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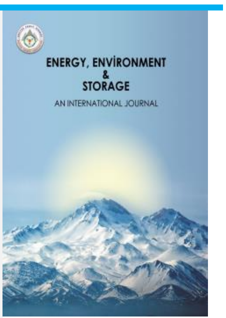

Effects of Magnetic Fields and Nanoparticle Additives on Diesel Engine Emissions and Performance: A Comprehensive Experimental Analysis

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ABSTRACT. In the present study, performance and emission changes in a compression ignition engine were investigated by combining two methods. The first method involves adding nanoparticle additives to diesel fuel. Titanium dioxide (TiO2) with a particle size of 21 nm was used as nanoparticle. TiO_2 was added to diesel fuel at doses of 50 mg and 100 mg per 1 kg (50 and 100 ppm). After adding the nanoparticle to the diesel fuel, each mixture was stirred with a mechanical stirrer for one hour. In the second method, a magnetic field of 1 tesla was created around the fuel. Neodymium magnets were placed circularly around the diesel fuel line to create the magnetic field. The experiments were carried out at 660 RPM engine speed and 100% torque. During the experiments, data on engine performance, in-cylinder pressure and emissions were recorded. This study aims to contribute to the development of alternative fuel applications to improve performance and emissions in compression ignition engines.

Keywords: Nanoparticle, Magnetic Field, Diesel, Emissions, Performance

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1. INTRODUCTION

The energy consumption of modern societies is vital for economic growth and social development. However, increasing energy demand poses a threat to environmental sustainability and presents significant challenges in combating climate change [1]. In this context, accelerating the transition to renewable energy sources and enhancing energy efficiency has become a critical necessity [2]. Sustainable energy management has emerged as an important issue, not only for reducing environmental impacts but also for ensuring a secure energy supply for future generations. Research focusing on alternative fuel sources, such as biodiesel, demonstrates the potential to replace fossil fuels [3].

In recent years, the effects of nanoparticles on biodiesel performance have attracted considerable research interest. In applications using nanoparticle-enhanced biodiesel, a notable reduction in motor emissions and a significant improvement in fuel efficiency have been observed [3]. Kumar et al. (2019) comprehensively investigated the effects of various nanoparticle types on biodiesel performance, revealing the positive impacts of titanium dioxide and aluminum nanoparticles on engine power and emissions [4]. These nanoparticles were found to enhance atomization during the combustion process, allowing for more homogeneous combustion and thereby facilitating more efficient energy conversion [3][4].

The effects of magnetic field applications on engine emissions and performance have also become an important area of research in recent years. Experimental studies conducted by Niaki et al. (2020) demonstrated that magnetic field applications positively influence performance, combustion dynamics, and emission characteristics in internal combustion engines [5]. It has been shown that magnetic fields improve fuel atomization, thereby increasing combustion efficiency and reducing emissions [6]. For example, experiments indicated that magnetic fuel conditioning resulted in a 19% reduction in NOx emissions and a 13% decrease in CO2 emissions, while mechanical efficiency increased by 7%. These results suggest that magnetic fields affect molecular structure, facilitating better atomization of the fuel and creating a

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more homogeneous fuel-air mixture. Additionally, the use of CuO nanofuel contributes to emission reductions and enhances engine performance, making a significant contribution to sustainable energy solutions. The integration of nanoparticle additives and magnetic field applications plays a critical role in enhancing environmental sustainability and improving the performance of internal combustion engines. This integration aims to increase the operational efficiency of engines while minimizing environmental impacts, thereby targeting reductions in emissions and improvements in engine efficiency [7].

