Journal of Agricultural Studies
ISSN 2166-0379
2021, Vol. 9, No. 1

Production and Characterization of Crop Residues Derived Biochars for Soil Amendment and Carbon Sequestration

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Received: Oct. 28, 2020 Accepted: Dec. 2, 2020 Published: Dec. 10, 2020

doi:10.5296/jas.v9i1.17890 URL: https://doi.org/10.5296/jas.v9i1.17890

Abstract

This study focused on the production and characterization of biochars from three types of crop residues comprising cotton stems, corn cobs and sorghum stems. The reactor used was a local cone kiln made from a 200-liter drum. The production parameters measured included the duration of pyrolysis, the amount of biochar produced and the production yield. The chemical characteristics of the biochars were determined using the usual analytical methods used for organic amendment analyses. According to the study, pyrolysis time, biochar quantities and production yields depended on the type of crop residues. The three types of biochar obtained showed high C/N values indicating that their use as soil amendment must be combined with mineral fertilizers to ensure good plant development and crop yield. The heavy metal contents of the three biochar types complied with the international standards recommended for biochars by the International Biochar Initiative (IBI) and by the European Biochar Certificate (EBC). The production and the use of Biochar from crop residues is an interesting alternative for sustainable soil fertility management in the Sahelian countries.

Keywords: soil fertility, organic amendment, biochar, crop residues, pyrolysis

1. Introduction

Soil fertility management in sub-Saharan African countries such as Burkina Faso remains one of the major concerns for agricultural development (Bikienga, 2002). In fact, the low level of agricultural production and the food security problems in this part of the world can be explained by the low level of soil fertility and its continuous decline due to both natural and anthropogenic factors (Yanggen *et al*, 1998). In response to this situation, national and international agricultural research centers have carried out numerous studies to understand and improve soil management and rehabilitation in these countries (Kumwenda *et al*, 1996). Several recommendations such as the application of organic amendments and mineral fertilizers to the soil have been drawn from the scientific results (Sedogo, 1993). Despite the attention given to this problem and the efforts made by most stakeholders, soil degradation continues to compromise the achievement of food security goals in sub-Saharan Africa. One of the causes of this soil degradation is the failure of farmers to comply with research recommendations. As a matter of fact, the recommended doses of mineral fertilizers and organic matter are far from being respected. The situation is further aggravated by the rapid mineralization of the applied organic matter to the soil (Sedogo, 1993). To address this critical issue, biochar is increasingly promoted as a new technology that can sustainably improve soil fertility while minimizing the negative impact of agriculture on the environment (Steiner *et al*, 2008; Wayne, 2012). Biochar is a by-product of pyrolysis, which is a carbonization process that captures the gaseous effluents resulting from the heat transformation of different types of biomass (Lehmann, 2007). It has very remarkable properties both agronomically and environmentally. Biochar incorporated into the soil persists longer and adsorbs cations better than other types of organic amendments (Lehmann *et al*, 2006; Lehmann, 2007, Mahmoud *et al*, 2018). The use of biochar as an amendment improves soil fertility and crop yields (Steiner *et al*, 2008; Glaser *et al*, 2002). It contributes to sequester carbon into the soil and improves soil properties to reduce greenhouse gas emissions (Lehmann, 2007; Laird *et al*, 2010; Collet and Rousseau, 2015; Naisse, 2015). Other studies show a beneficial effect of biochar on soil fertility and plant productivity when combined with fertilizer or manure (Novak et *al*, 2009; Badji, 2011; Xu *et al*, 2012;

Manka'abusi *et al,* 2019; Akoto-Danso *et al*, 2019; Lompo *et al,* 2020).

Biochar can be produced using different types of reactors including locally manufactured reactors and modern ones (International Biochar Initiative (IBI), 2013); Jeguirim and Limousy, 2017). Local reactor models allow for the production of biochar in batch mode that is in small piles of biomass, as opposed to modern reactors that produce biochar continuously. Local reactors are simple to manufacture, less expensive, and allow clean combustion. They are suitable for small farmers because they allow the production of biochar from crop residues and production can reach 1000 kg per day (Anderson, 2013; IBI, 2013).

