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Effects of Operational Conditions on Rice Husk Biochar Produced Using Charcoal Processing System with Internal Combustion Furnace

Wei-Puo Kuo[1]*, Yutaka Kitamura[2], Yoshiyuki Hara[3], Ching-Chen Hsieh[4], Yi-Hong Lin[1] and Chen-Pin Chen[5]

[1] *Department of Mechanical Engineering, National Pingtung University of Science and Technology, Taiwan*

[2] *Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan*

[3] *Hokkaido Central Agricultural Experiment Station, Takuhoku, Kita-ku, Japan*

[4] *Biomechatronics Engineering, National Pingtung University of Science and Technology, Takuhoku, Kita-ku ,Taiwan*

[5] *QI-MEI Cooperative of friendly farming manager, Qishan Dist., Kaohsiung City,Taiwan*

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***Corresponding author:** Wei-Puo Kuo, Department of Mechanical Engineering, National Pingtung University of Science and Technology, Taiwan

Abstract

This paper reports the biochar quantity and quality using rice husk as a raw material produced using the Charcoal Processing System with Internal Combustion Furnace (CPSICF), which was first used to produce rice husk biochar. The gate width in the CPSICF influenced air intake, which directly affected the temperature of the furnace and played a key role during the pyrolysis process. The biochar productive yield was 33.8%-36.5%. The pH and bulk density of the biochar ranged from 4.9 to 9.8 and 0.10 to 0.11g/cm3, respectively. These results are similar to those for other charcoal processing systems.

Keywords: Rice husk; Biochar; Pyrolysis; Charcoal processing system internal combustion furnace; pH; Bulk density

Abbreviations: CPSICF: Charcoal Processing System with Internal Combustion Furnace; COA: Council of Agriculture; ICF: Internal Combustion Furnace

Introduction

Taiwan, officially the Republic of China, is an island state in East Asia. From Council of Agriculture (COA) statistics, in 2017, the area of farmland in Taiwan was 793,000ha and crop acreage base were 750,000ha. Among the crop acreage base, rice farming accounted for 275,000 ha. In Taiwan, rice farming is divided into the two stages of rice. In 2018, the annual yield was 1.56 million tons, and rice husks accounted for 20% of rice weight [1] and resulted in 312,000 tons of rice husks. Most of the rice husk is used as bedding and fuel which may cause air pollution. The material used in this experiment, rice husk, is the hard-protective layer on rice grain, which could also be used as building materials, fertilizers, insulation, or fuel [2]. Rice husk is the protective layer of rice seeds or grains that protects the seeds during the growing season and is the outer part of the rice grain, also known as rough rice [3]. Rice husk is composed of hard materials, including milky white cerium oxide and lignin fibers, which account for about 20% and 60% [4], respectively.

At the 21st Conference of the Parties, the French Minister of Agriculture Stéphane Le Foll set an ambitious international research program, the “4 per mille Soils for Food Security and Climate” of the Lima-Paris Action Agenda. The “4 per 1000” aspired to increase global soil organic matter stocks by 0.4 percent per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources [5]. In response to this issue, Cao Qigong, the chairman of the COA, announced the new development direction of agricultural science and technology, “Biochar return to land”. He hoped to convert agricultural waste into biochar. By using the property that biochar was not easily decomposed, carbon dioxide in the atmosphere could be sustainably offset into soil. As rice husk production is stable and the production area is concentrated, it has the potential to be the raw material of biochar. Biochar, a porous carbonaceous solid material with a high degree of aromatization and a strong ant decomposition ability, is produced through decomposition of biomass from plant or animal waste under limited oxygen conditions [6]. Biochar can be distinguished from charcoal, used mainly as fuel, as a primary application for a soil amendment with the intention to improve soil function and reduce emissions from biomass that would otherwise naturally degrade to greenhouse gases [7]. Biochar has been under investigation as an approach to carbon sequestration because it has the potential to mitigate climate change. These investigations have resulted in processes related to pyrogenic carbon capture and storage independently. Biochar can increase the soil fertility of acidic soils (low pH soils) and agricultural productivity and provide protection against some foliar and soil-borne diseases [8]. In addition, carbon, oxygen, and CO_2 have atomic masses of 12, 16, and 44, respectively. That means if we stored 1kg of carbon in soil, we could reduce 44/12 × 1kg = 3.67kg of CO_2 in the atmosphere. Indeed, pyrolysis converts 10-50% of the original biomass C into biochar C, which persists in soils for hundreds to thousands of years [9]. Nartey [10] reported that the presence of biochar can decrease the leaching losses of nitrogen and phosphorous in soil and the releases of greenhouse gases (N_2O and CH_4) from soil. Biochar can also be used as a soil improvement material. Because of its porosity and high specific surface area, it can absorb soil nutrients and improve fertilizer utilization [11]. It can also be used as a carrier for microbial fertilizers and as a soil microbial habitat. Biochar chemical alkaline can be used as a material to improve acidic soil [12]; its porous structure can adjust to different soil structures; improve the physical, chemical, and biological functions of soil; and enhance soil fertility [13]. With potassium, calcium, barium, and other elements, it could directly supplement plant nutrients [14].

