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Metal Oxide Nanoparticles in Diesel: Emission Impact Study

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Abstract

The use of metal oxide nanoparticles as diesel fuel additives has emerged as an effective strategy to enhance combustion and mitigate emissions. In this study, Cupric Oxide (CuO) and Aluminum Oxide (Al_2O_3) nanoparticles were dispersed in diesel at concentrations of 25, 50, and 75 ppm, and their effects on engine emissions were evaluated under varying load conditions. The results indicate a consistent reduction in carbon monoxide (CO) and hydrocarbon (HC) emissions, with HC levels reduced to ~7–11 ppm for Al_2O_3 blends and ~8–12 ppm for CuO blends at higher loads, compared to neat diesel. Carbon dioxide (CO_2) emissions increased by up to ~6.6%, confirming improved combustion efficiency. However, nitrogen oxides (NO_x) emissions increased significantly, reaching peak values of ~1200 ppm for nanoparticle blends, compared to ~1068 ppm for neat diesel, due to elevated in-cylinder temperatures and enhanced oxidation kinetics. Among the tested conditions, CuO at 25 ppm demonstrated the most favorable trade-off, offering reduced CO, HC, and smoke emissions with a comparatively lower increase in NO_x, whereas Al_2O_3 at 75 ppm exhibited superior combustion efficiency but the highest NO_x emissions. The study highlights the inherent trade-off between improved combustion and NO_x formation, emphasizing the need for optimized nanoparticle dosing to achieve cleaner and more efficient diesel engine operation.

Keywords: *Emission Analysis, Aluminum Oxide, Cupric Oxide, Diesel fuel, Environmental Impact*

1. Introduction

The global demand for energy is increasing rapidly due to population growth, industrialization, and urbanization, placing significant pressure on conventional fossil fuel resources and raising concerns about sustainability and environmental impact (Khalife et al., 2017; Saxena et al., 2017). Diesel engines, widely used in transportation, power generation, agriculture, and industry, play a crucial role in meeting this demand because of their high efficiency and reliability. However, their extensive use contributes significantly to environmental pollution through emissions of nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC) (Reşitoğlu et al., 2015; Geng et al., 2017). These emissions pose serious risks to human health, including respiratory diseases, cardiovascular disorders, and premature mortality (World Health Organization, 2021; Zhang & Balasubramanian, 2015). Among these pollutants, particulate matter (PM), particularly fine and ultrafine particles, plays a critical role in atmospheric processes such as particle growth, droplet formation, and deposition, thereby significantly affecting air quality and public health.

In response to these challenges, alternative fuels, such as biodiesel, have gained considerable attention as sustainable energy sources. Biodiesel offers advantages, such as renewability, biodegradability, and reduced emissions. However, its application may lead to slight compromises in engine performance and combustion efficiency (Dewangan et al., 2020). To overcome these limitations, recent research has focused on enhancing fuel properties by incorporating metal oxide nanoparticles.

Fuel additives with at least one dimension below 100 nm are classified as nanoscale additives (Khan et al., 2019; Ağbulut & Sarıdemir, 2020). Due to their high surface area-to-volume ratio and unique catalytic properties, nanoparticles promote more complete combustion, thereby improving engine performance and reducing pollutant emissions. Metallic nanoparticles are particularly attractive for their high reactivity and energy density. Studies have shown that nanoparticle-assisted combustion can significantly enhance oxidation reactions and improve overall combustion characteristics (Bergthorson et al., 2015).

Recent investigations have demonstrated the effectiveness of various metal oxide nanoparticles as fuel additives. Özgür (2021) studied nickel iron oxide ($NiFe_2O_4$) and nickel zinc iron oxide ($Zn_{0.5}Ni_{0.5}Fe_2O_4$) nanoparticles in a turbocharged diesel engine and reported significant emission reductions at optimized concentrations. Similarly, Fayad et al. (2023) investigated titanium dioxide (TiO_2) nanoparticles blended with biodiesel in a common-rail direct-injection engine and observed reductions in NO_x emissions and particulate matter when combined with exhaust gas recirculation. Husain et al. (2020) reported that cerium-coated zinc oxide (Ce–ZnO) nanoparticles improved brake thermal efficiency and reduced CO, HC, and smoke emissions in soybean biodiesel blends. Furthermore, Mehta et al. (2014) demonstrated that the addition of metallic nanoparticles, including aluminum, iron, and boron, significantly reduced ignition delay and

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enhanced combustion in diesel engines. These findings indicate that adding nanoparticles to fuel acts as a combustion catalyst, improving combustion efficiency and reducing pollutant emissions. However, despite extensive studies on various nanoparticle additives, a comparative understanding of CuO and Al_2O_3 nanoparticles at low concentrations under varying engine load conditions remains limited. In particular, the underlying mechanisms governing emission variations, especially particulate matter and NO_x trade-offs, require further investigation.

Therefore, the present study aims to investigate the effects of CuO and Al_2O_3 nanoparticles on diesel engine emission characteristics under different operating conditions. The study focuses on understanding how nanoparticle additives enhance combustion behavior and mitigate harmful emissions, with particular emphasis on particulate matter and nitrogen oxides.

2. Materials and Methods

2.1 Materials

Cupric Oxide (CuO) and Aluminum Oxide (Al_2O_3) nanoparticles (with a specific surface area of approximately 30-50 m^2/g and an average particle size of 20-30 nm) were selected as fuel additives for their distinct physicochemical properties and their ability to enhance combustion through multiple catalytic and thermal mechanisms.

1. Lattice Oxygen Donation → Catalytic Oxidation (Bitire et al., 2022)

   CuO has a non-stoichiometric crystal structure that can release bound oxygen ions from its lattice into the combustion zone. This additional oxygen oxidizes CO → CO_2 and unburned HC → H_2O + CO_2, even in fuel-rich zones where free oxygen is locally scarce. Furthermore, CuO reduces particulate matter (PM) formation through a dual pathway: (i) lattice oxygen oxidizes soot precursors, such as acetylene (C_2H_2) and polycyclic aromatic hydrocarbons (PAHs) before they nucleate into primary soot particles, and (ii) a catalytic Cu^{2+}/Cu^{+} redox cycle continuously oxidizes deposited soot via $C + 2CuO \rightarrow CO_2 + Cu_2O$, followed by regeneration: $Cu_2O + ½O_2 \rightarrow 2CuO$. This cyclic oxidation mechanism enhances in-situ soot burnout and reduces overall smoke emissions.

2. High Thermal Conductivity → Heat Transfer Boost (Zhu et al., 2018)

   CuO has one of the highest thermal conductivities among metal oxides (~76 W/m·K for bulk Cu-based materials). When suspended in fuel, it improves heat distribution within the cylinder, ensuring the entire fuel charge heats uniformly and ignites more completely.

3. Higher Calorific Value → Lower Activation Energy (Ramachandran et al., 2023)

   CuO nanoparticles have intrinsic stored chemical energy that contributes to the overall heat release of the blended fuel. They also lower the activation energy barrier for combustion reactions, meaning fuel molecules ignite faster and at lower temperatures. Smoke and PM reductions of approximately 17–21% have been reported at a dosage of 50–75 ppm.

4. Secondary Atomization → Finer Fuel Spray (Li et al., 2024)

   Al_2O_3 nanoparticles adsorb onto fuel droplet surfaces and create surface tension instabilities, causing large droplets to break into much finer ones. This in turn eliminates fuel-rich droplet cores, which are primary sites for soot nucleation. The resulting finer droplets evaporate rapidly and mix more uniformly with air, significantly reducing PM formation.

5. Active Surface Sites → Catalytic Oxidation (Gad et al., 2021)

   The high surface area of Al_2O_3 nanoparticles provides abundant reactive adsorption sites for CO and HC molecules. These molecules are adsorbed and oxidized on the nanoparticle surface, functioning as distributed micro-catalysts within the combustion chamber.