Biochar can be produced with any kind of plant biomass. However, the quantity and quality of biochar depend on several factors such as the type of raw material used (Singh *et al,* 2010; Wu *et al*, 2012). Indeed, the characteristics of biochar vary much more with the type of biomass used for its production and therefore have different effects on soil properties (Schimmelpfennig and Glaser, 2012). Therefore, the characterization of biochars resulting from the pyrolysis of different feedstock is necessary to adapt the types of biochar suitable for a particular soil type. In Burkina Faso, little is known about biochar technology and scientific research on biochar production and characterization is almost non-existent. The present study was initiated in this framework to produce and characterize biochar from crop residues available in Burkina Faso.

2. Material and Method

2.1. Study Sites

The study was conducted in the INERA research station, Farako-Bâ, Burkina Faso. This research station is about 10 kilometers south of Bobo-Dioulasso and covers an area of 475 hectares. The INERA-Farako-Bâ research station is located at 04° 20' West longitude and 11° 06' North latitude with an altitude of 505 meters above sea level.

2.2 Biomass Types

Three types of crop residues were used which included cotton stems, corn cobs and sorghum stems. These crop residues are available in Burkina Faso, particularly in the western and south-western zones. Also, apart from sorghum stems, cotton stems and corn cobs are so far scarcely or not at all used for animal feed and firewood. Cotton stems are most often burned in the fields during soil preparation while corn cobs are usually discarded or burned by women to collect the ash for potash.

Crop residues were collected in farmer fields and stored in the open air for drying. The cotton and sorghum stems were cut into small pieces of 10 to 15 cm and corn cobs were used without further modification.

2.3 Type of Reactor

The type of reactor used in this study was a local cone kiln made from a 200-liter barrel (Anderson, 2013). This type of kiln is essentially made up of three components: a column or barrel with a perforated bottom and a cut-out upper rim, a cone-shaped lid, and a chimney of

20 cm. These components properly put together as shown in Figure 1 allow good air circulation through the reactor from bottom to top (Anderson, 2013; Frogner and Clayton, 2013). Five cone reactors were locally made for this study.

Figure 1. Type of reactor used in this study: a cone kiln model

This type of kiln allows incandescent pyrolysis or flame pyrolysis to be carried out with a low oxygen supply. The column is filled with dry biomass that is ignited from the top. This fire, deprived of oxygen, heats the underlying biomass leading to the production of pyrolytic gases. The pyrolytic gases move upwards due to a flux air coming from the bottom of the perforated column. These upwardly displaced gases burn and form a clean, smokeless flame due to a second air flux that enters the kiln at the tears located at the upper edge of the column. The dry biomass is thus gradually pyrolyzed from top to bottom (Anderson, 2013).

2.4 Biochar Production Procedure

10 kg of each type of residue was introduced into a reactor in five replicates. The production was made in three steps.

Step 1: The biomass introduction into the kiln. The biomass was carefully introduced without too much compression to allow air circulation. The stems were placed vertically inside the kiln whereas the corn cobs were placed in bulk;

Step 2: The activation of the combustion and carbonization itself. Activation of the carbonization was done by using an easily flammable straw that had been placed above the biomass previously put in the kiln. The charring had already started with the ignition of the activator. The ovens were then closed with their lids to limit the entry of air. At each furnace, the chimneys were placed last to channel the flames. The carbonization was thus carried out from top to bottom until the biomass at the bottom of the furnace was reached.

Step 3. It consisted of stopping the combustion. The charring process was stopped when all the biomass introduced into the kiln had been charred. To know this, straw had been deposited on the ground under de kiln at the beginning of the carbonization. This straw burned when the biomass at the bottom of the kiln was charred. To stop the charring process the embers that is the biochar were turned over and immediately sprinkled with water to prevent them from turning into ash. The produced biochars were weighed and then dried in the open air.

2.5 Biochar Production Parameters

The measured production parameters included the pyrolysis duration (PD), the biochar quantity (BQ), and the biochar production yield (BY). The pyrolysis duration (PD) was measured by recording the start and end times of pyrolysis and using formula (1) to calculate it.

$$PD\ (mn) = (Hend - Hstart) \times 60 \quad (1)$$

Where: PD = Pyrolysis duration in minutes;

Hstart = pyrolysis start time;

Hend: pyrolysis end time.