Farmers use abandoned petrol cans to produce biochar. However, via this process, the quality of biochar is not stable, and the smoke emitted during the combustion process can volatilize in the air, causing air pollution. Furthermore, due to the high temperature the petrol can reach during burning, attention should be paid to the occurrence of fire. In order to mitigate the above disadvantages, the CPSICF was designed in two layers, inside and outside, to prevent the temperature of the outer furnace becoming too high. The chimney was used to collect the exhaust gas and avoid secondary pollution. In addition, by using the CPSICF, operational adjustment and quality could be effectively controlled. The CPSICF is a self-burning equipment that does not need fuel as outer combustion burners or outdoor burning systems do. The most attractive advantages of the CPSICF were its

a) energy-saving ability,

b) human effort–saving ability, and

c) ease of operation.

In this article, rice husk was used as raw material to produce biochar by referring to the CPSICF. The operational conditions were controlled to determine the effect of gate width and vapor cooling in the CPSICF. As a preliminary study of CPSICF, the main purpose of this experiment was to effectively improve the productivity and quality of rice husk biochar and also reduce production costs. The productivity and quality of CPSICF will be revealed.

Materials and Methods

Study site description

The experimental site was in Cishan District, Kaohsiung City, Taiwan. The experiment date was conducted over April 25 to June 13, 2019. Before the experiment, according to Central Weather Bureau weather forecast, data were only accepted on fair weather days: rainfall probability < 10% and no thunderstorms in the afternoon. This helped in reducing the influence of humidity changes during the experiment. During the experiment, the temperature recorded by the Portable Data Station (Yokogawa Electric Co., Ltd, Japan; model Yokogawa XL122-D) was 25°C-35°C. The CPSICF was placed in a tin house to avoid the inference of external airflow with the intake air volume of the CPSICF opening. The rice husk was from the Kaohsiung Cishan Farmer's Association. Care was taken to avoid differences in the experimental results because of the differences in rice husk quality and experimenters' behavioral errors.

CPSICF

(Figure 1) displays the CPSICF structure. Rice husk is placed in the Internal Combustion Furnace (ICF) (6). After burning, the smoke collected by the ICF cover (4) goes through the chimney (3) supported by a strong rod (5) and into cooling water and exhaust purification tank (8). Cooling water is pumped from a cooling water and exhaust purification tank (8) and goes into a cooling water input port (2) and exits from both above and below the cooling water output port (1). The cooling water was divided into two directions. Some went along the chimney to the upper output port, and then back to the tank along the water pipe, which was designed to reduce the temperature of the chimney. The rest was evenly sprinkled on the ICF cover from the output port below, with the water along the edge of the ICF cover recycled back into the tank. This was designed to reduce the temperature of the ICF cover. The effect of the cooling water is discussed in this paper.

Experimental procedure

First, rice husk was filled in the ICF. Then, wood charcoal was placed in the upper section of the ICF in a spiral manner and ignited. The ICF was filled with approximately 40 kg of rice husk. In general, the rice husk completely burned in approximately 1 day. Thereafter, the residual material was sprayed with water to be cooled down and turned into charcoal. If the burning time was too long, the residue became rice ash that could not be collected. In the initial experiment, the effect of the gate width was unclear and preset at 15mm. In this experiment, most of the rice husk turned into ash which couldn't be

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collected. Rafiq et al. [15] reported that ash content increased with increasing temperature. Therefore, pre-experiment revealed that too much air was supplied and the temperature in the furnace was too high, resulting in the rice husk becoming ash. However, because of the pre-experiment result, the gate widths were set to 5.0, 7.5, and 10.0 mm. Each gate width was studied three times and an additional experiment at 5.0 mm without the cooling water was performed to understand the effect of the cooling water. The burning time was controlled to 21 hours to avoid overturning. After then, ICF cover was removed and the inner furnace was sprayed with water.