In this study, six experiments were conducted to evaluate the performance and emission characteristics of diesel fuel. In the first phase, pure diesel fuel was used as a reference to investigate combustion performance. In the second phase, four neodymium magnets were employed to create a magnetic field of 1 Tesla around the fuel line. Pure diesel was subjected to this magnetic field during combustion, and the combustion characteristics were recorded. In the third phase, pure diesel fuel with 50 ppm TiO2 was burned in the same magnetic field, and the effects of TiO2 on the combustion process were examined in detail. The obtained data were compared with those of pure diesel. Finally, a similar procedure was performed with 100 ppm TiO2, and the combustion efficiency and emission characteristics of this mixture were compared with previous experiments. This process represents an important step in understanding the effects of TiO2 concentration on combustion, providing significant findings regarding the roles of magnetic fields and TiO2 additives in the combustion process of diesel fuel. The obtained data aim to contribute to the development of alternative fuel mixtures and applications to enhance the performance of diesel engines and reduce emissions.

2. MATERIALS AND METHODS

2.1 Experimental Setup

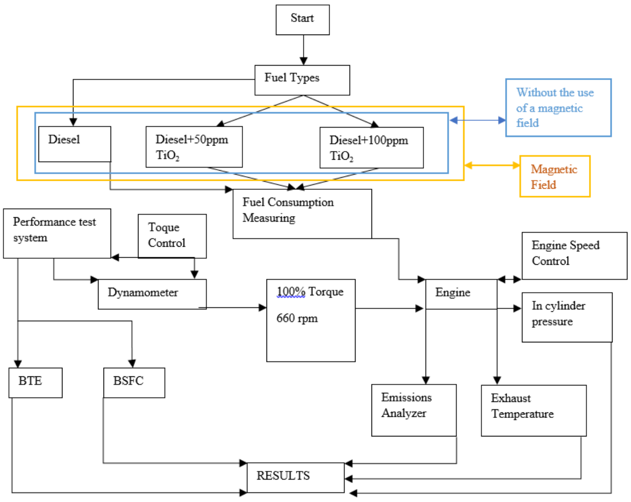

Fig. 1 The Experimental Workflow

In the present study, the workflow schematically shown in Fig. 1 was followed. A six-cylinder compression ignition engine was used in the experiments. 50 mg and 100 mg TiO2 were added for every 1000 g of diesel fuel. Titanium dioxide (TiO2) with a particle size of 21 nm was used as nanoparticle. The mixtures were mixed with a mechanical stirrer at 1000 RPM for one hour. The fuels were coded as D for diesel, D_50ppm + 50 ppm TiO2 for diesel, and D_100ppm + 100 ppm TiO2 for diesel. Neodymium magnets were placed around the diesel fuel line to create a magnetic field of 1 tesla. In the experiments conducted with a magnetic field, the label "Magnetic" was added to the fuel codes to indicate the type of experiment. These three fuel types were tested in a compression ignition engine with and without a magnetic field. The experimental results are discussed in Section 3. A balance with a sensitivity of 0.5 g was used for fuel consumption measurement. Exhaust emissions were measured using a Bosch BEA 60 analyzer. Recording of engine performance data was facilitated by the PCS engine performance measurement system.

2.2 Fuel and nanoparticles properties

Table 1 represents the properties of fuel and nanoparticles used in the study.

Table 1. Diesel and TiO_2 specifications

Properties	TiO_2	Diesel
Boiling point	1600 °C (1013 hPa)	-
Particle size	21 nanometer	-
Density	4,500 kg/cm3 (25 °C)	820-845 kg/m3
Stoichiometric ratio	-	14,92 (app.)
Molar mass	233.38 g/mol	-
Flash point	-	55 °C
ignition Temperature	-	Auto-186–230 °C
Higher Heating Value	-	45.6 MJ/kg
Low heat Value	-	42.7 MJ/kg
Melting Point	1560 °C	-
Cetane Number	-	51
Viscosity	-	2.0- 4.5 mm^2 /s

2.3 Uncertainty analysis

Uncertainty analysis is presented in Table 2. To calculate uncertainty analysis use Eq.1 and to calculate total uncertainty use Eq. 2 [17, 18].

