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PERFORMANCE ANALYSIS OF THE CRDI DIESEL ENGINE'S PERFORMANCE AND EMISSION PARAMETERS BLENDED WITH LEFTOVER COOKING OIL, ADDITIONAL NANOPARTICLES, AND HYDROGEN ENRICHMENT

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The low cost and wide availability of used cooking oil make it a desirable feedstock for the generation of biodiesel. In this study, Three distinct hydrogen enrichment values (*4 lit/min*, *6 lit/min*, and *8 lit/min*) and nanoparticle concentrations of *50*, *100*, and *150 PPM*) are combined with used cooking oil blends (*10%*, *15%*, and *20%*) to evaluate the CRDI single-cylinder diesel engine's efficiency and emission properties. Split injection technique was used in the experiments to investigate the impact on emissions and engine efficiency. The outcomes reveal a significant improvement in brake thermal efficiency over standard diesel fuel, up to *8%*. In addition, a noteworthy decrease was noted in particular fuel consumption and emissions parameters, including smoke, hydrocarbons (HC), and carbon monoxide (CO), under all experimental setups. On the other hand, there was a minor rise in nitrogen oxide (NOx) emissions. With encouraging gains in performance and emissions characteristics, this study clarifies the feasibility of using used cooking oil blends with hydrogen nanoparticle enrichment as a sustainable alternative fuel for CRDI diesel engines. Increased environmental friendliness and overall efficiency could be achieved with this alternative fuel technology with additional refinement and optimization of engine operating parameters.

Key words: CRDI single cylinder diesel engine, waste cooking oil, hydrogen, TiO_2 nanoparticles, performance characteristics.

1. Introduction

Significant advancements have been made in internal combustion engines to improve efficiency and reduce emissions [1]. This study explores a novel method to evaluate a common rail direct injection (CRDI) diesel engine by blending used cooking oil with nanoparticles and adding hydrogen enrichment. Our goal is to assess how these components affect engine performance and environmental impact. This research addresses waste oil disposal and aims to develop cleaner, more efficient fuels, offering insights into the benefits and applications of this innovative fuel blend for modern diesel engines.

A review of the literature shows a history of research aimed at improving diesel engine performance and emissions through alternative fuels and technologies [2-5]. This evolution began with biodiesel from animal fats and vegetable oils, and has progressed to include waste cooking oil (WCO) blends, nanoparticle additives, and hydrogen enrichment [6, 7]. Early research focused on biodiesel as a direct replacement for diesel, showing it could reduce particulate matter (PM) and carbon monoxide (CO) but slightly increase nitrogen oxide (NOx) emissions [8-10]. Later studies shifted to exploring various biodiesel feed stocks, especially waste cooking oil (WCO), which was found to be economically and environmentally beneficial.

Research by Zhang *et al.* [11, 12] showed WCO biodiesel performs similarly to diesel and reduces hydrocarbons (HC), smoke, and CO. However, issues with NOx emissions and engine durability led to further investigations into fuel additives and advanced combustion techniques [13]. Recent advancements have explored the combined effects of nanoparticle additives and hydrogen enrichment in biodiesel blends. Das and Das [14] found these additives improve engine performance and reduce harmful emissions. Praveena *et al.* [15] reported that hydrogen-enriched biodiesel boosts combustion efficiency and reduces HC and CO, though it increases NOx emissions. Arslan and Çelik [16] showed that cerium oxide (CeO2) nanoparticles improve engine torque and thermal efficiency while reducing CO, HC, and soot, but increase NOx emissions. These studies demonstrate that nanoparticles and hydrogen enrichment can enhance biodiesel's performance and viability [17]. Hydrogen, known for its high flame speed and diffusivity, can significantly improve combustion efficiency and reduce emissions when used in combination with diesel or biodiesel blends [18]. The pioneering work of Akar *et al.* [19] and subsequent studies by Elnajjar *et al.* [20] demonstrated that hydrogen-enriched combustion could lead to substantial reductions in PM, HC, and CO emissions, along with improved thermal efficiency. However, challenges related to safety concerns and hydrogen storage remain. Combining the advantages of WCO biodiesel, nanoparticles, and hydrogen enrichment, recent studies have aimed to create synergistic effects to maximize performance and minimize emissions. Researchers such as Mehra *et al.* [21] and Zhang *et al.* [22] analyzed the combined performance of nanoparticle additives and hydrogen enrichment in biodiesel-fueled engines. Their findings suggested that this multi-faceted approach could lead to significant improvements in brake thermal efficiency (BTE) and reductions in NOx, CO, HC, and PM emissions. These studies emphasize the importance of optimizing fuel blends and combustion strategies to achieve sustainable and efficient engine performance. In the context of CRDI diesel engines, which offer precise control over fuel injection and combustion processes, the integration of WCO biodiesel, nanoparticles, and hydrogen presents a particularly promising avenue for research [23, 24]. Recent studies, including those by Chetia *et al.* [25] and Bharti *et al.* [26], highlight the benefits of integrating WCO biodiesel with hydrogen enrichment and nanoparticle additives. For example, Sharma *et al.* [27] found that adding titanium oxide (TiO2) nanoparticles to waste cooking oil-based biodiesel significantly reduced emissions, including a *25%* decrease in carbon monoxide, a *16.6%* reduction in hydrocarbons, and a *3.75%* reduction in nitrogen oxides compared to standard biodiesel and diesel. Similarly, Chetia *et al.* [28] examined the effects of adding hydrogen and CeO_2 nanoparticles to waste cooking palm biodiesel in a CRDI engine. Their results indicated that the combined use of hydrogen and CeO_2 in a B20 biodiesel blend enhanced brake thermal efficiency by *3.53%* and reduced brake fuel consumption by *16.12%* compared to diesel. Emissions of CO, HC, and smoke were significantly reduced, though NOx emissions increased by *11%*. Moreover, recent reviews by Abhishek *et al.* [29] explored the effects of adding aluminum oxide (Al_2O_3) and titanium dioxide (TiO_2) nanoparticles to biodiesel derived from Guizotia abyssinica oil. The GAB20A blend demonstrated the highest energy efficiency of *29.5%* at *1600 rpm*, with the lowest fuel consumption of *203 g/kWh*. While NOx and CO emissions were low, there was a slight increase in CO_2. The results were validated using an artificial neural network (ANN), showing minimal differences in energy efficiency, exergy efficiency, and sustainability index. Subsequent experimental studies by Das *et al.* [30] investigated the effects of adding iron nanoparticles (INP) and hydrogen enrichment to a waste cooking palm biodiesel (WCB) blend in a CRDI diesel engine. The findings showed that this combination enhanced brake thermal efficiency (BTE) by *7.1%* and significantly reduced CO and HC emissions, though NOx emissions increased by *27.4%*. Jayabal *et al.* [31-33] incorporated aluminum nitrate nanoparticles and graphene oxide nanoplates as catalysts into the biodiesel blend. Their findings indicated increased in-cylinder pressure and heat release rate, improved brake thermal efficiency, reduced brake specific fuel consumption, and decreased emissions of carbon monoxide, hydrocarbons, and smoke, although nitrogen oxides emissions increased slightly.