Temperature

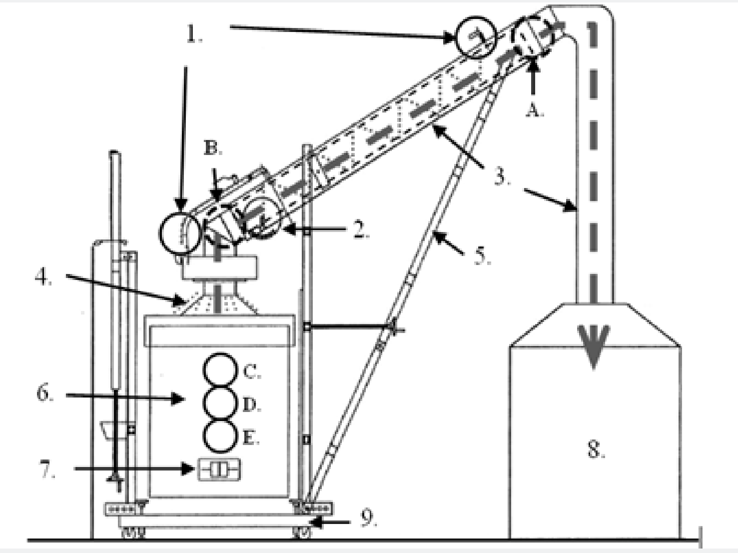

Figure 1: Charcoal Processing System With Internal Combustion Furnace (CPSICF) structure and temperature measurement points.

Legends: 1. Cooling water output port, 2. Cooling water input port, 3. Chimney, 4. ICF Cover, 5. Support, 6. ICF, 7. Air flow gate, 8. Cooling water and exhaust purification tank, 9.Trolley, A. Chimney (FRONT) Temp.1, B. Chimney (END) Temp.2, C. Furnace (TOP) Temp.3, D. Furnace (CTR) Temp.4, E. Furnace (BTM) Temp.5

The temperature change during burning was recorded using the Portable Data Station. The temperature measure points are noted in (Figure 1) at Points A and B (Temp 1 and 2) and they occurred on a chimney. Because of the two-layer design, the temperature change of the outer furnace was nonsignificant. Points C to E (Temp 3-5) in the furnace revealed the actual temperature change. After experiment, temperature changes were arranged into a graph to compare the differences in curve changes under same gate width. If the difference was found to be too large, the experiment would be redesigned. If there was no obvious difference, the result would be averaged to analysis.

Weight

After wet biochar was removed from the furnace and collected, it was spread on tarpaulin and put in tin shelter for air dried. Care was taken to avoid the influence of wind and dust fall. According to COA statistics during experiment date, the temperature and average relative humidity was 20-35°C and 74-81%, respectively. After one month, the dried biochar was collected, and the weight was measured. The results of the same gate width were averaged for analysis.

Biochar yield

The biochar yield was calculated after weight was measured by using the formula:

$$\text{Yield}(\%) = 100 \times \frac{M_{\text{Biochar}}}{M_{\text{Rice husk}}}$$

where Yield (%) is the basis yield of biochar, M_{Biochar} (kg) represents the weight been measured in chapter 2.4., and $M_{\text{Rice husk}}$ (40kg) is the weight of rice husk filled in furnace.

Ash content

After 21 hours of burning, the inner furnace was sprayed with water. Most of the ash flowed to the bottom of the furnace which could not be collected. Because of the design of ICF, there would have a distortion on the real ash content of final product. Therefore, the ash content in this experiment was estimated visually by the same experimenter. The ash content was graded after air dried. The scale was from 1-5 with 5 being the highest ash content obtained. The ash content estimated after each experiment would be recorded and compared in the future to see if there was a difference under the same gate width.

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pH

When the rice husk biochar was removed from the furnace, we collected 20g of biochar from the top, central, and bottom layers, placed it in a 50-mL beaker, added 20g water, and continuously stirred the suspension for 5min. The pH value was measured by pH meter (Thermo Fisher Scientific Inc., America; model Orion Star A329) after the samples were left standing for 30 minutes to allow most of the suspended clay to settle out from the suspension [16]. The value measured each was recorded and averaged for analysis.

