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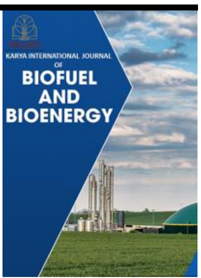

Evaluation of Catalytic Converter Utilization in Biomass Combustion Flue Gas Treatment

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ABSTRACT

Agriculture contributes to 17% of the world GHG emissions, with sugarcane plantations contributing approximately 11% of the total emissions from the agricultural sector. Bagasse, a biodegradable waste generated from sugar production, has potential as a biomass fuel. Biomass has gained attention as a renewable energy source due to its sustainability and availability. However, optimizing combustion efficiency while minimizing emissions remains a challenge. This research investigates the effects of a catalytic converter from a gasoline engine and excess air on particulate emissions from bagasse combustion in a fixed grate furnace. The primary objective is to determine the optimal combustion configuration that minimizes particulate emissions while maintaining high combustion efficiency. The study was done experimentally by varying excess air percentage combined with a catalytic converter. Temperature, PM_{10}, CO, and CO_2 emissions were measured to explain the effects of a catalytic converter and excess air. The results indicate that the catalytic converter effectively reduces CO emissions by enhancing oxidation, thus converting CO into CO_2, while significantly reducing PM_{10} concentrations. Excess air improves the combustion and also oxidation process in the catalytic converter, but it does not have a significant impact on reducing PM. The combination of catalytic converter with 100% excess air produced optimal results in terms of lowest PM concentration and highest CO_2 levels. This study highlights the advantages of a catalytic converter combined with excess air in improving combustion efficiency and reducing emissions. The findings provide valuable insights into cleaner biomass combustion technologies, contributing to the development of sustainable and environmentally friendly energy solutions for future applications.

1. Introduction

Indonesia's energy demand across every sector is expected to increase over time [1]. Due to the rising of energy demand, alternative energy sources are essential to ensure a reliable and sustainable

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energy supply. Renewable energy offers a feasible solution, not only to meet energy demand but also to reduce dependence on fossil fuels.

The increasing energy demand also correlates with rising greenhouse gas emissions and increased levels of particulate matter (PM), contributing to air pollution [2]. Air pollution occurs when harmful chemicals or particulate matter are present in the air, posing risks to human and animal health while also disrupting natural ecosystems [3]. There is a correlation between air pollution and the occurrence of respiratory and cardiovascular diseases. Research on the impact of air pollution on human health indicates that the risk of mortality increases with exposure to smaller particles compared to larger ones. Smaller air pollution particles have a higher likelihood of entering the respiratory system and interacting with lung cells, potentially leading to lung diseases caused by inflammation [4].

World Health Organization (WHO) has established Air Quality Guidelines (AQG) to protect human health. It recommends a safe limit for $PM_{2.5}$ of 5 µg/m³. However, in Yogyakarta, Indonesia, the $PM_{2.5}$ concentration exceeds the recommended limit, reaching approximately 31 µg/m³ [5]. This situation highlights the urgent need for more serious efforts to reduce air pollution in Indonesia to meet AQG standards and create a cleaner and healthier environment.

Biomass is a form of renewable energy with significant potential in Indonesia due to its abundant availability and can serve as a viable solution for sustainable energy needs and also to reduce air pollution. One type of biomass that can be utilized is waste from the agricultural sector, particularly plant-based residues. Agriculture contributes to 17% of the world GHG emissions, with sugarcane plantations contributing approximately 11% of the total emissions from the agricultural sector [6]. Sugarcane plantations are one of the sectors that can be utilized as a biomass energy source due to their high production availability. According to the Central Bureau of Statistics of Indonesia [7], the total area of sugarcane plantations in Indonesia reached 490.01 thousand hectares in 2022. Sugarcane production itself amounted to 2.34 million tons in the same year, with an average annual growth rate of 2.08% [8]. Bagasse, a biodegradable waste generated from sugar production, has potential as a biomass fuel.

