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# Effect of Hydrogen Enrichment and Titanium Dioxide Nanoparticles on Diesel Engines Running on Pyrolysis-Derived Plastic Oil

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This paper discusses the application of the pyrolysis oil mixed with Titanium Dioxide ($TiO_2$) nanoparticles in addition to hydrogen gas as an alternative fuel in a conventional, single, direct-injection diesel engine without any modifications. The main goal is to determine the impact of this fuel mix on the performance, combustion, and emission characteristics of a diesel engine fueled with pyrolysis-derived plastic oil blends. During the experiment, a constant rate of 30 liters per minute is maintained in the flow of hydrogen in the intake manifold. The engine reaction to different concentrations of the pyrolysis oil, 10 % and 30 %, by volume are studied, and the engine noise and vibrations are monitored in the entire process to gain insight into effects of its operation. The distribution of these nanoparticles is done evenly through an ultrasonication process with a frequency of 35 kHz. The synergistic effect of hydrogen and $TiO_2$ nanoparticles increases the oxygen content in the fuel, resulting in a complete combustion process. In addition, $TiO_2$ will add to the enhanced latent heat of vaporization, which ultimately will reduce the rate of evaporation and moderate the rate of combustion. Experimental results indicate that plastic oil blends exhibit lower brake thermal efficiency compared to diesel; however, the combined addition of hydrogen and nanoparticles mitigates this drawback by enhancing combustion kinetics. Improved heat release characteristics and in-cylinder pressure were observed for optimized blends. Emission analysis revealed reductions in carbon monoxide and unburned hydrocarbons with the hybrid approach, although a slight increase in nitrogen oxides was noted. Overall, the proposed strategy demonstrates a promising pathway for utilizing plastic waste-derived fuels in compression ignition engines.

**Keywords:** Hydrogen enrichment, plastic oil, pyrolysis, nano particle, diesel engine, $TiO_2$

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The world plastic production has surged to about 390.7 million metric tons in 2021, which is highly high in comparison to the past years [1]. According to Statista data, the number of plastic wastes increased by 20% in 2021 compared to 2015, indicating an acute growth trend that is also consistent with other reports in the energy sector. Such an accelerated rate of plastic waste production underlines the urgency of seeking effective methods to control it and turn it into a valuable resource. Pyrolysis has become one of the most popular methods of plastic waste treatment and energy recovery among the possible solutions [2]. Nevertheless, even with its benefits, the extensive implementation of pyrolysis is discouraged due to various limitations [3], especially restricting financial means. To overcome these constraints, a comprehensive approach is needed to maximize the use of pyrolysis as a component of a sustainable and a circular economy [4]. Pyrolysis is a promising and environmentally friendly technology of plastic waste management, which has been justified by numerous studies, primarily based on life cycle assessments [5, 6]. Depending on the operating temperature, pyrolysis may be of various sorts: slow, fast, flash, catalytic and hydrothermal processes. Screw reactors are particularly efficient in the treatment of mixed solid plastic waste, which is due to the possibility of uniform feeding and complete mixing. They have one of their major advantages in the fact that they

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have a controlled residence time of working [7, 8]. These reactors are usually best operated at about 500 0C in pyrolysis. Indicatively, they can process an approximate 300 grams of mixed plastic per hour, and have a residence time of only 15 seconds. Screw reactors have the potential to be an efficient choice to convert plastic waste into energy, which can be used. These systems have been used in a number of experimental studies that have proven to produce pyrolysis oil. Value-added product-generation, particularly the bio-oil derived by pyrolysis contributes to the sustainability. Refining of the pyrolysis oil in this process was done by heating the oil with 1 % of anhydrous sodium hydroxide until the evaporation point of the oil reached 230ºC. This oil was then tried in diesel engines and was found to perform as well as the conventional fossil fuels [9]. Mangesh et al. researched on mixtures of pyrolysis oil and diesel in different proportions (5, 10 and 15 %) in order to determine their influence on engine performance. They found that the rate of heat release (HRR) was significantly higher and the combustion delayed much thanks to alkenes in the bio-oil. But this increased viscosity and low calorific value of the blend resulted in slightly lower brake thermal efficiency (BTE) compared to pure diesel. Nonetheless, the emission of nitrogen oxide (NOx) was always lower with varying loads on the engines [8]. Conversely, high emissions of NOx were recorded in Janarthanan and Sivanandi and they attributed this to the higher adiabatic flame temperatures caused by the use of plastic-derived oil in diesel engines. According to other research, it is possible to reduce the emission of greenhouse gases through the selection of appropriate feedstocks and reactor designs [9]. The use of pyrolysis oil made of plastic waste helps in creating sustainable fuels, which is in line with the concept of a circular economy since it transforms waste into energy [10]. The present research is rare as it entails pyrolysis oil extraction of solid plastic by use of screw-like reactor. This is the first time that such oil containing cerium oxide ($TiO_2$) nanoparticles have been experimented in diesel engine, as far as the authors know. The study assesses engine performance, combustion behaviour and emissions of various brake power outputs. The results were contrasted to determine the viability of this pyrolysis oil as alternative fuel source towards supporting sustainable development objectives [11].