$$\boldsymbol{W_R} = \left[\left(\frac{\partial R}{\partial x_1} * w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} * w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} * w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} * w_n\right)^2\right]^{1/2}$$
(1)

$$TU = \sqrt{UNO^2 + UCO^2 + UHC^2 + UCO_2{}^2 + UBte^2 + UBsfc^2}$$
(2)

Table 2. Uncertainty analysis [16]

Item	Uncertainty ratio
NO_x	0.71%
CO	1.73%
HC	1.26%
CO_2	0.54%
Bte	1.68%
Bsfc	1.47%
Total Uncertainty	**%3.22**

3. RESULTS, FIGURES AND TABLES

3.1 Engine Performance

In this section, three key parameters related to engine performance will be discussed. The first is Brake Thermal Efficiency (BTE), which is calculated as shown in Equation 3 and serves as a crucial factor in evaluating engine performance. The second is Brake Specific Fuel Consumption (BSFC), as presented in Equation 4. It is expected that the BTE and BSFC values will exhibit an inverse relationship. The graphs obtained from this experiment align with this expectation. [8]

$$\eta_{th} = \frac{P_b}{\dot{m}_f \times LHV} \qquad (3)$$

P_b: braking power,
$\dot{m}_f$: fuel mass flow rate,
LHV: the lower heating value of the fuel

$$bsfc = \frac{\dot{m}_f}{P_b} \qquad (4)$$

P_b: braking power,
$\dot{m}_f$: fuel mass flow rate,

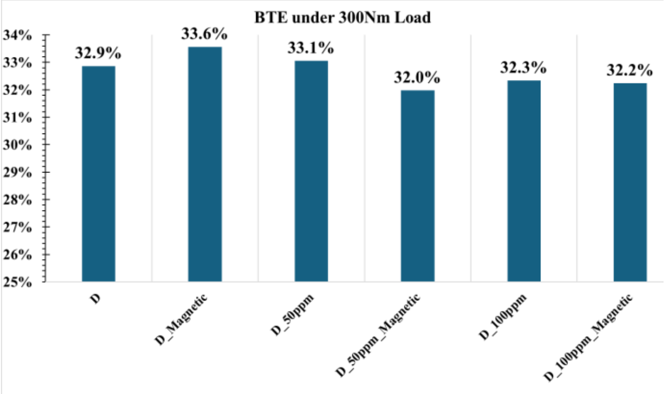

Fig.2 BTE under 300Nm Load

The effects of different fuel mixtures and magnetic field applications on the brake thermal efficiency (BTE) under a constant load of 300 Nm were analyzed. The BTE values for each configuration, including pure diesel (D), magnetic field applied diesel (D_Magnetic), diesel with 50 ppm and 100 ppm TiO2 additives (D_50ppm and D_100ppm), and these fuel mixtures subjected to magnetic field conditions, are summarized in **Fig.2.**

The baseline BTE value for pure diesel (D) under 300 Nm load was recorded at 0.3287, serving as the reference point for further comparisons. When a magnetic field was applied to the pure diesel (D_Magnetic), the BTE increased significantly to 0.3357. This result demonstrates the positive influence of the magnetic field on the combustion efficiency of pure diesel. The increase in BTE suggests that the magnetic field may enhance fuel atomization and promote better combustion, leading to a more efficient energy conversion process.[5]

The addition of 50 ppm of an additive to the diesel fuel (D_50ppm) resulted in a slight increase in BTE, with a value of 0.3305. This suggests that the additive improves the combustion characteristics of diesel, leading to better thermal efficiency than pure diesel without additives. The improved efficiency could be attributed to the catalytic effects of the additive, which likely enhances the combustion process, reducing unburnt hydrocarbons and improving fuel-air mixing.[9]