Bulk density

Bulk density is defined as the dry weight of soil per unit volume of soil. It can represent the biochar weight of per unit volume. The result can also compare with rice husk bulk density to understand if there are any changes after burning. Biochar was scattered through sieve freely into the Confirmed Volume (V_0) and weight (M_0) vessel until it overflows and carefully scraped the excess powder from the top of the vessel [17]. The weight of biochar and vessel (M_1) was measured by digital scale (A&D Company, Limited Japan; model EK-600i). The bulk density was calculated by using the formula (M_1-M_0)/V_0. Because gate width 5.0, 7.5 and 10.0 was done for three times, the biochar sample was taken averagely. The biochar was scattered at the height of 10, 15, and 20 centimeters. At each height, every sample was done for 10 times and the result was averagely analyzing.

Heat treatment

To understand the effect of heat treatment, the biochar, chosen randomly with completely rice husk shape, obtained images using an electron microscope (JEOL Ltd., Japan; model JSM-6510). Then, it was put in an oven (CHANNEL BUSINESS CO., Ltd., Taiwan; model DV-902) to dry at 105°C for 24 hours and obtained images. The experiment was done without any further study in this article. Only the structural differences before and after heat treatment would be determine.

Results and Discussion

Temperature change in the chimney

(Table 1) lists the temperature recorded on the chimney at points A and B (Temp 1 and 2). Temperature change under same gate widths and between different gate widths was nonsignificant. Most of the temperature change was within the room temperature change. As a result, only the maximum and minimum values are listed in the table. With the addition of the cooling water, the maximum temperature at points A and B (Temp 1 and 2) did not significantly differ between the gate widths (<3**°C**). However, without the cooling water, the maximum temperature of point B (Temp 2) was higher than that with the cooling water (approximately 10**°C** difference). The overall difference between points A and B was approximately 20**°C**. This confirmed that cooling by water affected the temperature on the chimney.

Table 1: Temperature recorded on chimney.

Gate width (mm)	A. Temp 1 (°C)		B. Temp 2 (°C)	
	Min	Max	Min	Max
5	29.4	34.1	28.3	34.8
7.5	29.7	34.9	29	36
10	32.6	36	31.8	38.9
5.0 (no cooling water)	26	31.3	29.7	48.2

After arranged the temperatures recorded in the furnace, it was found that there were few differences in the same width. As a result, the temperature record in gate width 5.0, 7.5 and 10.0mm was averaged. Figure 2 presents the temperatures recorded in the furnace at different gate widths points C, D, and E (Temp 3, 4, and 5). When gate width was 5.0mm, Temp 3 demonstrated a slow upward trend from 32.1°C to 100.7°C. By contrast, Temp 4 increased suddenly after 1 hour 20 minutes of burning; indeed, it only took 60 minutes for the temperature to increase from 34.0°C to 252.1°C; it then decreased gradually after reaching the highest temperature. Temp 5 started rising suddenly after 4 hours 50 minutes, and the temperature was maintained between 350°C and 370°C for 2.5 hours before increasing to 505.7°C after 9 hours. It remained in the range of 505°C-535°C for 7 hours 30 minutes and began decreasing after 16 hours 30 minutes. At gate width of 7.5mm, Temp 3 showed a slow upward trend from 34.3°C to 118.2°C. Temp 4 increased suddenly after 1 hour 50 minutes of burning; it took 45 minutes to rise from 46.4°C to 135.4°C and remained in the range of 125°C-135°C for 2 hours. Temp 4 started its second stage by increasing to up to 199.8°C after 6 hours before slowly decreasing. Temp 5 started increasing suddenly after 4 hours 35 minutes, after which the temperature was maintained between 200°C and 235°C for 2 hours and increased to 523.4°C after 8 hours 50 minutes. It remained at 520°C-553°C for 11 hours 20 minutes and started to decrease after 20 hours 10 minutes.

At gate width of 10.0mm, Temp 3 demonstrated a slow upward trend from 44.4°C to 130.0°C. Temp 4 rose suddenly after 1 hour 40 minutes of burning; after 30 minutes, it increased from 47.6°C to 167.1°C and remained at 130°C-200°C until the end of the experiment. Temp 5 started increasing suddenly after 4 hours 35 minutes and accelerated at 6 hours 15 minutes. After 8 hours, the temperature was maintained in the range of 580°C-632°C until 15 hours 15 minutes, and then started to decrease rapidly.