In biomass processing and combustion, understanding key combustion parameters and methods is crucial to achieving optimal efficiency while minimizing emissions. Previous studies have investigated the effects of catalytic converters on biomass combustion. Research by Bindig *et al.*, [9] found that the use of catalytic converter can reduce the carbon monoxide (CO) emissions for up to 92.6%. Other studies have demonstrated a high potential for emission reduction through the use of catalytic converters, achieving conversion rates of over 95% for CO, 60% for gaseous organic compounds (OGC), and approximately 30% for particulate matter (PM) [10]. Additionally, Bensaid *et al.*, [11] demonstrated that the use of catalytic converters can reduce PM concentrations by an average of more than 90%.

Other methods that have been studied to reduce emissions include adding excess air. For liquid and solid fuels, a greater amount of excess air is generally required. Although excess air is necessary, it can lead to fuel wastage. This occurs because the additional air absorbs heat from the combustion process and carries it away through the exhaust, effectively cooling the system. The more air supplied, the greater the cooling effect, which can reduce combustion efficiency and overall performance [12]. Therefore, optimizing excess air usage is one of the simplest and most effective ways to achieve significant fuel savings. A study by Prakoso [13] found that the optimal excess air percentage for bagasse combustion is 100%, as excessive excess air can lead to incomplete combustion.

Several studies have examined the effects of excess air on biomass combustion. Additionally, research has explored the use of catalytic converters to reduce combustion emissions. However, the combination of these two approaches has not been widely studied. This study bridges the gap by experimentally validating how excess air optimizes oxygen distribution to enhance the oxidation process within the catalytic converter, leading to improved CO and PM reduction. By integrating these two emission control strategies, the findings of this research are expected to serve as a reference for achieving optimal, clean, and environmentally friendly biomass combustion conditions. Furthermore, this study aims to enhance public awareness of biomass as a viable renewable energy source.

2. Methodology

2.1 Fuel

This study utilizes bagasse as fuel. Proximate and ultimate analysis was conducted to determine its composition, as shown in Table 1. The bagasse used in this study was provided by local bagasse producer. Before combustion and introduction into the combustion chamber, the bagasse undergoes a pretreatment process, including drying to reduce its moisture content. Each biomass sample was dried under direct sunlight for about 8 hours to reduce its moisture content. Lowering moisture is essential, as excessive levels can hinder efficient combustion. Additionally, the biomass was shredded using a chopper to decrease its size, ensuring it fits the combustion chamber’s capacity.

Table 1
Proximate and ultimate analysis of bagasse

Parameter	Unit	Results	Method
Total Moisture	%, ar	11,5	ASTM D 3302 - 17
Proximate Analysis			
Moisture in Analysis	%, adb	7,6	SNI 8951-2020
Ash Content	%, adb	1,6	SNI 8951-2020
Volatile Matter	%, adb	79,7	SNI 8951-2020
Fixed Carbon	%, adb	11,1	SNI 8951-2020
Total Sulfur	%, adb	0,20	SNI 8951-2020
Gross Calorific Value	Kcal/kg, adb	4140	SNI 8951-2020
Gross Calorific Value	Kcal/kg, ar	3965	SNI 8951-2020
Ultimate Analysis			
Carbon (C)	%, adb	43,62	ASTM D 5373 - 16
Hidrogem (H)	%, adb	6,26	ASTM D 5373 – 16
Nitrogen (N)	%, adb	0,31	ASTM D 5373 – 16
Oksigen (O)	%, adb	48,01	ASTM D 5373 - 16

