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Investigative Study for Low Particulate Matter Emission
in Rice Husk CombustionEmmanuel Owoicho ABAH^{*1*3}, Tofael AHAMED^{*2}, and Ryoza NOGUCHI^{*2†}

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Biomass combustion is one of the major sources of particulate matter (PM) emission, which forms a crucial part of air pollution. This study investigated the effects of particle size of rice husk and bran impurities on the emission trend of PM_{2.5}. Rice husk from the Koshihikari variety, *Oryza sativa* was prepared into 3.00 g as rice husk samples from Japan (JPN). JPN had no bran impurities and consisted of normal sized Japonica husk particles (4.00 – 5.50 mm). Rice husk from the Nerica rice variety (a hybrid of *O. sativa* and *O. glaberima*) was imported and was prepared into 3.00 g as Nerica rice husk samples from Nigeria (NGR). The samples were smooth rice husk particles (0.10 – 2.00 mm) and had bran impurities. Rice husk briquette was made from JPN samples without a binding material, was prepared into 3.00 g as rice husk briquette (RB) sample. Three samples were combusted in temperatures between 600 °C and 1000 °C for a 3 minutes duration. The experimental set up comprised a Yamato F100 fixed bed electric furnace, Dust Track II aerosol analyzer and Testo 350 flue gas analyzer. Higher PM_{2.5} emission (32.4 mg/g) was recorded for the combustion of RB at 700 °C compared to that of NGR husk (23.7 mg/g) at 800 °C, and JPN (13.6 mg/g) at 900 °C. That is because, RB had a lower surface area and pore volume, which affected its air-fuel mixing during the combustion phases. JPN emitted higher carbon monoxide (1592.4 ppmv) due to higher Sulphur content (0.2wt%db). That caused additional competition for oxygen in the oxidation process of Sulphur from SO₂ emission.

バイオマス燃焼は、大気汚染の主要な原因となる粒子状物質 (PM) の排出源の一つである。本研究では、籾殻の粒径と糠の不純物が、籾殻燃焼時の PM_{2.5} の排出傾向に及ぼす影響を調べた。日本産籾殻試料 (JPN) として、コシヒカリ (*Oryza sativa*) の籾殻 3.00 g を用いた。JPN は糠の不純物を含まず、普通の大きさの籾殻粒子 (4.00 ~ 5.50 mm) であった。ネリカ米 (*O. sativa* と *O. glaberima* の交配種) の籾殻を、ナイジェリア産ネリカ籾殻試料 (NGR) として 3.00 g を用いた。NGR は糠の不純物を有し、小さな籾殻粒子 (0.10 ~ 2.00 mm) であった。籾殻ブリケット (RB) として、結合材を含まない JPN を高温圧縮したものを 3.00 g を用いた。ヤマト F100 固定床電気炉、ダストトラック II エアロゾル分析装置、Testo350 排ガス分析装置を用いて燃焼実験装置を構成し、JPN、NGR、RB を、600 °C から 1000 °C の間の温度で 3 分間燃焼させた。その結果、RB は表面積や気孔容積が小さく、燃焼段階での空燃比に影響を与えていることから、RB の 700 °C 燃焼での PM_{2.5} 排出量は 32.4 mg/g となり、NGR の 800 °C 燃焼 (23.7 mg/g)、JPN の 900 °C 燃焼 (13.6 mg/g) に比べて高くなった。また、JPN 燃焼では、より高い硫黄分 (0.2 wt%db) と高濃度の一酸化炭素 (1592.4 ppmv) が排出されるとともに、SO₂ 排出量が増加した。

Key Words

Temperature, PM_{2.5}, Combustion, Surface area, Particle size, Pore volume, Emission

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1. Introduction

The total world capacity of renewable energy was 2,006,202 MW in 2016, with bioenergy having a share of 109,731 MW¹⁾. Biomass combustion is proven as the most popular technology for heat and power generation. Biomass combustion systems range from small to medium scale plants. The efficiency of heat production from biomass combustion is reasonably high and economically sustainable.

