Global J. Environ. Sci. Manage. 10(3): 1047-1066, Summer 2024, Serial #39

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Particulate matter emission in agricultural biomass residue combustion

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ARTICLE INFO

Article History:
Received ***
Revised ***
Accepted ***

Keywords:
Agricultural residue
Air quality
Biomass combustion
Emission factor
Open burning
Particulate matter

DOI: 10.22034/gjesm.2024.03.08

ABSTRACT

BACKGROUND AND OBJECTIVES: Agriculture significantly contributes to global economies, yet it concurrently generates waste in the form of crop residues. Conventional waste disposal methods, such as open burning, contribute to atmospheric particulate emissions, impacting air quality regionally and potentially globally. Exposure to these pollutants poses substantial risks to human health, including respiratory illnesses, cardiovascular diseases, and premature mortality. This study aims to assess the environmental implications of biomass waste combustion in Yogyakarta, Indonesia. Additionally, the study aims to investigate potential enhancements in biomass burning practices through experimental campaigns conducted in both open and closed burning conditions.

METHODS: The study evaluates Yogyakarta's regional air quality using data from the Meteorology, Climatology, and Geophysical Agency for the period spanning from 2020 to 2022. Emission factors from open and closed burning practices are assessed using an experimental furnace equipped with real-time combustion parameters monitoring, including temperature, particulate matter concentration, and oxygen and carbon dioxide levels. The openburning experiments involve various combustion conditions for bagasse, leaf litter, and rice straw, encompassing variations in ignition location, initial mass, and air supply methods. Closed burning experiments explore variations in reloading frequency, air-fuel ratio, and air staging.

FINDINGS: Yogyakarta's air quality assessment involves comparing rice harvest trends with atmospheric particulate matter concentrations during 2020-2022. Open burning practices in Yogyakarta exhibit a correlation with heightened rainfall, which in turn leads to higher emissions from April to August due to reduced rain frequency. Experimental campaigns have revealed that open burning practices result in a significant amount of emissions, ranging from 3 to 29 grams of particulate matter per kilogram of biomass.. Meanwhile, the utilization of closed combustion systems has been demonstrated to decrease the emission factor within the range of 0.37 to 1.98 grams of particulate matter per kilogram of biomass. This highlights the importance of operating conditions altering particulate emissions. Moreover, the emission reduction by factor nine, emphasizing the efficacy of controlled combustion techniques in comparison to open burning methods, in mitigating particulate emissions.

CONCLUSION: The study identifies that greater initial biomass mass, mid-ignition, and natural airflow contribute to lower emissions in open burning practices. o achieve optimal closed combustion conditions, it is recommended to reload biomass more frequently with100 percent excess air allocation, distributing 30 percent to primary air and 70 percent to secondary air. These findings not only propose better practices for disposing of agricultural waste and minimizing air pollution but also emphasize the potential of utilizing biomass waste for energy conversion.

NUMBER OF REFERENCES
37

NUMBER OF FIGURES
8

NUMBER OF TABLES
6

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Note: Discussion period for this manuscript open until October 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Agriculture serves as the backbone for economies worldwide, , yet it is also a significant generator of waste in the form of crop residues. Traditional methods of agricultural waste disposal, particularly open burning, are facing growing scrutiny due to their negative environmental consequences (Adejumo *et al.,* 2020). These practices significantly contribute to atmospheric particulate emissions, affecting air quality on a regional and potentially global scale. Public health concerns are also part of the broader consequences of open burning, going beyond just environmental impacts. (Bhuvaneshwari *et al.,* 2019). Numerous studies have elaborated on the harmful constituents of smoke produced by biomass combustion, including volatile organic compounds, carbon monoxide (CO), nitrogen oxide (NOx), sulphur oxide (SOx) (Williams *et al.,* 2012) and a range of fine and ultrafine particulate matter (Panessa-Warren *et al.,* 2022). Exposure to such pollutants presents a significant threat to human well-being, resulting in respiratory ailments, cardiovascular disorders, and in severe instances, untimely mortality. (Sigsgaard *et al.,* 2015). The global scale of agricultural activities necessitates a comprehensive understanding of emission profiles during harvesting periods. Harvest seasons, often accompanied by the combustion of agricultural residues, have been correlated with elevated levels of particulate matter and greenhouse gases in various regions worldwide (Amnuaylojaroen and Parasin, 2023). Studies conducted in China illustrate a significant rise in pollutants during these periods, which alligns with findings from this study (Zhuang *et al.,* 2018). For example, the researchers have noted a 30 percent (%) increase in regional particulate matter (PM) levels during rice straw burning post-harvest. Among the range of pollutants emitted during the combustion of biomass, PM is one of the most concerning pollutants due to their direct and measurable impact on human health and environmental quality (Kouao *et al.,* 2019). Particulate matter, especially fine particulate matter ($PM_{2.5}$) and particulate matter (PM_{10}), constitutes another major byproduct of biomass combustion. These fine particles can penetrate deeply into the respiratory system, causing various health issues such as asthma and cardiovascular diseases. (Bai *et al.,* 2015). Recent studies have even linked high exposure to $PM_{2.5}$ with increased mortality rates due to respiratory and heart diseases (Taylor *et al.,* 2022). The environmental repercussions are equally alarming, as these emissions contribute to atmospheric brown clouds, a type of air pollution that not only has local effects but also influences regional climate patterns (Chen *et al.,* 2017). Moreover, these emissions are a significant source of greenhouse gases, contributing to global warming and climate change (Laborde *et al.,* 2021). It is of utmost importance to comprehend the severity of these harmful substances and grasp their emission traits, dispersal patterns, and ultimate destiny in order to effectively address public health concerns and preserve the environment. This study aims to assess the potential impact of biomass burning on air quality in the Yogyakarta area during both the dry and harvest seasons. Despite agriculture's prominence as the primary source of income for a significant populace in the region, the prevalence of open-burning techniques for biomass waste disposal exacerbates the degradation of local air quality (Mendez-Espinosa *et al.,* 2019). The COVID-19 pandemic period also gives opportunity to evaluate the air quality impact due to agricultural practices when other antrophogenic emission sources was decreased due to human mobility reduction (Robinah *et.al.,* 2021). The formation of PM in solid fuel combustion is considered as complex phenomena (Sippula *et al.,* 2007). In general, the PM emission level is determined by the fuel characteristics (chemical composition and size distribution) (Trubetskaya *et al.,* 2020) and the combustion conditions (Koppejan and Loo, 2012). The lignin composition in biomass is responsible for PM formation due to lignin conversion into PM precursors i.e., acetylene (Deng *et al.,* 2020). The combustion conditions which affected PM formation is linked to biomass combustion phases: drying, pyrolysis, and oxidation. PM formation is associated with pyrolysis, in which thermal decomposition occurs and volatile components release to the gas phase which can initiate chain reactions to PM formation and decomposition simultaneously (Farzad *et al.,* 2016). Factors such as temperature fluctuations, oxygen availability, and the heterogeneous nature of the biomass itself play a pivotal role in the level of emissions (Nugraha *et al.,* 2021). It is crucial to optimize turbulence, time, and temperature, the three key factors in combustion, in order to minimize the negative environmental effects of biomass combustion.. Turbulence ensures that oxygen is evenly distributed, facilitating complete combustion and lowering emissions (Nugraha *et al.,* 2021). Time, or residence time, determines how long biomass remains exposed to combustion conditions, with longer times typically resulting in reduced pollutant formation. Temperature is also critical; while elevated temperatures facilitate complete oxidation, they also risk forming nitrogen oxides, another class of pollutants (Koppejan and Loo, 2012). Evaluation of PM emissions level in open burning practices has been summarized by previous study (Andreae, 2019), which involve nine different biomass, including agricultural residues. More specific and detailed evaluation regarding of PM characteristics in rice straw open burning has been also provided by another research (Oanh *et al.,* 2011). However, fluctuations in PM levels during open burning are anticipated as a result of variances in turbulence, time, and temperature conditions. In practice, these three factors are evident through variations in the initial moisture content of biomass, biomass loading, burning duration, and weather conditions such as wind speed. (Oanh *et al.,* 2011). There are no efforts recorded to evaluate the influence of these variation to the final PM emissions. There is a pressing need for more advanced controlled waste treatment methods to mitigate the elevated emissions associated with biomass combustion. Closed combustion systems, such as biomass furnace, offer a promising option in this regard, since it can be utilized further for energy conversion (Hidayat *et al.,* 2024). Extensive regulation of the combustion system has been scientifically proven to significantly reduce the emission levels in comparison to the uncontrolled burning methods. This can be evaluated from two different studies in rice straw burning which reported emission factor (EF) about 1.1 grams particulate per kilogram of fuel (g PM/kg fuel) in a drop tube furnace system (Migo-Sumagang *et al.,* 2020) compared to up to 20 g PM/kg fuel in open burning condition (Oanh *et al.,* 2011). In a closed combustion systems, airflow into the combustion chamber can be precisely regulated to align with theoretical combustion models. Moreover, closed combustion systems typically feature primary and secondary combustion zones (air stagging). This enchances the potential to achieve optimal conditions in terms of temperature, time, and turbulence for complete combustion (Jiang *et al.,* 2024). Each biomass type has its own unique set of combustion conditions that result from variations in chemical and physical composition. The adjustment of certain combustion conditions, such as the air fuel ratio and air staging, has been shown to have a significant impact on combustion behavior and the release of particulate emissions (Houshfar *et.al.,* 2011). Based on the aforementioned gaps found in the literature review, this study is designed to uncover the environmental effects of disposing biomass waste, primarily through open burning methods and its consequences to one of harmful component concentration in Yogyakarta air, i.e., particulate matter. The lab-scale experimental campaign is also designed to offers practical recommendations for minimizing emissions of particulate matter generated during biomass combustion processes both in open and closed burning practices. The agricultural residues that used in the current study, i.e., rice straw, bagasse, and leaf litter, are obtained to be disposed frequently in open burning by the farmer after harvest periods. The most optimum combustion conditions identified in this study can be implemented in industrial furnaces e.g., cofiring applications in power plants. These significant findings can assist industrial communities in promoting the use of agricultural biomass waste as a viable energy source. his study comprised three sub-parts of operational conditioning aimed at determining combustion characteristics resulting in minimal emissions. These sub-parts included variations in reloading time, the application of excess air as the combustion air supply, and the utilization of different air staging methods, consisting of primary and secondary zones. This study was conducted in the Energy Conversion Laboratory, Mechanical and Industrial Engineering Department, Universitas Gadjah Mada, Indonesia, during 2023–2024.