The biochar quantities (BQ, fresh weight) were determined by weighing the biochar at the end of the pyrolysis process. The pyrolysis yields (PY) were determined using formula (2).

$$PY\ (\%) = BQ/RQ \times 100 \quad (2):$$

Where: BQ = biochar quantity ;

RQ = residue quantity.

2.6 Chemical Analysis of Biochars

The pH of the biochars were determined using a glass electrode pH meter with a biochar/solution ratio of 1/2.5 (McLean, 1982). Total nitrogen (total N), total phosphorus (total P) and potassium (total K) were extracted by digestion in a complex of sulphuric acid, salicylic acid, hydrogen peroxide, and selenium. The determination of nitrogen was carried out by the micro-KJELDAHL method. Total phosphorus was determined calorimetrically using the molybdo-phosphate reduced ascorbic acid method. Potassium was determined by flame emission spectrophotometry (BUNASOLS, 1987). The organic matter content of the biochar was determined using the loss on ignition method by calcination at 650°C. The organic matter (OM) and organic carbon (Corg) contents were calculated with formulae (3) and (4), respectively (Bell, 1964; Conseil des Productions Végétales du Québec, 1988).

$$OM\ (\%) = ((PC+E)-P650)/((PC+E)-PCv) \times 100 \quad (3)$$

Where :

OM = organic matter in %.

PC = dome and sample weight

P650 = weight of the dome and sample after calcination in the furnace at 650°C

PCV = weight of the empty dome

$$Corg\ (\%) = MO/1.7274 \tag{4}$$

Where:

Corg = organic carbon

OM= Organic matter content

The exchangeable cations Ca^{2+}, K^+, Na^+, Mg^{2+} contained in the biochar were displaced by a solution of silver thiourea [Ag $(H_2NCSNH_2)_2^{+2}$]. Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry and K^+ and Na^+ by flame photometry (BUNASOLS, 1987). The trace elements Cu, Fe and Zn were determined by the dry calcination mineralization method. The ashes obtained are first treated with 1N nitric acid HNO_3. After passing through a muffle oven at 673K, the ash was re-dried a second time with 1N hydrochloric acid (HCl). The extraction was done with 0.1 N HCl and the determinations of Cu, Fe and Zn were obtained by atomic absorption spectrophotometry (Pinta, 1972).

2.7 Statistical Analysis

The data were analyzed using IBM SPSS Statistics 22 software (IBM Corporation, Armonk, NY, USA). Data normality tests were performed using the Shapiro-Wilk method. An analysis of variance using the general linear model was performed when the data were normally distributed, and the mean comparisons were performed using the Tukey method. Non-parametric tests were performed for parameters where the data were not normally distributed using the Kruskal-Wallis multiple comparison test for the mean separations.

3. Results

3.1 Variation of Biochar Production Durations According to the Type of Biomass

The differences in biochar production durations were very highly significant ($p < 0.000$). The highest average value of residence time was obtained with corn cobs. The pyrolysis durations of cotton and sorghum stems were statistically equivalent (Table 1).

Table 1. Variation of biochar production duration according to the type of crop residues. Each value represents the mean value (n=5) followed by one standard error of the mean in brackets

Crop residue	Pyrolysis duration (mn)
Corn cobs	37 (1.5) a
Cotton stems	23 (1.8) b
Sorghum stems	20 (1.3) b
P (5%)	0.000
Significance	VHS

Means followed by the same letter do not differ significantly according to Tukey method at the 5% probability (P) threshold; VHS=very highly significant.

3.2 Variation of the Biochar Quantity and the Production Yield According to Crop Residue Types

The biochar quantity was affected by the crop residue type. The amounts of biochar obtained from cotton stems and corn cobs were equivalent ($p>0.05$) but significantly higher than the amount of sorghum derived-biochar ($P<0.05$). The same trends were observed for biochar production yields (Table 2).