2.2 Catalytic Converter

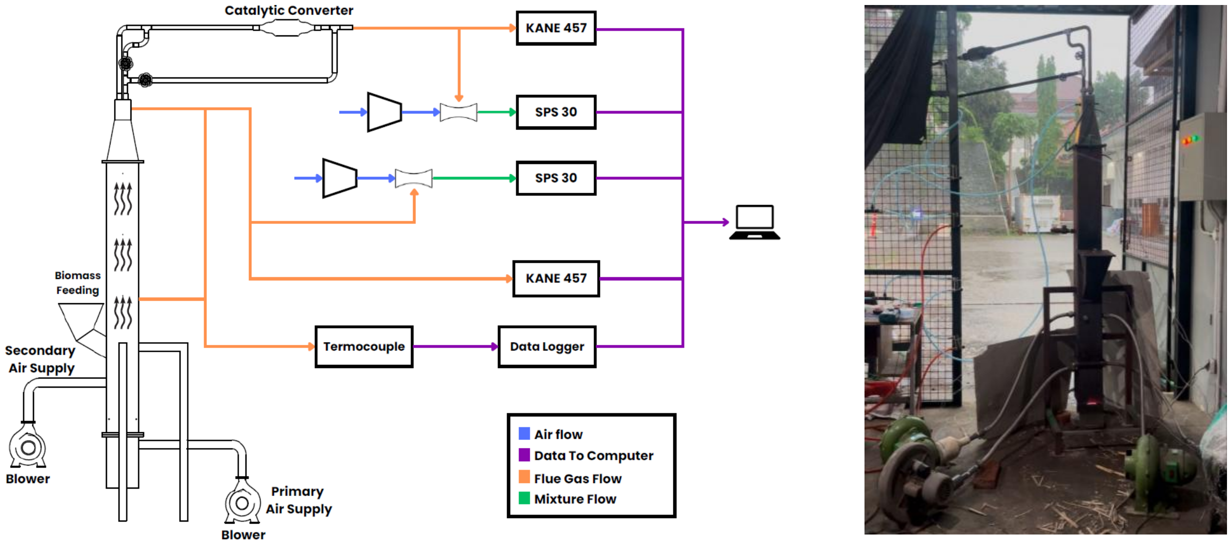
The monolithic catalytic converter is an emission control device used in exhaust systems to reduce harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx). This device utilizes oxidation and reduction reactions to convert pollutants into less harmful substances [14]. The term "monolith" refers to a cylindrical honeycomb structure made of ceramic material, coated with catalytic substances such as platinum, palladium, or rhodium. This structure provides a large surface area, allowing for maximum contact between exhaust gases and the catalyst. This study utilizes a modified catalytic converter from a gasoline vehicle.

2.3 Experimental Method

2.3.1 Furnace

This study utilizes fixed grate furnace. This furnace is specifically designed and constructed to support controlled combustion experiments, with a particular focus on achieving close burning conditions, as shown in Figure 1. The furnace has dimensions of 150 mm × 150 mm × 200 mm (W × L × H) and features a dual-layer construction, with an internal stainless steel layer and an external mild steel layer. The lower section and chimney are entirely stainless steel, optimizing flue gas flow and temperature control. Biomass is loaded through a hopper onto a fixed grate that facilitates ash removal. The furnace has two air supply zones, a primary zone with two opposing holes and a secondary zone with two opposing holes, ensuring turbulent airflow. Airflow is regulated via flexible stainless steel hoses connected to a blower, with the air velocity controlled by a single-phase dimmer adjusting the blower's speed.

To enable real-time monitoring of combustion parameters, various sensors are integrated into the design. Temperature measurements are taken using Type K thermocouples positioned at two different heights, one 30 cm above the grate and the other one 5 cm from the top of chimney. Carbon dioxide levels are analyzed using a Kane 457 gas analyzer, while particulate matter (PM) concentration is measured through a Sensirion SPS30 PM sensor with a venturi vacuum system ensuring accurate readings. CO_2 and PM data is collected and processed by an Arduino UNO microcontroller while temperature readings by Omron ZR-RX45, facilitating precise data acquisition and analysis.



(a) (b)

Fig. 1. (a) Schematic view (b) Real picture of experimental setup

2.3.2 Method

The close burning methodology for this study follows previous research by Nugraha *et al.*, [15]. During close-burning combustion, multiple phases were observed. Initially, the furnace was preheated using an LPG stove at the bottom to reach the required operating temperature. Next, 250 g of biomass was loaded in two loading cycles to accelerate combustion. Data recording began by identifying the unsteady phase until a stable temperature was reached, after that all sensors were activated. Six loading cycles with 3 minutes reloading time interval were performed before cooling, which involved stopping biomass input while keeping the blower running. Excess air levels were adjusted by varying the air velocity from 6.28 m/s (50%) and 8.37 m/s (100%). The experimental design is shown in Table 2.

In this study, the catalytic converter consists of three configuration variations. The first is the full catalytic converter setup, where all flue gas flows entirely through the converter. The second is the bypass configuration, where the flue gas flow is a mix of pathways with and without the catalytic converter. The third configuration excludes the catalytic converter, directing the flue gas entirely through a non-catalytic pathway.

This study also utilizes gas chromatography (GC) to validate the data obtained from sensors during experiments. GC enables the measurement of gas concentrations, including CO, CO_2, CH_4, and H_2, ensuring the accuracy of the collected data.