MATERIALS AND METHODS

The current study include the evaluation of Yogyakarta's air quality profile which utilized secondary data collected from governmental agencies reports. To enhance comprehension regarding the impact of biomass burning practices on atmospheric particulate concentrations, additional experimental campaigns were conducted to examine both open and closed burning scenarios. Various combustion conditions were tested to investigate the correlation between operating conditions and emission levels.

Data acquisition for local emission profile in Yogyakarta

Yogyakarta, located at 110.334° E longitude and 7.875° N latitude on Java Island, Indonesia, covers an area of 3170.65 square kilometers (km^2) or 12.55 square miles (mi^2) (Wulandari *et al.,* 2021) as presented in Fig. 1. The city had a population of approximately 434,000 as of the 2020 census, with a density of 13,354 people per km^2. Administratively, the city is divided into 14 districts and, comprises 45 urban villages (Zein *et al.,* 2020).

This study utilized daily rainfall data from the Meteorology, Climatology, and Geophysical Agency (BMKG) of Indonesia. The BMKG collects information using a network of ombrometers (rain gauges) that operate continuously (Yudhana *et al.,* 2019). These gauges capture rainfall, which is recorded either manually or automatically. All collected data underwent quality assurance checks by the BMKG before their inclusion in the study. For $PM_{2.5}$ data, this study employed the Continuous Ambient Particulate Monitor, specifically the Model 5014i, from ThermoScientific-USA (Intra *et al.,* 2018). This model operates on the principle of particle measuring method for real-time, continuous monitoring of $PM_{2.5}$ concentrations in ambient air. A flow of ambient air is directed into the instrument, where $PM_{2.5}$ particles are isolated and collected on a glass-fiber filter tape. The mass of these particles is then determined using a beta ray source and detector within the instrument. The Model 5014i records data at 10-minute intervals, thereby providing highly granular, real-time information. After validation and processing, the gathered $PM_{2.5}$ and rainfall data were utilized to analyze the correlations and environmental patterns in Yogyakarta for the 2020-2022 period. Due to the limitations of the monitoring equipment available at BMKG Yogyakarta, the measurement of other critical air pollutants such as NOx, SOx, and CO was not possible to be included in the current study.

Open burning experiment

Detailed construction information on open burning furnace, as depicted in Fig. 2**.**, has been described in previous research (Nugraha *et al.,* 2023). This type of furnace is designed to facilitate open burning

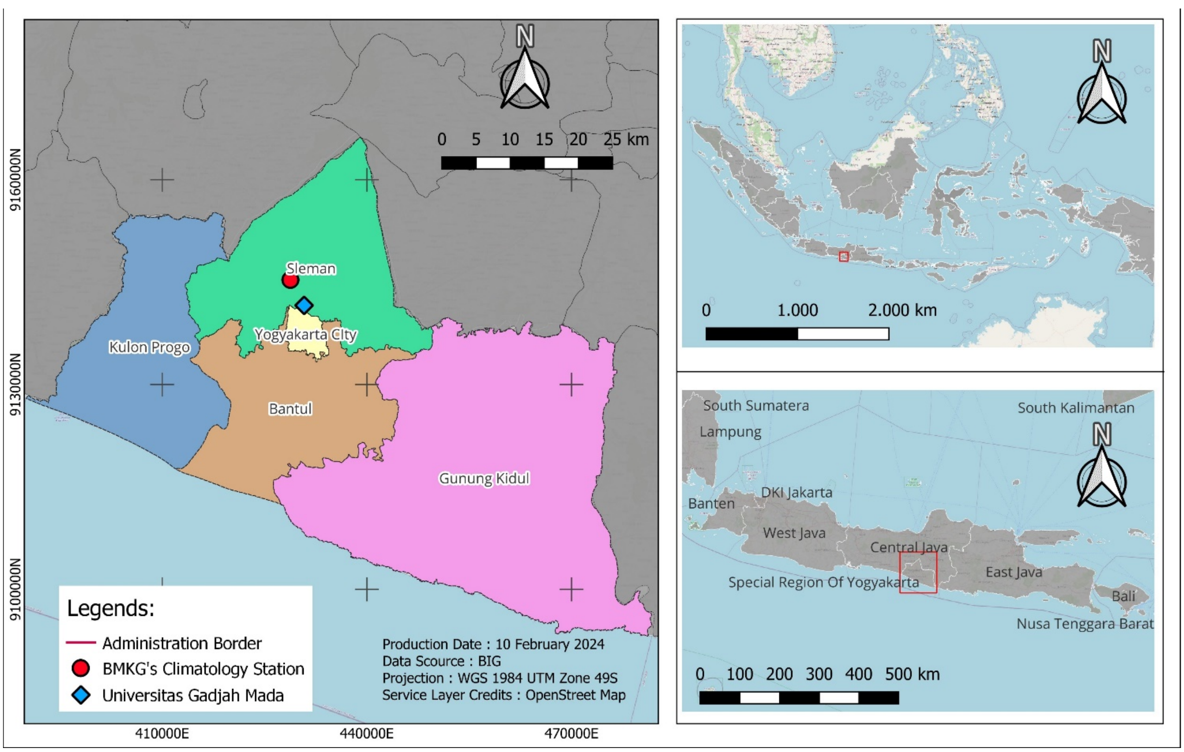

Fig. 1: Geographical location of study area of Yogyakarta, Indonesia

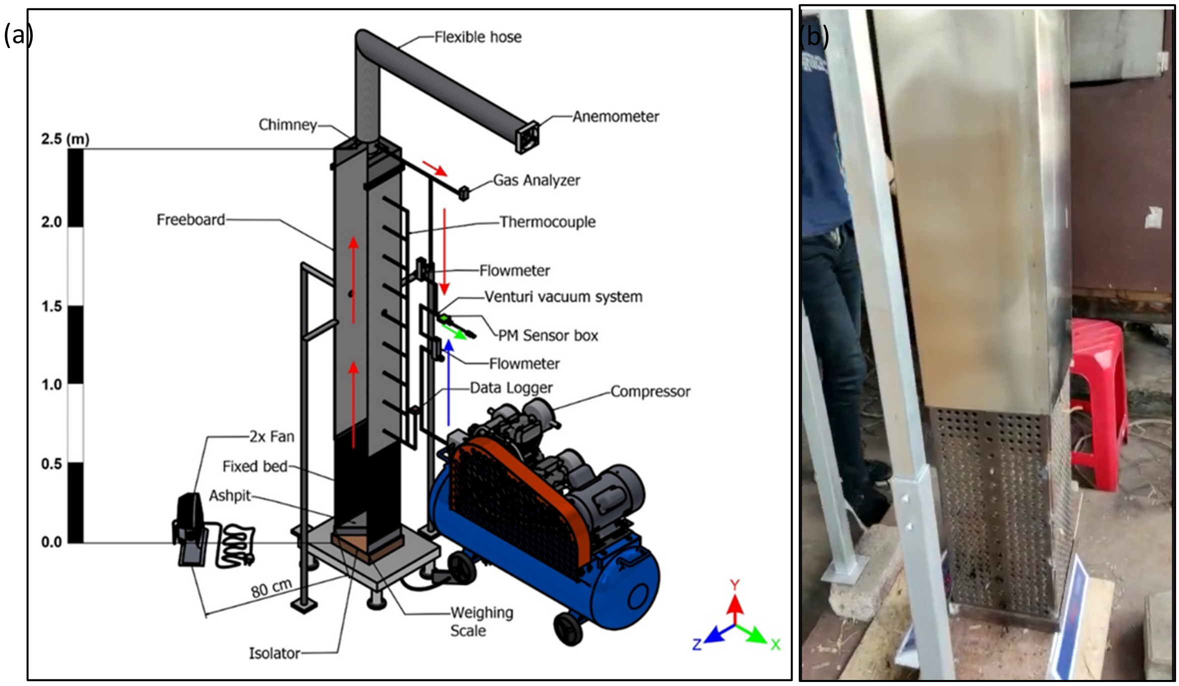

Fig. 2: (a) Schematic view and (b) real picture of open burning furnace (Nugraha *et al.,* 2023)