6. Micro Heat Sink → Thermal Redistribution (Chohan et al., 2026)

   Al_2O_3 absorbs localized thermal spikes in the combustion chamber and re-radiates heat more uniformly. This eliminates dangerous "hot spots" —high-temperature zones (>1800 K) where the Zeldovich mechanism drives thermal NO_x formation

2.2 Preparation of Fuel Blends

The fuel blends were formulated by dispersing the nanoparticles in commercially available diesel fuel using a magnetic stirrer. The nanoparticle concentration used was 25, 50, and 75 ppm (parts per million) by weight in the diesel fuel.

From here on, the fuel blends will be denoted as follows:

Neat Diesel	Run 0
Diesel + 25 ppm CuO	Run 1
Diesel + 50 ppm CuO	Run 2
Diesel + 75 ppm CuO	Run 3
Diesel + 25 ppm Al_2O_3	Run 4
Diesel + 50 ppm Al_2O_3	Run 5
Diesel + 75 ppm Al_2O_3	Run 6

Engine Setup and Testing:

A single-cylinder, four-stroke, direct-injection diesel engine was used for the emission tests. The engine was coupled to a dynamometer to control load and speed. Engine operating conditions were carefully controlled. The engine was run at various load levels (0 %, 25%, 50%, 75%, and 100% of rated load) at a constant speed of 1500 rpm.

It should be noted that the present experimental study was conducted under steady-state operating conditions and did not consider cold-start behavior. Cold-start conditions are known to significantly influence emission characteristics due to lower combustion temperatures and incomplete fuel oxidation, particularly affecting particulate matter (PM) and hydrocarbon (HC) emissions.

Exhaust Emission Measurement:

Carbon dioxide (CO2), carbon monoxide (CO), nitrous oxide (NOx), sulfuric compounds, particulate matter (PM), and unburned hydrocarbons (UHCs) are the most prevalent emissions from fossil fuels (Reşitoğlu et al., 2015) ((Geng et al., 2017)

The high temperature in the combustion chamber and the surplus availability of oxygen are the causes of the formation of NOx emissions (Sudalaimuthu et al., 2018).

CO2 is formed during the complete combustion of fuel when oxygen is adequate, whereas CO emissions result from incomplete combustion or a deficiency of oxygen (Dey and Dhal, 2019; Bradley et al., 1999).

Due to environmental concerns, PM emissions are a major concern. PM is usually a complex mixture of sulfur compounds, various HCs, elemental carbon, and other species (Wang et al., 2016; Wei and Geng, 2016). UHCs, considered a main pollutant that significantly affects the environment, result from incomplete combustion (Reşitoğlu et al., 2015).

In the present study, an Exhaust Gas Analyzer(AVL444N) was used to measure the concentrations of gaseous pollutants, including CO, HC, CO_2, O_2, and NOx; a smoke meter (AVL437) was used to measure the smoke emission.

Figure 1. Smoke meter (AVL437) & Exhaust gas analyzer (AVL444N)

3. Results & Discussion

The detailed interpretation of the individual runs along with their experimental data (represented graphically) is as follows:

1- Run 0 (Neat Diesel)

Carbon monoxide (CO) levels initially drop from 0.08% at no load to 0.03% at 9 kg, suggesting improved combustion efficiency. However, at 12 kg, CO slightly increases to 0.04%, indicating incomplete combustion under peak-load conditions. Hydrocarbon (HC) emissions show a steady rise, increasing from 1 ppm at no load to 9 ppm at 12 kg, indicating higher levels of unburned fuel residues with increasing load. Carbon dioxide (CO_2) levels increase from 1.3% at no load to 6.1% at 12 kg, indicating more complete combustion. Simultaneously, oxygen (O_2) levels decline from 18.93% to 12.18%, demonstrating greater oxygen consumption with higher loads. Nitric oxide (NO) emissions surge significantly, from 80 ppm to 1068 ppm, likely due to elevated combustion temperatures at increased loads. Smoke emissions, which remain low at lower loads, rise sharply from 0.2 at no load to 33.2 at 12 kg, suggesting increased particulate formation and incomplete combustion at higher loads. These trends indicate that while higher loads enhance combustion efficiency, they also lead to substantial increases in NO and smoke emissions, which can adversely affect both environmental quality and engine performance.

2- Run 1 (Diesel + 25 ppm CuO)

Carbon monoxide (CO) content decreases from 0.12% at no load to 0.04% at 9 kg, reflecting improved combustion efficiency. At 12 kg, CO increases marginally to 0.05%, which may result from incomplete combustion at maximum load. Hydrocarbon (HC) emissions gradually increase from 6 ppm at no load to 15 ppm at 12 kg, reflecting increased unburned fuel content with rising load. Carbon dioxide (CO_2) content increases steadily from 1.4% at no load to 6.6% at 12 kg, indicating better combustion. Oxygen (O_2) content decreases from 18.9% to 11.62%, showing greater oxygen consumption. Nitric oxide (NO) emissions rise sharply from 38 ppm at no load to 1244 ppm at 12 kg, probably due to increased combustion temperatures. Smoke emissions also trend similarly, increasing from 0.9 to 22.9, reflecting greater particulate formation at higher loads.

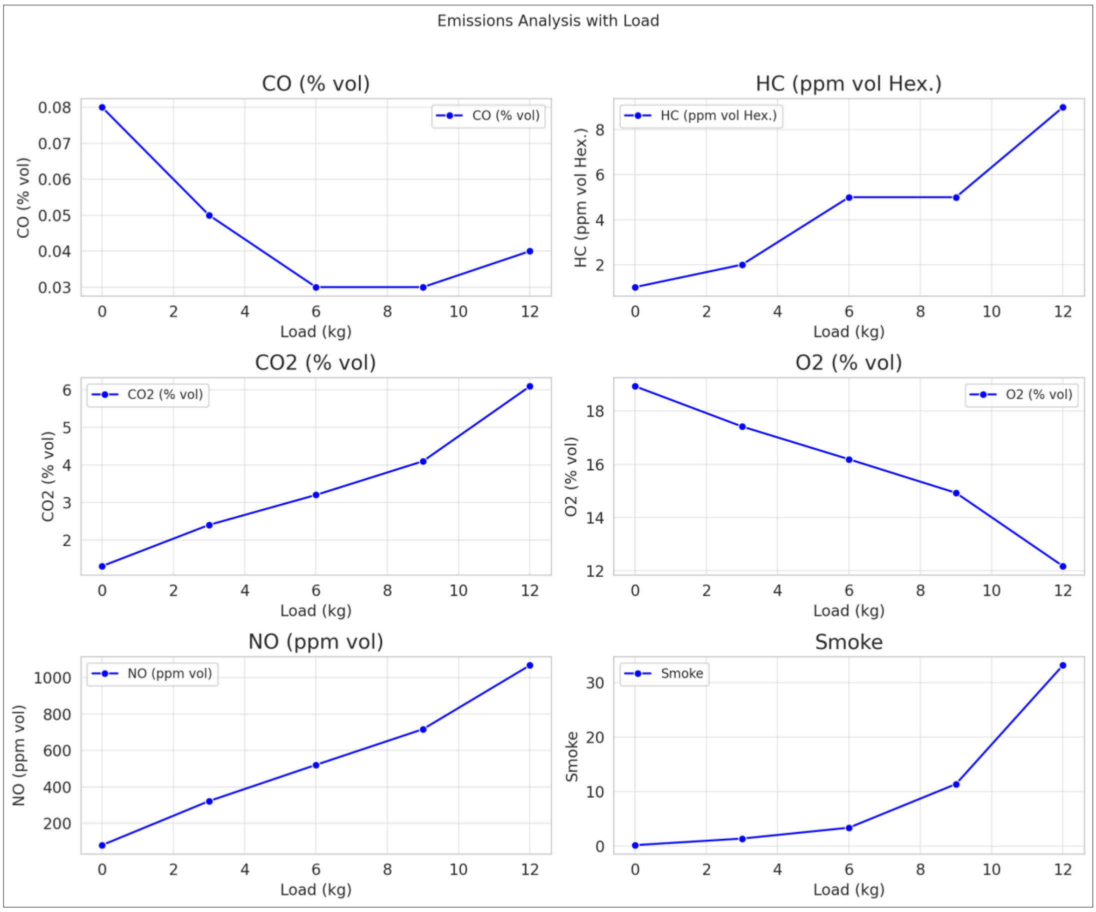

Figure 2. Variation of exhaust emission parameters with engine load for neat diesel fuel (Run 0)