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At gate width of 5.0mm with no cooling water, Temp 3 increased to 206.4°C after 3 hours 30 minutes and decreased to <100°C at 7 hours 25 minutes and remained in the range of 75°C-100°C until the end. Temp 4 increased suddenly after 2 hours 50 minutes from 50.6°C to 424.3°C and then began decreasing rapidly but then decreased slowly after 8 hours 30 minutes. Temp 5 increased suddenly after 5 hours 10 minutes-100 minutes to increase from 44.2°C to 506.0°C-and then remained in the range of 470°C-545°C until the end. Temperature change in the ICF demonstrated that rice husk was burned from the top layer (point C) to the center (point D) and then reached the bottom (point E). The highest temperature was at the bottom layer (point E). At gate widths of 5.0, 7.5, and 5.0 mm without cooling water, there was no significant difference in Temp 5. However, at gate width of 10.0mm, the highest temperature was 631.93°C; this was 18.63% higher than the highest temperature at gate width of 5.0mm. As the air supply increased in the pyrolysis region, the heat energy received from the oxidation zone increased. This was characterized by an increase in the temperature of the pyrolysis zone [18]. The difference in Temp 3 between different gate widths was nonsignificant. However, without cooling water, the temperature increased to 206.4°C after 3 hours of burning. Thus, the cooling water flowing on ICF cover could ease the burning condition of the top layer.

Table 2: presents the relationship between gate width and physical–chemical characteristics of the biochar.

Gate width (mm)	Biochar Weight (kg)	Yield (%)	Ash (Scale)	pH (-)			Bulk Density (g/cm3)		
				Top	CTR	BTM	10 cm	15 cm	20 cm
5	14.4	36	1	4.9	6	8.8	0.1	0.1	0.1
7.5	13.8	34.5	2	6.9	7.8	8.9	0.11	0.11	0.11
10	13.5	33.8	3	8.6	8.5	9.8	0.1	0.1	0.11
5.0 (no cooling water)	14.6	36.5	1	6.4	7.6	9.1	0.1	0.1	0.1

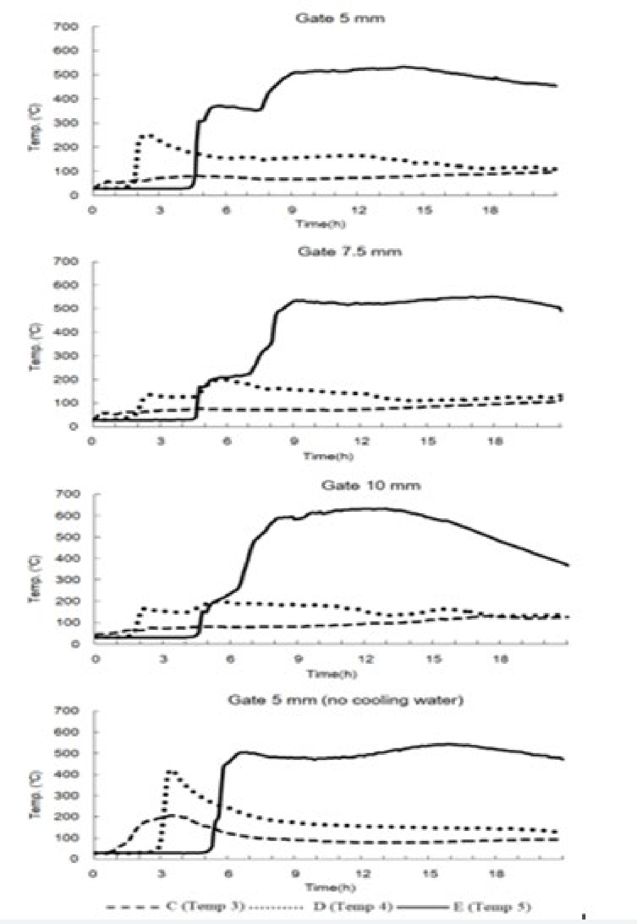
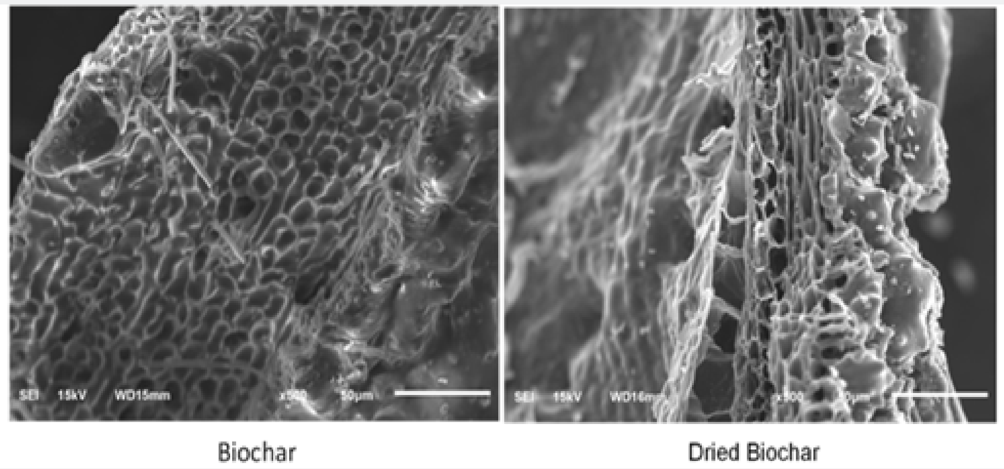