and consists of two main parts, namely the biomass bed region and exhaust gas channel. The biomass bed region is constructed from multi-holeds steel plates to ensure that biomass is retained in its place while allowing air to penetrate the bed without any significance resistance. The exhaust gas channel is used to collect exhaust gas and consequently, monitor the exhaust gas characteristics such as temperature and gas composition. The addition of several instruments to open burning furnaces has been highlighted in previous studies (Nugraha *et al.,* 2023).

Closed burning experiment

The design and construction of this type of furnace are tailored to facilitate controlled combustion experiments, focusing particularly on close burning conditions as depicted in Fig. 3. To this end, both the detailed engineering design (DED) and manufacturing processes are meticulously developed to minimize risks, such as air leakage into the furnace and premature escape of flue gases. The furnace measures 150 millimeter (mm) x 150 mm x 200 mm (W x L x H) and features a dual-layer construction: an internal layer made of stainless steel and an external layer of mild steel. Notably, both the lower section and the chimney are fabricated entirely from stainless steel.

The design of the chimney is essential in facilitating the efficient upward flow of flue gas and reducing temperature. Additionally, there is a hopper externally connected to the furnace, serving as the entry point for biomass into the combustion chamber. The biomass is directed onto a fixed-type grate. This grate has a perforated surface engineered to allow the downward passage of residual combustion ash. The furnace incorporates two distinct air supply zones: primary and secondary. The primary zone features two opposing holes on different sides, whereas the secondary zone utilizes four opposing holes to generate a turbulent airflow pattern. Each hole has a diameter of 15 mm, approximately about 0.59 inch (in), and is adjustable to meet various testing conditions. Air is supplied via stainless steel flexible hoses connected to a blower. The requisite mass airflow rate is modulated by a single-phase dimmer controlling the blower's rotational speed. Air velocity is measured by an anemometer. A hinged opening mechanism at the bottom part of the furnace serves

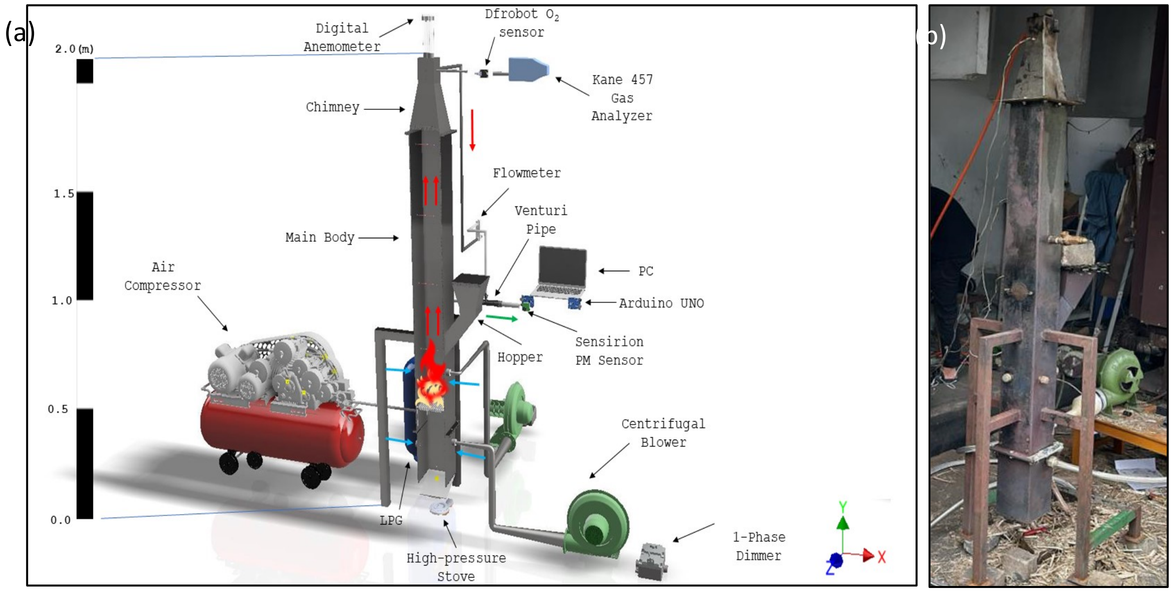

Fig. 3: (a) Schematic view and (b) real picture of closed burning furnace. Red arrows indicate exhaust gas flow; blue arrows indicate natural air flow; green arrow indicates diluted gas flow

Table 1: Experimental design for open burning condition

Experiment ID	Ignition point	Air intake	Initial mass (g)	Biomass type
A_1	Bottom	Natural	500	Sugarcane bagasse
A_2	Middle	Natural	500	
A_3	Middle	Forced	500	
A_4	Middle	Natural	250	
B_1	Bottom	Natural	500	Leaf
B_2	Middle	Natural	500	
B_3	Middle	Forced	500	
B_4	Middle	Natural	250	
C_1	Bottom	Natural	500	Rice straw
C_2	Middle	Natural	500	
C_3	Middle	Forced	500	
C_4	Middle	Natural	250	

dual purposes: facilitating the disposal of residual combustion ash and easing the pre-heating phase via an liquefied petroleum gas (LPG) stove. The design facilitates the instantaneous gathering of diverse combustion parameters, such as temperature, concentration of particulate matter, and levels of oxygen (O2) and carbon dioxide (CO2), through the utilization of a range of sensors. Temperature is monitored using Type K thermocouples placed at three distinct heights above the grate. Oxygen concentration in the exhaust gas is determined through a DFrobot Gravity sensor, which utilizes infrared radiation technology. Particulate matter concentration is gauged using a Sensirion SPS30 PM sensor, with a gas flow diluted in a venturi vacuum system for accurate measurement. CO_2 content is quantified using a Kane 457 gas analyzer, integrated in series with the oxygen sensor. Data acquisition from these sensors are executed by an Arduino UNO microprocessor.

Experimental method

The open burning methodology for this study follows previous research (Nugraha *et al.,* 2023).

Table 2: Experimental design for closed burning condition

Experiment ID	Reloading time interval	Excess air (%)	Air staging	
			Primary (%)	Secondary (%)
X_1	5 min	-	100	-
X_2	3 min	-	100	-
Y_1	3 min	50	30	70
Y_2	3 min	75	30	70
Y_3	3 min	100	30	70
Y_4	3 min	200	30	70
Y_5	3 min	250	30	70
Z_1	3 min	100	70	30
Z_2	3 min	100	60	40
Z_3	3 min	100	50	50
Z_4	3 min	100	40	60

In open burning combustion, biomass is initially placed in a fixed bed, and combustion is started using an ignition torch. In this study, data sampling was stopped when no mass reduction was obtained in the weighing scale. Aside from the experimental parameters investigated in prior studies, this research encompasses various supplementary conditions, i.e., various initial biomass mass, ignition point location and air flow injection method. The experimental design for open burning conditions is summarized in . Forced convection was achieved using two fans positioned symmetrically and diagonally 80 centimeter (cm), or about 2.62 feet (ft), from the fixed bed. Ignition was executed at two locations for varying conditions: mid-level ignition occurred at approximately 25 cm (9.84 in) above the base of the fixed bed, while bottom-level ignition occurred 5 cm (1.97 in) above the same point.