## MATERIALS AND METHODS

In this experiment, the plastic wastes used were high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC). The plastic materials were first washed and then dried before processing to eliminate any contaminants. The waste was then loaded into a screw type pyrolysis reactor to generate oil, gas and char. The pyrolysis was the thermal degradation of plastics in a screw reactor. This system included a single-screw feed system in which a motorized feeder was used to feed the system with finely shredded plastic waste. In order to provide homogeneous feeding and processing, the input material was homogenized in composition and particle size [12]. The screw speed of the reactor and the residence time could be varied, based on the desired operating temperature. Nitrogen gas was added into the reactor continuously in order to ensure that the atmosphere was inert and thus no oxidation would occur. When the thermal decomposition process was finished, the reactor produced three main products, i.e., pyrolysis oil, combustible gases, and solid char residue. This experiment adheres to the same methodology as the one already developed in our previous research in order to generate pyrolysis oil. Table 1 shows the detailed comparison of fuel qualities of the normal diesel and the pyrolysis oil obtained. The pyrolysis oil was analyzed by spectroscopy, which showed that the oil contained C-H stretching vibrations, especially related to the $CH_2$ alkane groups [13]. There was also weaker absorption bands observed which are associated with the vibrational modes of C-H bonds in the CH2 molecular structure. The Table 1 summarizes the most important physiochemical characteristics of the fuels including the density, viscosity, calorific value, and the flash point. The high viscosity of raw pyrolysis oil is one of the greatest constraints of direct usage in diesel engines as compared to conventional diesel fuel. This high viscosity has adverse impact on fuel injection and atomization leading to low efficiency in combustion [14]. To overcome this problem, the pyrolysis oil was blended with diesel in a good proportion to enhance its spray properties and guarantee a better atomization when injecting. This mixing strategy assists in ensuring that the fuel mixture is more compatible with the conventional engine systems, which boost performance of the engine and stability of combustion.

$$\text{Purity (\%)} = \left(\frac{\sum Ais\ X\ mis}{Ais\ X\ ms}\right) X100$$

Where: Ais = Area of the internal standard, mis = Mass of the internal standard, ms= Mass of the sample, ∑Ais = Total peak area of the compound of interest in comparison to the internal standard.

**Table 1. Comparison on fuel properties**

| Properties | Diesel | PO | ASTM |
|---|---|---|---|
| Kinematic Viscosity at 400°C (mm$^2$ /s) | 2.2 | 2.67 | D445 |
| Cetane number | 54 | 50.5 | D6890 |
| Calorific Value (kJ/kg) | 43,324 | 44,350 | D240 |
| Flash point (0°C) | 46 | 41 | D93 |

## ENGINE SPECIFICATION

A detailed series of performance and emission tests were conducted under different load conditions, that is, at 1.2 kW, 2.51 kW, 3.7 kW, and 5.1 kW of a single-cylinder diesel engine as detailed in Table 2 with the aid of an eddy current dynamometer to provide the required loading [15]. The consumption rate of fuel was also taken properly with the aid of digital flow meter to be sure that the measurements were taken correctly. The testing procedure started with a 5-minute idling period with pure diesel fuel to stabilize the engine then the trials on various fuel blends were conducted. The in-cylinder pressure changes were recorded with a Kistler 6056A piezoelectric pressure sensor and engine speed was measured at every crank angle position with a Kublar crank angle encoder. Shock impulse methods were used to analyze engine vibration characteristics and the data were analyzed by a Fast Fourier Transform (FFT) with a Kistler vibration analyzer. Simultaneously, the aural performance of the engine was measured through the level of the sound intensity with a digital sound level meter. A National Instruments (NI) data acquisition system (DAS) connected all sensing equipment and instruments and allowed real-time data acquisition [16]. A LabVIEW software platform was used to monitor, process, and store data efficiently with the integration of the DAS. The pressure sensors, crank angle encoders and charge amplifiers sent signals into the DAS to measure the fluctuations and the behavior of combustion on a cycle-by-cycle basis[17]. Hydrogen gas was used as a by-fuel in this study. A rotameter was used to introduce it into the intake manifold of the engine and the flow rate was kept constant at 30 liters per minute. A special settling chamber was used to reduce the risk of the high flammability of hydrogen, as well as a flashback arrestor. The experiment aimed at measuring different performance and emission parameters, such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), Heat Release Rate (HRR), in-cylinder pressure, noise, vibration levels, hydrocarbon (HC) emissions, carbon monoxide (CO), nitrogen oxides (NO$_x$), and smoke opacity. The following assessments were made: pure diesel (D), diesel mixed with 30 LPM hydrogen (DH), a mixture of 90% diesel and 10% pyrolysis oil (D10), D10 with 30 LPM hydrogen (D10H), a mixture of 70% diesel and 30% pyrolysis oil (D30), D30 [18].