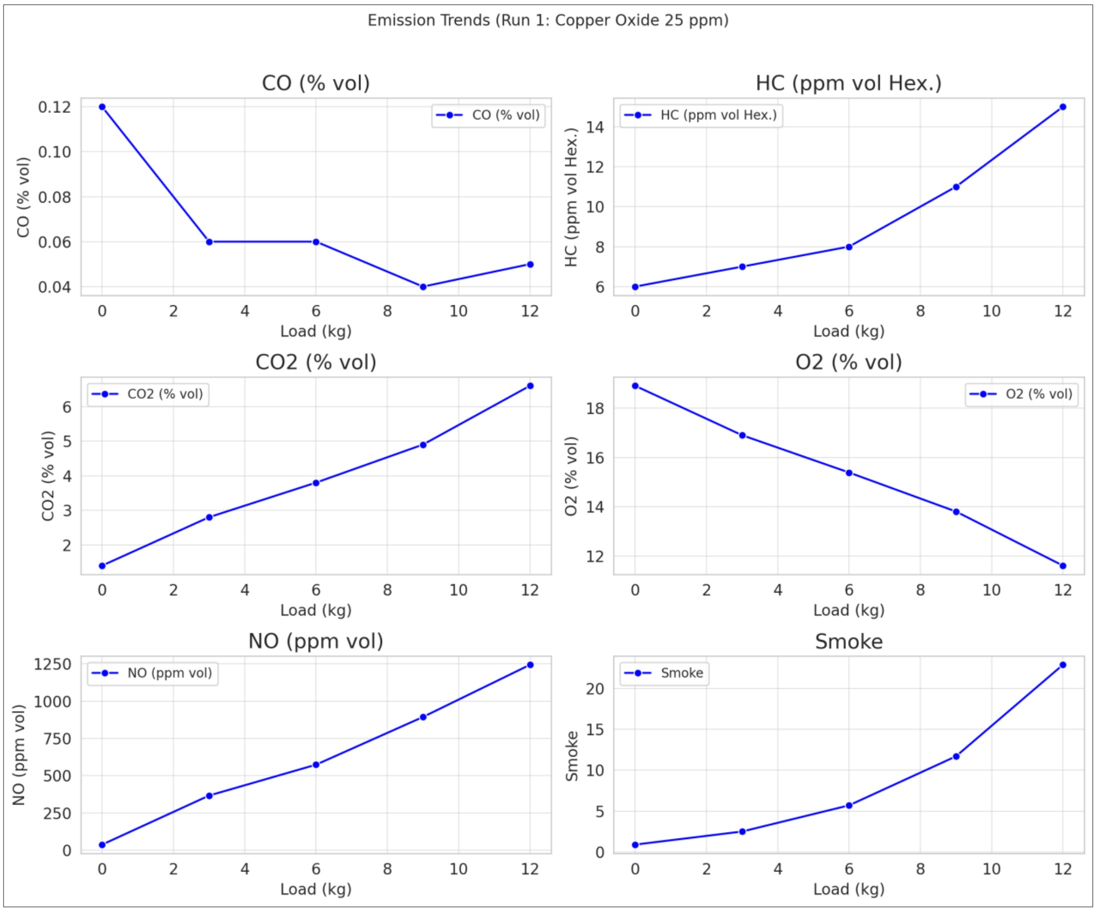

Figure 3. Emission characteristics of diesel blended with 25 ppm CuO nanoparticles (Run 1)

3- Run 2 (Diesel + 50 ppm CuO)

CO emissions decrease with load, from 0.13% at no load to 0.06% at 12 kg, indicating better combustion efficiency. HC emissions are fairly constant but rise slightly with increasing load, reaching 12 ppm vol Hex. at 12 kg, likely due to incomplete combustion at extreme loads. CO2 emissions increase from 1.4% at no load to 6.5% at 12 kg, confirming greater fuel oxidation and improved combustion. O2 decreases with load, from 18.73% to 11.68%, indicating more oxygen is consumed during combustion. NO emissions increase substantially with load, from 39 ppm at no load to 1207 ppm at 12 kg, as expected with higher combustion temperatures with CuO. Smoke emissions also increase steeply from 0.5 to 26.2, reflecting elevated particulate matter generation at high loads.

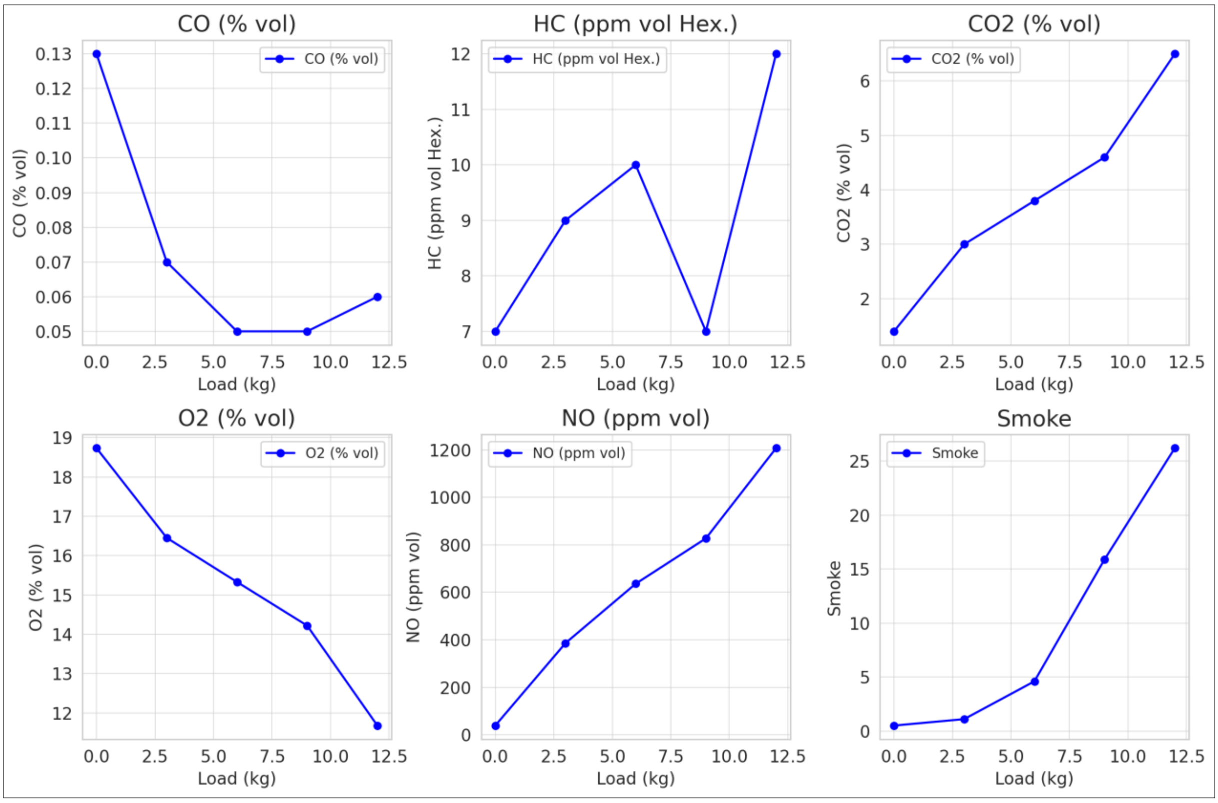

Figure 4. Emission characteristics of diesel blended with 50 ppm CuO nanoparticles (Run 2)

4- Run 3 (Diesel + 75 ppm CuO)

CO emissions initially rise to 0.17% at zero load but decrease significantly as load increases, stabilizing at 0.05%–0.06% beyond 6 kg. This indicates better oxidation of CO at higher loads. HC emissions remain relatively stable at lower loads (7–9 ppm) but rise slightly to 11 ppm at 12 kg, suggesting some incomplete combustion at higher loads. CO2 levels increase steadily from 1.6% at 0 kg to 6% at 12 kg, reflecting improved combustion efficiency as load increases. O2 levels show a consistent decline from 18.35% to 12.32%, indicating increased oxygen consumption during combustion. NO emissions rise significantly from 34 ppm to 1117 ppm as load increases, due to the higher combustion temperature. Lastly, smoke emissions rise from 0.6 at no load to 28.3 at full load, suggesting increased soot formation with increased load due to a richer fuel-air mixture.