Figure 2: Time course of Temperature recorded in furnace at 3 levels.

The results include biochar weight, yield ash content, pH, and bulk density. The temperature would affect the quality and yield of biochar [19]. Based on Table 2 and Figure 2, we found that the larger the gate width, the higher was the temperature, and it resulted in the yield decreasing from 36.0% to 33.8%. In addition, the ash content increased when the gate width increased from scale 1 to 3. According to Abrishamkesh [20], high temperature and severe pyrolysis conditions enhance biomass decomposition, leading to more ash and fine particles and low yield. Saletnik [21] reported that biochar is a better fertilizer than biomass ash because it has a wider spectrum of activity. At gate width of 5.0mm with and without cooling water, biochar characteristics did not differ. The pH of the bottom layer was higher and that of the top layer was lower compared with other layers. At gate width of 10.0mm, the pH was higher than at other gate widths. Figure 2 and Table 2 reveal that the higher the burning temperature, the higher is the pH of the biochar. A study found that the pH of biochar typically ranges from 4 to 12m [22] and the results of the present study fell within that range. The pyrolysis temperature range at which significant changed in the content of acidic and basic substances were observed was 300°C-500°C [19]. At gate width of 10.0mm, the bottom temperature increased to up to 600°C after 8 hours of burning and this burned out the acidic and basic substances. Asa shown in Figure 2, at gate width of 5.0mm with no cooling water, the temperature of top and central layer was higher than that with cooling water. This resulted in higher pH in the absence of cooling water.

Bulk density obtained at each gate width did not differ much. The bulk density of rice husk was 90–150 kg/m^3 (0.09-0.15g/cm^3) [23]. Thus, the bulk density between rice husk and its biochar was not different. Figure 3 displays biochar and dried biochar taken by electron microscope images (500 × magnification). The multilayer structure and pore space were more obvious after heat treatment. Furthermore, Intani [24] reported the phytotoxic potential of biochar before and after heat treatment and reported that it can reduce the levels of volatile organic compounds and polycyclic aromatic hydrocarbons, thus changing the physicochemical properties such as hydrophobicity and hydrophilicity, in the biochar. Thus, dried biochar may have several potential uses and the utility and efficiency should be further study.



Biochar

Dried Biochar

Figure 3: Biochar and dried Biochar EM photo

Conclusions

In this experiment rice husk was used as raw material and CPSICF to produce biochar. The process characteristics were revealed as follows:

1. The physical properties of biochar in this study included yield, pH value, and bulk density, which were 33.8%-36.5%, 4.9-9.8, and 0.1-0.11g/cm^3, respectively. These results were similar to those of other charcoal processing systems.
2. The International Biochar Initiative [25] revealed the biochar standards including product definition and specification standards. The biochar produced by CPSICF should be tested in the future by using the above standards.
3. According to result of heat treatment, the efficiency on biochar can be further study and focus on the increase of specific surface area and porosity.
4. The temperature change during pyrolysis affected the physical properties of the biochar. The operating procedure of the CPSICF was much easier, and the quality of the obtained material was efficiently controlled by adjusting the gate width.
5. The quality of the biochar obtained from CPSICF gate widths of the 5.0 and 7.5 was not very different. It can be inferred that attention should just be paid to the gate width: A gate width of 5.0-7.5mm provides a high-quality biochar.

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6. Absence of cooling water affected the temperature inside the furnace, but the biochar quality was not affected significantly. However, cooling water could mitigate temperature increase in the chimney.
7. Responding to “4 per 1000”, the rice husk biochar productivity and quality of CPSICF demonstrates a potential. It would be easy for farmers to learn how to use CPSICF making biochar for agricultural use. Furthermore, to reach achievement of sustainable agriculture, the utility of rice husk biochar produced by the CPSICF should be discussed in the future.

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Conflicts of Interest

The authors declare has no conflict of interest.

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