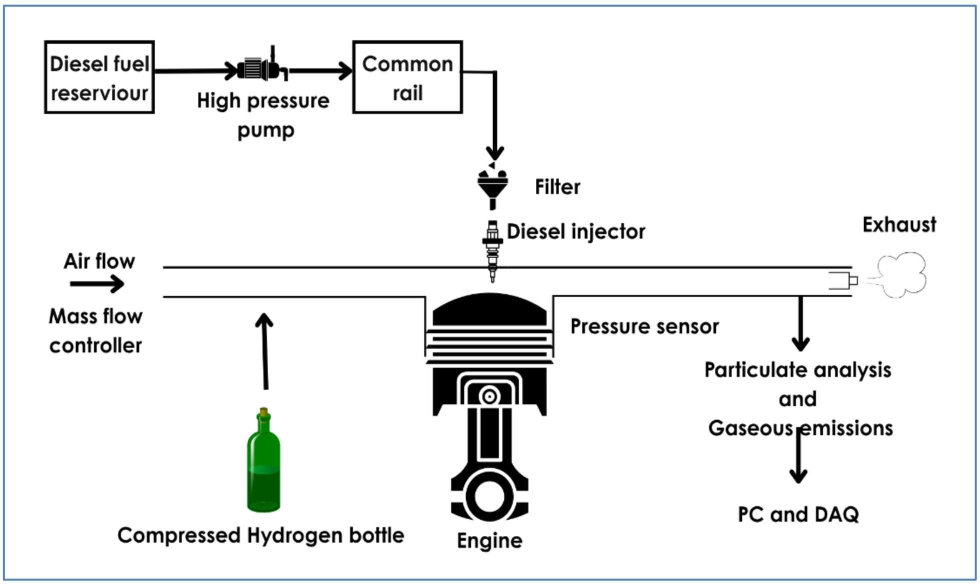

**Figure 1.** Experimental test setup layout.

**Table 2.** Engine Specifications.

| Parameter | Specification |
|---|---|
| Engine Type | Single Cylinder, Four Stroke Diesel Engine |
| Make & Model | Kirloskar TV1 Engine |
| Cooling System | Water Cooled |
| Rated Power | 3.5 – 5.2 kW |
| Rated Speed | 1500 rpm |
| Bore | 87.5 mm |
| Stroke | 110 mm |
| Compression Ratio | 17.5:1 |
| Combustion Type | Direct Injection |
| Fuel Used | Diesel (or blends if applicable) |
| Injection Pressure | 200 – 220 bar |
| Starting Method | Electric Start |

## RESULT AND DISCUSSION

### Combustion Characteristics

Higher in-cylinder pressure is likely to increase the combustion temperature, which is mainly caused by the influence of latent heat in the vaporization cycle. Interestingly, the effect of different blends of test fuels on this pressure behavior is also observed. The presence of alkanes and alkenes in pyrolysis oil greatly affects combustion characteristics. In comparison to these blends, conventional diesel fuel has a more advantageous atomization and it takes less energy to vaporize; its range is between 41.5 kJ/mol and 101.80 kJ/mol as compared to pyrolysis blends which have a higher energy range of 109.4 kJ/mol - 162.2 kJ/mol. This increased vaporization energy reduces the rate of evaporation of pyrolysis-based fuels which in the end influences their combustion behavior. The chemical analysis shows that in pyrolysis oil, unsaturated hydrocarbons that have a double bond are quite a few. The energy needed to break these bonds is more, which results in increased chemical reaction times and contributes to the delay in combustion. The increased ignition delay of the pyrolysis oil-air mixture facilitates better mixing that subsequently results in maximum combustion [19]. As the percentage of pyrolysis oil in diesel is high, the total latent heat of vaporization increases. The latter leads to increased heat release rate (HRR) in the diffusion flame phase and increased in-cylinder pressure. These effects may be reduced by either subjecting the pyrolysis oil to hydrocracking, or by incorporating nanoparticles in the fuel mixture. Nanoparticles are used to enhance the combustion process by increasing the atomization of the fuel and accelerating the evaporation process. Moreover, it is possible to add nanoparticles to the fuel mix to reduce the total carbon content of the mixture.