Biomass combustion consists of consecutive heterogeneous and homogeneous reactions. These reactions include drying, combustion of volatile substance, and char/ash combustion. Therefore, biomass combustion has become an important source of particulate matter (PM) emissions. PM is a significant part of air pollution. Air pollution has been a major cause of diseases and deaths especially in the developing countries due to the inability to afford cleaner sources of energy.

Biomass such as rice husk is combusted, using inefficient combustion techniques which emits PM and smoke. Air pollution from biomass combustion is regarded as the third largest contributor to the global burden of disease²⁾. Inefficient combustion of biomass fuels emits a complex mixture of carbon monoxide (CO), PM, and other harmful gases³⁾. The combustion of biomass with high silica ash content such as rice husk, can lead to the emission of chemical compounds⁴⁾.

Studies have shown that emissions from biomass combustion is dependent on temperature³⁾, fuel properties, furnace design and air-to-fuel ratio⁵⁾. Knowledge of specific fuel properties is required in developing measures for emission reduction since pollutant emission (CO, soot and polycyclic aromatic hydrocarbons PAHs) occurs due to incomplete combustion. Studies have been done on advanced combustion systems to study the effect of pelletization, moisture content, nature of the biomass on combustion rates and energy optimization⁶⁾.

However, natural draught systems such as open-air combustion or simplified brick combustion and other similar fixed bed combustion systems are still being used extensively in the developing countries, especially in

rural areas. The inefficiency of these systems becomes a major source of indoor and outdoor pollutions. Therefore, biomass combustion systems require assessments in terms of emission of PM and toxic gases. There is a need to investigate the best-case scenario of biomass combustion in these systems that emits lower PM emissions in a shorter time duration. Also, to understand how to control PM emissions in scenarios where the biomass fuel has been altered during its formation process.

Therefore, the aim of this study is to investigate the effects of particle size, surface area, pore volume and bran impurities of rice husks on PM_{2.5}, carbon monoxide and oxides of nitrogen emissions from briquettes combustion in a fixed bed combustor for a shorter duration.

2. Materials and methods

2.1 Rice husk properties

2.1.1 Physical properties

Three different groups of samples were used in the experiment to control PM and gaseous emissions since the biomass fuel can be easily altered during the process of its formation. In this regard, Japanese and African Nerica rice husks were used in this study. The rice husk briquettes were used for the combustion experiments to solve the problems of low bulk density and extra cost of transportation of rice husk.

The first group of samples refers to the rice husk from Japanese rice Koshihikari variety of the *Oryza sativa* and was prepared into 3.00 g samples and labeled as JPN. JPN samples have no bran impurities and consisted of normal size Japonica husk particles from 4.00-5.50 mm (Table 1).

The second group of samples refers to the African rice husk of the Nerica rice variety (a hybrid of *O. sativa* and *O. glaberrima*) and was imported and prepared into 3.00 g as NGR samples. The samples were smooth rice husk particles between 0.10-2.00 mm size and had bran impurities. The rice husk was obtained from rural milling centers in Nigeria. The NGR particle size was smaller due to the type of rice milling technology used in the rural

Table 1 Properties of JPN, NGR, RB rice husk samples

	JPN	NGR	RB
Variety	Koshihikari	Nerica	Koshihikari
Method of formation	Integrated milling system Non parboiled	Single pass milling system Parboiled	Briquetting (grinding and compressing at 300 °C) Non parboiled
Impurities	-	Bran	-
Average particle size (mm)	4.0-5.5	0.1-2.0	<2.0
Bulk density (g/mL)	0.1	0.3	0.8
Sample weight (g)	3.0	3.0	3.0

areas (single pass milling machines). Single pass milling involves the removal of husk and bran in a single operation.

The third group of samples refers to rice husk briquettes made by grinding and compressing JPN husk temperatures of 300 °C. 1 kg of the rice husk briquette was obtained from a Japanese company and was prepared into 3.00 g per sample. The samples were labelled as RB. The JPN, NGR and RB samples were within the standard moisture content of 10% required for paddy milling. Fig. 1 shows the physical appearance of the three rice husk samples.