Current literature lacks comprehensive studies on the combined effects of waste cooking oil (WCO), hydrogen, and TiO_2 nanoparticles on CRDI diesel engines. While individual benefits are recognized, their synergistic impact on combustion efficiency and emissions is unexplored. This study addresses this gap by testing various concentrations of WCO, hydrogen, and TiO_2 nanoparticles in a small-cylinder CRDI engine. Energy and exergy analyses are used to optimize fuel blends, improve engine performance, and enhance sustainability, offering valuable insights for future research in sustainable engine technologies.

2. Materials and method

As illustrated in Fig.1, leftover cooking oil from restaurants was transformed into biodiesel. These assessments included measurements of viscosity, specific gravity, water and sediment content, total acidity, ash content, sulphur content, flash point, and cloud point.

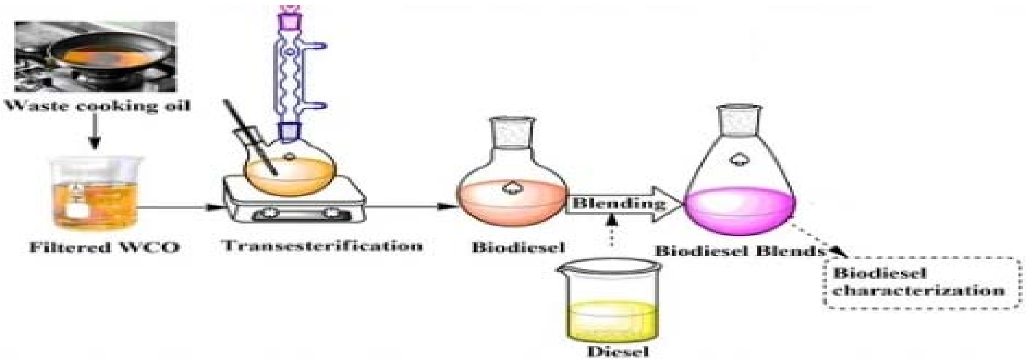
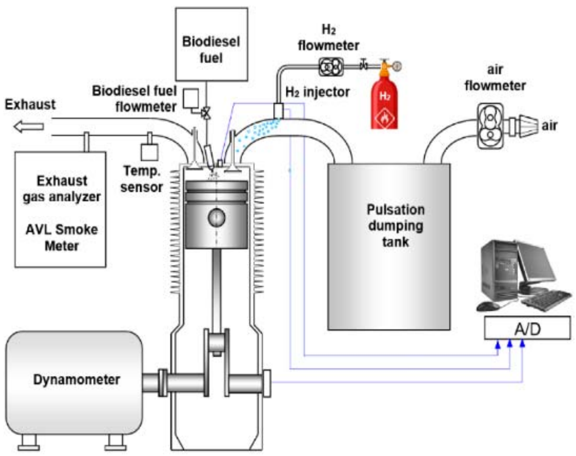


Fig.1. Transformation of WCO into a biodiesel.

To prepare a biodiesel blend (diesel and waste cooking oil) with titanium dioxide (TiO_2) nanoparticles at concentrations of *50*, *100*, and *150 ppm*, begin by accurately weighing the required amounts of TiO_2 nanoparticles, which should preferably be in the size range of *20-50 nm*. Disperse these nanoparticles in a small volume of biodiesel using an ultrasonicator for *20-30* minutes to ensure uniform dispersion and break any agglomerates. Transfer the nanoparticle suspension into a larger beaker containing the remaining volume of biodiesel. Stir the mixture on a magnetic stirrer with heating at *40-50°C* and moderate speed (*300-500 rpm*) for *1-2* hours. Optionally, use the ultrasonicator for an additional *20-30* minutes post-stirring to achieve even dispersion. Verify the dispersion visually and through sample analysis techniques like Scanning Electron Microscopy.