Comparative Analysis of Emission Trends: Run 0 vs. Run 1 (CuO 25 ppm) vs. Run 2 (CuO 50 ppm) vs. Run 3 (CuO 75 ppm)

CO Emissions: Run 3 (CuO 75 ppm) shows slightly higher CO emissions at low loads compared to the other runs, especially at 0 kg load (0.17% vol). However, at higher loads, CO levels remain similar to those in Runs 1 and 2, suggesting that CuO improves oxidation at higher temperatures.

HC Emissions: Hydrocarbon (HC) emissions remain relatively stable across all CuO-doped runs, with Run 3 showing an average of 8.8 ppm. This is slightly lower than Run 1 (9.4 ppm) and Run 2 (9 ppm), suggesting moderate effectiveness in reducing unburned hydrocarbons.

CO_2 Emissions: CO_2 emissions increase with load in all runs, indicating better combustion efficiency with CuO addition. Run 3 shows slightly lower CO_2 levels than Run 2 but still higher than Run 0, suggesting that the combustion-efficiency gain starts to saturate at higher CuO concentrations.

O_2 Levels: Oxygen levels decrease with increasing load, as expected. Run 3 maintains an average O_2 of 15.516%, slightly higher than Run 2 but lower than Run 0, indicating that more oxygen is being utilized in combustion, albeit at a diminishing rate beyond 50 ppm CuO.

NO Emissions: NO levels rise significantly as CuO concentration increases. Run 3 averages 573.4 ppm, slightly lower than Run 2 (619 ppm) but still much higher than Run 0. This suggests that excessive CuO concentrations may reach a threshold beyond which additional oxidation no longer increases NO formation.

Smoke Emissions: Smoke emissions continue to increase at higher loads, with Run 3 averaging 10.44, higher than Runs 1 and 2. The high smoke levels at full load (28.3) suggest that 75 ppm CuO may cause incomplete combustion due to excessive nanoparticle agglomeration.

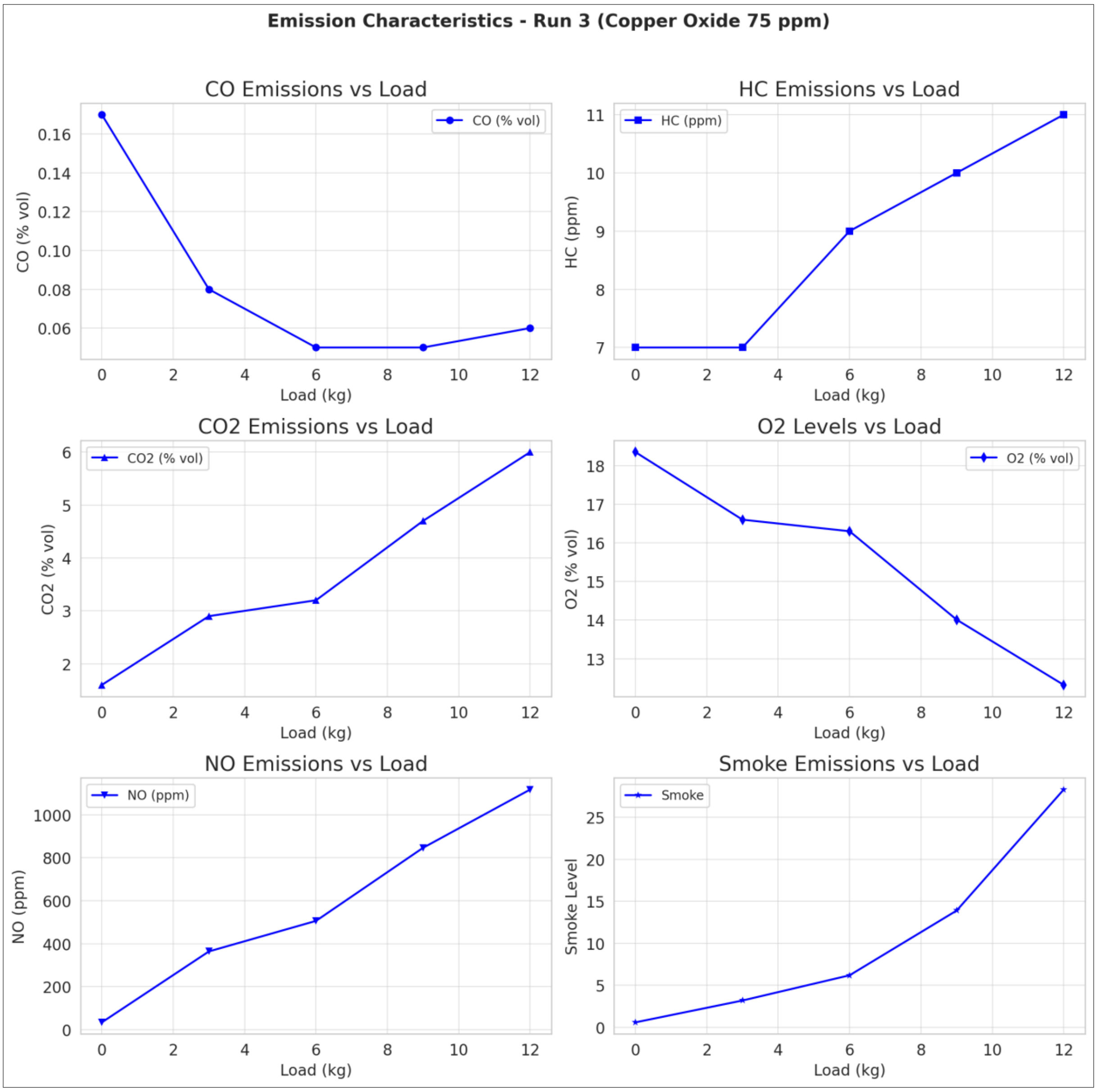

Figure 5. Emission characteristics of diesel blended with 75 ppm CuO nanoparticles (Run 3)

Concluding Remark:

While CuO additives improve combustion efficiency by increasing CO_2 production and reducing unburned HC and O_2 levels, diminishing returns beyond 50 ppm indicate that excessive CuO does not further enhance performance. Instead, it increases NO emissions and smoke levels at higher loads. Run 1 (CuO 25 ppm) remains the most balanced option, offering a good trade-off between efficiency and emissions control.

5- Run 4 (Diesel + 25 ppm Al_2O_3)

CO emissions decrease from 0.12% at 0 kg load to 0.04% at 12 kg, showing improved combustion efficiency at higher loads. The HC emissions start at 3 ppm at a 0 kg load and rise to 7 ppm at a 12 kg load, indicating increased unburned hydrocarbons at higher loads. The CO_2 levels increase with load, peaking at 6.4% at 12 kg, suggesting more complete combustion. The O_2 concentration decreases from 18.48% at 0 kg to 11.58% at 12 kg, consistent with fuel consumption. The NO emissions increase significantly with load, from 59 ppm at 0 kg to 1176 ppm at 12 kg, due to higher combustion temperatures. Smoke emissions also increase from 0 at no load to 22.8 at full load, indicating increased particulate matter formation.