2.1.2 C-H-N-S (ultimate) analysis

Ultimate analysis of the samples was determined using the Unicube elemental analysis equipment. Unicube applied elemental's proprietary and improved Temperature Programmed Desorption (TPD) technology for maximum dependability and performance for gas separation. In combination with the most powerful detector available, it has the ability of determining samples with C:N and C:S elemental ratios. The C-H-N-S analysis of all the samples are presented in Table 2. Carbon content represented the quantity of matter from which coke was formed during combustion. Fuel samples containing higher carbon content were expected to have longer coke combustion phase.

Fig. 1 Physical appearance and numerical value of bulk density (g/mL) for JPN, NGR, and RB samples prepared for combustion

Table 2 C-H-N-S elemental of JPN, NGR and RB samples in (wt.%db)

Element	JPN	NGR	RB
C	37.53	39.41	39.37
H	5.05	5.59	5.41
N	0.18	0.67	0.34
S	0.23	0.16	0.11

JPN had lower carbon content (37.53 wt.%db.) than RB (39.37 wt.%db.) and NGR (39.41 wt.%db.). Consequently, RB and NGR samples were expected to have longer coke combustion which serves as additional PM emission source.

2.1.3 Particle size distribution

Particle size distribution was determined using the Beckman Coulter SA3100 experimental gas analyzer. Prior to the analysis, the rice husk samples were oven dried at 105 °C for 5 hours. Gas sorption is the most popular and accurate method for total surface area measurements and pore size, within a range of 0.4 to 200 nm diameter particles. The Coulter SA3100 applied the gas sorption method, which involves the adsorption of gas (adsorbate gas) onto the surface and into the pores of the samples. Adsorption is the condensation of gas molecules onto a sample's surface, while desorption is the removal of gas molecules from the sample. The resultant data is termed adsorption/desorption isotherm. The sample tube assembly was weighed before the rice husk samples were added to the sample tube. Next, the samples were logged for the outgassing procedure. The weight of the outgassed samples was recorded before the analysis.

The Coulter SA3100 analyzer assumed that all the adsorptions were detected as a result of the physically adsorbed gas. It applied the static fully equilibrated volumetric method for adsorption and desorption isotherms. The adsorption process was measured in volumes, using the static fully equilibrated method. The ideal gas law was used in calculating both the free-space and the volume of adsorptive dosed. The amount of gas in moles n , dosed into the measuring manifold is giving by equation (1);

$$PV = nRT \quad (1)$$

where P , V , T and R correspond to pressure, volume, temperature of the dose manifold, and gas constant respectively. The volume statistics (Arithmetic) for JPN, NGR and RB samples are presented in Table 3.

2.1.4 Surface area and pore volume analysis

The surface area and pore volume analysis were determined using the Beckman Coulter SA3100. The Langmuir surface area calculation was applied to the adsorption isotherms data with type 1 properties. Type 1 isotherm can be obtained when the measured sample is

Table 3 The volume statistics (Arithmetic) of JPN, NGR and RB

	JPN	NGR	RB
Volume (mL/g)	0.0243	0.0237	0.0230
Mean (nm)	18.51	24.14	27.09
Median (nm)	10.39	10.72	13.33
Mode (nm)	75.42	81.94	77.77
Calculation range (nm)	3.695-155.8	3.671-146.7	3.807-117.4

microporous, characterized by a rapid rise in the adsorbed volume at low pressure. The Langmuir calculation assumed that only a monolayer is formed. The equation is given below, where V_M is the volume of the monolayer, P_s is the sample pressure, b is the Langmuir constant, and V_A is the volume adsorbed.

$$\frac{P_s}{V_A} = \frac{1}{bV_M} + \frac{P_s}{V_M} \quad (2)$$

Therefore, a linear plot of P_s/V_A vs P_s or P_s/P_o produces the gram monolayer volume V_M . The surface area was then calculated using the equation (3), where $S_{Langmuir}$ is the Langmuir surface area and M_v is the gram molecular volume.