The experimental setup used a single-cylinder, four-stroke Compression Ignition (CI) engine with a Common Rail Direct Injection (CRDI) system as shown in Fig.2. An electromagnetic dynamometer with a speed sensor measured load and speed, while the CRDI system parameters were adjusted via ECU software. Hydrogen was introduced through a dedicated inlet port, with flow rate measured by a hydrogen-calibrated rotameter. Smoke opacity was measured with an AVL meter, and emissions were analyzed via a gas analyzer connected to the exhaust. Experimental trials were carried out with varied injection system parameters as mentioned in Tab.1 with the engine running at *1500 rpm* and a constant load of *12 kg*.



engine make	Kirloskar
cylinders	single (01)
combustion type	direct injection
cylinder bore	*80 mm*
cylinder stroke	*110 mm*
compression ratio	*12 to 18*
rated speed	*1500 rpm*
power	*3.5 kw*
injector used	Bosch (Mahindra Maxximo)
operating pressure range	*300-1400 bar*
loading device	Electric (Eddy current dynamometer)

Fig.2. Experimental Setup for hydrogen and waste cooking oil biodiesel analysis with specification.

Table 1. Factors consider along with their level for experimental work

factors	level			other injection system parameters		
	1	*2*	*3*	injection timing (°CA BTDC)	pilot injection	*35*
IP (*bar*)	*400*	*500*	*600*		main injection	*15*
WCO (*%*)	*10*	*15*	*20*	injection quantity (%)	pilot injection	*15*
H_2 (*litre/min*)	*3*	*6*	*9*		main injection	*85*

3. Results and discussions

3.1. Brake thermal efficiency (BTE)

The combined effect on BTE of a small cylinder CRDI diesel engine when blended with used cooking oil (WCO), titanium dioxide (TiO_2) nanoparticles, and hydrogen enrichment demonstrates significant improvements in engine performance. Blending diesel fuel with WCO has shown a notable impact on BTE.

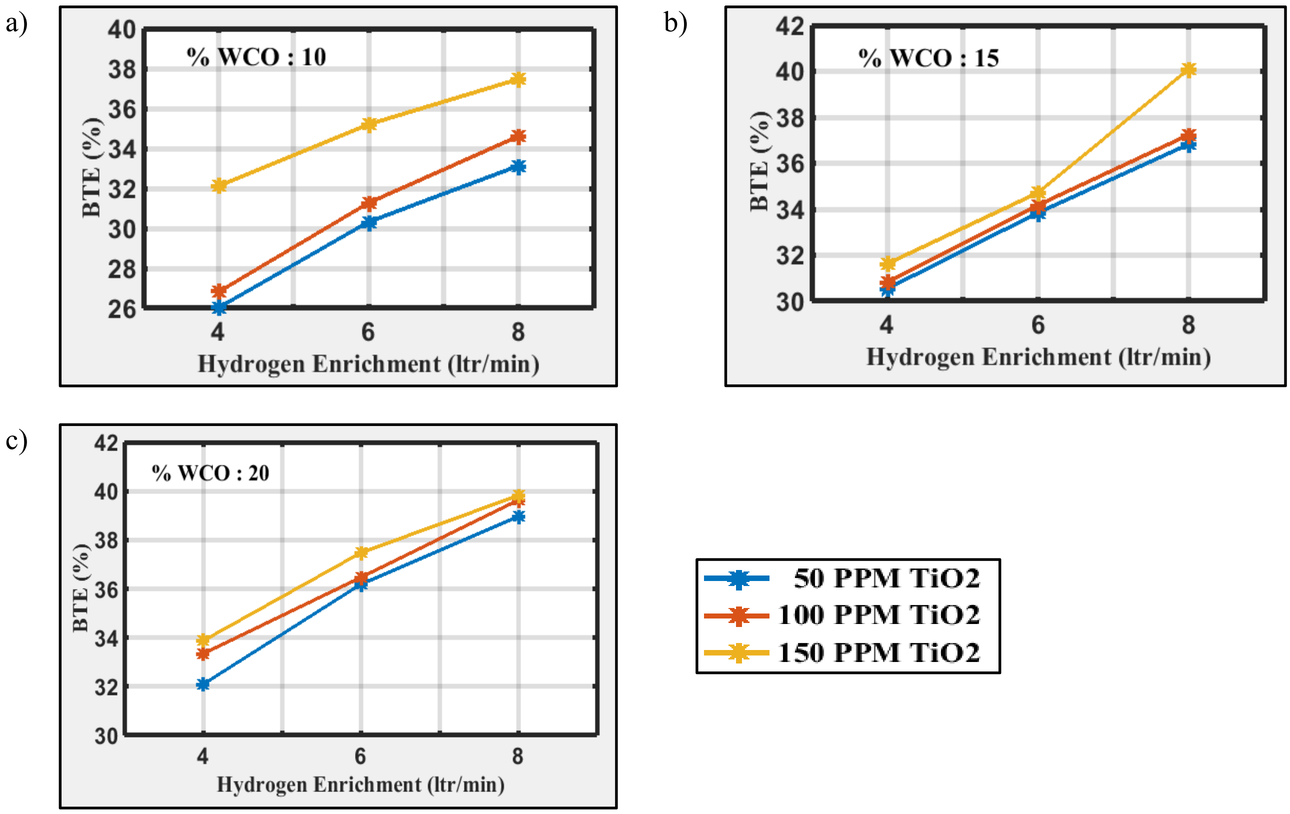


Fig.3. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on BTE (a-c).