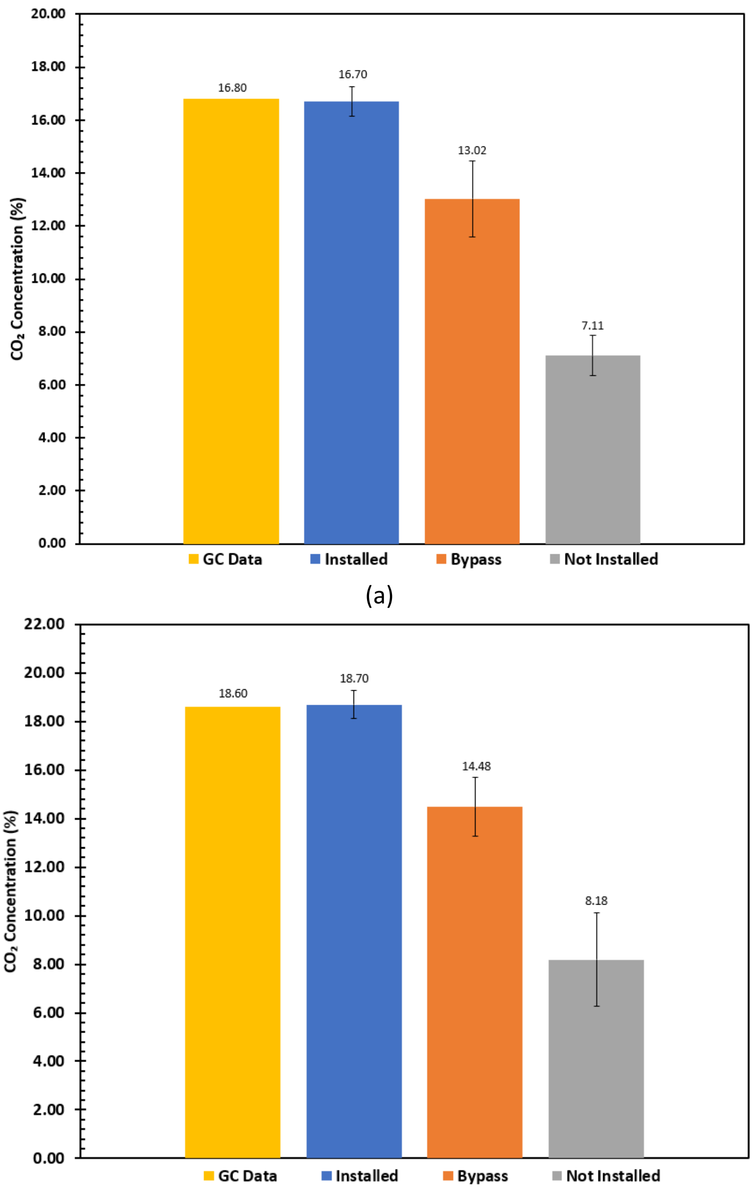
To maintain experimental accuracy, the effects of atmospheric temperature and humidity were minimized by conducting tests during clear daytime conditions. The recorded average air temperature was approximately 30°C, while humidity levels ranging between 60% and 75%.

Table 2
Experimental design

Experiment ID	Catalytic converter	Excess air, (%)
X1	Installed (full flow)	50
X2	Bypass (partial flow)	50
X3	Not installed	50
X4	Installed (full flow)	100
X5	Bypass (partial flow)	100
X6	Not installed	100

2.3.3 Validation

The validation of the experimental data in this study was conducted using Gas Chromatography (GC), a widely recognized analytical technique for accurately measuring gas concentrations. GC was utilized to verify the levels of CO_2 in the exhaust gas, ensuring the reliability of sensor-based measurements. This approach enhances the credibility of the results by cross-checking sensor data with a high-precision laboratory method. The data obtained from GC analysis, comparing the measured concentrations under different experimental conditions show in Figure 2.



(b)

Fig. 2. (a) Average CO_2 concentration for 50% excess air (b) Average CO_2 concentration for 100% excess air

3. Results

3.1 Temperature Analysis

A temperature analysis was conducted to evaluate the impact of excess air on combustion conditions. Temperature measurements in this study were conducted using two thermocouples placed at different locations: one positioned 25 cm above the grate to represent the combustion chamber temperature and another located 8 cm from the chimney outlet. A comparison of the average temperature distribution in the combustion chamber and chimney is presented in Figure 3, while the average recorded temperature data is shown in Figure 4.