Meanwhile, in closed burning combustion, multiple combustion phases were observed. In the initial phase, the furnace was heated using an LPG stove located at the bottom. This initial heating aimed to raise the furnace temperature to the working temperature, thus initiating combustion. The subsequent step involved introducing 250 grams (g) of biomass during two loading cycles to accelerate the attaining maximum combustion temperature. The data recording process was initiated by identifying the unsteady phase, during which the steady temperature point was established within a specific biomass loading cycle. Once the steady phase was reached, data recording commendced by activating of all installed sensors. The data collection stage involved six loading cycles. The final stage included cooling the furnace by halting the biomass input and maintaining the blower operation running until the temperature of the furnace decreased. Variations in excess air were determined on the required mass airflow rate supplied to the combustion chamber, ranging from 3.23 grams per second (g/s) for 50% excess air to 11.33 g/s for 250% excess air. Table 2. summarizes the experimental design in the closed burning condition.

To ensure the accuracy of experimental campaigns, the influence of atmospheric air temperature and humidity is minimized by conducting the experiments during clear daytime. The average air temperature during these experiments is approximately 31 degrees Celsius (°C), while the humidity ranges from 60 to 75%.

Biomass materials

A comparative analysis was conducted in this study, examining three different types of biomasses: bagasse, rice straw, and leaf litter. The analysis is detailed in Fig. 4. Bagasse and rice straw were harvested from sugarcane and rice cultivation areas, respectively, in the vicinity of Yogyakarta, Indonesia. Leaf litter was sourced from the campus of Universitas Gadjah Mada. These types of biomasses are traditionally subjected to open-field combustion, an unsustainable practice with potential environmental ramifications.

To ensure methodological rigor, each biomass sample underwent both proximate and ultimate analyses, the results of which are encapsulated in Table 3.

These analytical data served as the benchmark against which the empirical findings of the subsequent combustion experiments were compared. To ensure consistency and uniform quality across samples, all biomass categories underwent a standardized

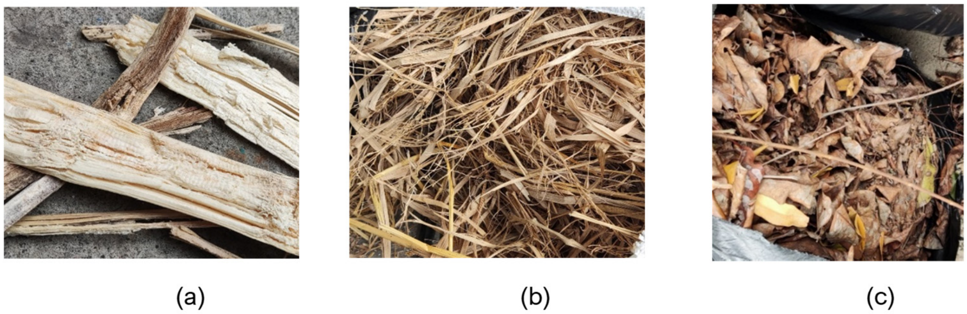

Fig. 4: Biomass used in the study (a) bagasse (b) rice straw and (c) leaf litter

Table 3: Proximate, ultimate and calorific value analysis for utilized biomass residues

Parameter	Unit	Bagasse	Rice straw	Leaf litter
Higher heating value	Mega Joules per kilogram (MJ/kg)	17.3	13.9	15.3
Proximate analysis				
Moisture	%mass, as dry basis (adb)	7.6	8.3	9.9
Ash content	%mass, adb	1.6	15	11.9
Volatile matter	%mass, adb	79.7	60.4	62.6
Fixed carbon	%mass, adb	11.1	16.3	15.6
Ultimate analysis				
Carbon	%mass, adb	43.62	34.8	40.11
Hydrogen	%mass, adb	6.26	5.55	6.03
Oxygen	%mass, adb	48.01	43.55	39.8
Nitrogen	%mass, adb	0.31	0.98	1.97

pre-treatment protocol before being subjected to the combustion tests. This pre-treatment regimen consisted of four essential steps:

1. Visual Inspection: Biomass samples were meticulously sorted to exclude any portions displaying mold, indicative of excessive moisture accumulation and extended storage duration.

2. Mechanical Processing: A specialized cutting apparatus was used to reduce the biomass size, thus facilitating its systematic placement within the combustion chamber.

3. Solar drying: Each biomass sample was exposed to direct sunlight for approximately 8 hours to lower its inherent moisture content. Moisture reduction is crucial as elevated moisture levels may impede effective combustion.

4. Storage Protocols: Post-treatment, the biomass samples were stored in desiccated environments, utilizing containers specifically designed to retain the optimized moisture profile of the material.

RESULTS AND DISCUSSION

The results obtained from this research are deemed extremely significant for the progress of sustainable practices in agriculture and energy generation. By examining the composition and environmental impacts of emissions associated with biomass burning, scientists can develop techniques and technologies to minimize air pollution. This valuable knowledge aids in the development of efficient biomass combustion systems that effectively decrease the release of particulate matter, thereby mitigating potential health hazards and environmental harm. Additionally, improved combustion technologies contribute to cleaner energy production, fostering a more sustainable and environmentally friendly approach to meet energy demands. Ultimately, this study assists in directing policymakers, farmers, and industries towards embracing methods that harmonize the advantages of biomass energy with environmental responsibility, fostering a more sustainable future for both the agricultural and energy fields.

Correlation of harvest period to atmospheric emission in Yogyakarta, Indonesia

In the 2020-2021 period, the rice production in

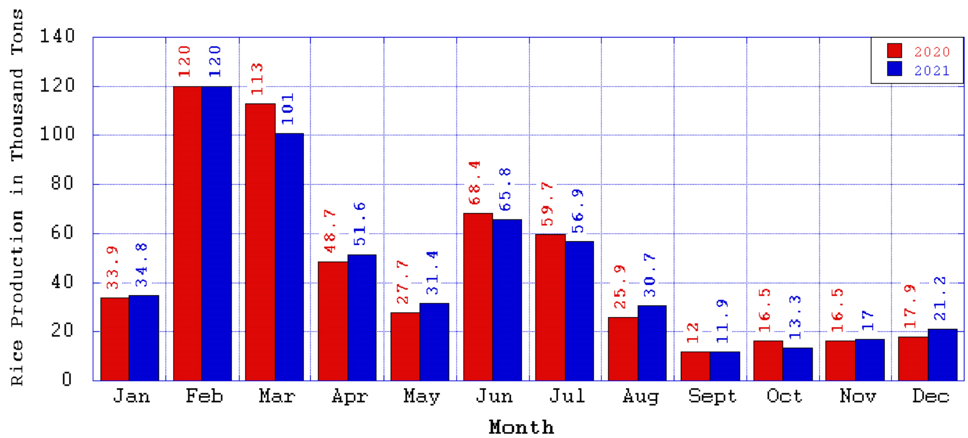

Fig. 5: Rice production in Yogyakarta, Indonesia from 2020 to 2021

Yogyakarta exhibited a notable temporal variability as presented in Fig. 5. The data is generatred from Yogyakarta's Central Bureau of Statistics (BPS). January demonstrated a substantial output of 33.9 thousand tons, followed by a remarkable rise until March with 113 thousand tons. Following March, there was a noticeable decline in production during April and May. Nevertheless, this downward trend was short-lived, as production experienced a resurgence in June and July. The latter part of the year, commencing in August, marked the onset of a declining phase that persisted until December.

Notably, the agricultural sector in Yogyakarta demonstrated remarkable resilience in the face of the global disruptions wrought by the COVID-19 pandemic. Rice production, a cornerstone of both the regional economy and food security, remained unaffected. The resilience of Yogyakarta's agriculture sector is emphasized by this persistence, indicating that crucial economic endeavors like rice cultivation have remained steadfast despite the various uncertainties brought about by the pandemic.Yogyakarta's rice production and environmental emission trends exhibit a strong interdependence, intertwined significantly with the region's meteorological patterns. An observational analysis conducted between January and December for the period of three years (from 2020 to 2022) revealed a complex and reciprocal relationship between rice production, rainfall, and emissions as depicted in Fig. 6.