As observed in Fig.3a, b, an increase in the WCO concentration from *10%* to *20%* leads to a rise in BTE. This enhancement can be attributed to several factors. WCO possesses a higher cetane number compared to conventional diesel fuel [34]. A shorter ignition delay is indicated by a higher cetane number, which promotes smoother and more effective combustion processes. Both WCO and TiO_2 nanoparticles contribute to better atomization, leading to finer droplet formation and improved air-fuel mixing [35]. The higher cetane number of WCO and the catalytic properties of TiO_2 nanoparticles reduce ignition delay and promote more efficient combustion. The addition of TiO_2 nanoparticles to the fuel blend further boosts the BTE. This can be seen in Fig.3b and Fig.3c, where nanoparticle concentrations of *150 PPM* result in higher BTE compared to lower concentrations. TiO_2 nanoparticles act as catalysts in the fuel, improving atomization and producing finer fuel droplets. This leads to a more homogenous air-fuel mixture and more efficient combustion [36]. Hydrogen enrichment significantly impacts BTE, as depicted in Fig.3a-c. The addition of hydrogen from *4* to *8* litres per minute results in a gradual *8%* increase in BTE across various WCO and nanoparticle concentrations. Hydrogen addition raises the peak combustion temperature, which enhances the thermal efficiency by converting more heat into useful work.

3.2. Specific fuel consumption (SFC)

The influence of nanoparticle addition and hydrogen enrichment on the specific fuel consumption (SFC) of a CRDI small-cylinder diesel engine in conjunction with split injection technology, blended with waste cooking oil (WCO) at concentrations of *10%*, *15%*, and *20%*, reveals significant trends and underlying physical mechanisms. As hydrogen enrichment increases, there is a consistent reduction in SFC. For instance, at a hydrogen supply rate of *8 litres/min*, the SFC is significantly lower compared to lower hydrogen enrichment levels, such as *4 litres/min*. This trend is consistent across all WCO concentrations and nanoparticle additions. The most substantial reduction in SFC is observed when hydrogen enrichment increases from *4* to *8 litres/min*, indicating hydrogen's dominant role in improving combustion efficiency. The addition of nanoparticles at *150 PPM* leads to a noticeable decrease in SFC. The decrease in SFC becomes more pronounced with higher hydrogen enrichment levels, indicating a synergistic effect between nanoparticles and hydrogen. Varying the WCO levels such as *10%*, *15%*, and *20%* have only a minimal effect on SFC. Hydrogen has a high flame speed and diffusivity, which leads to a more complete and efficient combustion process.