Table 2. Variation of biochar quantity and the production yield according to crop residue types. Each value represents the mean value (n=5) followed by one standard error of the mean in brackets

Crop residue	Biochar quantity (kg)	Production yield (%)
Corn cobs	3.1 (0.29) a	31(2.92) a
Cotton stems	3.3 (0.30) a	33 (3.00) a
Sorghum stems	1.8 (0.12) b	18 (1.23) b
P (%)	0.0001	0.0001
Significance	VHS	VHS

Means followed by the same letter within the same column do not differ significantly at the 5% probability (P) threshold; VHS=very highly significant.

3.3 Variation of Biochar Corg, OM, C/N and pH Levels According to the Type of Crop Residues

The Corg contents of biochar varied significantly between 31% and 51% depending on the type of crop residue. The highest level of Corg (51%) was obtained with corn cobs, followed by cotton stems. The lowest level of Corg was obtained with sorghum stems. The same trend was observed in the OM of biochars. The highest C/N ($p<0.05$) was recorded with biochar from corn cobs. Biochars obtained from cotton stems and sorghum stems had statistically equivalent C/N values ($p>0.05$). The C/N values for the three types of biochar ranged from 41 to 88. Significant differences were also observed between the pH values of the produced biochars, which ranged from 7.8 to 10. The highest pH value was recorded with the corn cobs derived biochar followed by sorghum stems-based biochar which was higher ($p<0.05$) than the pH value of the cotton stems-derived biochar (Table 3).

Table 3. Variation of biochar Corg, OM, C/N and pH levels according to the type of crop residues. Each value represents the mean value (n=5) followed by one standard error of the mean in brackets

Crop residue	Corg	OM	C/N	pH
	%			
Corn cobs	50.97 (0.270) a	87.80 (0.583) a	88.20 (0.490) a	10.0 (0.02) a
Cotton stems	49.42 (0,268) b	85.20 (0.374) b	69.40 (4.366) b	9.4 (0.06) c
Sorghum stems	31.49 (0.187) c	54.40 (0.245) c	63.20 (3.734) b	9.7 (0.03) b
P (5%)	*0.000*	*0.000*	*0.000*	*0.000*
Significance	VHS	VHS	VHS	VHS

Means followed by the same letter within the same column do not differ significantly at the 5% probability (P) threshold; VHS=very highly significant.

3.4 Variation of Biochar Nutrient Contents According to the Type of Crop Residue

The total N and total P contents of the three types of biochar were between 0.50% and 1.0% and 0.52 mg.kg^{-1} and 2.61 mg.kg^{-1}, respectively. The cotton stems and corn cobs biochars had identical levels of total N. The biochar derived from corn cobs had a higher total P content as compared to the cotton stems-derived biochar (Table 4).

Table 4. Variation of biochar nutrient contents according to the type of crop residue. Each value represents the mean value (n=5) followed by one standard error of the mean in brackets

Type of biomass	N total	P total	K total	Na	Ca	Mg
	%	------------------------mg.kg^{-1}------------------------			------------g.kg^{-1}------------	
Corn cobs	0.68 (0.069) ab	1.54 (0.081) a	18.67 (0.568) b	0.32 (0.148) ab	1.37 (0.108) c	1.26 (0.052) c
Cotton stems	0.72 (0.046) a	1.03 (0.081) b	32.47 (0.996) a	0.46 (0.075) a	10.32 (0.254) b	4.78 (0.087) b
Sorghum stems	0.52 (0.037) b	1.33 (0.060) a	20.06 (0.531) b	0.08 (0.009) b	11.88 (0.346) a	6.58 (0.161) a
P (5%)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Significance	VHS	VHS	VHS	VHS	VHS	VHS

Means followed by the same letter within the same column do not differ significantly at the 5% probability (P) threshold; VHS=very highly significant.

3.5 Variation of Biochar Heavy Metal Contents According to the Type of Crop Residue

The sorghum stems biochar had the highest Cu content ($p<0.05$) followed by the corn cobs biochar. The lowest Cu content was registered in the cotton stem biochar. The Cu levels ranged from 0.56 mg.kg^{-1} to 23.36 mg.kg^{-1}. The highest Fe content was obtained with sorghum stem biochar ($p<0.05$) and the lowest with cotton stem biochar ($p<0.05$). The Fe contents of the biochars varied between 1.95 $mg.kg^{-1}$ and 6.96 $mg.kg^{-1}$. For Zn, the corn cobs biochar had the highest content ($p<0.05$) followed by sorghum stems biochar ($p<0.05$). The Zn contents of the three biochars fluctuated between 25.64 $mg.kg^{-1}$ and 111.66 $mg.kg^{-1}$ (Table 5).