From January through March, Yogyakarta experienced heightened rainfall, correlating with a period of robust rice production. The comparatively low emissions can be attributed to the deterrence of open burning practices caused by the high levels of precipitation experienced during these months. This suggests that the surplus moisture conditions posed challenges for farmers who typically employ open burning as a post-harvesting method. Nevertheless, as the region shifted towards the arid period spanning from April to August, a noticeable disparity became evident. The lack of precipitation during this time frame presented farmers with a favorable opportunity to engage in the practice of open burning of rice residues from previous harvests, resulting in a significant increase in emissions. This hypothesis is further substantiated by our field observations, which indicated an increase in burning practices during these drier months. The subsequent drop in emissions during the October-December period can be attributed to the absence of significant rice production activities. Given the interplay of these factors, it is evident that Yogyakarta's agricultural and environmental dynamics are irreversibly linked, influenced by both anthropogenic activities and natural climatic rhythms. In light of the World Health Organization (WHO) air quality guidelines, the atmospheric pollution data from Yogyakarta gain additional significance. The WHO sets stringent standards for air quality, with the current guidelines stating that annual average concentrations of $PM_{2.5}$ should not exceed 5 microgram per cubic meter (μg/m^3), while 24-hour average exposures should not exceed 15 μg/m3 more than 3 - 4 days per year. These benchmarks are instrumental in guiding efforts

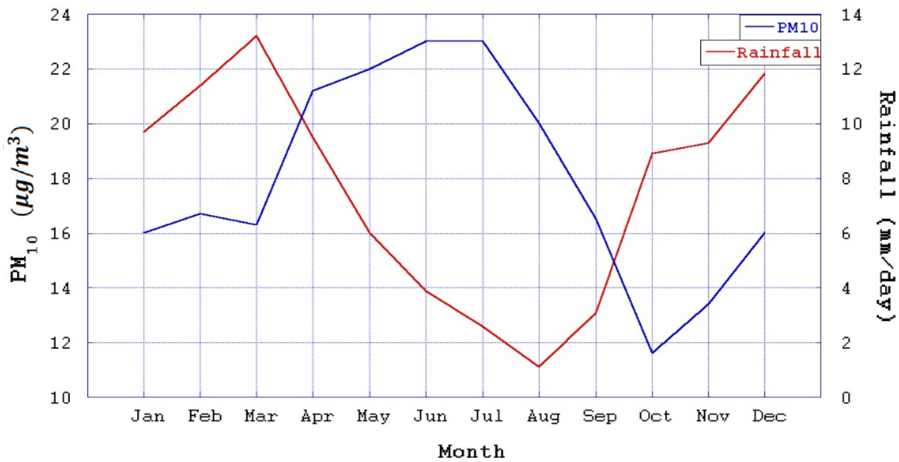

Fig. 6. Average atmospheric PM emission and rainfall magnitude profile in Yogyakarta from 2020 to 2022

towards cleaner air, especially in regions grappling with high levels of pollution. Despite these international standards, our findings indicate that throughout the year, the PM concentration in Yogyakarta consistently exceeds the WHO threshold limit, underscoring the critical need for enhanced pollution control measures and the adoption of sustainable agricultural practices to mitigate the adverse effects of open burning on air quality. Generally, Yogyakarta's central and southern urban areas exhibit significant anthropogenic emissions attributable to vehicle use, contributing to approximately 21% of ambient PM concentrations (Nurjani *et al.,* 2021). Over time, various events have led to reductions in vehicular traffic, which in turn influenced emission contributions. Interestingly, in 2022, emission profiles revealed that open burning practices in agricultural sectors became the predominant source of PM pollutants. As farmers maintained their open burning practices during this period, the agricultural sector's contribution to the city's PM concentrations increased significantly. This presented an exceptional chance to investigate the influence of these agricultural practices on air quality, particularly when other notable sources of anthropogenic emissions were minimized. Despite the significant reduction in mobility trends due to the COVID-19 pandemic, as reflected by lockdown measures implemented across Yogyakarta, emission levels remained surprisingly consistent. The unwavering rice production figures during the lockdown period of 2020 serve as a testament to the persistence of local farmers' open burning practices, which stands in stark contrast to the declining trend in mobility. This consistency can be emphatically attributed to their unwavering commitment to these practices. While urban activities paused, agricultural emissions continued, underscoring the environmental implications of open burning in the face of global disruptions. With most anthropogenic pollution sources momentarily dormant, agricultural open burning emerged as the primary contributor to contributed to PM_{10} levels during this phase. The environmental emissions resulting from rice agricultural waste are deemed substantial due to its extensive coverage, accounting for over 35% of Yogyakarta's total area. The estimation of agricultural waste, specifically rice straw, became crucial given the vast rice cultivation in 2020, with 110.55 thousand hectares harvested and a total paddy production of 523.40 thousand tons. Taking into account the 70% efficiency of paddy processing in converting it to white rice, the remaining 30% consisting of hulls, bran, and straw is deduced to contribute significantly to agricultural waste. Specifically, if 20% of the paddy weight accounts for hulls, the remaining agricultural waste, including straw, constitutes a considerable amount of the total paddy weight. This calculation concluded that Yogyakarta produced approximately 157.02 thousand tons of biomass waste from rice production in 2020. This statistic not only highlights the magnitude of agricultural waste generated, but also emphasizes the necessity for implementing sustainable management techniques to address the environmental consequences, particularly in relation

Table 4: Average value of combustion parameters in various combustion conditions using different biomass

Biomass type	Experiment ID	Mass loss rate (g/s)	CO_2 (%)	Bed temperature (°C)	Freeboard temperature (°C)
Sugarcane Bagasse	A_1	0.4974	2.530 ± 0.056	231 ± 102	137 ± 2
	A_2	0.5233	2.841 ± 0.118	403 ± 28	328 ± 22
	A_3	0.5250	3.6 ± 1.74	209 ± 35	365 ± 39
	A_4	0.3326	2.957 ± 0.14	188 ± 57	211 ± 5
Leaf Litter	B_1	0.2071	1.42 ± 0.03	391 ± 12	105 ± 7
	B_2	0.2486	1.294 ± 0.109	365 ± 29	112 ± 9
	B_3	0.3301	1.209 ± 0.02	120 ± 4	107 ± 5
	B_4	0.1921	1.482 ± 0.465	217 ± 23	149 ± 54
Rice Straw	C_1	0.2421	1.797 ± 0.18	377 ± 5	84 ± 13
	C_2	0.2553	1.513 ± 0.137	412 ± 74	99 ± 16
	C_3	0.3724	1.142 ± 0.154	373 ± 48	61 ± 7
	C_4	0.1979	2.684 ± 0.311	181 ± 37	101 ± 23

to air quality as indicated by the analysis of PM data.

Evaluation of open burning combustion

In this study, combustion and emission characteristics of biomass combustion in open air were investigated using a furnace designed and constructed to replicate the open burning conditions depicted in Fig. 2. Several combustion parameters were recorded during the combustion at different operating conditions, namely mass loss rate, temperature of biomass bed and exhaust gas, gas composition of exhaust gas including CO_2 and PM concentration. The operating parameters were adjusted to simulate a range of scenarios that could potentially arise during combustion in an open-air setting. These scenarios encompassed variations in air flow caused by wind, diverse ignition points, and discrepancies in the initial biomass mass. The transient profile of mass evolution during combustion is depicted in Fig. 6 and the average mass loss rate value is summarized in

. Varied mass loss rates were observed due to differences in biomass composition and combustion conditions. Bagasse combustion consistently displayed the highest mass loss rate up to 0.5250 grams per second through utilization of forced air in combustion. This can be attributed to the elevated heat content and presence of volatile compounds in bagasse, surpassing those found in rice straw and leaf litter.

The speed of combustion in all biomass combustion experiments was adversely affected by the shift in ignition position from the middle to the bottom. Among these experiments, the combustion of leaf litter experienced the most significant impact, with a reduction in combustion time of approximately 20% as a result of the change in ignition position. This can be attributed to the lack of room for air to penetrate during the ignition period from the bottom of the bed. Meanwhile, it has been scientifically demonstrated that the application of forced air can significantly enhance the rate of combustion, with an increase of up to 45% observed in various biomass combustion experiments. The improvement of air and fuel gas mixing is expected to occur due to higher turbulent intensity and therefore higher air flow velocity. The transient profile of mass loss evolution in Fig. 7. demonstrates that different combustion conditions affect the final residue mass at the end of combustion. There were remaining residues at the end of combustion which was expected due to the contribution of ash content. Based on the proximate analysis summarized in Table 3, the minimum theoretical biomass residues that can potentially remain at the bed are 1.6, 15, and 11.9% of initial biomass mass for bagasse, rice straw, and leaf litter, respectively. However, differing combustion conditions are proven to influence the final residue mass be ascribed not only to the presence of ash but also to the unburnt char and volatile components that were not subjected to devolatilization.