$$S_{Langmuir} = \frac{N_A \times A_M \times V_M}{M_v} \quad (3)$$

The t-plot procedure was used for the calculation of the micropore volume and micropore area. It was used for categorizing and sizing the sample pore structure. The t-plot calculated data (surface area of the meso and macropores, and micropore volume) was then used together with the BET surface area to measure the micropore surface area. The surface area and pore volume analysis of all the samples are presented in Table 4. JPN had higher surface area than NGR and RB samples. Also, the total pore volume of JPN was higher than that of NGR and RB samples. Increasing internal pore volume lead to a decrease in bulk density, hence, JPN had lower density, followed by NGR and RB.

2.1.5 Thermo-gravimetric analysis (TGA)

The Thermo-gravimetric analysis of all the samples was performed using the TGDTA 7300 (differential thermal balance) system. The TGDTA 7300 system was used to measure thermo-gravimetry (TG)/change in mass and DTA (temperature difference) in the sample simultaneously. These were done as a function of temperature or time while changing the temperature of the sample and the reference material according to a preset program. TGDTA can detect, at high sensitivity, chemical changes such as dehydration, decomposition, oxidation and sublimation, evaporation, adsorption and desorption. This model has an auto-sampler

that allows for continuous measurement. The weight of the samples for the thermo-gravimetric analysis was between 10 and 15 mg, using argon gas and air environment. The data was analyzed using the TA-Data analyzing software.

Thermal analysis is a group of techniques that study the properties of materials as they change with temperature. These properties include enthalpy, thermal capacity and mass changes. The furnace was heated up to 700 °C. The typical heating rate was controlled between 10 and 40 °C/min. The decomposition starting and finishing temperatures were determined by the TGA curve. For biomass such as rice husk, the first combustion stage is drying. The moisture content of the samples was released until about 150 °C (Fig. 2). The second combustion stage is the decomposition of the volatile matter. The decomposition starting temperature is the temperature at which the volatile matter combustion was activated (volatile matter temperature). From Fig. 2, the volatiles decomposition started after 150 °C. The decomposition finishing temperature is the temperature at the final curve of the TGA before carbonization. The volatiles decomposition terminal temperature for the samples were 376.3 °C, 424.7 °C and 388.4 °C for JPN, NGR and RB respectively.

The dynamic thermal analyses (TG and DTG) data were obtained for JPN, NGR and RB samples and presented in Fig. 2a – c. It is evident that the volatiles decomposition and TG total loss of the samples varies significantly. From the DTG curve (Fig. 2), JPN and RB underwent a two-stage degradation, compared to NGR which had a four-stage degradation. RB samples had higher TG-loss of 5.4% at 151.2 °C than JPN (5.0%) and NGR (4.6%). This loss is mainly moisture. Consequently, RB volatiles decomposition was lower than that of NGR and JPN. Incomplete combustion of volatiles can lead to more PM emission. The TG curves of all the 3 samples experienced a gradual weight (TG) losses as the temperature was increased. JPN had higher volatiles decomposition (51.1%) than NGR (49.8%) and RB (48.8%), and suggest that, JPN underwent a more efficient thermal degradation than NGR and RB. Therefore, JPN had higher TG loss (63.6%) than NGR (62.0%) and RB (61.2%). JPN had lower density and its drying process started earlier (54.1 °C) than NGR (63.0 °C) and RB (70.0 °C). This implies that, JPN had an overall better drying and decomposition.

