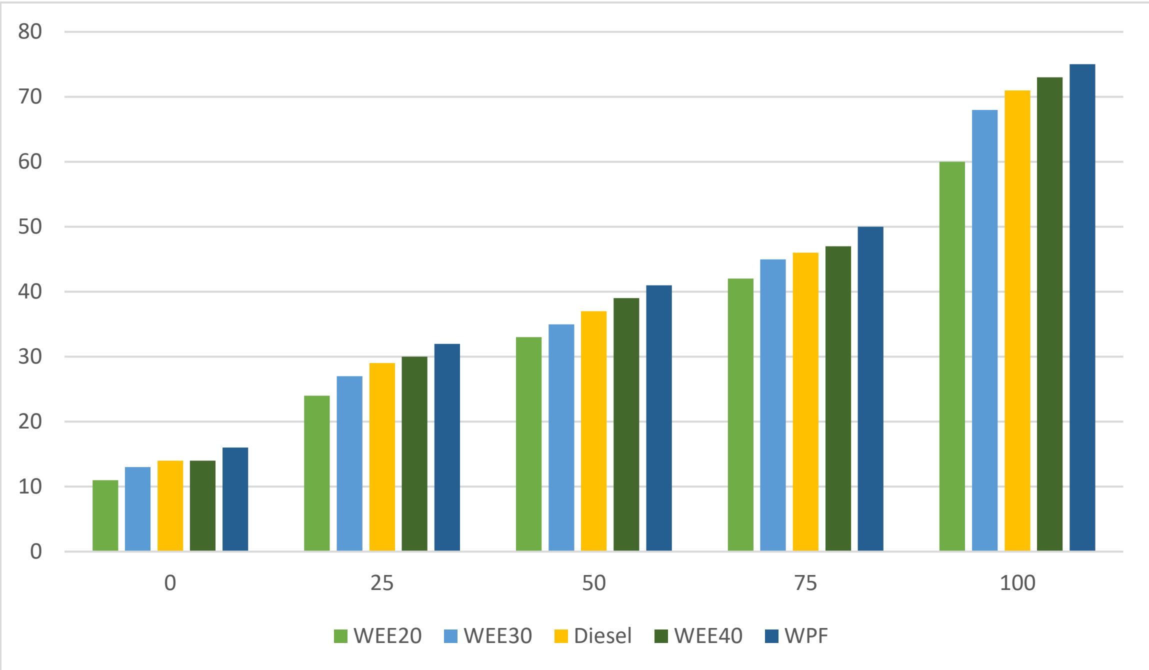

Fig 10. Fluctuations in Emissions of Smoke Based on Engine Loads.

The exhaust of the engine serves as a visible manifestation of the engine's process of combustion. Smoke is generated by the inefficient combustion of fuel, leading to the formation of unburned particles of carbon. Smoke is generated inside engines during the combustion phase of diffusion. The atomized fuel droplets undergo a process where they are divided into individual carbon atoms and then undergo oxidation in the ignition zone. Discharges from smoke in the ignition-rich zone result from factors such as inadequate air supply, a greater carbon-to-hydrogen ratio, hypered fuel viscosity, inadequate fuel atomization, and unrestricted fuel accretion inside the ignition chamber. According to data in **Fig 10**, the smoke emissions from WEE30 and WEE20 blends are reduced by about 4.44% to 7.69% and 8 to 9.38%, as than diesel fuel. Nonetheless, WEE40 recorded a little 2% rise in smoke levels.

Quaternary blends generate a lower amount of smoke as compared to diesel fuel. The main objective of this is the combined effect of a greater number of cetane and the concentration of O_2 in blends of fuel. The number of cetane is a measure of agitation quality, with greater values indicating more gasoline flammability. As the number of cetane increases, the fuel's ability to ignite advances. Enhancing the lighting intensity of the fuel leads to increased efficiency in the combustion chamber during fuel burning. Consequently, the engine generates a reduced number of unburned particles of carbon. Moreover, the presence of O_2 in the fuel facilitates the process of fuel burning, hence reducing the emission of smoke. According to Ravikumar and Saravanakumar [23] observed a decrease in smoke emissions ranging from 8.6% to 21.28% in the engine with the coating compared to a regular diesel engine. Waste plastic fuel generated a much higher quantity of smoke, ranging from 18.8% to 39% more than diesel. The fuel has a higher concentration of aromatic components, leading to improper spray generation and fuel mixture formation [24]. As a result, inefficient combustion occurs, resulting in substantial smoke emissions. The incomplete combustion of WPF is caused by its high viscosity and low volatility.

V. CONCLUSION

This paper shows that using recycled plastic as fuel in a diesel engine has potential for mitigating emissions and advancing sustainable transportation. The experiment revealed that the fuel characteristics of Waste Plastic Fuel (WPF) closely mirror those of diesel fuel, and the engine can be efficiently fueled by pure pyrolysis oil derived from waste plastics. The research also analyzed the use of quaternary fuel blends using oxygenate additives, which demonstrated enhanced performance characteristics in comparison to WPF alone. The research findings suggest that the incorporation of oxygenates into fuel mixes enhances combustion efficiency and decreases emissions. The quaternary blends demonstrated improved thermal efficiency during breaking and reduced emissions of carbon dioxide, carbon monoxide, hydrocarbon, and nitrogen oxide in comparison to diesel fuel and WPF. Nevertheless, research has shown that the elevated viscosity of waste plastic oil might result in ineffective atomization and heightened carbon monoxide emissions. In summary, the study indicates that using recycled plastic as a fuel in a diesel engine may serve as a sustainable and environmentally beneficial substitute for conventional diesel fuels. Additional investigation and advancement are required to enhance the fuel characteristics and combustion qualities of waste plastic fuel mixtures, with the aim of increasing efficiency and decreasing emissions.

CRediT Author Statement

The authors confirm contribution to the paper as follows:
Conceptualization: Ji-hoon Kim and Anandakumar Haldorai; **Methodology:** Ji-hoon Kim; **Writing- Original Draft Preparation:** Ji-hoon Kim; **Visualization:** Anandakumar Haldorai; **Investigation:** Ji-hoon Kim and Anandakumar Haldorai; **Supervision:** Anandakumar Haldorai; **Validation:** Anandakumar Haldorai; **Writing- Reviewing and Editing:** Ji-hoon Kim and Anandakumar Haldorai; All authors reviewed the results and approved the final version of the manuscript.

Data Availability

No data was used to support this study.

Conflicts of Interests

The authors declare no conflict of interest.

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Competing Interests

There are no competing interests.

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