Utilizing more air flow due to forced convection and dividing the biomass waste into smaller groups of mass could in general produce a lower final mass of residue, which also represents the high degree of complete combustion. This can be attributed the improved mixing

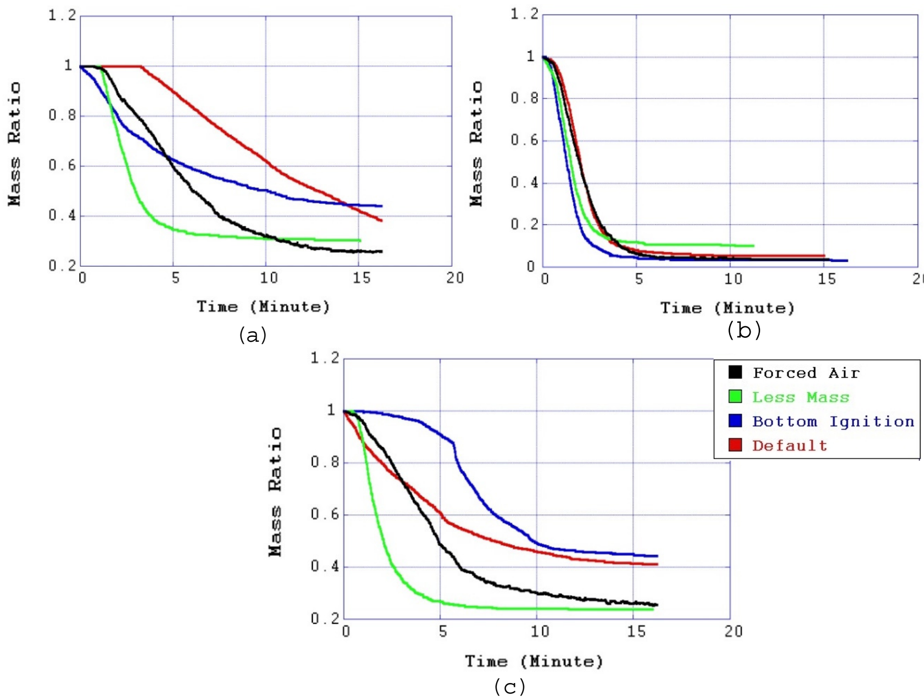

Fig. 7: Mass evolution profile during open burning combustion in various combustion conditions using different biomass: a) bagasse b) rice straw and c) leaf litter

of air and fuel. In the smaller initial mass combustion experiments, biomass occupied the same volume of the perforated biomass box compared to the experiment with higher initial mass. Consequently, air penetration was predicted to improve due to this treatment. A slight manual initial compression was employed initially to compact the biomass stack in order to accommodate the biomass holder during the experiments with higher initial mass. The average temperature recorded in the area close to the flame may reach 365 $^{\circ}$C with the utilization of forced air. Meanwhile, the temperatures in the other biomass combustion experiments are lower than 150 $^{\circ}$C. This elevated temperature also reflects the better volatile matter oxidation, which is also proven by the higher CO_2 formed and monitored in the sampling point in the chimney. Despite the implementation of diverse experimental conditions, the residue pile resulting from the combustion of rice straw and leaf litter still contained over 10% of combustible materials, namely volatile and char. Meanwhile, a higher degree of complete combustion was identified in bagasse combustion with approximately 2-8% combustible materials left in the residue. Fig. 8 provides a summary of the particulate emission that was monitored in the exhaust gas. The exhaust gas was sampled from the main flow and diluted with clean air to reduce the PM concentration. The final concentration monitored in the sensor was therefore kept within the maximum limit of particulate sensor concentration range i.e, 2000 μg/m^3. Fig. 8**.** presents the emission factor data, namely total particulate emissions generated from open burning per kilogram biomass that is burned. The emission factor ranges from 3 to 29 g PM/kg of fuel. This is relatively consistent with previous research which showed approximately 8 g PM/kg fuel, with standard deviation of 4, for emission characteristics in agricultural residue open burning (Andreae, 2019). The more accurate comparison can be conducted with previous study in rice straw open burning which obtained around 6.21 to 13.27 g PM/kg fuel as emission factor (Oanh *et al.*, 2011). This result is consistent with the finding in the current study by neglecting the extreme combustion conditions due to higher air flowrate, which also did not included in the same comparative study (Oanh *et al.*, 2011). The current study shows that the emission factor span around 11 to 13.9 g PM/kg fuel for rice straw open burning.

In general, when it comes to the combustion of

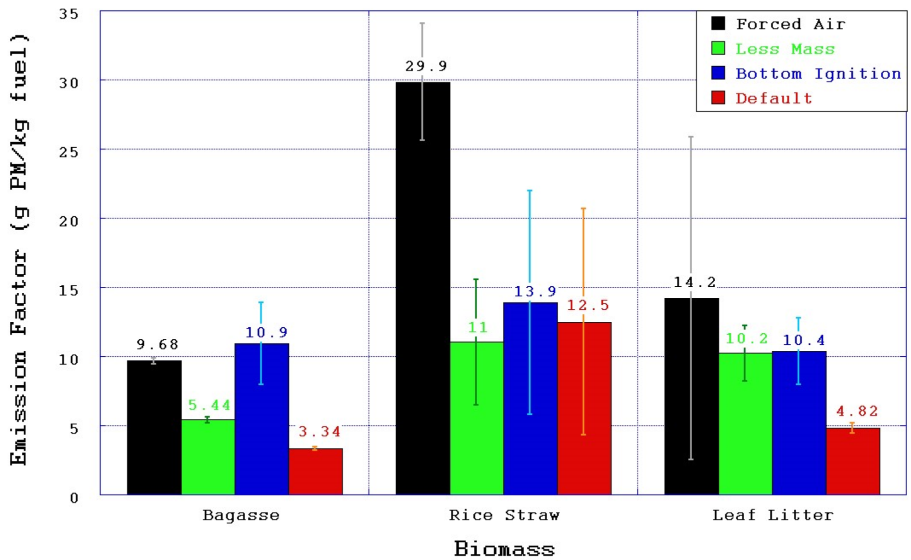

Fig. 8: Particulate emission factor profile from open burning combustion

biomasses, the open burning of bagasse tends to result in superior emissions compared to other biomasses. However, it is worth noting that the least amount of particulate emission was observed across all biomasses during open burning when a higher initial biomass mass was utilized, along with a middle ignition and natural air flow. Meanwhile, the use of forced air flow resulted in higher particulate. This can be attributed to the lower temperature in the experiments with forced air flow due to higher content of inert nitrogen. Particulate matter in the form of soot particles is oxidized in a higher temperature region in the flame areas (Wang *et al.,* 2014). Therefore, the temperature level in biomass combustion is crucial in determining the final level of emissions. Additionally, there is a higher likelihood that fly ash is blown together with exhaust gas due to higher air flowrate. A higher emission trend was observed by application of bottom ignition. As observed in the mass evolution and temperature characteristics profile, the bottom ignition generated lower degree of complete combustion. It is well-established that a high degree of complete combustion is consistently linked to improved combustion, which in turn leads to enhanced energy conversion and reduced emission levels. (Nussbaumer, 2003). Similarly, the utilization of lower initial biomass mass is equally proven to not improve the quality of the final emission level. Lower initial biomass mass experiments resulted in a slower combustion rate as depicted in

. Meanwhile, the total air flow recorded by the flowmeter at the end of flexible hose did not show a significant flow reduction compared to the experiments with higher initial mass. Consequently, lower temperature levels were captured in areas close to the flame, strongly contributed to the higher emission level. Even though open burning practices are forbidden in many areas and countries, the findings of this research can serve as a valuable suggestion for improving open burning practices in situations where alternative waste treatment methods are not readily accessible. The use of more initial mass produces better emission level compared to separating biomass piles into smaller initial mass. An additional suggestion for mitigating the release of pollutants from open burning activities involves initiating the ignition process from the central portion of the biomass heap instead of the lower section. Ultimately, conducting biomass open burning during calm weather conditions is highly recommended as it effectively minimizes the emission of particulate matter (PM).

Evaluation of closed burning combustion

Combustion characteristics

Closed burning combustion characteristics were evaluated through sugarcane combustion in a designated furnace as depicted in Fig. 3. The combustion was initiated by LPG heating from the bottom part of the furnace and continued with the loading of 100 grams biomass every three minutes. The collection of data began once the thermocouple reached a state of stability after several cycles. During steady operation, several parameters were recorded, including exhaust gas concentrations of CO_2, O_2, and particulate matter as well as temperature at several positions. The average of these parameters are summarized in Tables 5 and 6. Recorded parameters from different operating conditions are also tabulated in Table 5, which includes reloading interval, air fuel ratio, and percentage of air staging. The average values in Table 5 were generated from sensor readings over at least for 18 minutes or six reloading periods. The standard deviation provided in Table 5 is computed by considering the average value within each reloading period.

The combustion dynamics observed in sugarcane waste biomass are deeply rooted in its intrinsic properties, primarily its elevated higher heating value (HHV). which results in an intense combustion rate, particularly evident during material reloading for variation X_1, the data show an average thermocouples temperature of 328 ± 25.9 °C. The rapid combustion, inherent in this material necessitates a prolonged interval before the next reloading, subsequently leadings to a drop in the average temperature within the combustion chamber.