The heat release characteristics of the test fuel blends tend to follow two separate stages, namely, premixed combustion and diffusion combustion. The negative heat release rate (HRR) is observed in the initial stages of the cycle at 15oCA to 12oCA which is due to the delay in ignition that is present in all pyrolysis oil mixtures as shown in Fig. 3. This means that the burning cycle of these blends is much longer than that of pure diesel [1]. The HRR of all blends is greater than the one of neat diesel, mainly because of the presence of alkanes and also the alkene compounds with the double bonds in the chemical structure of the pyrolysis oil. Further, the long ignition delay of these blends leads to the increased volume of fuel injected, which facilitates more vigorous premixed combustion. Most of the heat is emitted in this premixed stage in fuels that have pyrolysis oil, because the double bonds that make the fuel molecules are more difficult to break than single bonds. The degree of pre-combustion mixture is directly influenced by the percentage of the pyrolysis oil in the mixture. Moreover, nanoparticles also reduce the heat release rate (HRR) by a small percentage by dealing with those factors that cause ignition delay and increasing the efficiency of combustion by increasing flame stability.

### Engine Performance

The difference in Brake Thermal Efficiency (BTE) was noticed over a broad spectrum of brake power outputs. The application of, 10 % and 30 % pyrolysis oil mixtures showed a slight reduction in BTE, which was mainly due to their increased viscosity and the occurrence of aromatic compounds. These blends however at increased load conditions tended to enhance atomization which enhanced a more vigorous combustion process. Nonetheless, the amount of energy per unit mass was still lower than that of pure diesel. The addition of hydrogen to the diesel blend resulted in a small increase in BTE- around 1.25%. In contrast, the 30% pyrolysis oil blend led to a more noticeable decline in BTE, mainly because of its lower calorific value and associated heat losses. This decrease in the efficiency can also be attributed to the high oxygen content and the increased molecular composition of the pyrolysis oil.

Also, since pyrolysis oil is very viscous, full combustion might not take place and thus unburnt particles of fossil fuel are propelled out in the exhaust. BSFC values of conventional diesel are always constant. Pyrolysis plastic oil low re action rate is an ideal reason for the higher BSFC. The pyrolysis oil introduction alters the kinetics of combustion in the engine during combustion process. Aromatic compounds and C=C molecules of pyrolysis oil modify the combustion process, which results in alterations in the ignition delay, flame propagation, and heat release properties [8]. Increased flame speed and increased flammability range than traditional hydrocarbon fuels such as diesel improves the combustion process that ultimately results in more efficient fuel combustion. Titanium oxide (TiO2 nanoparticles) is added to increase the surface area-to volume ratio of fuel blends. The nanoparticle Titanium oxide ($TiO_2$) engages in a redox cycle to optimize oxidation reactions which helps to promote the efficiency by consuming less amount of fuel.

Moreover, pyrolysis oil is very viscous, which may not burn off, meaning that the fuel particles that are not burned are released to the exhaust. Compared to traditional diesel, Brake Specific Fuel Consumption (BSFC) is likely to be greater with the use of pyrolysis oil. This increase is mainly due to the lower reactivity of pyrolysis-derived plastic oil. The pyrolysis oil addition changes the combustion properties of the engine, which affect the chemical kinetics of the combustion phase. The characteristics of its aromatic structures and unsaturated (C=C) bonds influence ignition delay and flame speed parameters as well as the overall heat release pattern. Conversely, hydrogen adds a positive effect to combustion because it has a higher flame speed and a wider flammability range than the regular hydrocarbon fuels such as diesel. This results in higher and efficient fuel combustion. In addition, the addition of titanium dioxide (TiO2) nanoparticles to the fuel mix increases the surface area-volume ratio and this increases the interaction between the fuel and air. TiO2 is also involved in redox reactions during combustion, which facilitated the enhancement of better oxidation and also provides improved efficiency in terms of the quantity of fuel needed to produce the same amount of power.

