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The Performance Investigation of Biochar/Copper Metal Catalyst Stabilized On Monolith in Reducing Exhaust Emissions

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ABSTRACT

The rapid growth of the population, urban expansion, industrialization, and increasing urbanization have significantly contributed to rising pollution levels in metropolitan areas. Among various pollution sources, vehicles account for approximately 70% of air pollution, with internal combustion engine vehicles playing a major role in environmental degradation. To mitigate vehicle emissions, modern automakers have integrated metallic catalytic converters that transform harmful pollutants into less toxic or non-toxic substances. This study examines the effectiveness of a copper-based catalyst and biochar stabilized on a monolith in altering the composition of exhaust gases (O_2, CO, CO_2, HC, and NOx) emitted by the XU7 engine. Two key variables are analyzed: copper metal content (1 mmol and 2 mmol) and catalyst thickness (8 cm and 16 cm). The results indicate that the developed catalyst significantly reduces exhaust gas emissions from the XU7 engine, aligning with environmental standards. Specifically, the catalyst facilitates the absorption of 0.002 grams of carbon monoxide (CO), which is oxidized into carbon dioxide (CO_2). Additionally, 0.7375 grams of hydrocarbons (HC) react with oxygen to form carbon dioxide and water vapor. Furthermore, manganese oxides in the catalyst aid in the reduction of nitrogen oxides (NOx), leading to the absorption of 0.0019 grams of NOx pollutants. By implementing the findings of this study and adhering to the recommended guidelines, significant pollution reduction can be achieved, paving the way for enhanced environmental sustainability.

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INTRODUCTION

The transboundary transfer of pollutants, whether from industrialized countries to developing nations or vice versa, is a major factor contributing to environmental pollution. Population growth in certain countries, increasing demand for food, expansion of intensive agriculture, industrial development, deforestation, urbanization, improper exploitation of natural resources, and excessive use of chemicals in various industries are among the key factors exacerbating this crisis. Industrialization plays a significant role in polluting soil, air, and water sources, and the contamination caused by toxic substances may take years to be remedied (Zhao et al., 2020; Zuo et al., 2019; Zuo et al., 2020). The proliferation of automobiles worldwide has raised serious concerns due to several advancements in the post-treatment of exhaust gases, particularly in mitigating pollutants such as carbon dioxide and nitrogen oxides (Gao et al., 2019; Isgoren et al., 2023; Jeyakumar et al., 2022; Khoshkname et al., 2022). These contaminants significantly impact urban air quality, leading to increased risks of respiratory illnesses such as asthma and bronchitis, heightened dangers of life-threatening disorders like cancer, and a substantial financial burden on the healthcare system (Manojkumar et al., 2021; Naveenkumar et al., 2020).

One of the simplest methods to reduce greenhouse gas emissions from internal combustion engines is the use of catalytic converters. These converters facilitate the reaction of harmful exhaust gases with the catalyst surface through a process known as catalysis. Typically, automotive catalytic converters contain an active catalytic material housed within a specially designed metal structure that directs the flow of exhaust gases through the catalytic substrate. The presence of the catalyst lowers the activation energy required for chemical reactions, accelerating the process of converting pollutants into less harmful substances (Alves et al., 2025; Dey & Dhal, 2020; Gomes et al., 2025; Ibrahim et al., 2018; Iodice et al., 2018; Kumar et al., 2014; Senthil Kumar et al., 2022).

Monolithic structures emerge as a compelling alternative to conventional catalyst pellets or powders, boasting a host of enhanced properties. Unlike their traditional counterparts, monoliths exhibit superior mechanical strength, reduced pressure drop, heightened mass transfer efficiency, and enhanced thermal stability. These uniform blocks, composed of parallel channels that can be extruded into diverse sizes and shapes, offer versatility in material selection—ranging from ceramics and metals to carbon or zeolites. The geometric configuration of monoliths, available in square, hexagonal, triangular, and circular shapes, plays a pivotal role in shaping mass and heat transfer characteristics, thereby influencing catalytic performance. Notably, hexagonal channels, with their superior thermal mass efficiency over square channels, stand out as a preferred choice for catalytic converters (Govender & Friedrich, 2017; Saba et al., 2015).