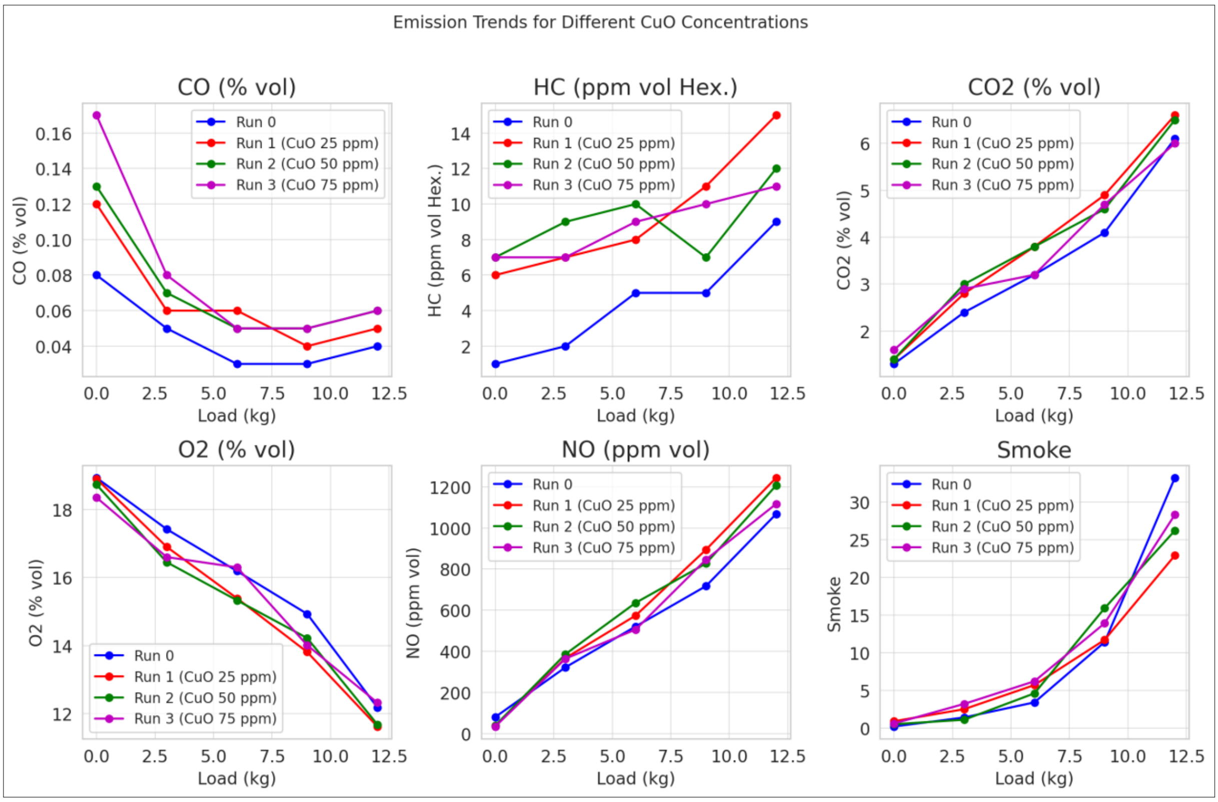

Figure 6. Comparative analysis of emission parameters for neat diesel (Run 0) and CuO nanoparticle blends (25, 50, and 75 ppm)

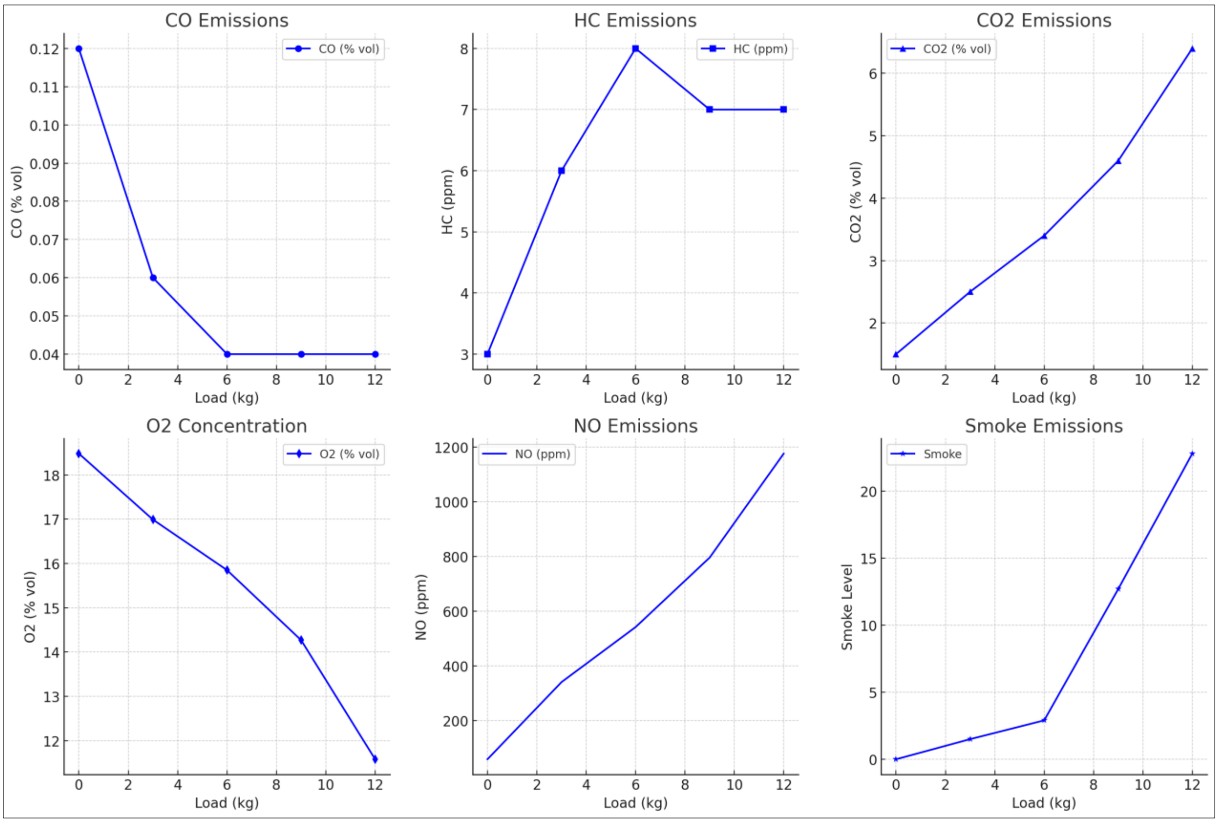

Figure 7. Emission characteristics of diesel blended with 25 ppm Al_2O_3 nanoparticles (Run 4)

6- Run 5 (Diesel + 50 ppm Al_2O_3)

Carbon Monoxide (CO) emissions decreased from 0.11% vol at 0 kg load to 0.04 - 0.05% vol at higher loads, indicating improved combustion efficiency at elevated loads. Hydrocarbon (HC) emissions increased with load, rising from 7 ppm at 0 kg to 13 ppm at 12 kg, suggesting increased fuel decomposition at higher engine loads. Carbon Dioxide (CO_2) emissions increased, peaking at 6.6% vol at a 12 kg load, indicating enhanced combustion efficiency. Conversely, Oxygen (O_2) levels decreased from 18.61% vol at no load to 11.43% vol at full load, further confirming better fuel utilization. Nitric Oxide (NO) emissions increased significantly from 54 ppm at 0 kg to 1213 ppm at 12 kg, which is a result of higher combustion temperatures at higher loads. Lastly, smoke emissions rose sharply from 0.5 at no load to 39.9 at full load, indicating incomplete combustion and increased soot formation under heavy-load conditions.