Table 4 Surface area and pore volume analysis of JPN, NGR and RB samples

	JPN	NGR	RB
t-plot surface area (m ² /g)	9.829	8.704	8.004
Pore size (Desorp.) vol. (mL/g)	0.02447	0.02368	0.02392
Pore size (Adsorp.) vol. (mL/g)	0.02422	0.02258	0.02245
Total pore vol. (mL/g)	0.0216	0.0193	0.0184
Micropore volume (mL/g)	-0.00329	-0.00305	-0.00272
Langmuir surface area (m ² /g)	0.935	0.378	0.602

2.2 PM_{2.5} and flue gas analysis

This study was limited to particulate matter of size fraction of 2.5 µm. The combustion experiment was limited to temperature range of 600 – 1000 °C. The experimental conditions were limited to laboratory environment and using a small-scale fixed bed incinerator. Consequently, the size

Fig. 2 a: Thermogravimetric analysis of JPN rice husk sample, b: Thermogravimetric analysis of NGR rice husk sample, and c: Thermogravimetric analysis of RB rice husk briquette sample

per sample was limited to 3.00 g. However, the study gives insight and discussed the practical issues with the quantity of rice husk combusted at specific combustion temperatures.

For $PM_{2.5}$ and flue gas samplings, combustion experiments were performed using all the samples. The samples were separately combusted in an electric furnace in temperature categories of 600 °C, 700 °C, 800 °C, 900 °C and 1000 °C. These temperature categories were selected since most biomass is combusted within this temperature

range. The duration of each experiment under each temperature category was 3 minutes. This study adopted the experimental set-up of a previous study³⁾, and a Testo 350 flue gas analyzer was used in this experiment.

The Testo 350 was mounted at the top of the exhaust for flue gas analysis and for the measurement of the flue gas velocity (Fig. 3). The Testo 350 flue gas analyzer is suitable for wide range of professional measurements of industrial emissions. The analyzer consists of two key

Fig. 3 Experimental set-up for flue gas analysis

Fig. 4 Equation derivation illustration for the calculation of PM_{2.5} emission in mg/g

components namely, the control unit and the analysis box. The analysis box comprised sensor system and electronics essential for carrying out emission measurement.

The targeted gaseous emission measurement for these experiments were carbon monoxide (CO) and oxides of nitrogen (NO, NO₂, NO_x). The login interval for the data collection for the dust track II instrument was set at 10 secs mode. A total of 18 points data for 180 secs (3 minutes) was recorded by the instrument for each temperature category (600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C). PM_{2.5} emission (mg/ g) represents the sum of the values from the 18 points data (180 secs) recorded for each temperature category. The total emission for JPN, NGR and RB samples was calculated for each temperature category, using equation (4) and (5) and the illustration presented in Fig. 4.

$$\text{PM}_{2.5} \text{ emission (mg/g)} = \frac{\int_0^{t_1} g(t) * V_t * S * dt}{W_{\text{sample}}} \quad (4)$$

$$= \frac{\sum_{i=1}^{18} g_i * V_i * S * \Delta t}{W_{\text{sample}}} \quad (5)$$

where Δt is the time interval in secs ($\Delta t = 10$ s in this study) and, g_i , V_i , and S are PM_{2.5} concentration at i , flue gas velocity at i , and cross-sectional area of the exhaust pipe (0.00061575 m²), respectively. $g(t)$ is the PM_{2.5} concentration and V_i is the flue gas velocity at time t .

3. Results and Discussion

3.1 PM_{2.5} emission analysis

Fig. 5 shows the result from the combustion of JPN samples and PM_{2.5} emission trend at the different stages of the combustion process. PM_{2.5} peaked between 20 and 60 s (depending on the temperature category) and declined rapidly. The peaked concentration occurred during the brief smoldering phase. The total period of emission as shown by the dotted line was between 10 and 80 secs. That is because, from the surface area and pore volume analysis, JPN had higher surface area and pore volume.

Consequently, a greater portion of JPN samples interacted actively with the combustion air. Also, the large interparticle space of the JPN samples resulted in its lower density, and improved turbulence thus, emitted lower PM_{2.5}. Furthermore, JPN sample had lower carbon content which may have contributed to its low PM_{2.5} emission. Particle size was linearly related to pore space. Also, pore spaces had a negative linear relationship with bulk density.