A novel strategy to address rising pollution involves the use of eco-friendly modifiers to mitigate environmental contamination. Due to its slower decomposition rate compared to other organic materials, this substance presents a significant opportunity to reduce greenhouse gas emissions, such as carbon dioxide and methane, generated during waste disposal (Joseph et al., 2010). Furthermore, it has the ability to sequester carbon for an extended period. However, the high costs of palladium, platinum, and rhodium create challenges in catalytic converter production. To improve the economic feasibility of these converters, alternative materials like biochar can be incorporated. Thanks to its prolonged decomposition rate, biochar demonstrates strong potential in curbing greenhouse gas emissions (Ahmad et al., 2014). In this study, a catalytic converter was developed using copper metal and biochar, and its effectiveness in reducing pollutants O_2, CO, CO_2, HC, and NO_x was examined.

MATERIALS AND METHODS

Solvents and other chemicals related to the experiment were procured from Floka, Merck, and Aldrich.

Synthesis of Biochar/Cu Catalyst:

In this experiment, biochar material was sourced from Ilam University. Initially, 5 g of biochar and 1.241 g of copper (II) nitrate, along with 150 ml of deionized water, were combined in a 250 ml flask. The mixture was then stirred with a magnetic stirrer for 24 hours at a temperature of 75 °C. Subsequently, the resulting product was filtered, washed multiple times with distilled water, and dried at 80 °C. The sediment obtained was calcined at 550 °C for 5 hours (Figure 1) (Hajjami et al., 2017).

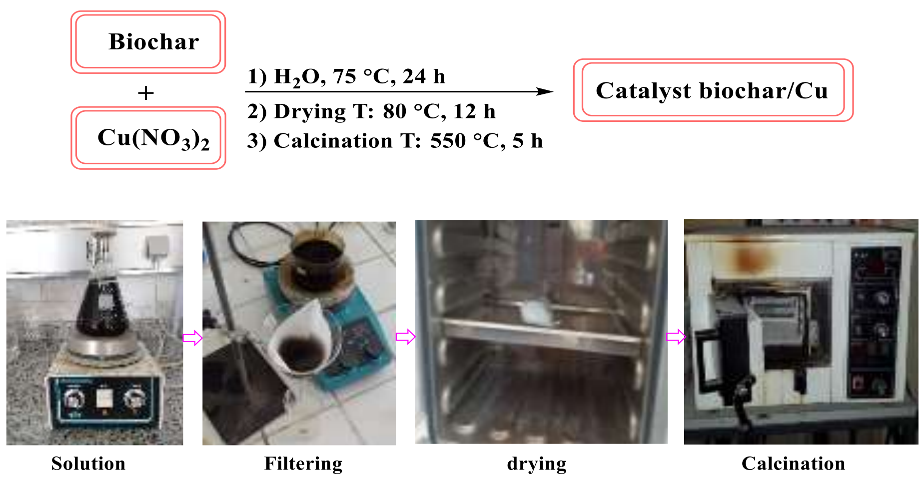

Figure 1. Biochar/Cu Catalyst Preparation.

Spray-Assisted Deposition of Copper and Biochar Nanoparticles onto Monoliths:

One hundred grams of a copper-biochar composite, consisting of copper nanoparticles (particle size <100 nm) and highly porous biochar with a large surface area, was ground and homogenized into a fine powder. The powder was then dispersed in 500 mL of Merck alcohol and applied to the monolith using a pressurized air sprayer. To ensure the stabilization of copper and biochar on the monolith substrate, the coated monolith was heated in a furnace at 500°C for 2 hours.

After designing and fabricating the biochar/Cu catalyst, its characterization was conducted using ICP-AES and EDX techniques.