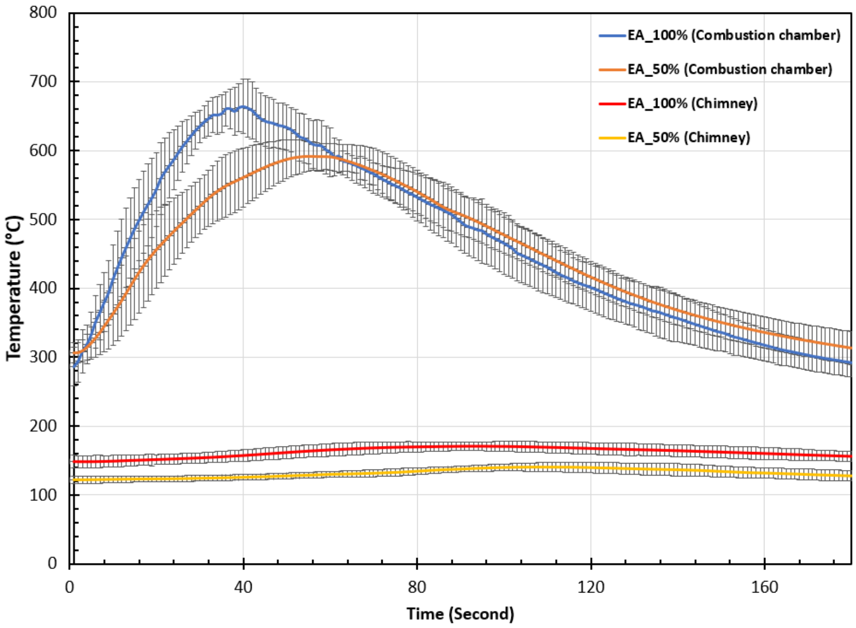


Fig. 3. Comparison of temperature distribution of combustion chamber and chimney

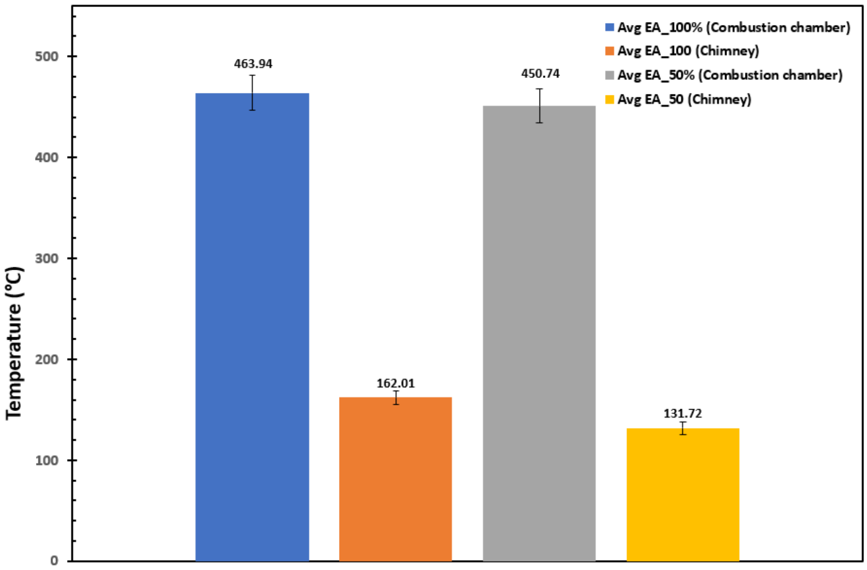


Fig. 4. Average temperature data

Based on the temperature distribution graph, an increase in excess air supply accelerates the combustion process, as indicated by the shorter time required to reach peak temperature. The average temperature in the chimney is assumed to represent the operating temperature of the catalytic converter. Study by Jamilatun *et al.*, [16] found that a higher pyrolysis temperature leads to an increased conversion rate.