In contrast, when 100 ppm of the additive was introduced into the diesel fuel (D_100ppm), the BTE dropped to 0.3234. This result indicates that while the additive has a positive impact at lower concentrations (50 ppm), increasing its concentration to 100 ppm does not yield further improvements and, in fact, slightly reduces the combustion efficiency compared to both pure diesel and the 50-ppm mixture. This could be due to potential over-saturation of the fuel with the additive, leading to incomplete combustion or unfavorable reactions in the combustion chamber.[10]

When 50 ppm and 100 ppm boron additions were compared in a prior study, the 50 ppm additive showed the maximum efficiency. Additionally, 50 ppm is more efficient than 100 ppm, according to this study. It was shown once more that lower ppm concentrations have a more favorable effect on efficiency, notwithstanding the element's difference. In order to ensure the comparability of the results, the 50 and 100 ppm additive levels were also chosen to enable comparison with the boron additive ratios used in the study by Kül and Akansu (2022).[10]

The application of a magnetic field with 50 ppm of the additive (D_50ppm_Magnetic) resulted in a BTE of 0.3198, lower than both pure diesel and the 50 ppm additive without the magnetic field. This indicates that the combination may interfere with optimal combustion conditions. For the 100 ppm mixture (D_100ppm_Magnetic), the BTE slightly increased to 0.3224, but remained below that of pure diesel and the 50 ppm additive, suggesting limited enhancement at higher concentrations.

The magnetic field showed the most notable positive impact when applied to pure diesel, significantly improving BTE. While lower concentrations of additives (50 ppm) can enhance efficiency, their combination with a magnetic field may lead to performance reduction. At higher concentrations (100 ppm), the benefits diminish, with the magnetic field providing only marginal improvements. These findings highlight the importance of carefully optimizing both additive concentrations and magnetic field applications for optimal combustion efficiency.

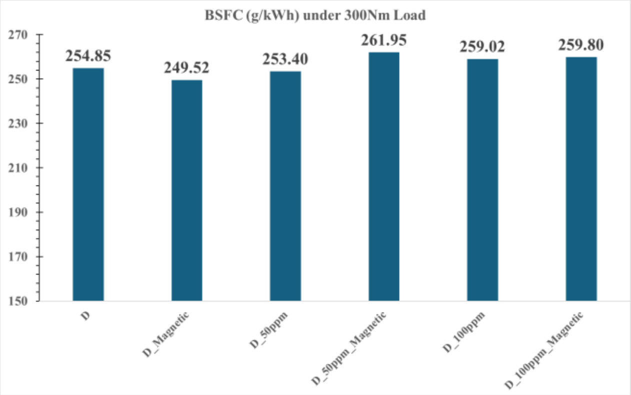

Fig. 3 BSFC under 300Nm Load

Magnetic field applied to pure diesel (D_Magnetic) reduced BSFC to 249.5192, indicating that the fuel molecules were organized for more efficient combustion (Fig. 3). The literature also supports that magnetic fields enhance atomization of hydrocarbon fuels, leading to increased combustion speed [11].

The BSFC of diesel fuel with 50 ppm additive (D_50ppm) was recorded as 253.3981. Additives, especially nanoparticle-based ones, are known to enhance combustion efficiency. For example, TiO_2 nanoparticles can catalyze the combustion process, leading to better energy conversion, thereby reducing BSFC.[12]

The BSFC of diesel fuel with a 50 ppm additive under a magnetic field was recorded at 261.9512, representing the highest value observed. This indicates that the simultaneous use of the additive and magnetic field may interfere with optimal combustion conditions, potentially leading to increased fuel consumption.

The BSFC of diesel with a 100 ppm additive was measured at 259.0244, indicating higher fuel consumption compared to pure diesel and 50 ppm additive. This suggests that the 100 ppm additive may disrupt combustion conditions and reduce fuel efficiency.

The BSFC of diesel with a 100 ppm additive under a magnetic field is 259.8039, which is higher than pure magnetic diesel and similar to 100 ppm without magnetic treatment. This indicates no significant improvement in fuel consumption.