Characterization of Biochar/Cu Catalyst

Inductively Coupled Plasma Atomic Emission (ICP-AES) Spectroscopy:

Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) is an elemental analysis technique utilizing emission spectroscopy and plasma atomization (Kovacevic et al., 2008). This method quantitatively and qualitatively analyses elements by utilizing plasma as an excitation source. According to the ICP-AES measurements, the copper metal immobilized on biochar was determined to be 0.043 mmol/g for 1 mmol and 0.079 mmol/g for 2 mmol.

Energy Dispersive X-Ray (EDX) Analysis:

Energy Dispersive X-Ray (EDX) analysis is employed to examine the structure or chemical composition of a sample through X-ray diffraction spectroscopy. This technique generates distinctive X-rays that reveal components in the samples. The analysis, based on the unique atomic structure of each element, produces peaks in the X-ray spectrum (Khan et al., 2020).

An EDX study of the catalyst revealed the presence of C, N, O, and Cu. The mass percentages of these components for 1 mmol were (6.23, 4.48, 49.99, and 39.29), and for 2 mmol were (11.41, 2.01, 25.08, and 61.5), respectively. Figure 2 displays the EDX diagram illustrating Cu immobilized on charcoal at concentrations of 1 and 2 mmol.

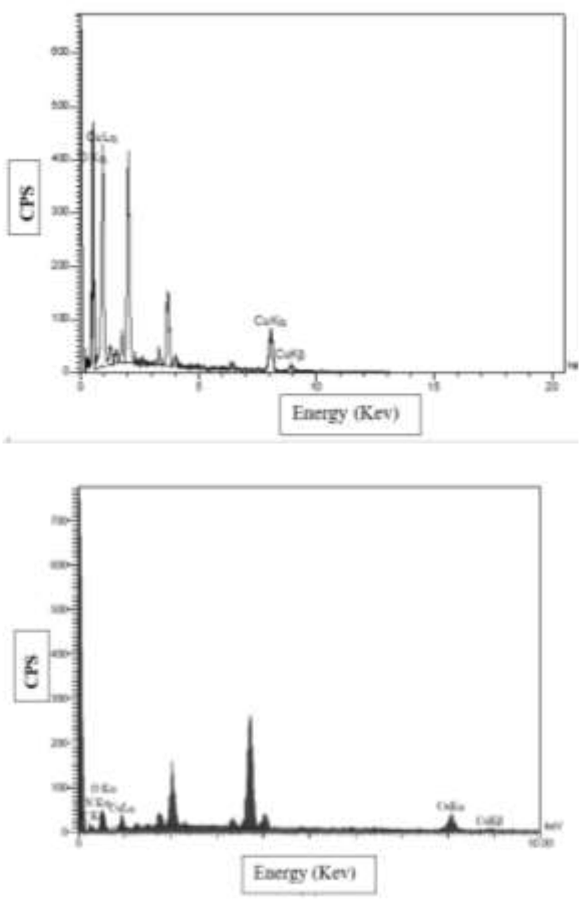

Figure 2. EDX plots of one (a) and two mmol copper (b)

Mold Design and Installation:

The initial design of the catalyst mold was created using SolidWorks software (Figure 3). The mold, constructed from an iron pipe, features a circular shape with dimensions of 200 × 25 cm. A tube with a diameter of 2 inches (5.08 cm) was connected to the mold's inlet and outlet.

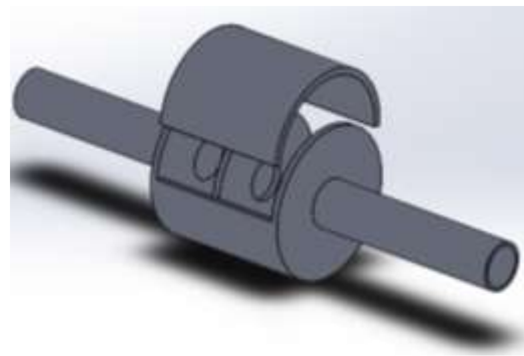

Figure 3. Mold Image Designed with SolidWorks

Catalyst Implementation:

A refractory blanket was utilized to channel the gas from the catalyst mold, replacing the test samples in both open and closed sections. The prepared units were placed inside the mold for engine testing.