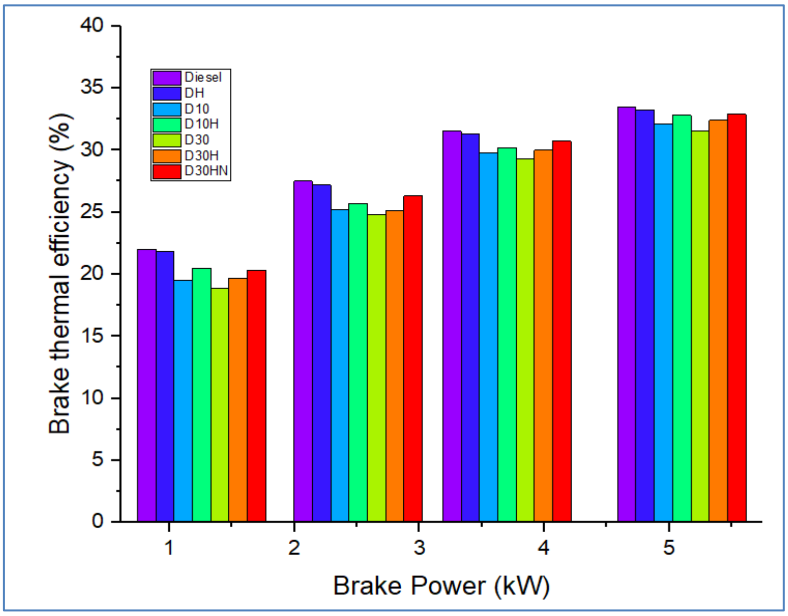

**Figure 2.** Brake thermal efficiency of different blends of fuels vs brake power.

## Noise and Vibration Characteristics

The levels of noise recorded with the various fuel mixtures at the different power outputs showed that when hydrogen was added to diesel, there was a significant reduction of about 6 dB. This steady decrease means that hydrogen plays a significant role in reducing engine noise. The primary causes of this accomplishment are the improvement in the combustion behavior, optimization of engine configuration, and the timing of fuel injection. The effect of hydrogen on the rate of pressure increase during combustion is significant- it facilitates a more smooth combustion process by controlling the development of pressure within the combustion chamber which consequently results to a much quieter engine operation. Titanium dioxide (TiO2) with its high surface area, also enhances this process by providing more oxygen when it burns. This not only aids in the prevention of knocking, but also allows the burning to be more controlled, so that the inner cylinder pressure swings are minimized, and consequently, the vibration rates as well. Nevertheless, higher vibration can be observed in fuel blends that have pyrolysis oil. This is probably because of the uneven shape of the pyrolysis oil molecules and their irregular combustion properties that lead to irregular pressure formation in the cylinder. This aberration contributes to unsteady combustion and increased levels of vibration.