In Terms of in Cylinder Pressure

Fig. 4 shows the change in In-Cylinder Pressure (ICP) representing the combustion processes of diesel fuels. The graph reveals the relationship between crank angle and in-cylinder pressure for an engine under a load of 300 Nm. The combustion processes of different fuels are divided into six main phases:

Phase 1: Ignition Delay

In the fuels D_50ppm_Magnetic, D_100ppm_Magnetic, the ignition delay occurs approximately 1 degree earlier compared to other fuels. This early ignition can be attributed to the nanoparticle additive TiO_2 , which accelerates the combustion reaction. TiO_2 can reduce ignition delay by promoting a more homogeneous and efficient combustion process, leading to earlier fuel ignition and positively impacting engine performance. [13]

Phase 2: Combustion Initiation and Fuel Vaporization

During this phase, TiO_2 nanoparticles enhance the fuel's surface area, thereby improving evaporation and combustion efficiency. The magnetic effect polarizes the fuel molecules, improving the air-fuel mixture. Both additives contribute to a more homogeneous combustion, optimizing the pressure curve. [13,14]

Phase 3: Complete Combustion of the Fuel

This phase represents the stage where the fuel is fully combusted, resulting in a complete explosion. Efficient fuels have been observed to exhibit a steeper slope during this phase. The higher combustion curves of the D_Magnetic and D_50ppm fuels enable these fuels to accelerate complete combustion, generating higher pressure. This phase, characterized by high efficiency, reflects the fuel's maximum energy output.

Phase 4: Work Production and Peak Point

In this stage, where work is produced and the graph reaches its peak, it is preferable for this section of the graph to be as flat as possible for diesel engines. The flatter peak points of the D_Magnetic and D_50ppm fuels help optimize engine performance. A flat peak indicates a smooth explosion and prevents sudden pressure changes, which allows for more efficient engine operation. [15]

Phases 5 and 6: Pressure Decline

Following the completion of combustion, these phases begin with a rapid and then gradual decrease in pressure. The rate of pressure decline is similar across different fuels during this phase. The process continues as the cylinder pressure returns to atmospheric pressure. [15]

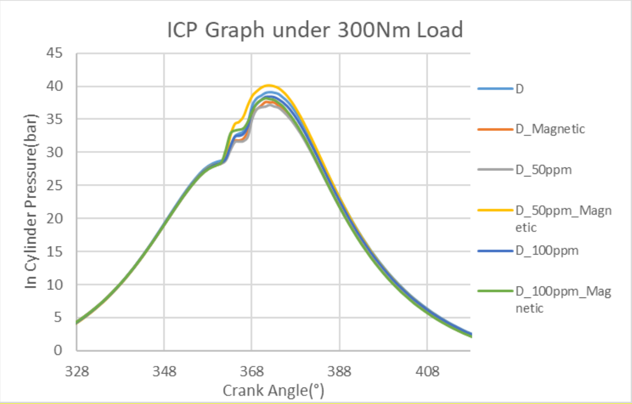

Fig. 4 ICP Graph under 300Nm Load

3.2 Exhaust Emissions

HC Emission

Hydrocarbon (HC) emissions are harmful gases released into the atmosphere because of incomplete combustion.

Pure diesel (D) fuel produced the highest HC emissions. This result is closely related to the high carbon content and combustion characteristics of diesel fuel, which contribute to incomplete combustion and, subsequently, the release of a higher quantity of hydrocarbons into the atmosphere.

The magnetic field application (D_Magnetic) significantly reduced HC emissions. The application of a magnetic field improved fuel combustion efficiency, reducing incomplete combustion. The magnetic field aids in better atomization of the fuel and promotes a more homogeneous combustion process, thus effectively lowering HC emissions.