The thermal gravimetric analysis of JPN showed a two-stage differential thermal degradation (DTG). The first combustion stage (drying) of JPN occurred at an earlier temperature of 54.1 °C (Fig. 2a). And this suggested that the combustion cycle was rapid and efficient. Consequently, JPN had a total TG loss and decomposition rate of 63.6% and 51.1% respectively. Confirming that JPN underwent a rapid decomposition process due to its advantaged pore volume and surface area.

Fig. 6 shows the result from the combustion of NGR samples and PM_{2.5} emission trend at different stages of the combustion process. PM_{2.5} peaked between 20 and 70 s (depending on the temperature category) and declined slowly. The peaked concentration for each temperature category corresponds to the longer smoldering phase of the combustion process. The total period of emission is shown by the dotted line and was between 10 and 130 s

Fig. 5 PM_{2.5} emission trend from the combustion of JPN rice husk for 3 min

Fig. 6 $PM_{2.5}$ emission trend from the combustion of NGR rice husk for 3 min

and signify higher emission as compared to JPN. That is because NGR husk had higher density with smaller particle size rice husk and bran impurities. Which reduced the interparticle space, consequently decreasing the air-fuel mixing.

The bran impurities increased the carbon content of NGR as seen from the C_H_N_S analysis. Also, from the surface area and pore volume analysis, NGR had lower surface area and pore volume compared to JPN. That resulted in low efficiency and delayed flaming combustion stage as confirmed by the TG analysis. NGR had a four-stage DTG, having its first combustion stage at 63.7 °C (Fig. 2b). Thus, compared to JPN, it had a lower volatiles decomposition. Consequently, it had a lower TG- total loss of 62.0%.

Result from the combustion of RB samples and $PM_{2.5}$ emission is presented in Fig. 7. $PM_{2.5}$ peaked between 30 and 140 s (depending on the temperature category). The peaked concentration lasted for longer periods compared to that of JPN and NGR. The peaked concentration for each

Fig. 7 $PM_{2.5}$ emission trend from the combustion of RB samples over 180 secs (3 min)

temperature category corresponds to the longer smoldering phase of the combustion process. The total period of emission as shown by the dotted line was between 30 and 150 s, signifying higher emission.

The surface area and pore volume of RB was less compared to that of NGR and JPN. Consequently, the air-fuel interaction of RB was lower compared to that of NGR and JPN. Therefore, the first combustion stage of RB occurred at 82.9 °C (Fig. 2c). Comparatively, RB had a delayed initial combustion stage compared to NGR and JPN. That can be seen from the lower TG loss and decomposition rate of 61.2% and 48.8%, respectively. Also, the combustion of higher volatile matter fuels emits higher amount of flammable substances which requires the supply of additional air for the complete combustion of these substance⁷. This explains why RB emitted higher $PM_{2.5}$.

Fig. 8 presents the combine comparative result of $PM_{2.5}$ emission in mg/ g, from the combustion of JPN, NGR and RB samples. $PM_{2.5}$ emission from the combustion of JPN increased from a minimum of 5.5 mg/ g at 600 °C to a maximum of 13.6 mg/g at 900 °C. Temperature increase at constant supply of combustion air can affect oxygen availability. Emission from NGR was higher at 800 °C (23.7 mg/g). The high $PM_{2.5}$ emission from NGR was due to the low pore volume and surface area, resulting in low turbulence between the combustion air and the rice husk fuel particles.

JPN had higher pore volume that aided the air-fuel mixing, thus, low emission. Therefore, particle size, fuel density, and interparticle space are not limited to combustion rate only, but also affect $PM_{2.5}$ emission. For RB, emission decreased as temperature increased. High density fuel like RB, requires high temperature for complete combustion. This explained why RB combustion at 1000 °C emitted lower $PM_{2.5}$ (24.4 mg/g) compared to its combustion at 700 °C (/g). These key factors are listed in Table 5.