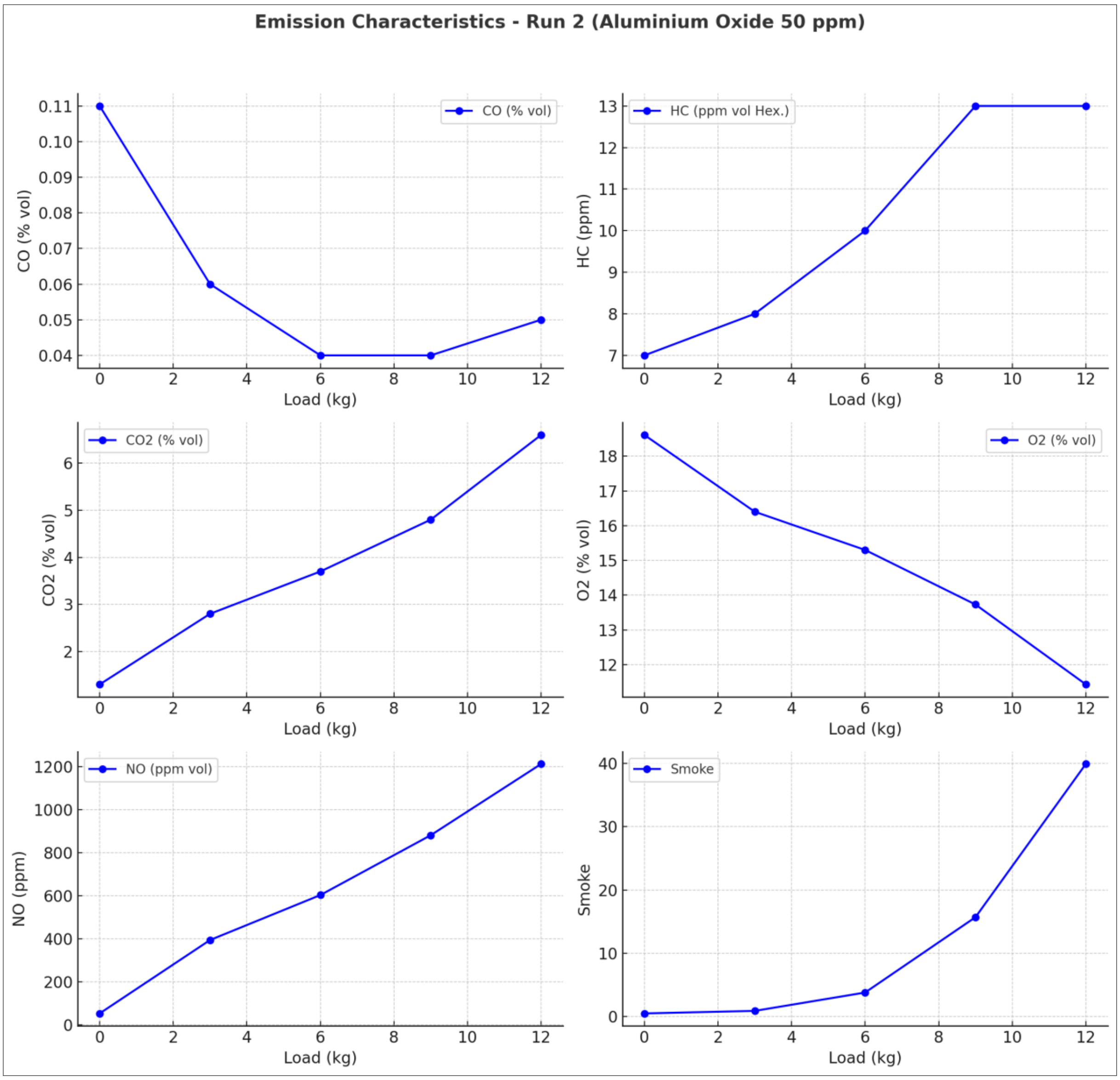

Figure 8. Emission characteristics of diesel blended with 50 ppm Al_2O_3 nanoparticles (Run 5)

7- Run 6 (Diesel + 75 ppm Al_2O_3)

Carbon Monoxide (CO) emissions gradually decrease from 0.09% at 0 kg to 0.05% at 9 kg, indicating better combustion efficiency at moderate loads, but a slight rise to 0.06% at 12 kg suggests incomplete combustion at higher fuel injection rates. Hydrocarbon (HC) emissions remain relatively low, ranging from 0 to 11 ppm, with slight increase at 12 kg, possibly due to incomplete oxidation. Carbon Dioxide (CO_2) levels increase from 0.9% at 0 kg to 6.4% at 12 kg, confirming improved fuel combustion at higher loads. Oxygen (O_2) concentration decreases as load increases, showing higher oxygen consumption due to more complete combustion. Nitric Oxide (NO) emissions rise significantly from 25 ppm at 0 kg to 1192 ppm at 12 kg, indicating higher combustion temperatures at greater loads. Smoke levels increase from 0.1 at no load to 28.2 at full load, which may be attributed to incomplete combustion and increased particulate matter formation at higher loads.

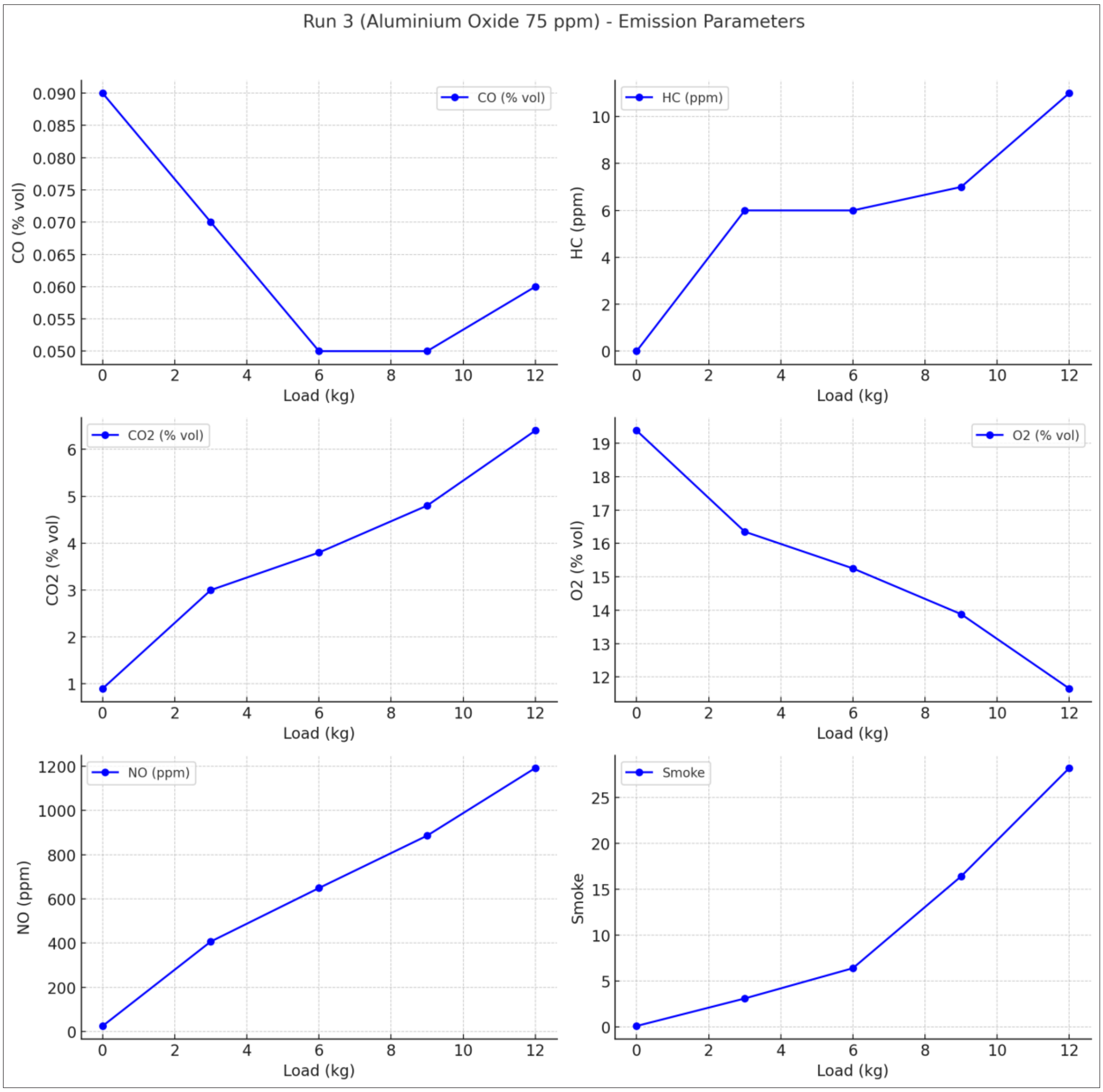

Figure 9. Emission characteristics of diesel blended with 75 ppm Al_2O_3 nanoparticles (Run 6)

Comparative Analysis of Emission Trends: Run 0 vs. Run 1 (Al_2O_3 25 ppm) vs. Run 2 (Al_2O_3 50 ppm) vs. Run 3 (Al_2O_3 75 ppm)

1. CO Emission: The emission trends of Carbon Monoxide (CO) indicate that Run 0 (Baseline) had the highest CO emissions. With the introduction of Al_2O_3 at 25 ppm (Run 4), a noticeable reduction in CO levels was observed, highlighting its catalytic effect. A further decrease in CO emissions was observed in Run 5 (Al_2O_3 50 ppm), with the average emission level stabilizing at 0.06% vol. In Run 6 (Al_2O_3 75 ppm), a slightly lower CO emission trend was observed compared to Run 5, suggesting a diminishing effect with increasing dosage.