Engine Preparation:

To enhance engine efficiency, reduce fuel consumption, and minimize emissions, the test engines underwent technical preparation. Adjustments were made to the ignition system and air filters.

Automotive Engine Test Method:

The tests in this study were conducted on the XU7 engine installed on the 405 vehicle (Figure 4) and its technical specifications are detailed in Table 1.

Figure 4. XU7 engine used in testing.

Table 1. Technical specifications of the tested XU7 engine.

Parts	Specification
Vehicle class code	25634
Engine volume (cc)	1761
Maximum engine power (horsepower)	100 hp at 6000 rpm
Maximum torque (Nm)	153 Nm at 3000 rpm
Compression ratio	9.3
Number of valves	8
Emission limit standard	*Euro 4*
Maximum speed (Km/h)	190
Acceleration from zero to hundred (seconds)	11
power transfer system	5 manual gears
Average combined fuel consumption per 100 km	7.5
Fuel tank capacity	70

Data were gathered while the vehicle was in operation and in neutral gear (860 rpm). Prior to the test, the engine was run for 15 minutes to attain the appropriate temperature. The engine temperature during the test was approximately 85.4 °C, as it is recognized that the operation and environment of an engine vary when it is cold. The ambient air temperature was around 27.3 °C at the time of the test.

To measure the exhaust gases (O_2, CO, NO_x, CO_2, and HC), an Italian-made QRO-401 device was employed. The device's suction-powered probe was inserted into the car's exhaust system for this purpose (Figure 5).

Figure 5. Five-gas test device connected to the catalyst.

The various levels of variables for measuring the exhaust gases resulting from the combustion of the engines under test are outlined in Table 2. In this study, a total of 24 tests were conducted, each with 3 repetitions.

Table 2. Different levels of measured variables.

Variables	Levels of variables	
Engine type	XU7	-
Metal percentage	1 mmol of Cu	2 mmol of Cu
Thickness	Level 1 (8 cm)	Level 2 (16 cm)

RESULTS AND DISCUSSION

Analysis of CO Emission:

Carbon monoxide (CO) is an odorless, tasteless, and colorless gas with a chemical formula CO, molecular weight of 28.01 g/mol, a melting point of -205.02°C, and a boiling temperature of -191.5°C. Upon inhalation, it interacts with red blood cells, reducing their capacity to carry oxygen, and can lead to slow absorption into the body, ultimately resulting in death. Generally, carbon monoxide can cause fetal harm, fibrin breakdown, cardiovascular illness, and neurological issues (Rose et al., 2017).

The average volume percentage of CO pollutant concentration emitted from an XU7 engine's exhaust is compared in Figure 6, depending on the types of catalyst, both with and without a catalyst. Notably, the average volume percentage of CO pollutants in the XU7 engine is below the permitted level, which is less than 2.5%. It is essential to note that carbon monoxide is produced in the engine when the combustion mixture of fuel and air is rich, and there is insufficient oxygen for the combustion cycle. This gas burns with a blue flame and is flammable.

At the 1% probability level, the findings from all experimental treatments regarding CO gas emission from the engine showed a significant reduction.

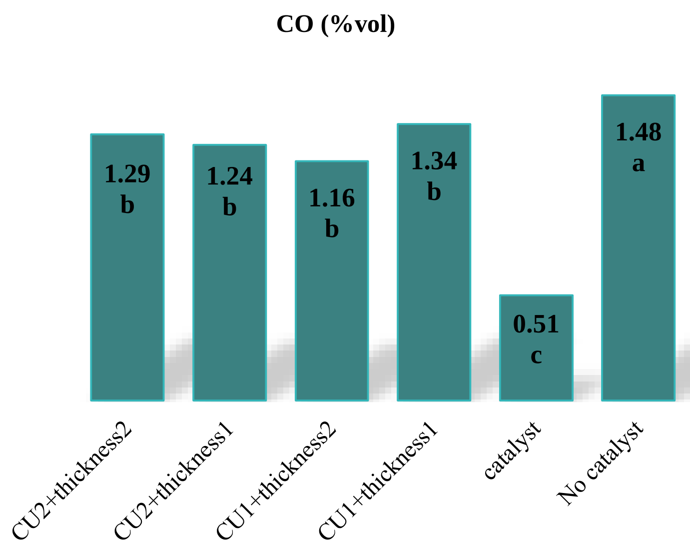

Figure 6. CO Gas Emission Levels for XU7 Engine

Analysis of HC Emission:

During the combustion of the fuel mixture (air and gasoline) in the cylinder, the outer **molecules** of carbon branches exposed to oxygen burn well, resulting in the production of carbon dioxide and water. However, incomplete combustion can occur, preventing the molecules in the center of the hydrocarbon branches from burning completely. As a result, unburned hydrocarbons are expelled from the exhaust, becoming a primary source of air pollution in urban areas—a phenomenon known as raw burning. In some cases, unburned hydrocarbons may also be present in combustion products if the available air is significantly less than required. The number of unburned hydrocarbons varies based on factors like combustion process disruptions, combustion chamber conditions, and mixing efficiency.

Figure 7 compares the average concentration of unburned HC hydrocarbons in the exhaust from the XU7 engine, depending on different types of catalysts, both with and without catalysts. The average level of HC pollutants in the XU7 engine is below the permissible limit (less than 250 ppm), according to the data. This can be attributed to the absence of various factors contributing to hydrocarbon production, including non-stoichiometric air-to-fuel ratio, incomplete combustion, volumes associated with seams and cracks, leakage through the outlet valve, simultaneous open presence of valves, deposits, and the presence of oil on the combustion chamber wall.

The results indicate a significant difference between the average treatments with a 99% confidence level, suggesting that the effect of the HC gas coefficient on the amount of gas leaving the engine is significant at a 1% probability level.

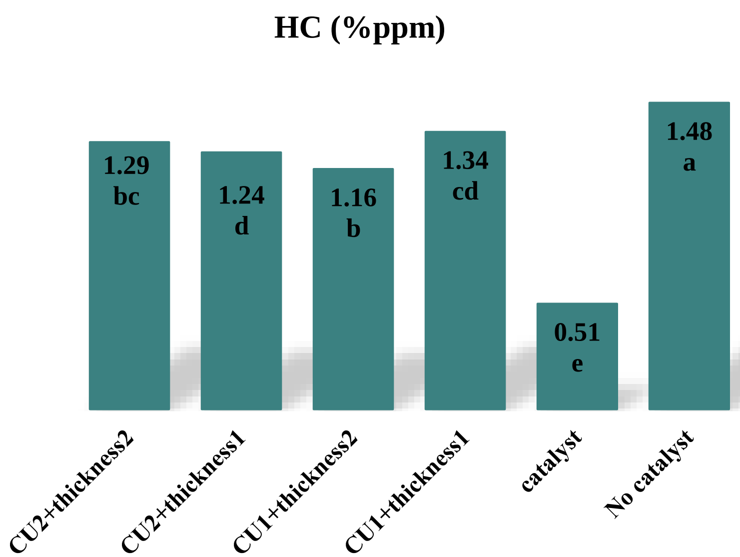

Figure 7. HC Gas Emission Levels for XU7 Engine

Analysis of CO_2 Emission

Carbon dioxide (CO_2) is an odorless, colorless gas with an extremely sour taste, part of the atmosphere with a chemical formula of CO_2, a molecular weight of 44.01 g/mol, a melting point of -54°C, and a boiling point of -78°C. This gas is produced when organic material burns in the presence of sufficient oxygen.

Figure 8 compares the average volume percentage of CO pollutant concentration from the XU7 engine's exhaust with different types of catalysts, both with and without catalysts. With the exception of the absence of a catalyst, the data indicates that the XU7 engine produces carbon dioxide below the legal limit (less than 14%). Carbon dioxide, being odorless and colorless, affects the environment, and its excessive increase is linked to the issue of greenhouse gases and the global warming crisis.

The results indicate a significant difference between the average treatments with a 99%

confidence level, suggesting that the effect of the CO2 factor on the amount of gas output from the engine is significant at a 1% probability level.