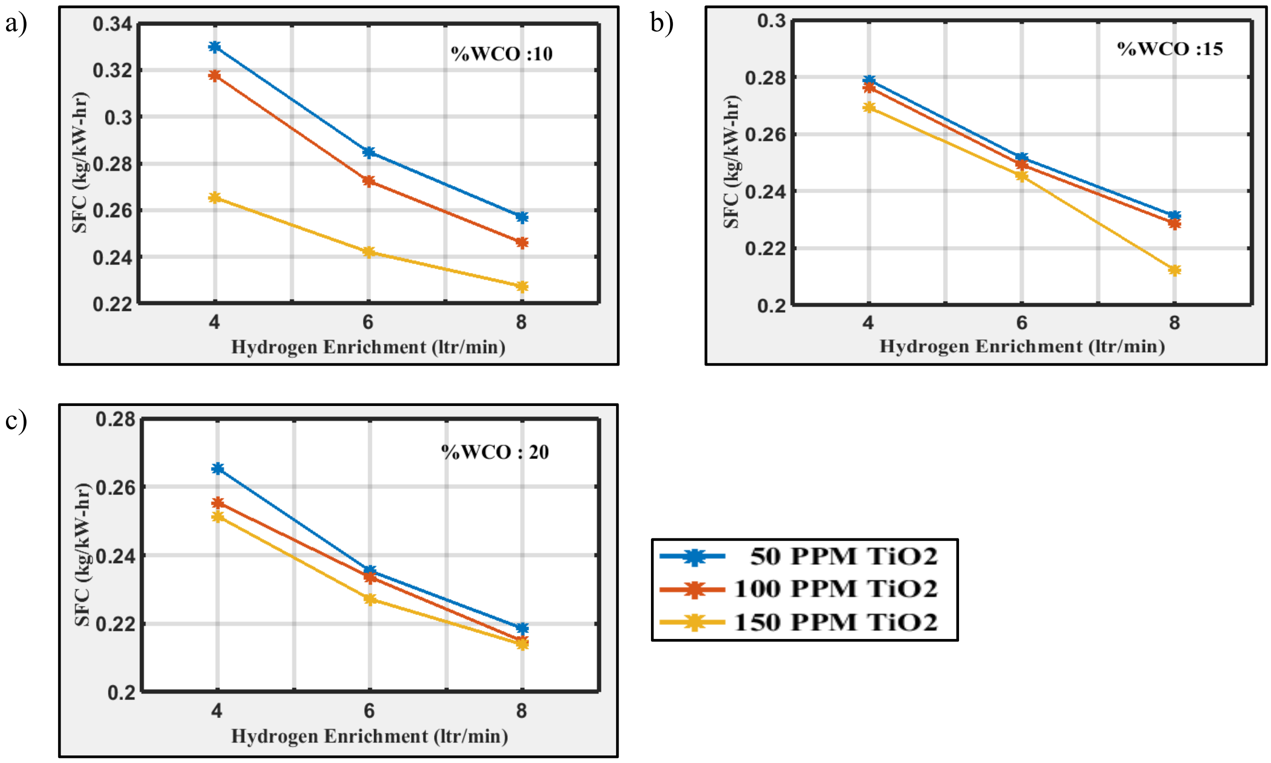


Fig.4. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on SFC (a-c).

The presence of hydrogen in the combustion chamber facilitates the rapid propagation of the flame front, reducing the ignition delay and promoting thorough combustion of the air-fuel blend [37]. The combination of hydrogen enrichment and nanoparticle addition leads to a synergistic effect. While hydrogen improves the flame speed and overall combustion efficiency, nanoparticles aid in better fuel atomization and oxidation [38]. This combination results in a significant reduction in SFC, as evidenced by the notable decrease when both hydrogen enrichment and nanoparticle addition are at their optimal levels.

3.3. Carbon monoxide (CO)

The addition of nanoparticles and hydrogen enrichment significantly influences CO emissions from a CRDI diesel engine operating with WCO blends. The data in Fig.5a-c reveals that CO emissions are generally higher with the addition of *50 PPM* nanoparticles across all WCO blend percentages. However, these emissions decrease progressively as hydrogen enrichment is increased from *4* to *8 PPM*. Notably, among all the combinations, the *20%* WCO blend consistently exhibits lower CO emissions compared to other blend ratios. The combined presence of nanoparticles and hydrogen results in a synergistic effect that further enhances combustion efficiency. Nanoparticles aid in the better dispersion and utilization of hydrogen in the combustion process, leading to more effective oxidation of CO [38]. Hydrogen addition reduces the quenching distance in the combustion chamber, which helps in minimizing the formation of CO by ensuring that the flame propagates more effectively throughout the entire fuel-air mixture. The initial increase in CO emissions with *50 PPM* nanoparticles might be due to the enhanced combustion temperatures and rates, which initially increase the production of CO before it is oxidized to CO_2. As hydrogen enrichment increases, its beneficial effects on combustion efficiency become more pronounced, leading to a substantial decrease in CO emissions. The *20%* WCO blend likely provides an optimal balance between the biofuel's oxygen content and the combustion characteristics, leading to inherently lower CO emissions compared to higher WCO blends.