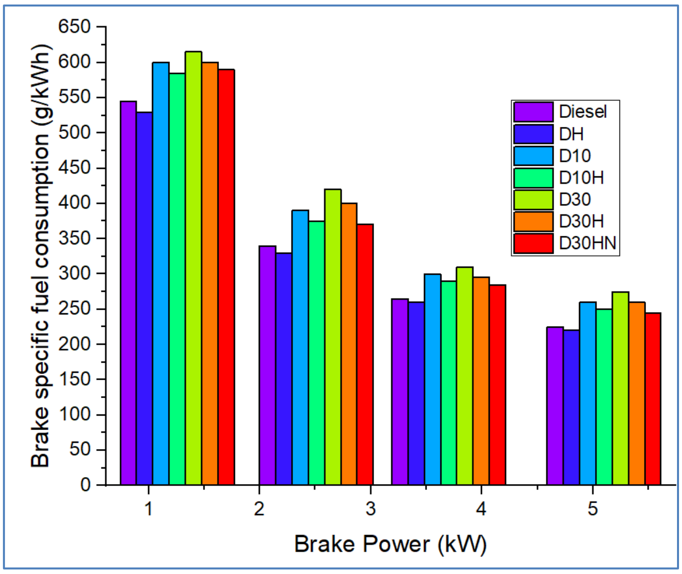

**Figure 3.** Brake specific fuel consumption for various types of fuel blends vs brake power.

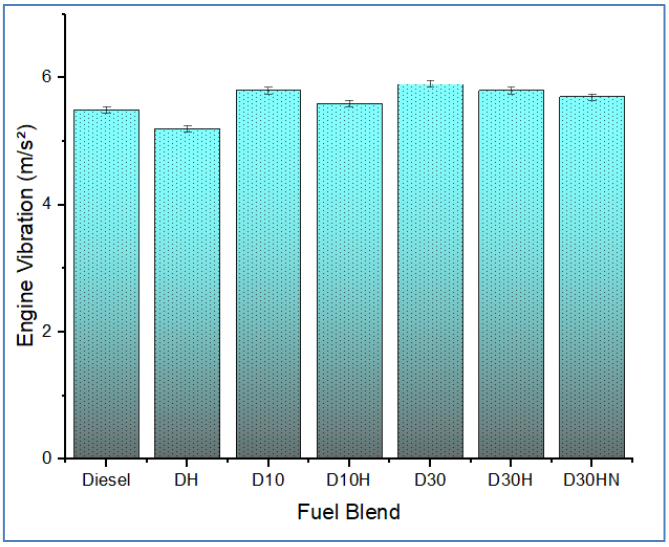

**Figure 4.** Fuel blend vs Engine Vibration (m/s$^2$).

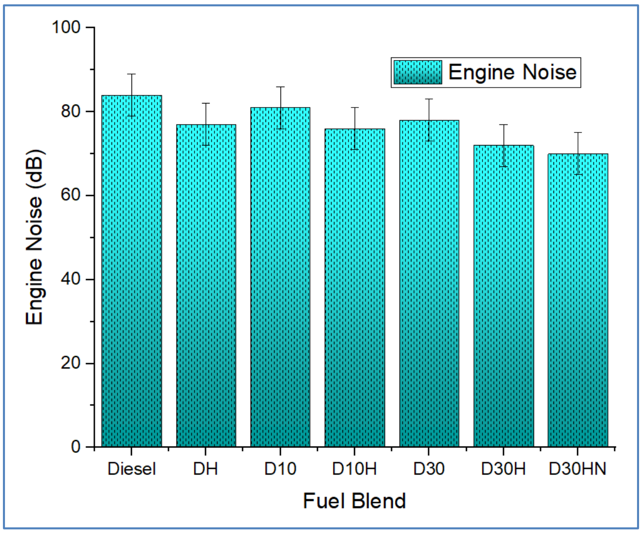

**Figure 5.** Fuel blend vs Engine Noise (dB).

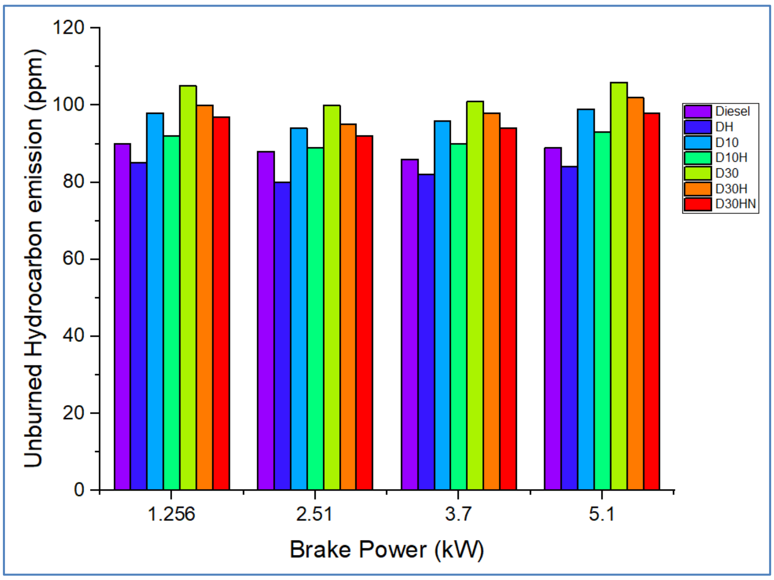

**Figure 6.** Brake Power vs UHC (ppm).

Aromatic hydrocarbons are well-established precursors to unburnt hydrocarbon (UHC) and particulate matter (PM) emissions in internal combustion engines. In this research, the blending of pyrolysis oil with diesel at 10 % and 30 % concentration was observed to give greater UHC emissions compared to neat diesel at all engine power levels as shown in Fig. 8. The main reason that causes such a behavior is the higher aromatic composition of the pyrolysis oil as compared to the conventional diesel fuel. Moreover, unsaturated compounds containing carbon-carbon double bond in pyrolysis oil enhance the energy used in dissociation of molecular bonds during combustion. This increased energy requirement and the unavailability of oxygen in some areas of combustion encourages the partial oxidation of the fuel. The resultant low oxygen levels cause an increase in the percentage of uncombusted hydrocarbons going to waste in the exhaust stream. The latter effects are more pronounced with increasing blending ratios, which explains why it is important to optimize fuel composition and combustion parameters carefully, when adding pyrolysis oil to diesel engines. The addition of hydrogen to pyrolysis oil, with the use of Titanium oxide (TiO2) nanoparticles, allowed appreciating a significant increase in the quality of combustion and emissions [20]. Hydrogen was present and served to effectively dilute the concentration of aromatic hydrocarbons, and TiO2 was present as an oxygen-releasing catalyst, which reduced the local concentration of fuel-rich pockets in the combustion chamber. This increased the availability of oxygen to help the fuel oxidation be more complete, which directly led to reduced pollutants. Experimental findings indicated that the hydrogen-enriched D10 blend had much lower unburnt hydrocarbon (UHC) emissions than the baseline D10 blend and neat diesel. This decrease shows the synergistic effect of hydrogen addition that counteracts the negative impact of the aromatic and unsaturated compounds of the pyrolysis oil on the combustion efficiency [21]. Hydrogen and TiO2 complement each other mechanistically in the development of combustion kinetics. Hydrogen enhances quicker propagation of flames and leaner combustion, $TiO_2$ also catalytically breaks down unsaturated double bonds and higher molecular weight hydrocarbons that exist in pyrolysis oil. The disintegration of these complicated structures not only minimizes the ignition delay, but also inhibits the formation of uncomplete combustion products. This two-fold process highlights how hydrogen-nanoparticle-aided pyrolysis oil mixtures could present a feasible solution to achieving cleaner and more efficient diesel engine operation [22].