Fig. 8 Comparative analysis of $PM_{2.5}$ emission from JPN, NGR and RB combustion

Table 5 Key factors affecting PM_{2.5}, CO and NO_x emission from JPN, NGR and RB samples

	JPN	NGR	RB
PM _{2.5} (600-700 °C)	Oxygen availability, pore vol. (carbon content, Improved air-fuel mixing)	Oxygen availability, pore vol. (carbon content, less air-fuel mixing)	Oxygen availability, pore vol. (carbon content, poor air-fuel mixing)
PM _{2.5} (800-1000 °C)	Oxygen deficiency, pore vol. (less air-fuel mixing)	Oxygen deficiency, pore vol. (poor air-fuel mixing)	Oxygen deficiency, pore vol. (poor air-fuel mixing and less volatile matter combustion)
CO(600-700 °C)	Incomplete oxidation (temp. and Sulphur content)	incomplete oxidation (temp. and Sulphur content)	Incomplete oxidation (temp., Sulphur content)
CO(800-1000 °C)	Char combustion (Sulphur content)	Oxidation (temperature, Sulphur content)	Improved oxidation (temperature, Sulphur content)
NO _x (600-1000 °C)	Flaming, smoldering (shorter smoldering)	Flaming smoldering (shorter smoldering)	Flaming smoldering (longer smoldering)

3.2 Carbon monoxide emission analysis

Fig. 9 shows the result of CO emission from the combustion of JPN, NGR and RB samples. CO emission from the combustion of JPN decreased from an initial value of 523.2 ppm-v at 600 °C to 217.3 ppm-v and rapidly increased as temperature increase to 1000 °C. That is because of the incomplete oxidation of the carbon element in the fuel (smoldering phase) caused by oxygen deficiency (Table 5). This result agreed with Mitchella *et al.* (2016)⁸⁾ that during the smoldering phase, the external layer of a fuel particle (char and unreacted fuel particles) decomposed at the center of the particle.

CO emission from RB samples recorded lower emission especially at higher temperatures. That is because the density of RB was higher (0.8 g/mL). RB combustion was gradual and stable than that of NGR and JPN. The higher Sulphur content of JPN as stated in Table 5 indicate that, there was more competition for oxygen during JPN oxidation than that of NGR and RB. The combustion of NGR or RB, which had smaller pore volume/particle size and surface area implies that, the char ignition occurred before the total combustion of volatiles. Also, low competition for

oxygen was observed from Sulphur during the oxidation reaction.

Therefore, char and volatiles combustion occurred simultaneously. Consequently, the volatiles combustion was not completed. Thus, resulted in high PM_{2.5}. JPN emitted lower PM_{2.5} and higher CO emission. Other studies also found weak correlation between PM_{2.5} and CO emission (2, 10). However, Bignal *et al.* (2008)¹¹⁾ found moderate correlation between PM_{2.5} and CO emission.

3.3 Oxides of Nitrogen

Fig. 10 shows the result from the measurement of oxides of Nitrogen (NO₂, NO, NO_x) during the combustion of JPN, NGR and RB samples. RB emitted lower oxides of nitrogen because the combustion was characterized by higher smoldering phase and lower flaming phase. Consequently, lower gaseous emissions. Bignal *et al.* (2008)¹¹⁾ reported that the flaming phase of combustion emitted higher NO compared to the smoldering phase. NO, NO₂ and NO_x originated from the nitrogen in the fuel, therefore, more NO_x was emitted during the flaming phase.

Fig. 9 Comparative analysis of carbon monoxide (CO) emission from JPN, NGR and RB samples

Fig. 10 Comparative analysis of oxides of Nitrogen emissions from the combustion of JPN, NGR and RB samples

3.4 Relationship among rice husk properties, PM_{2.5} and flue gas emission

From the C-H-N-S analysis, NGR and RB had higher carbon content than JPN. Although, this difference was smaller, however, was influential. Also, fuel samples that have higher carbon content, requires longer coke combustion. And coke combustion generates more PM. This partly explains why NGR and RB had higher PM_{2.5} emission compared to JPN. Also, JPN had higher sulphur content (0.23 wt.%db.) compared to NGR (0.16 wt.%db.) and RB (0.11 wt.%db.). This suggest more competition for oxygen as SO₂ was also emitted. Therefore, creating a shortage of oxygen needed for the oxidation of CO into CO₂. This explain why JPN emitted higher CO than NGR and RB. NGR had higher nitrogen content (0.67 wt.%db.) compared to RB (0.34 wt.%db.) and JPN (0.18 wt.%db.). Bran impurities in NGR was a factor and suggested that NGR had more emission of oxides of Nitrogen. Although RB had more nitrogen content than JPN however, JPN emitted more oxides of nitrogen than RB.