3.2 CO_2 Percentage Analysis

The concentration of CO_2 in combustion is a key indicator of combustion efficiency. The percentage of CO_2 can also serve as a parameter for evaluating the effectiveness of oxidation reactions occurring within the catalytic converter. The summary of the average CO_2 percentage comparison is presented in Table 3.

Table 3
Average temperature and gas concentrations at various combustion conditions

Experiment ID	Grate, (°C)	Chimney, (°C)	CO_2, (%)
X_1	450.74 ± 16.76	131.72 ± 5.95	16.70 ± 0.56
X_2	450.74 ± 16.76	131.72 ± 5.95	13.02 ± 1.43
X_3	450.74 ± 16.76	131.72 ± 5.95	7.11 ± 0.76
X_4	463.94 ± 17.42	162.01 ± 6.87	18.70 ± 0.58
X_5	463.94 ± 17.42	162.01 ± 6.87	14.48 ± 1.21
X_6	463.94 ± 17.42	162.01 ± 6.87	8.18 ± 1.93

The results indicate that the catalytic converter functions effectively, as evidenced by the increase in CO_2 levels after its installation. This increase demonstrates a reduction in CO concentration due to oxidation reactions occurring within the converter. The results indicate that the fully installed catalytic converter, where all flue gas flows through, is the most effective configuration for increasing CO_2 levels while reducing CO emissions. The usage of this configuration can increase CO2 levels by up to approximately 234%, indicating a significant improvement in the oxidation process within the catalytic converter. Study by Reichert *et al.,* [10] found that catalytic converter can convert over 95% of CO into CO_2, highlighting their high efficiency in reducing CO emissions. Additionally, the catalytic converter performs more effectively when sufficient oxygen is available, enhancing CO oxidation [17].

3.3 PM_{10} Concentration Analysis

In this study, PM_{10} was used for comparison as it includes particles smaller than 10 µm, encompassing PM_1, $PM_{2.5}$, and PM_4. The catalytic converter effectively reduced PM_{10} concentrations, with no significant difference between the full and bypass configurations. Experimental results showed that the catalytic converter reduced PM concentration by an average of 98%, demonstrating its efficiency in minimizing particulate emissions. Although excess air slightly reduces PM_{10} concentrations after passing through the catalytic converter, the effect is not significant. Instead, higher excess air increases the emission factor due to the greater exhaust gas volume, which disperses particles but does not reduce the total PM_{10} mass. The results are summarized in Table 4.

Table 4
Average concentration of PM and its corresponding emission factor

Experiment ID	PM_{10} concentration in milligrams per cubic meter, (mg/m3)	Emission factor
X_1	2.82 ± 0.15	0.0094 ± 0.0023
X_2	2.84 ± 0.15	0.0095 ± 0.0032
X_3	270.22 ± 19.87	0.9025 ± 0.2108
X_4	2.69 ± 0.49	0.0120 ± 0.0027
X_5	2.98 ± 0.44	0.0133 ± 0.0034
X_6	157.30 ± 65.23	0.7002 ± 0.3231

Study by Bensaid *et al*., [11] found that catalytic converter able to reduce over 90% of PM emissions. The reduction in PM occurs due to the concentration gradient of CO and CO_2 in the exhaust gas, resulting from the catalytic conversion process. This gradient leads to increased particle deposition on the catalyst surface, effectively lowering PM emissions [10]. The effectiveness of the catalytic converter is also reflected in the emission factor, where the full catalytic converter configuration achieves the lowest values.

4. Conclusions

This study demonstrates the effectiveness of a catalytic converter and excess air variation in optimizing bagasse combustion. The catalytic converter significantly reduced CO and PM_{10} emissions, achieving an average PM reduction of 98%. While excess air enhances oxidation and combustion efficiency, it has a minimal effect on PM reduction and can increase the emission factor due to a higher exhaust gas volume.

Among the tested configurations, the configuration with 100% excess air with catalytic converter provided the best results, yielding the highest CO_2 levels, the lowest PM_{10} concentration, and the most stable combustion temperatures. This configuration ensured optimal oxygen distribution, enhancing both combustion efficiency and catalytic conversion performance.

These findings highlight the potential of integrating catalytic conversion and excess air to improve biomass combustion technologies. Implementing this approach in industrial-scale biomass combustion systems could contribute to reducing air pollution and increasing the sustainability of biomass as a renewable energy source.

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