In variation X_2, the composition of exhaust gases merits particular attention. Our findings indicate a CO_2 concentration of 7%±1.6 juxtaposed against an

Table 5: Average temperature and gas concentrations at various combustion conditions

Experiment ID	CO_2 (%)	O_2 (%)	25 cm (°C)	85 cm (°C)	Freeboard Average (°C)	Chimney (°C)
X_1	5.1 ± 1.3	15.8 ± 1.1	433.1 ± 33.4	222.9 ± 18.4	328 ± 25.9	143.6 ± 2.2
X_2	7.0 ± 1.6	10.8 ± 1.5	474.8 ± 28.5	212 ± 15.3	343.4 ± 22	121.8 ± 2.3
Y_1	7.2 ± 0.75	11.1 ± 1.4	422 ± 36.2	211.4 ± 16.7	316.7 ± 26.4	116 ±2.2
Y_2	7.3 ± 1.1	12.5 ± 0.8	432.6 ± 36.1	199 ± 22.5	315.8 ± 29.3	108.4 ± 2.5
Y_3	8.2 ± 2.8	11.5 ± 1.4	506.8 ± 32.5	216.5 ± 12.4	361.7 ± 22.5	119.6 ± 2.1
Y_4	7.2 ± 2.2	13.1 ± 0.74	492 ± 48.2	211.5 ± 13.8	351.8 ± 31	117.2 ± 2.4
Y_5	6.8 ± 1.4	15.4 ± 0.76	490.3 ± 36	210.9 ± 17.2	350.6 ± 26.6	120.4 ± 2.8
Z_1	7.2 ± 2.1	14.4 ± 0.8	474 ± 34	210 ± 15.6	342 ± 49.6	94.4 ± 2.7
Z_2	6.4 ± 1.2	13.6 ± 0.7	486.6 ± 38.6	203.1 ± 16.3	344.9 ± 27.4	101.1 ± 2.8
Z_3	6.1 ± 1.3	13.2 ± 1.3	494.5 ± 42.3	209 ± 18	351.8 ± 30	102 ± 2.3
Z_4	6.6 ± 0.8	12.8 ± 1	493.2 ± 39	210.8 ± 20.7	352 ± 29.85	101 ± 2.5

Table 6: 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	1.98 ± 0.69	3.57 ± 1.24
X_2	0.99 ± 0.6	1.79 ± 1.09
Y_1	0.68 ± 0.23	1.23 ± 0.41
Y_2	0.47 ± 0.17	0.85 ± 0.32
Y_3	0.37 ± 0.17	0.67 ± 0.31
Y_4	0.47 ± 0.19	0.85 ± 0.35
Y_5	0.59 ± 0.3	1.07 ± 0.55
Z_1	0.95 ± 0.49	1.79 ± 0.89
Z_2	0.68 ± 0.19	1.24 ± 0.34
Z_3	0.67 ± 0.39	1.21 ± 0.71
Z_4	0.5 ± 0.3	0.91 ± 0.3

O_2 concentration of 10.8±1.5. The exhaust gas for this variation, reflects the biomass's distinct combustion characteristic, showing CO_2 concentrations observed between 12.18% and 18.22%. These result in a summarized average concentration of 16.06% for CO_2, while O_2 concentrations demonstrate variability, with a derived aggregate average of 3.71%. In scenarios with reduced excess air supply, combustion efficiency is compromised due to the limited availability of oxygen, resulting in the presence of residual unburned carbon compounds. Conversely, when there is an increased excess air supply, the temperature of the combustion chamber can be reduced due to the presence of an air-rich environment.. Specifically, the nitrogen content in the air acts as a temperature depressant post-peak combustion. With regard to variation Y data, it is noteworthy that temperatures recorded at the 85 cm from ash pit (T85) location are half of those at the 25 cm from ash pit (T25). This disparity is attributed to subdued turbulent effects and the premature generation of flue gases resulting in a decline in flue gas temperature by the time it reaches the chimney. A surge in excess air invariably heightens bed velocity, a phenomenon generated by the low density and granularity of the solid carbon constituent. Such an environment promotes the entrainment of fine particulates such as fly ash, vacating the combustion chamber prematurely. An analytical overlay of the temperature data with carbon dioxide (CO_2) concentrations defines the intimate link between combustion quality and gas evolution. Focusing on our dataset, variation Y_3 exhibits an optimal CO_2 concentration of 8.2 ± 2.8, emblematic of an ideal combustion equilibrium characterized by adequate residence time and homogeneity. Nevertheless, heightened excess air proportions give rise to specific irregularities. Although a preliminary analysis of the temporal aspect may indicate a consistent level of peak CO2 concentrations despite the augmented excess air, a more comprehensive examination focusing on the average reveals a decline in CO2 levels. This simultaneous observation can be explained in the following manner:

1. Reaffirming earlier temperature assessments, elevated excess air influx results in a drop in combustion temperatures, creating an air-rich surroundings post the completion of fuel combustion.
2. The short residence time limits the beneficial interaction between fuel and oxygen, leading to incomplete combustion.

The interplay between secondary air flow rate and combustion temperature is a complex phenomenon that involves both thermodynamics and fluid dynamics. When the rate of secondary air is increased, the combustion temperature is inevitably raised. This can be primarily attributed to the expansion of the flame zone and the improvement in the uniformity of gas mixing. However, it is paramount to exercise prudence; an overly aggressive secondary air influx can paradoxically lower temperatures. Regarding to variation Z data, it becomes evident that the temperatures registered by thermocouple T85 rise systematically with escalating secondary air rates. This underscores the pivotal role of secondary air in amplifying combustion efficiency. By supporting air-fuel interactions and extending flame duration, secondary air instills a more uniform heat distribution throughout the combustion chamber, as demonstrated by the temperature readings at T85. The auxiliary secondary air introduces turbulence, setting the stage for a uniform combustion ambiance. Delving deeper into our dataset, variations Z_1 and Z_3 are particularly illustrative. Z_1, with a CO_2 concentration of 7.2%±2.1, and an O_2 level of 14.4%±0.8, defines an equilibrium of fuel-air dynamics, indicative of the enhanced air matrix surrounding the combustion zone in its early stages. This interplay manifests as a slow decline in average CO_2 concentrations, inversely tracking the decrease in primary air rates, culminating at a turning point marking the optimal combustion equilibrium.

Emission profile

Within the purview of variation X, complex dynamics emerge when evaluating the reload rate of sugarcane bagasse biomass. An elongated reload interval precipitates a marked decline in the combustion chamber's temperature, intricately tied to the bagasse's inherent combustion tendency. This biomass tends to combust rapidly, occasionally leading to incomplete burn cycles. Consequently, unburned carbonaceous residuals infiltrate the exhaust stream. Facilitated by the blower's pressure dynamics, these residuals are measured as particulate matter emissions. Specifically, experiments X_1 and X_2 register PM_{10} concentrations of 1.98 ± 0.69 mg/m^3 and 0.99 ± 0.6 mg/m^3, respectively, with corresponding emission factors of 3.57 ± 1.24 and 1.79 ± 1.09. The data underscore the symbiotic relationship between reload rates and particulate emissions, emphasizing the importance of meticulously calibrated operational parameters for sugarcane bagasse combustion. CO_2 concentrations serve as pivotal indicators of combustion efficiency. A meticulous analysis of variation Y reveals that configurations with decreased excess air percentages tend to exhibit attenuated CO_2 yields, symptomatic of less-than-optimal combustion. The accumulation of unburned carbon residues within the combustion chamber is facilitated by these conditions. As these residues linger, their extended residence and increased tendency for coalescence become apparent, engendering the genesis of more substantial particulate matter (PM) entities. Examining specific sub-variations, Y_4 and Y_5 present with PM concentrations of 0.47 ± 0.19 mg/m^3 and 0.59 ± 0.3 mg/m^3, respectively, elucidating enhanced combustion kinetics relative to their counterparts, Y_1 (0.68 ± 0.23 mg/m^3) and Y_2 (0.47 ± 0.17 mg/m^3). Such heightened efficiency is attributed to the sustained interplay between carbon residues and ambient air, producing a more homogeneous flame front. However, it warrants a mention that the reloading cadence for Y_4 and Y_5—set at a 3-minute interval—poses challenges. During this limited period of residence, there is a temporary constraint that leads to a rapid discharge of particulate matter (PM) through the chimney. This dynamic has the potential to negatively impact the efficiency of combustion. An intricate examination of variation Z underscores Z_4 as the peak of combustion proficiency. With a PM concentration of 0.5 ± 0.3 mg/m^3, this variation's wise air distribution strategy causes heightened turbulent flow conditions, proving instrumental in augmenting the combustion continuum (Khodaei *et al*., 2017). Such enhanced turbulence catalyzes the systematic oxidation partially combusted fuel constituents. The emissions that ensue from this process are characterized by reduced levels of particulate matter, which are further distinguished by their finer texture. This pattern aligns with the findings of previous research, which also demonstrated that incorporating a higher proportion of secondary air in the 25 kiloWatt (kW) wood-fueled grate type furnace leads to more effective reduction of PM emissions. (Lamberg *et al.,* 2011). Increasing allocation of secondary air from 50% to 65%, is obtained to reduce half of PM emissions. Yet, extrapolating from the overarching trends, it is evident that an excessive influx of either primary or secondary air can be harmful. Such an air preponderance tends to gravitate towards and saturate specific locales within the combustion chamber. The localized concentration of fuel and air in a combustion process leads to a shortened dissemination of the overall combustion, leaving more peripheral regions of the chamber less engaged and potentially cooler. Consequently, this can jeopardize the uniformity and efficacy of the combustion profile, rendering certain regions less optimal in terms of combustion efficiency. Comparing with the findings in open burning combustion and Andreae (Andreae, 2019), the concentration of PM_{10} recorded in the closed burning study was markedly reduced. The reduction by a factor of 9 in PM emission by utilization the best combustion condition in closed burning compared to the open burning's best condition. The aforementioned disparity emphasizes the inherent difficulties in achieving consistent combustion circumstances during unrestricted burning, accentuating the effectiveness of regulated combustion techniques in diminishing particulate discharges. The result of the more controlled combustion can also be used further as the basis for exploration in process modelling and simulation framework (Perera *et al.,* 2021), in order to find the more optimum combustion conditions and also better furnace design.