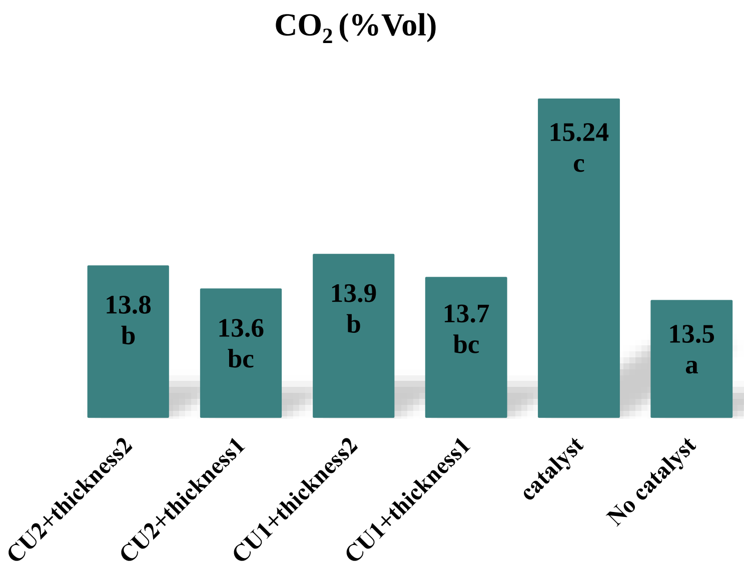

Figure 8. CO_2 Gas Emission Levels for XU7 Engine

According to the combustion reaction of gasoline, all oxidation reactions produce CO_2 gas, contributing to its elevation. The results presented in Figure 6 indicate that in the absence of a catalyst, the gas rise was 0.0019 grams per catalyst, assuming that the copper-biochar catalyst increased the gas amount to 0.0025 grams per catalyst.

Combustion Reaction:

$2C_8H_{18}+28O_2 \rightarrow 4CO+4CO_2+8HC+14H_2O+15O2$

Due to the inherent and well-defined porosity of porous materials, CO_2 can be absorbed into them. These compounds, with their special qualities and the presence of copper metal on their surface, demonstrated excellent results in absorbing CO2 (López-Olvera et al., 2017).

Analysis of NOx Emission:

Nitrogen oxide (NOx) is one of the most significant air pollutants generated during combustion reactions at high temperatures. Nitrogen oxides, including nitric oxide (NO) and nitrogen dioxide (NO2), are produced during combustion processes due to the conversion of nitrogen in the fuel structure and atmospheric nitrogen under specific reaction conditions (high heat and high oxygen). While colorless and odorless when exiting the engine, nitrogen oxides transform into higher-grade oxides with a reddish-brown color and pungent smell upon reaching the atmosphere and combining with more oxygen. Inhaled, it damages the respiratory system, and when combined with water vapor, it forms nitric acid, causing harm to the trachea and lungs (Kumar et al., 2014).

Figure 7 shows the average nitrogen oxide (NOx) emission from the XU7 engine's exhaust, comparing different types of catalysts, with and without catalysts. The results indicate that the XU7 engine produces NOx below the legally allowed limit (less than 50 ppm). The findings suggest little effect of the NOx gas component on engine gas output.