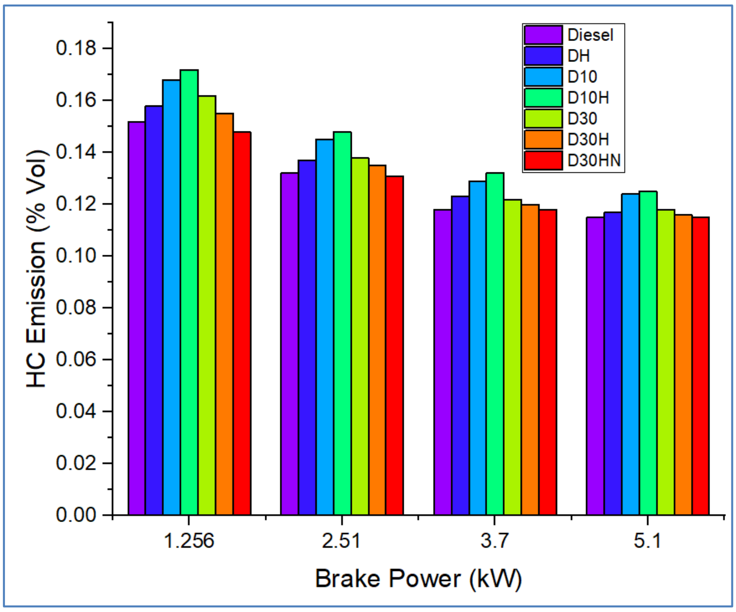

**Figure 7.** Brake power (kW) vs HC Emission (% Vol).

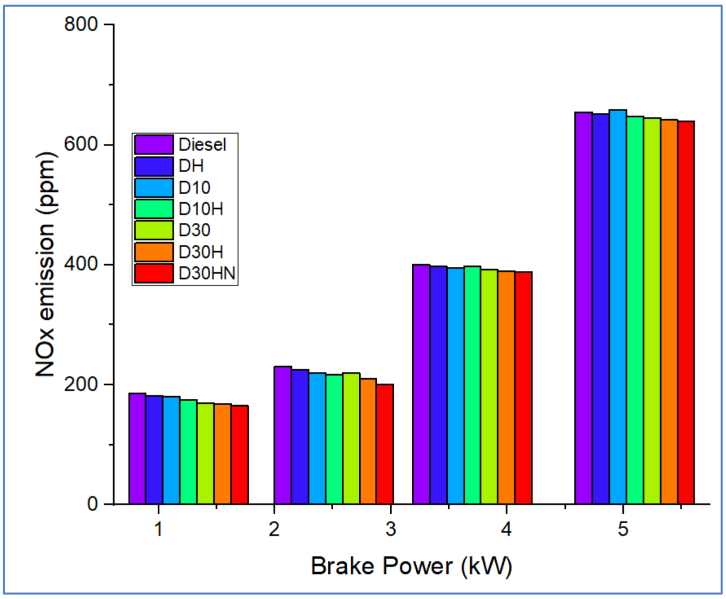

**Figure 8.** Brake Power (kW) vs (NOx Emission (ppm).

As indicated in the figure, the higher the percentage of pyrolysis oil in the fuel mix, the higher the carbon monoxide emissions (CO) will be. This pattern may be explained by the fact that the aromatic content of pyrolysis oil is higher than that of conventional diesel that is likely to cause incomplete combustion. Aromatic hydrocarbons typically take a longer period to burn to completion and this may lead to an incomplete oxidation of the fuel leading to an increase in the production of CO. But the incorporation of hydrogen in the fuel mixtures can unanimously counteract the emissions of CO at all loads of operation. This decrease is mainly because of the high ignition qualities of hydrogen which has a broader flammability zone and greater speed of flames compared to diesel. Hydrogen presence enhances the rate of combustion onset, ignition delay, and even spreads the flames. This increased uniformity in combustion promoting the further oxidation of carbon-based intermediates thus reducing CO emission. Moreover, in the blends of cerium oxide (TiO2) nanoparticles and hydrogen, an extra enhancement in the quality of combustion is noticed. As an oxygen releasing catalyst, TiO2 elevates the cetane number of the fuel, which helps in reducing ignition delay. This synergistic interaction between hydrogen enrichment and catalytic activity has also been observed by Zhang et al. where the higher the rate at which the combustion process was initiated and the more effectively the oxidation process, the greater the reduction in the CO emissions. The fact that CO patterns of various fuel blends are similar, i.e., the higher the brake power (BP), the lower the CO levels, shows that the CO levels are typically lower with all the test fuels. When the BP is lower, incomplete combustion caused by lower temperatures in-cylinder results in increased CO emissions. Increase in BP leads to increase in temperature during the in-cylinder process, which enhances the further burning of carbon to $CO_2$, thus decreasing CO emission. Of the blends, fuels with hydrogen and TiO2 nanoparticles exhibited significant decrease in COs emissions in comparison to diesel. Hydrogen has a high diffusivity and flame velocity, which increases the mixing and combustion process, and $TiO_2$ nanoparticles are catalysts with a high surface area and hence they more effectively oxidize CO. But those blends that had a greater percentage of pyrolysis oil at lower BP had a little more CO which could be due to the fact that the heavier fractions were not fully oxidized and the pyrolysis oil had unsaturated compounds [23]. The trend of the difference in the NOx emissions of the same blends has an opposite pattern with the level of NOx rising drastically as the BP increases[24]. This is due to the increase in in-cylinder temperatures and availability of more oxygen which further enhances the formation of thermal NOx. The increase in temperature is more pronounced at higher BP because of high rates of combustion of fuel and high heat release. Mixed with more pyrolysis oil, especially the 30% blend, had a slight increase in NOx emissions as compared to diesel. This can be attributed to increased ignition delay and a higher proportion of premixed combustion that lead to higher heat release rates (HRR) and high temperatures of combustion. The more natural oxygen in the pyrolysis oil also plays a part in the formation of NOx. The combustion of hydrogen with diesel also caused slight rise in NOx emissions since the flame speed and diffusivity of hydrogen are high