2. HC Emission: The HC levels exhibited a decreasing trend with increasing Al_2O_3 concentration. Run 4 showed a moderate reduction in HC emissions, while Runs 5 and 6 showed a significant decline. Among them, Run 6 (Al_2O_3 75 ppm) recorded the lowest HC emissions, indicating enhanced combustion efficiency.

3. CO_2 Emissions: A progressive increase in CO_2 emissions was observed, indicating improved combustion efficiency. Run 6 recorded the highest CO_2 emission levels, confirming enhanced oxidation of CO and HC into CO_2.

4. O_2 Concentration: As the load increased, O_2 levels decreased across all runs, indicating improved fuel utilization. Run 6 recorded the lowest O_2 levels, signifying the highest combustion efficiency among all runs.

5. NO Emission: NO emissions exhibited an increasing trend with rising Al_2O_3 concentration. Run 6 recorded the highest NO emissions (1192 ppm at 12 kg load), attributed to higher combustion temperatures. This highlights a trade-off: Al_2O_3 enhances combustion efficiency but also increases NO formation.

6. Smoke Opacity Trends:

A significant reduction in smoke was observed as the Al2O3 concentration increased.

Run 6 had the lowest smoke emissions, confirming better fuel combustion and reduced soot formation.

Concluding Remark:

The comparative analysis shows that Al_2O_3, as a fuel additive, significantly improves combustion efficiency by reducing CO, HC, and smoke emissions, while increasing CO_2 and NO emissions. Run 6 (Al_2O_3 75 ppm) showed the best results in terms of reduced CO, HC, and smoke but had the highest NO emissions. Future optimizations can focus on balancing combustion efficiency with NO emission control.

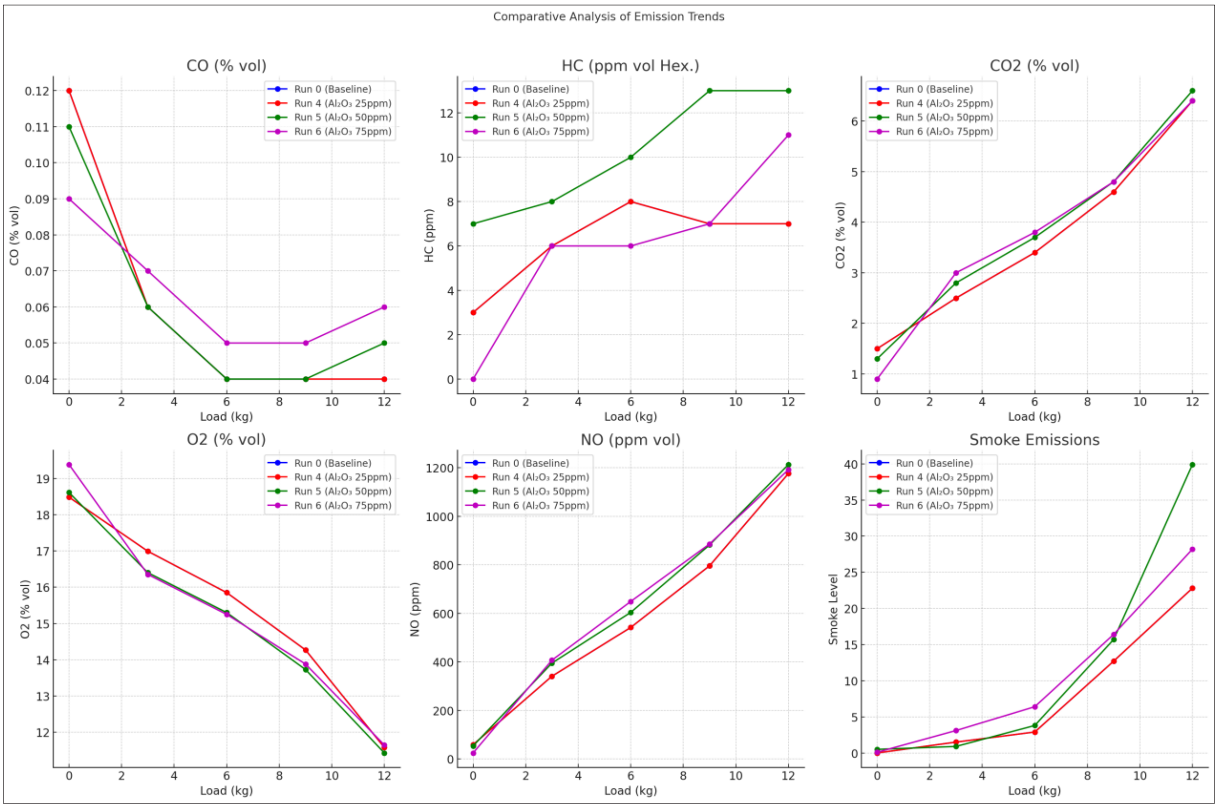

Figure 10. Comparative analysis of emission parameters for neat diesel (Run 0) and Al_2O_3 nanoparticle blends (25, 50, and 75 ppm)

Comparative Analysis: Run 1 (CuO 25 ppm) vs. Run 6 (Al_2O_3 75 ppm)

Carbon Monoxide (CO) Emissions : Run 1 has slightly higher CO emissions at lower loads compared to Run 6.

Both runs show a decreasing trend in CO emissions as the load increases, stabilizing at around 0.05-0.06% vol.

Hydrocarbon (HC) Emissions: Run 6 shows consistently lower HC levels than Run 1, except at 12 kg load, where both converge.

This indicates that Al_2O_3 (75 ppm) may improve combustion compared to CuO (25 ppm).

Carbon Dioxide (CO_2) Emissions: CO_2 increases with load in both runs.

Run 6 has slightly higher CO_2 emissions, which indicates better combustion efficiency.

Oxygen (O_2) Levels : O_2 levels decrease with increasing load, as expected.

Run 6 shows a faster decline in O_2 levels, which aligns with its higher CO_2 emissions and reinforces the idea of improved combustion efficiency.

Nitric Oxide (NO) Emissions: NO emissions increase significantly with load in both runs.

Run 6 has higher NO levels, suggesting a higher combustion temperature compared to Run 1.

Smoke Opacity: Run 6 shows higher smoke emissions at higher loads than Run 1, possibly due to incomplete combustion at peak loads.

This suggests a need to optimize the fuel-air ratio for Al_2O_3 (75 ppm) at higher loads.