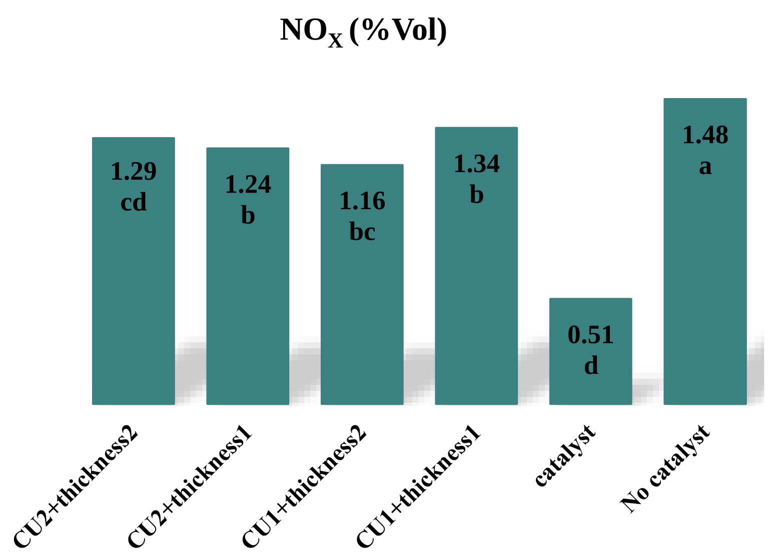

Figure 9. NO_x Gas Emission Levels for XU7 Engine

Among the recognized solid adsorbents, carbonaceous materials, particularly biochar, emerge as environmentally favorable sorbents. Biochar is specifically produced through the inert process of biomass pyrolysis, with its precursor derived from urban and agricultural waste, abundantly generated worldwide. Due to its high yield and adaptability, biochar has found applications in various fields, including soil amendment and NO_x capture (Zhang & Duan, 2022).

Analysis of O_2 Emission:

The average volume of oxygen gas concentration in the exhaust of the XU7 engine is compared in Figure 10, considering different types of catalysts, both with and without catalysts. Less than 3% of the oxygen produced by the XU7 engine is emitted, falling below the standard limit. It is crucial to emphasize that the emission of this O_2 gas does not pose a threat to any life forms.

The results indicate a substantial difference between the average treatments with a 99% confidence level, suggesting that the effect of the O_2 gas component is significant at the 1% probability level on the amount of gas production from the engine.

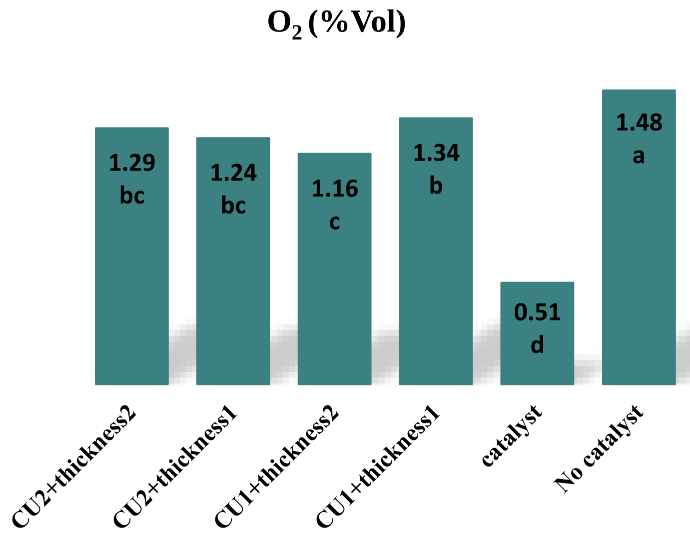

Figure 10. O_2 Gas Emission Levels for XU7 Engine

CONCLUSION

In this study, the emissions of pollutants from the XU7 engine were measured for four types of catalysts, including catalysts with different thicknesses (1 mmol 1, 1 mmol 2, 2 mmol 1, and 2 mmol 2), without a catalyst, and with the catalyst. The pollutant levels were investigated and compared against the Euro 4 standard. The reduction in CO and HC pollution emissions with the use of copper catalyst immobilized on biochar indicates the catalyst's role in oxidizing carbon monoxide to carbon dioxide and promoting the reaction of hydrocarbons with oxygen.

The addition of stabilized manganese catalysts to biochar resulted in nitrogen oxide emissions below the allowable limit, and copper oxides also contributed to the reduction of nitrogen oxides. Catalysts play a crucial role in oxidation and reduction reactions in chemical processes. The primary substrate, biochar, facilitated the oxidation process by burning oxygen, while the metal (Cu) played a role in reducing carbon monoxide pollutants.

Based on the study's findings, it can be concluded that implementing the described methods and adhering to existing standards can effectively reduce greenhouse gas emissions from combustion and extend the life of engines.

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