resulting in rapid combustion and higher maximum flame temperature. On the contrary, blends with $TiO_2$ nanoparticles reduced a small amount of NOx although they contained oxygen. This decrease is explained by the catalytic nature and the large surface area that make $TiO_2$ more efficient in combustion and cools down local hot spots, preventing the formation of NOx thermal. Generally, the findings show that though hydrogen and TiO2 additions are effective in CO cutdown, their impacts on NOx are mixed, hydrogen mostly enhances NOx whereas TiO2 assists in fringe cutdown of NOx. Oil blends, especially those with high concentrations, are more likely to boost NOx emissions but might have to be optimized to balance the decrease in CO without impacting the NOx levels [18, 25].

## CONCLUSION

The study is aimed at understanding the effectiveness of pyrolysis oil, hydrogen, and $TiO_2$ nanoparticles together in influencing the performance and emissions of a diesel engine. Using the pyrolysis oil as an additive to the neat diesel affects the engine behavior because of the complex chemical composition of the pyrolysis plastic oil, which consists of alkanes, alkenes, and aromatic bonds. In its pure form, pyrolysis oil requires more power to rupture the alkenyl bonds, thus lowering the thermal efficiency of the engine. Hydrogen and $TiO_2$ nanoparticles are synergistically added to increase the decomposition of aromatic bonds contained in pyrolysis oil blends. Hydrogen also provides extra calorific value, and flame propagation properties, whereas $TiO_2$ nanoparticles, due to the high surface area, and catalytic properties, enhance the oxidation process. This mixture helps to enhance combustion stability and thermal conductivity of the fuel mixture. At all brake power (BP) levels, pyrolysis oil blends show a significant reduction in brake thermal efficiency (BTE) relative to neat diesel. Nonetheless, the addition of the hydrogen and nanoparticle reduces this reduction by improving the kinetics of combustion. High-carbon-chain compounds present in pyrolysis oil help in increasing the heat release rate (HRR) and peak in-cylinder pressure with the percentage of pyrolysis oil in the blend. Among the blends tested, B30 exhibits the best HRR and in-cylinder pressure since its composition has high levels of unsaturated hydrocarbons and the presence of double-bonds. The growth in the content of pyrolysis oil also increases the latent heat of vapour of the fuel mixture. Such characteristic delays the evaporation of fuels, thus reducing the rate of combustion and impacting the efficiency.

Regarding emissions, neat pyrolysis oil blends generate the greatest amounts of carbon monoxide (CO) and unburned hydrocarbons (UHC) because of the abundance of aromatic compounds and the tendency to create localized areas of high density of fuels. The addition of hydrogen and $TiO_2$ nanoparticles to the blends significantly decreases the CO and UHC emissions, which means a more complete combustion process. Although addition of hydrogen moderately increases nitrogen oxide ($NO_x$) emissions because of the rise in combustion temperatures and flame speed, the co-addition of $TiO_2$ nanoparticles partially reduces this increase by regulating local peak temperatures. Overall, the present study provides useful information about the possibility of using pyrolysis oil made of plastic waste in traditional diesel engines. When mixed with hydrogen and $TiO_2$ nanoparticles, one can enhance the efficiency of the combustion process, decrease some of the harmful emissions, and contribute to the ideals of a circular economy, turning plastic waste into a potential alternative source of fuel.

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