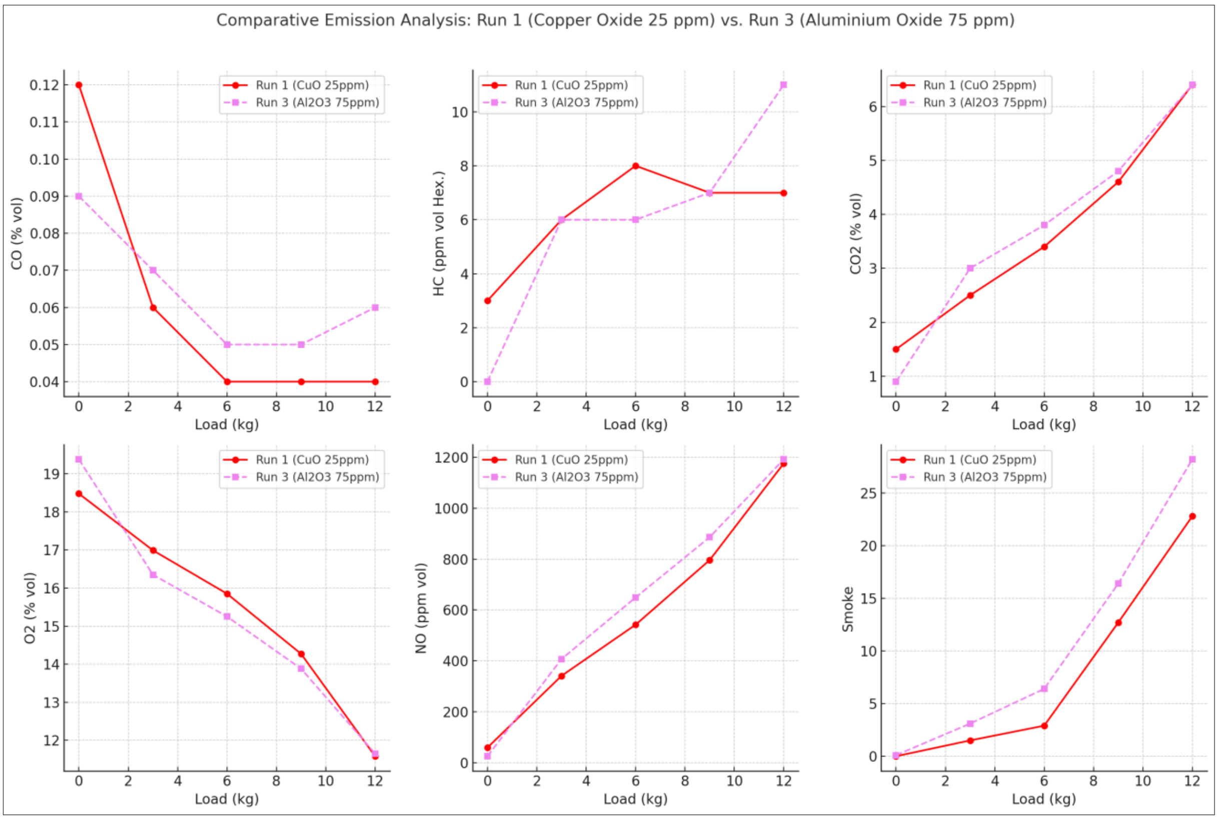

Figure 11. Comparative analysis of emission parameters for diesel blended with 25 ppm CuO nanoparticles (Run 1) and diesel blended with 75 ppm Al_2O_3 nanoparticles (Run 6)

Best Run: Run 1 (CuO 25 ppm) vs. Run 6 (Al2O3 75 ppm)

To determine the best run, we have evaluated the key emission parameters as follows:

1. Carbon Monoxide (CO): Lower CO is better (indicating better combustion)

Run 6 (Al_2O_3 75 ppm) has slightly lower CO emissions than Run 1 (CuO 25 ppm) at lower loads, indicating better oxidation of CO.

2. Hydrocarbons (HC) : Lower HC is better (indicating better fuel combustion).

Run 1 (CuO 25 ppm) has lower overall HC levels, indicating it burns fuel more completely than Run 6.

3. Carbon Dioxide (CO_2) : Higher CO_2 indicates better combustion but also more greenhouse gas emissions.

Run 6 (Al_2O_3 75 ppm) has slightly higher CO_2 levels, meaning better combustion efficiency but at the cost of more emissions.

4. Oxygen (O_2) Levels: Lower O_2 in exhaust suggests better combustion efficiency.

Run 6 has lower O_2 levels, indicating that it utilizes more oxygen for combustion than Run 1.

5. Nitric Oxide (NO) Emissions: Lower NO is better (since high NO emissions contribute to air pollution).

Run 6 (Al_2O_3 75 ppm) has higher NO emissions, which suggests a higher combustion temperature. Run 1 is better in this aspect.

6. Smoke Emissions: Lower smoke levels are preferred (indicating complete combustion).

Run 1 has lower smoke emissions at high loads, making it a cleaner option.

To summarize, if the goal is better combustion efficiency, Run 6 (Al_2O_3 75 ppm) is superior because it has lower CO, higher CO_2, and better oxygen utilization.

If the goal is lower emissions and environmental impact, Run 1 (CuO 25 ppm) is better due to lower NO and smoke emissions.

According to us, the Best Overall Choice is Run 1 (CuO 25 ppm), which maintains a better balance between efficiency and emissions. However, if maximizing combustion efficiency is the priority, Run 6 would be the preferred choice.

4. Challenges & Future Scope

Undoubtedly, the nanoparticle additives in diesel fuel reduce the engine emissions significantly. Further experimental efforts are needed to fill the knowledge gap about the type of nanoparticle used and its optimum dosage in fuel so that it serves the purpose of Complete Combustion as well as Lower Emissions and Environmental Impact. In addition, the stability characteristics of nanofluid fuels under various operating conditions should be addressed from a technical standpoint.

It is worth noting that, beyond engine emissions, performance, and combustion characteristics, most existing reviews have focused primarily on dispersion stability, wear and friction loss, corrosion, and cost-related issues with nanoparticles, with limited discussion of a very important aspect of these nano-additives, namely their toxicity and health impacts when they come into contact with humans and animals over a period of exposure. There is substantial evidence supporting the toxicity of these nanoparticles and the potential harm they could pose to an individual's health (Doshi et al., 2008; Karlsson et al.; Lin and Xing, 2007; Long, 2006a, 2006b; AZoNano). The harmful effects of exhaust emissions become more concerning when nanosize fuel additives are used (Zhang and Balasubramanian, 2015). The most probable entry sites for nanoparticles are the skin, gastrointestinal system, and lungs (Buzea et al., 2007). Nanoparticles, whether released or naturally occurring, can infiltrate and move within living organisms. Their minuscule size allows them to penetrate physiological barriers and enter the body (Kabir et al., 2018). According to reports, nanoparticles interact with several bodily systems, including the skin, brain, lungs, liver, kidneys, and blood, and may disrupt their normal functions (Schrand et al., 2010). Mauro et al. [31] demonstrated in a study that the skin is a negligible route for nanoparticle penetration and permeation. However, they found that Al2O3 nanoparticles can slightly permeate the skin (Mauro et al., 2019).

The present study does not account for cold-start conditions, which are critical in determining real-world emission performance. Future work should include transient and cold-start analysis to evaluate the effectiveness of nanoparticle additives under practical operating scenarios.

5. Conclusion

The concept of blending Aluminum Oxide and Copper Oxide Nanoparticles into neat diesel on the emission patterns was investigated in this study, and the results obtained during the trials are summarized.

1. A significant reduction in all emissions was observed by doping additives to diesel since metal oxide nanoparticles provide extra oxygen during combustion, and hence complete combustion was achieved.
2. It was observed that the NOx emissions were increased with the usage of metal oxide nanoparticles due to the liberation of extra oxygen.
3. As far as the experimental results are concerned, Run 6 (Al_2O_3 75 ppm) demonstrates higher combustion efficiency with better CO, CO_2, and O_2 emissions but at the expense of higher NO and smoke emissions, especially at higher loads. This run turned out to be more efficient in terms of fuel consumption, but it contributes to higher pollution levels. Run 1 (CuO 25 ppm), on the other hand, is cleaner overall, with lower HC, NO, and smoke emissions, making it a better option for minimizing pollution, especially at higher loads. While its CO and CO_2 emissions are slightly higher, it represents a more environmentally friendly choice.
4. Ultimately, Run 1 (CuO 25 ppm) appears to be the better option for cleaner combustion, particularly in reducing NO emissions and smoke opacity, while Run 6 (Al_2O_3 75 ppm) excels in combustion efficiency but requires optimization to reduce pollution at higher loads.

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