Fig. 5 shows HC values under the 300 Nm. TiO2 additive (D_50ppm and D_100ppm) demonstrated a considerable reduction in HC emissions, primarily due to its catalytic properties. The 100 ppm level of TiO2 was more effective than the 50 ppm, further reducing incomplete combustion. TiO2 enhances oxidative reactions during combustion, promoting a cleaner and more complete burn of the fuel.

Combination of TiO2 and Magnetic Field (D_50ppm_Magnetic and D_100ppm_Magnetic) achieved the lowest HC emissions. The combined catalytic effect of TiO2 and the efficiency boost from the magnetic field resulted in an optimized combustion process, both chemically and physically. This combination effectively minimized hydrocarbon emissions to their lowest levels.

The application of 100 ppm TiO2 combined with a magnetic field emerged as the most effective solution for reducing hydrocarbon emissions. This combination has the potential to significantly mitigate the environmental impact of diesel fuel, offering a viable strategy for minimizing HC emissions in diesel engines.

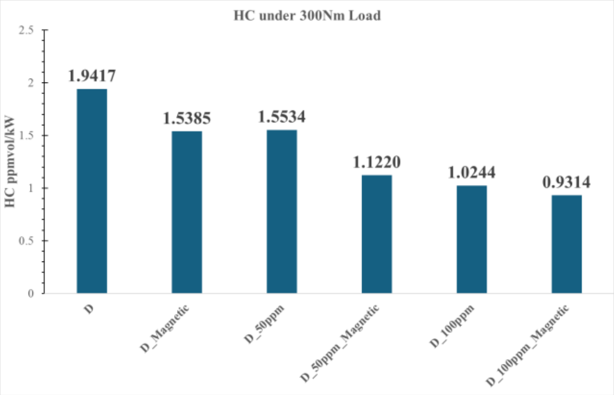

Fig. 5 HC Emission under 300Nm Load

CO Emission

Carbon monoxide (CO) emissions result from incomplete combustion, where carbon in the fuel does not fully convert to CO2 [19]. Pure diesel (D) produced the highest CO emissions, while the application of a magnetic field (D_Magnetic) significantly reduced emissions by enhancing combustion efficiency. TiO2 additives (D_50ppm and D_100ppm) further lowered CO emissions, with 50 ppm being slightly more effective. The combination of TiO2 and a magnetic field (D_50ppm_Magnetic and D_100ppm_Magnetic) achieved the lowest emissions, optimizing combustion through both catalytic and physical improvements. 100 ppm TiO2 with a magnetic field proved the most effective in reducing CO emissions and improving diesel efficiency (Fig. 6).

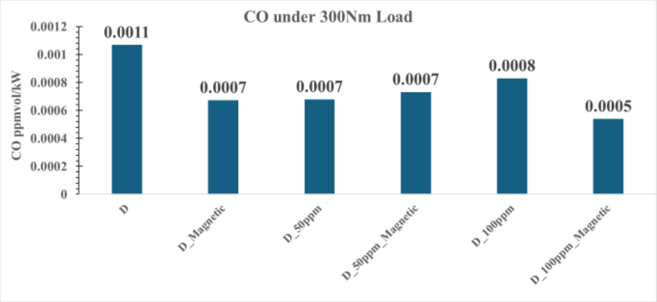

Fig.6 CO Emission under 300Nm Load

NO Emission

Nitrogen oxide (NOx) emissions arise from high-temperature combustion in diesel engines. This situation increases with in-cylinder conditions as well as fuel and air homogeneity [20]. This analysis shows that pure diesel (D) generates moderate NO emissions, while the application of a magnetic field (D_Magnetic) slightly increases them due to enhanced combustion efficiency and higher temperatures. TiO2 additives (D_50ppm and D_100ppm) also modestly raise NO emissions by improving combustion and increasing temperatures, with little difference between the two concentrations. The highest NO emissions occur with the combination of TiO2 and magnetic fields (D_50ppm_Magnetic and D_100ppm_Magnetic), which boosts combustion efficiency but leads to significant temperature increases. Overall, while these enhancements improve combustion performance, they also result in higher NO emissions, underscoring the need for balanced emission control strategies (Fig. 7).