Table 5. Variation of biochar heavy metal contents according to the type of crop residue. Each value represents the mean value (n=5) followed by one standard error of the mean in brackets

Type de Biomasse	Cu	Fe	Zn
		$mg.kg^{-1}$	
Corn cobs	12.37 (0.127) b	5.39 (0.307) b	111.66 (0.708) a
Cotton stems	0.56 (0.129) c	1.95 (0.057) c	25.64 (2.510) c
Sorghum stems	23.36 (1.196) a	6.96 (0.431) a	106.03 (0.711) b
P (5%)	*0.000*	*0.000*	*0.000*
Significance	VHS	VHS	VHS

Means followed by the same letter within the same column do not differ significantly at the 5% probability (P) threshold; VHS=very highly significant.

4. Discussion

4.1 Effects of Biomass Types on the Pyrolysis Duration

The pyrolysis duration varies according to the type of crop residue. This is due to the lignin content which differs from one type of residue to another. The higher the lignin content the longer the pyrolysis duration (Demirbas, 2006). The duration of charring depends on the size of the biomass fragments, which influences the air circulation in the kiln. As the corn cobs piled up in the kiln it reduced the airflow and thus the pyrolysis speed. This therefore resulted in an extension of the residence time of the corn cobs in the kiln.

4.2 Effects of Biomass Types on the Amount of the Produced Biochar, and the Production Yield

The differences in the lignin content of the different biomasses led to differences in the pyrolysis duration, the amount of the produced biochar and the pyrolysis yield (Demirbas, 2006). The same results were previously reported by Jindo *et al*, (2014) who found some incorporated silica elements into the chemical structure of rice husks.

4.3 Effects of Biomass Types on Biochar Corg, OM Contents, C/N and pH

The Corg content of biochar varied significantly according to the type of biomass and the same trend was observed for the OM in the biochars. Similar results were reported by Laghari *et al*, (2016) who indicated that biomass types induce different levels of Corg or nutrients. The Corg contents (31% to 51%) of the biochar produced in this study is in accordance with the standards of International Biochar Initiative (IBI, 2012) and the European Biochar Certificate (EBC, 2012). This implies that the three studied crop residues are suitable for biochar production as the resulting biochars meet the recommended criteria. The C/N ratios ranged from 41 to 88 for the three types of biochars produced and corroborates Bruun *et al*, (2012) who observed similar values. These high C/N values could lead to soil nitrogen immobilization (Kanouo, 2017) which could compromise good plant development if the use of this biochars is not combined with nitrogen fertilizers. The pH values of the three types of biochar are between 7.8 and 10 and are in line with those reported by most of the studies carried out on biochar (Laghari *et al*, 2016). Similar results were recorded by Singh *et al*, (2010) with tomato-derived biochar. According to Domingues *et al*, (2017) these high pH values of biochar are explained by their high ash content which enriches the biochar with compounds such as $KHCO_3$ and $CaCO_3$ with important alkalizing capacities. Indeed, Yuan *et al*, (2011a) had previously shown that carbonates are the main alkalizing compounds in biochar. The high and different pH values of the three types of biochar produced in the current study revealed their abilities to correct the pH of acidic soils at different levels (Domingues *et al*, 2017). Considering this, the use of these biochars with high pH values is an interesting alternative for raising the pH values of acidic soils in Burkina Faso and the other Sahelian countries.