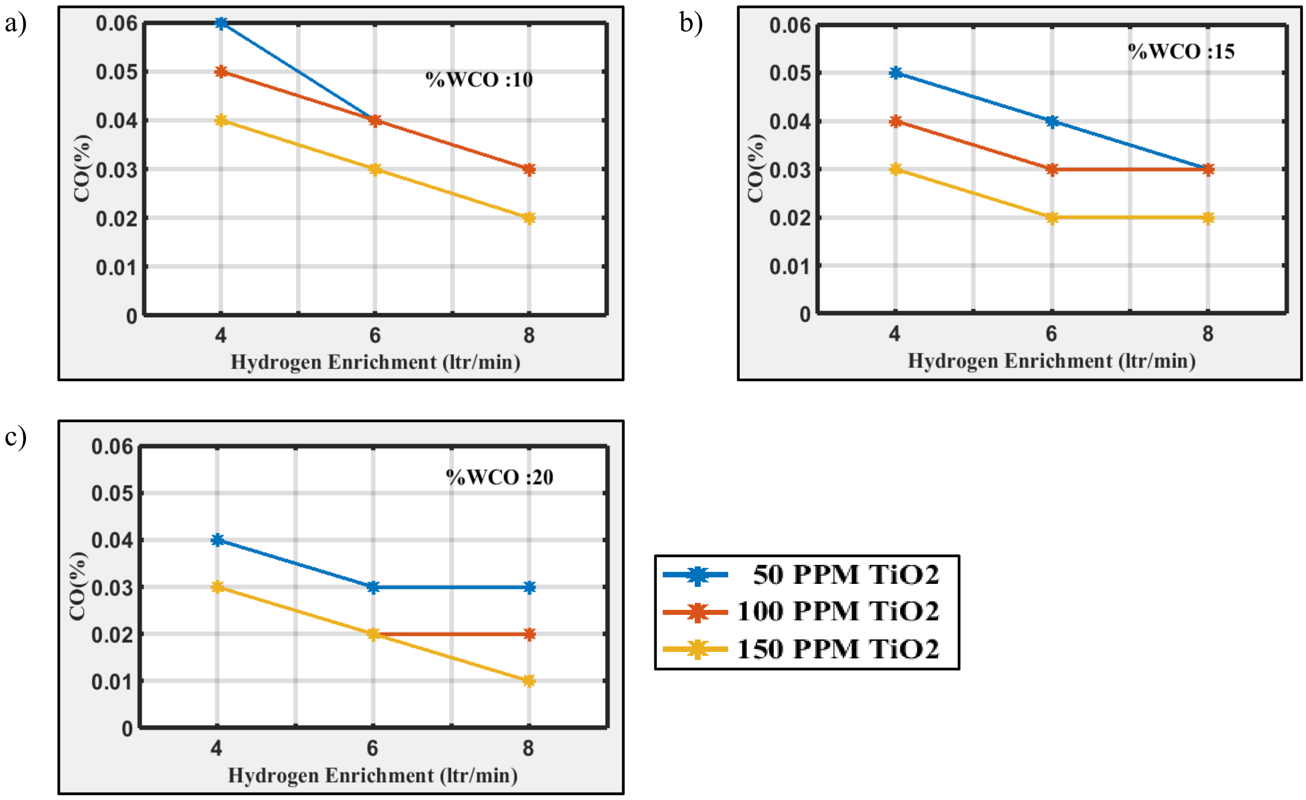


Fig.5. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on CO (a-c).

3.4. Hydrocarbon (HC)

The interactive effects of waste cooking oil (WCO), nanoparticle additives, and hydrogen enrichment on HC exhaust from a small cylinder CRDI diesel engine CRDI equipped with split injection were analyzed, as shown in Fig.6a-c. Figure 6a demonstrates that the addition of nanoparticles at *150 PPM* and *10%* WCO results in lower HC emissions. HC emissions decrease further with increasing nanoparticle addition in the midst of hydrogen at *4 litre/min*. However, when WCO percentage is increased from *10%* to *20%*, HC emissions rise. Hydrogen enrichment at *8 litre/min* consistently shows reduce HC emissions across all combinations of WCO with diesel, as indicated in Fig.6a. Figures 6b and 6c exhibit a similar trend to Fig.6a, with a slight increase in HC emissions for various parameter combinations. There is an approximately *6%* reduction in HC emissions when hydrogen enrichment is increased from *4 litre/min* to *8 litre/min*, suggesting that higher hydrogen enrichment aids in lowering HC emissions. HC emissions tend to increase as the biodiesel content (WCO) increases from *10%* to *20%*. The rate of increase in HC emissions due to higher WCO content is mitigated by the presence of nanoparticle additives. The combined use of nanoparticles and hydrogen enrichment helps in reducing HC emissions even with higher WCO percentages.

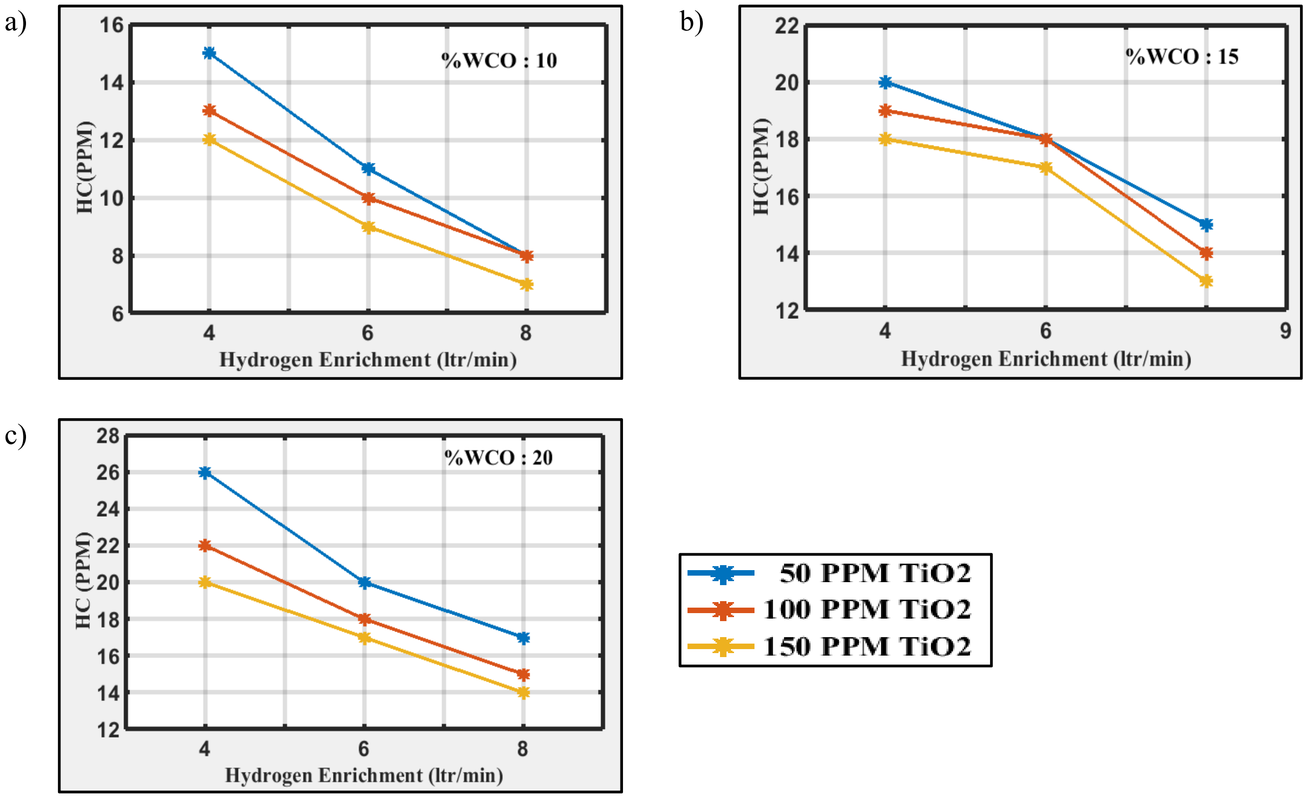


Fig.6. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on HC (a-c).