JPN had lower mean particle size of 18.51 nm compared to 24.14 nm and 27.09 nm of NGR and RB respectively. This confirms that JPN had higher interparticle space. From the surface area and pore volume analysis, JPN had higher t-plot surface area (9.829 m²/g) than NGR (8.704 m²/g) and RB (8.004 m²/g). Indicating that, a great portion of the JPN sample was in the active combustion phase. Thus, having a rapid flaming combustion phase therefore, emitted lower PM_{2.5}. Also, the total pore volume of JPN was higher (0.0216 mL/g) compared to NGR (0.0193 mL/g) and RB (0.0184 mL/g). Hence, JPN had lower density (0.10 g/mL) than NGR (0.30 g/mL) and RB (0.80 g/mL). Subsequently, JPN had a better air-to-fuel mixing that resulted to low PM_{2.5}.

Interestingly, from the thermo-gravimetric analysis, RB had lower volatiles decomposition (48.8%). This indicates that, RB required higher pressure and secondary air in order to increase its volatiles combustion. The electric furnace used in this study had a constant air speed of 1.5 m/s, which was not enough for adequate oxygen supply for all the studied combustion temperatures and rice husk samples. Therefore, this partly explains why RB emitted higher

PM_{2.5}. That is because, incomplete combustion of volatile matter leads to emission of PM.

As predicted, JPN had higher volatiles decomposition (51.1%) compared to NGR (49.8%) and RB (48.8%) samples. That was due to the lower density, higher surface area and pore volume. Consequently, the TG-total loss of JPN was higher (63.6%) than that of NGR (62.0%) and RB (61.2%). In general, carbon, sulphur and nitrogen contents of the samples affected PM_{2.5} and gaseous emission. Particle size, surface area and pore volume affected the combustion stages, as seen from the insight provided by the thermo-gravimetric analysis. The general effects of rice husk properties on PM_{2.5} and gaseous emission are summarized in Table 6.

4. Conclusions

This study investigated the effects of rice husk properties and bran impurities on PM_{2.5} and gaseous emission. The following points are summarized from this experimental research for JPN, NGR and RB rice husk samples.

- 1) Oxygen availability and pore volume had significant influence on PM_{2.5} at combustion temperature range from 600 – 700 °C.
- 2) JPN had higher pore volume and emitted low PM_{2.5} compared to NGR and RB.
- 3) Increased combustion temperature from 800–1000 °C lead to oxygen deficiency, causing low air-fuel mixing for JPN and NGR. However, RB had better performance because of its high volatile matter content.
- 4) High Sulphur content created competition for oxygen needed for the oxidation of CO to CO₂ and emission of SO₂.
- 5) JPN had higher Sulphur content and emitted higher CO than NGR and RB samples.
- 6) Fuel properties such as surface area, pore volume and density greatly influenced the combustion phases.

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Table 6 Summarized effects of rice husk properties on PM_{2.5} and gaseous emissions

	JPN	NGR	RB
CHNS	Low %Carbon favored low PM _{2.5}	Low %Sulphur favored low CO	Low %Sulphur favored low CO
Surface area, pore volume	High surface area/pore vol. improved air-fuel mixing and increased active combustion area	Low surface area/pore vol. led to Less air-fuel mixing, less active combustion area	Lowest surface area/pore vol. led to poor air-fuel mixing, less active combustion area
TGA	Rapid decomposition	Slow decomposition	Slow decomposition

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