4.4 Effects of Biomass Types on the Biochar Nutrient Contents

The nutrient contents of the biochars varied according to the type of crop residue. Similar results were observed by Singh *et al*, (2010); Wu *et al*, (2012). According to previous studies conducted by Zhao *et al*, (2013) and Laghari *et al*, (2016) on the pyrolysis of different types of biomass, the characteristics of the biomass including the yield of biochar, Corg content, nutrient content and pH vary according to the type of biomass. The levels of total N, total P, total K and Na were low and are consistent with those of Slavich *et al*, (2013) who found that biochars obtained from crop residues have low content in plant nutrients. However, the same authors have revealed that some biochars derived from crop residues (canola, rice and pea straw) can have high nutrient contents, particularly P and K. The chemical compositions of the biochar depended on the type of biomass but also on the pyrolysis temperature (Yuan *et al*, 2011b). According to Al-Wabel *et al*, (2013), the higher the pyrolysis temperature is, the higher the nutrient contents of the biochar are. However, pyrolysis temperatures above 700°C can lead to P and K losses from the biochar (Laghari *et al*, 2015). Unfortunately, the pyrolysis temperatures were not measured in this study due to the lack of adequate temperature meters. Taking into account the high C/N of the three Biochars produced in this study, it is clear that their use as an amendment must be associated with mineral fertilizers to ensure good plant development and crop yields.

4.5 Effects of Biomass Type on the Heavy Metal Content of Biochars

The biochars Cu contents varied from one type of crop residue to one another and the levels (from 0.56 $mg.kg^{-1}$ to 23.36 $mg.kg^{-1}$) were consistent with those reported by Luo *et al*, (2014) for corn residues (from 20.4-56.7 $mg.kg^{-1}$). The Fe content of the biochar varied between 1.95 and 6.96 $mg.kg^{-1}$ depending on the type of culture residue. López-Cano *et al* (2018) found Fe contents ranging from 0.0 $mg.kg^{-1}$ to 106.9 $mg.kg^{-1}$ in biochar from different biomass sources. The Fe content of the cotton stems biochar (1.95 $mg.kg^{-1}$) was consistent with those reported by Tan *et al* (2017). With respect to Zn, the contents of the three Biochars fluctuated between 25.64 mg.kg^{-1} and 111.66 mg.kg^{-1} and felt within the range of 0.94 mg.kg^{-1} to 207 mg.kg^{-1} reported by Freddo *et al* (2012). Moreover, a recent study by Zhang *et al* (2018) also revealed that the Zn contents of different biomasses varied between 4.91 mg.kg^{-1} and 173.50 mg.kg^{-1}. The three produced biochars from cotton stems, corn cobs and sorghum stems showed heavy metal contents which are in line with the international standards recommended for biochar by IBI (2012) and EBC (2012).

4.6 Agronomic Implications of the Study

The study revealed that the cone kiln reactor model was effective in producing biochar from the three types of crop residues considered in this study. This is valuable information for researchers and mostly for farmers in Burkina Faso who could now produce biochars as soil amendments from different crop residues instead of burning them during field preparations for sowing. The characteristics of the biochars produced depend strongly on the types of crop residues. Their use as agricultural amendments must take that into account to optimize their effectiveness. The produced biochars have alkaline pH and can be used to raise the pH of acidic soils, especially those of Sahelian countries whose pH values are generally very acidic ($4.2 < pH < 5.0$) and acidic ($5.0 < pH < 6.5$; Brady and Weil, 2008, Koulibaly *et al*, 2014). The nutrient contents of the three biochars produced are low, but their carbon contents are very good. Therefore, they should be used mainly for amendment purposes. Considering their high C/N, it is clear that their use as soil improvers must be combined with mineral fertilizers to ensure good plant development and therefore good agricultural yields.

5. Conclusion

The results achieved in this study indicate clearly that the cone kiln model is suitable for biochar production from different crop residues. The production yields obtained using a locally made reactor are related to the type of crop residue and meet the international standards. Moreover, the chemical characteristics of the produced biochars are crop residue-related and they are agronomically interesting. Because of their high C/N, these three biochars can be used as soil amendments but with the addition of mineral fertilizers. These biochars can buffer soils pH at different levels. In a context of climate change combined with poor soil fertility and low agricultural yields in Burkina Faso, the production and the use of biochar is a promising tool for a better valorization of crop residues improved soil fertility. Future investigations are needed with a focus on the opportunities and the risks related to the use of crop residues for producing biochar as soil amendments.

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