3.5. Nitrogen monoxides (NOx)

Figure 7a-c shows the effects of waste cooking oil (WCO), nanoparticle additives, and hydrogen enrichment on NOx emissions in a CRDI diesel engine with split injection. Adding *50 PPM* nanoparticles with *10%* WCO results in lower the NOx emissions. However, NOx levels increase with more nanoparticles and *8 liters/min* of hydrogen. At *20%* WCO, NOx emissions peak regardless of nanoparticles or hydrogen levels. Figure 7b indicates that *15%* WCO yields lower NOx compared to *10%* or *20%* WCO with *150 PPM* nanoparticles. Higher nanoparticle addition and *8 liters/min* hydrogen result in higher NOx emissions compared to *4 liters/min*. Nanoparticles enhance atomization and combustion temperatures, leading to higher

NOx due to thermal NOx formation. More WCO adds oxygen, leading to higher combustion temperatures and NOx emissions, with peak NOx at *20%* WCO.

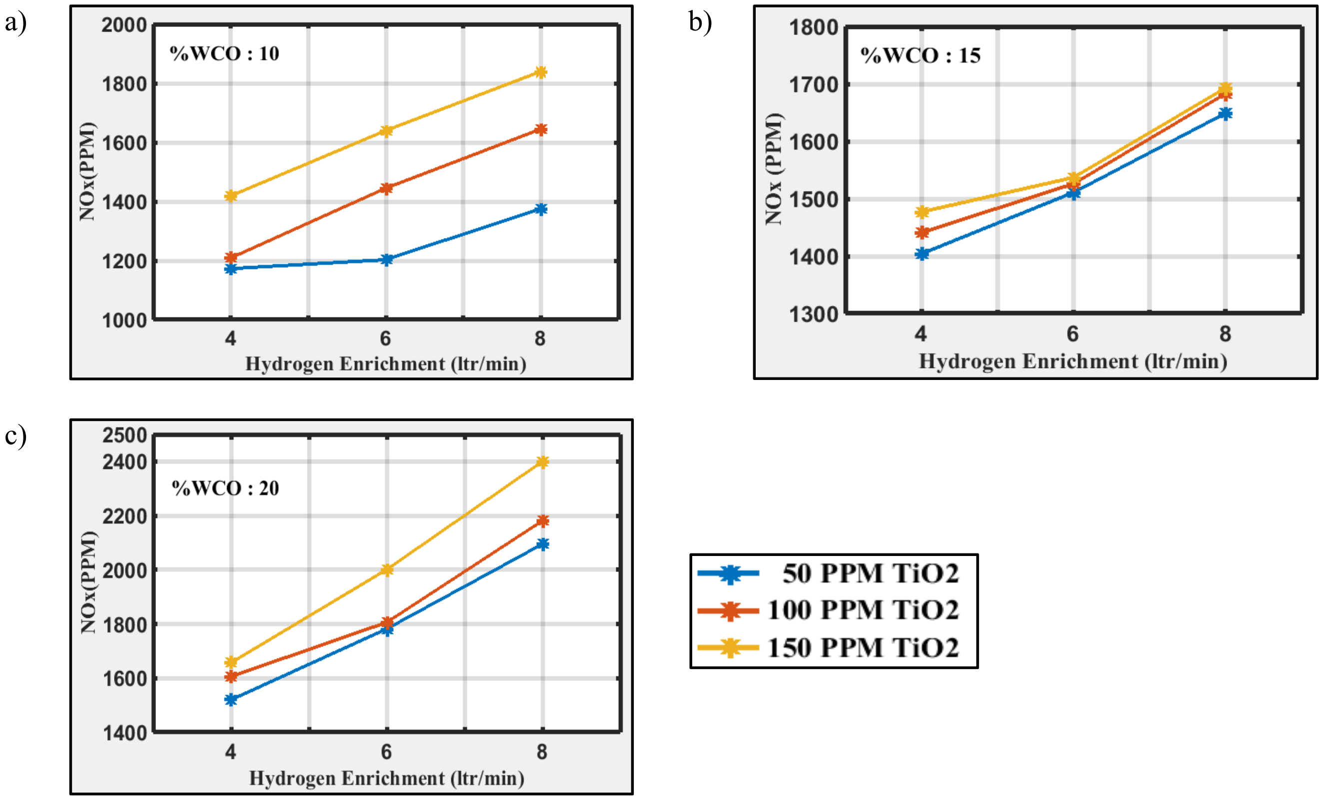


Fig.7. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on NO (a-c).