CONCLUSION

Agriculture contributes to global economies but also generates waste, including crop residues. Traditional waste disposal methods, like open burning, contribute to particulate emissions, affecting air quality. This study present a novel work to asses the influence of open burning practices to local (Yogyakarta) air quality. In addition, this work also provide a significant information about correlation of various combustion conditions to PM emission both in open and closed burning system. The assessment of Yogyakarta's air quality is conducted by comparing the rice harvest trend and the atmospheric PM concentration during 2020-2022 period. During the 2020-2021 timeframe, Yogyakarta experienced notable fluctuations in its rice production. Specifically, in January, there was a remarkable yield of 33.9 thousand tons.The agricultural sector remained resilient despite global disruptions caused by the COVID-19 pandemic, demonstrating its adaptive capacity. Yogyakarta's rice production and environmental emission trends are interconnected, with heightened rainfall from January through March deterring open burning practices. Nevertheless, the lack of precipitation from April to August resulted in a rise in the practice of burning rice residues, consequently leading to an escalation in emissions. The drop in emissions during October-December can be attributed to the absence of significant rice production activities. The unwavering rice production figures during the lockdown period of 2020 highlight the environmental consequences of open burning in the face of global disruptions. Despite the decrease in vehicular traffic caused by the pandemic, emission levels remained unchanged due to the ongoing open burning practices conducted by local farmers. This finding also highlight that open burning practices of agricultural biomass residues is major contributor of atmospheric particulate matter emissions in Yogyakarta. Therefore a serious action regarding of agricultural waste disposal should be taken seriously by local regulator. The contribution of biomass open burning practices to atmospheric emissions is also evaluated using the experimental campaign in laboratory to confirm the emissions factors of biomass burning under various combustion conditions. The study found that bagasse combustion displayed the highest mass loss rate, up to 0.5250 grams per second, due to its higher heat content and volatile compounds compared to rice straw and leaf litter. The speed of combustion in all biomass combustion experiments was adversely affected by shifting the ignition position from the middle to the bottom. Nevertheless, the application of forced air has been demonstrated to enhance the rate of combustion by as much as 45%. The dynamic pattern of mass reduction evolution indicated that varying combustion conditions have an impact on the ultimate residue mass upon completion of combustion. Despite various experimental conditions, more than 10% of combustible materials, such as volatile and char, remained in the residue pile in rice straw and leaf litter combustion. Bagasse combustion identified a higher degree of complete combustion with approximately 2-8% combustible materials left in the residue. In regards to emissions factor, the open burning practices emitted PM from 3 up to 29 g PM/kg fuel, which highlight the importance of different combustion conditions to PM emission. The study found that the use of more initial biomass mass, middle ignition, and natural air flow produced fewer emissions. The implementation of forced air flow led to increased levels of particulates as a result of lower temperatures in the experiments. This was attributed to the higher concentration of inert nitrogen. In contrast, experiments with lower initial biomass mass exhibited slower combustion rates without any significant reduction in flow compared to those with higher initial mass. The open burning experimental campaign unveiled alarming levels of PM emissions, providing valuable insights for policy makers to enhance regulations pertaining to open burning prohibition. Nevertheless, in the absence of a superior waste treatment approach, this study provides a pragmatic suggestion for enhancing open burning techniques. These recommendations include increasing the initial mass, initiating ignition from the central portion of the biomass pile, and conducting the burning process during tranquil weather conditions. The waste-to-energy disposal method also can be promoted by policy maker and industrial community based on this work's finding in more controlled combustion conditions. This work found that sugarcane bagasse biomass combustion involves intricate dynamics in variation of reloading frequency, air fuel ratio and air stagging. The PM emission factor in the utilized fixed bed furnace is recorded to span over 0.37 to 1.98 g PM/kg fuel. The combustion efficiency of sugarcane waste biomass is compromised due to the reduction of excess air supply caused by limited oxygen availability. However, an elevated excess air supply can reduce the temperature of the combustion chamber due to an air-rich environment. Elongated reload intervals lead to a decline in temperature, resulting in higher particulate matter infiltrating the exhaust stream. The presence of secondary air is of utmost importance as it enhances combustion efficiency by strengthening the interactions between air and fuel, while also introducing turbulence. The best combustion condition is attained by utilizing of more frequent biomass reloading with 100% excess air allocating 30% to primary air and 70% to secondary air. Closed burning combustion significantly reduces PM_{10} emission, up to 90% than open burning practices, highlighting the superiority of controlled combustion methods in reducing particulate emissions. This finding holds significant importance in the adoption of agricultural-waste-based industrial furnaces for energy conversion, thereby promoting the production of sustainable energy.

AUTHOR CONTRIBUTIONS

M.G. Nugraha is the main contributor to this work by conceptualizing the study, applying for funding, designing experimental work, analyzing the data, writing the initial manuscript, and finalizing the manuscript. A. Sharfan contributed to performing experiments, analyzing the data and supporting the manuscript writing. V.S.Y. Prakoso is contributed to performing experiments, analyzing the data and supporting the manuscript writing. M. Hidayat contributed to contributed to conceptualizing the study, supervising the experimental work and facilities, reviewing the manuscript. H. Saptoadi contributed to conceptualizing the study, supervising the experimental work and facilities, reviewing the manuscript.

ACKNOWLEDGEMENT

This study was supported in part by the Doctoral Competency Improvement Program Universitas Gadjah Mada Number [7743/UN1. P. II/Dit-Lit/PT.01.03/2023].

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interests regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
μg/m³	Microgram per cubic meter
adb	As dry basis
BMKG	Badan Meteorologi Klimatologi dan Geofisika (Meterological, Climatological and Geophysical Agency of Indonesia)
BPS	Badan Pusat Statistik (Central Bureau of Statistics)
cm	Centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
DED	Detailed engineering design
EF	Emission factor
e.g	Exempli gratia (for example)
ft	Feet
ID	Identity
i.e.	Id est (that is)
in	Inch
g	Gram
g/s	Gram per second
kg	Kilogram
km	Kilometer
km^2	Square kilometer
LPG	Liquiefid petroleoum gas
m	Meter
m^2	Square mile
mg/m^3	Milligram pper cubic meter
mi	Miles
mi^2	Square miles
MJ/kg	Mega Joule per kilogram
mm	Millimeter
NOx	Nitrous oxide
O_2	Oxygen
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter with a diameter of 2.5 microns
PM_{10}	Particulate matter with a diameter of 10 microns

PM/kg	Particulate matter per kilogram
SOx	Sulphur oxide
T25	Thermocouple or temperature reading located at 25 cm above ash pit
T85	Thermocouple or temperature reading located at 85 cm above ash pit
WHO	World Health Organization

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HOW TO CITE THIS ARTICLE

Nugraha, M.G.; Sharfan, A..; Prakoso,V.S.Y.; Hidayat, M.; Saptoadi, H., (2024). Particulate matter emission in agricultural biomass residue combustion. Global J. Environ. Sci. Manage., 10(3): 1047-1066.

DOI: 10.22034/gjesm.2024.03.08

URL: https://www.gjesm.net/article_711238.html