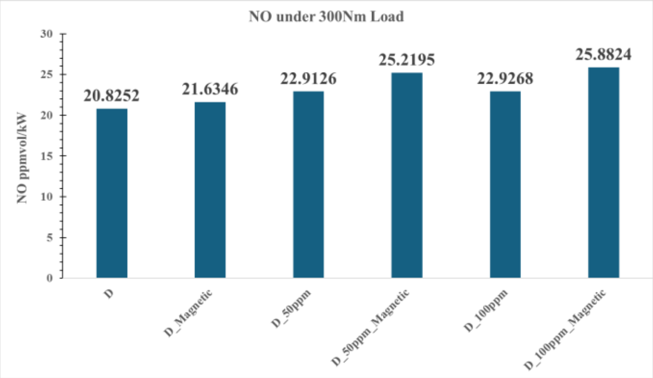

Fig. 7 NO Emission under 300Nm Load

4.CONCLUSION

This study examined the performance and emission characteristics of a compression ignition engine supplied with titanium dioxide (TiO_2) nanoparticle additives and subjected to magnetic field application. The experiments were conducted under a constant load of 300 Nm, analyzing key performance metrics such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), in-cylinder pressure (ICP), and exhaust emissions.

The findings indicated that the application of a magnetic field slightly increased the BTE of pure diesel fuel, rising from 0.3287 to 0.3357. The addition of 50 ppm of TiO_2 resulted in a slight increase in BTE to 0.3305, while increasing the concentration to 100 ppm decreased the BTE to 0.3234; this suggests that excessive TiO_2 may hinder combustion efficiency. It was observed that the interaction between TiO_2 and the magnetic field negatively affected performance, especially at lower additive concentrations; this combination resulted in lower BTE values compared to pure diesel. However, due to the lack of significant differences between the percentage values, the magnetic field application and nanoparticle addition did not provide a meaningful change in overall engine efficiency.

The results of the study demonstrate that smaller concentrations (ppm) of additives have a more favorable effect on efficiency, notwithstanding variations in the type of element utilized. Furthermore, enhanced efficiency was not a result of raising the dosage amount. In order to compare the findings with those of the study by Kül and Akansu (2022), 50 and 100 ppm additive concentrations were chosen. These kinds of comparisons show that further research is required in the future to determine whether low-dose applications have an efficiency-enhancing effect.

The in-cylinder pressure analysis revealed six combustion phases and demonstrated that TiO_2 nanoparticles reduced ignition delay and improved combustion initiation. Notably, the addition of 50 ppm TiO_2 achieved the best performance in the combustion processes, while combining TiO_2 with the magnetic field disrupted combustion dynamics and resulted in less favorable conditions; in this context, the observed differences were insufficient for significant interpretation.

In terms of exhaust emissions, pure diesel exhibited the highest HC and CO emissions, which were significantly reduced by the magnetic field and TiO_2 additives, particularly at 100 ppm. The combination of 100 ppm TiO_2 and a magnetic field provided the lowest HC and CO emissions, proving to be an effective strategy for mitigating environmental impact. However, it was also observed that the improvements in combustion efficiency due to TiO_2 and magnetic fields led to higher NO emissions due to increased combustion temperatures.

Overall, this study highlights the complexity of optimizing fuel formulations and combustion conditions in compression ignition engines. The findings suggest that TiO_2 nanoparticles and magnetic field applications can enhance combustion efficiency and reduce certain emissions, but careful evaluation of additive concentrations and interactions is necessary to balance performance and emission outcomes. Future research should focus on further improving these parameters to enhance the environmental sustainability of diesel engines.

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