3.6. Smoke opacity

Figure 8a-c illustrates how waste cooking oil (WCO), nanoparticle additives, and hydrogen enrichment affect smoke emissions in a CRDI diesel engine with split injection technology. Adding *150 ppm* nanoparticles with *8 liters/min* of hydrogen enrichment reduces smoke emissions, while lowering hydrogen to *4 liters/min* increases smoke levels. Adding *50 ppm* nanoparticles consistently increases smoke emissions, regardless of

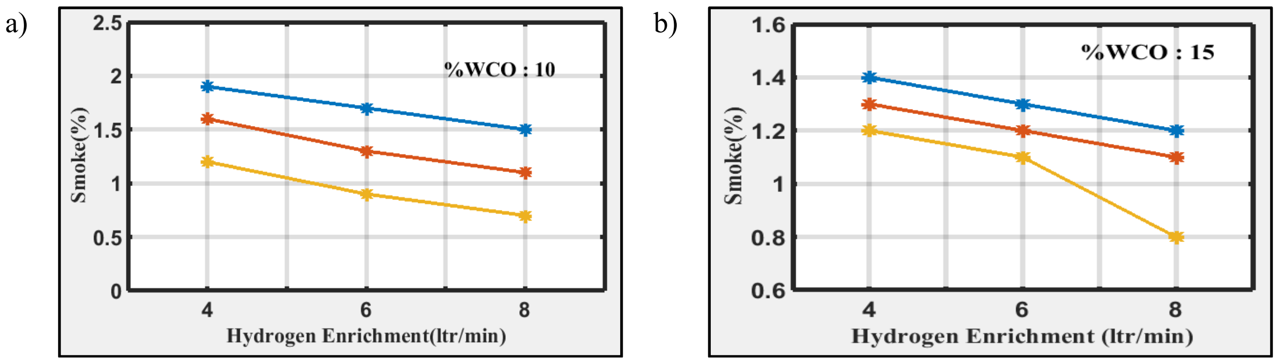


Fig.8. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on smoke (a-c).

c)

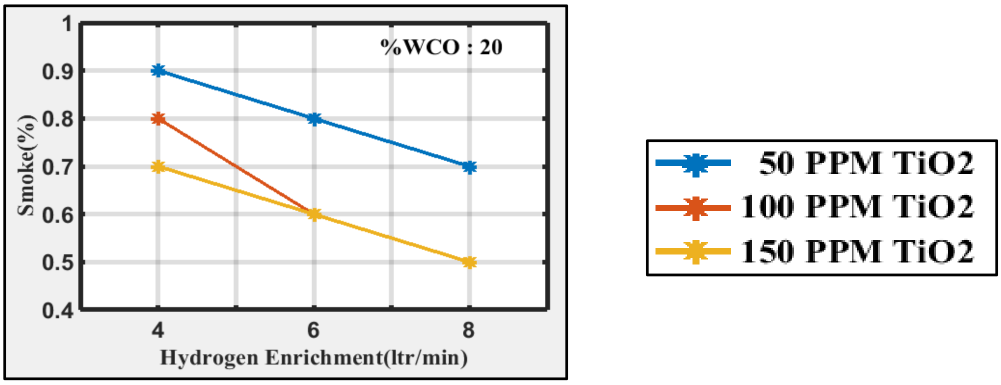


Fig.8 cont. Combined effect of WCO, hydrogen enrichment and nanoparticle addition on smoke (a-c).

WCO percentage or hydrogen levels. A *10%* WCO blend results in lower smoke emissions at all hydrogen levels, but decreasing WCO from *20%* to *10%* slightly increases smoke. Higher hydrogen enrichment (*8 liters/min*) enhances combustion and reduces smoke due to better atomization and complete combustion. WCO's oxygen content also aids in reducing smoke by promoting more complete combustion.

4. Conclusions

The study examined the effects of fuel supply system parameters on a CRDI small cylinder diesel engine, taking into account varying degrees of TiO_2 nanoparticle addition, hydrogen enrichment, and WCO. The following were the results reached after this analysis:

1) The combined addition of nanoparticles (*150 PPM*) and hydrogen enrichment (up to *8 liters/min*) significantly increases BTE and reduces SFC in a CRDI single-cylinder diesel engine using WCO biodiesel blends. These improvements result from enhanced flame speed, diffusivity, catalytic, and atomization benefits, and optimized combustion via split injection technology.
2) The combined addition of nanoparticles and hydrogen enrichment enhances combustion in a CRDI diesel engine using WCO blends, resulting in reduced CO emissions. This is due to the catalytic effects of nanoparticles and the superior combustion characteristics of hydrogen, leading to more complete and efficient combustion.
3) In a CRDI diesel engine with split injection technology, adding nanoparticles and hydrogen enrichment significantly reduces HC emissions. This combination counteracts the rise in HC emissions typically caused by higher WCO percentages, resulting in a more efficient and cleaner combustion process.
4) The addition of nanoparticles and hydrogen enrichment significantly enhances combustion efficiency, leading to reduced smoke emissions. However, the percentage of WCO and the level of hydrogen enrichment play crucial roles in determining the overall smoke emissions.

Future research should focus on optimizing the parameters such as the concentration of nanoparticles, the rate of hydrogen enrichment, and the proportions of WCO in the biodiesel blend. Investigating the effects of varying injection timings and pressures in the split injection technology could further enhance engine performance and emissions reduction.

Acknowledgements

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Nomenclature

BTDC – before top dead center

BTE – brake thermal efficiency
CA – crank angle
CO – carbon monoxide
CRDI – common rail direct injection
HC – hydrocarbon
IP – injection pressure
NOx – nitrogen oxides
PM – particulate matter
SFC – specific fuel consumption
TiO_2 – titanium dioxide
WCO – waste cooking oil

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