Production and Characterisation of Biochar from different Farm Wastes

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Abstract

Three different carbon-rich materials called biochars were produced from three different agricultural wastes using slow pyrolysis technique. The abundance of these wastes (maize cobs, maize stovers and cocoa pod husks) in most farms in Nigeria informed their choice. In this study, the biochars produced were characterized to determine their inherent nutrient potentials as soil amendments for high crop productivity. The percentage mass of biochars obtained were: maize cobs 27.6%, maize stovers 26.0% and cocoa pod husks 22.3% at 332°C, 361°C and 500°C temperature respectively. The highest carbon content (511.1 g kg^{-1}) and total nitrogen (12.1 g kg^{-1}) were obtained from maize stovers biochar, while cocoa pod husks gave the least values. Highest pH (11.98), moisture content (14.0%) and phosphorus (1150.0 mg kg^{-1}) were however obtained in the biochar from cocoa pod husks. We concluded that cocoa pod husks, maize cobs and maize stovers are feedstocks for making biochars of different physical forms and properties and these biochars are potential sources of valuable soil amendments in a humid tropical soil environment.

Keywords: Biochar, charcoal-fired reactor, cocoa pod husks, maize cobs, maize stovers, slow pyrolysis.

Introduction

The ever-increasing population of many countries of the world has necessitated the development of intensive agriculture technologies to sustain food yield. Increasing population and the consequent increased demand for food production and quality in Nigeria require that proposed agronomic strategies for improvement should in general avoid high input costs. Recently, attention has shifted from the use of inorganic fertilizers to organic fertilizers; although application of organic matters such as manure, mulches and composts have frequently been shown to increase soil fertility, the benefits usually last only for one or two growing seasons due to the rapid mineralization of organic matter under the hot, humid tropical environment (Bol et al., 2000; Diels et al., 2004).

In contrast however, biomass-derived black carbon otherwise called biochar, is much more stable. While biochar mineralizes in soil (Goldberg, 1985; Schmidt and Noack, 2000), a fraction remains in a very stable form with a ^{14}C age greater than that of the oldest soil organic matter fractions (Skjemstad et al., 1996; Pessenda et al., 2001; Krull et al., 2006). Instead of allowing agricultural wastes to decompose (which produces CO_2), pyrolysis allows the carbon to be captured in a more stable form which has been found to remain in the soil for a much longer time.

Shackley and Sohi (2010) defined biochar as the porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen depleted atmosphere having properties suitable for the safety, soil enhancement and long-term storage of carbon in the environment. Lehmann et al. (2006) also referred to biochar as a recalcitrant organic carbon compound, created when biomass (feedstock) is heated to temperatures usually between 300°C and 1000°C, under low oxygen concentrations. Biochar is increasingly receiving attention and highly being recommended as soil amendment because it cannot only mitigate climate change by sequestrating carbon from atmosphere into soil (Lehmann *et al*., 2007) but also improve soil properties and enhance soil fertility by improving moisture and nutrients retention capacities (Glaser *et al*., 2002; Lehmann et al., 2003; Bélanger et al., 2004; Major et al., 2010) and cation exchange capacity (Tryon, 1948; Mikan and Abrams, 1995; Glaser et al., 2002; Topoliantz et al., 2002). Other advantages of biochar include, enhanced soil microbial and mycorrhizal activity (Warnock et al., 2007; Thies and Rillig, 2009), soil acidity (Chan et al., 2009), and conductivity

(Asai et al., 2009). All these improve the growth performance and yield of crops (Lehmann et al., 2003; Rondon et al., 2007; Novotny et al., 2009).

The most important factors controlling the properties of the resulting biochar are the pyrolysis conditions (Winsley, 2007). Higher pyrolysis temperatures generally cause greater condensation of aromatic structures and even the formation of graphitic cores (Antal and Gronli, 2003). Benefits from biochar as soil amendments are dependent on biochar characteristics, which further rely on feedstocks and pyrolysis conditions (Lehmann and Joseph, 2009; Roberts et al., 2009; Sohi et al., 2009). Biochar feedstock (Keech et al., 2005; Gundale and DeLuca, 2006) and the maximum temperature attained during combustion influence biochar physical and chemical properties (Gundale and DeLuca, 2006; Lehmann, 2007).

Biochar could be an effective way to manage organic waste, especially given the increasing rate of waste generation in Nigeria, while also improving crop productivity and efficiently sequestering carbon. Despite the numerous uses of biochar in literature, there is dearth of information on the exploration of this valuable, environment-friendly and desirable technology in Nigeria. Biochars derived from various materials show different properties. However, the actual environmental function of biochar in soil has been shown to vary depending on the physical and chemical characteristics of the biochar. Thus, it is essential to well-characterise biochar prior to its incorporation into soils.

Methodology

Farm wastes collection and biochar production

The three organic materials [cocoa pod husk (CPH), maize stovers (MAS) and maize cobs (MAC)] for biochar production were obtained from the Teaching and Research Farm of the Obafemi Awolowo University, Ile-Ife, Nigeria. A charcoal-fired reactor designed and fabricated by Odesola and Owoseni (2010) for small-scale production of biochar was used in this experiment. The organic materials were sun-dried to remove moisture, and cut into small pieces before being fed separately into the reactor. This reactor was made of an insulated outer box with a cover and had two compartments: an inner cylinder compartment and an outer compartment with a space around the cylinder. There was a small opening at the side of the reactor to monitor the temperature; and a lower lid through which raw materials were fed in, and through which biochars were collected (Plate 1).

Cocoa pod husk (9,850 g), maize stovers (17,660 g) and maize cobs (10,940 g) were separately prepared into batches, packed as densely as possible and fed into the cylinder compartment of the reactor through an opening below the reactor and thereafter covered with a lid to prevent inflow of oxygen. Prepared burning charcoal was fed into the space around the cylinder. A stop-watch was used to monitor the time of the operation and the temperature was monitored with the aid of an intelligence digital multimeter which consists of a digital display and a flexible conductor used to sense the temperature during biochar production. The flexible conductor was inserted into a small opening at the side of the reactor made to monitor the temperature. Once the pyrolysis process commenced, the temperature began to increase steadily until it reached a maximum temperature, this was sustained until the flammable and visible gas flow from the non-condensable fractions had ceased and then the temperature began to decline. The maximum temperature reached was recorded as the pyrolysis temperature. After cooling, the biochar was collected via the bottom lid, quenched with water to prevent further combustion, sun-dried and weighed to determine the mass of the biochar produced using the equation (1) below. The un-charred materials were manually separated and weighed.

$$\text{\% mass of biochar} = \frac{\text{mass of biochar obtained}}{\text{mass of raw material}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1).$$

Plate 1: A locally fabricated reactor used for biochar production

Biochar analyses

The biochar was milled and sieved through a 0.05 mm sieve; and the physico-chemical properties of the biochar produced were determined using standard methods (Page *et al.*, 1982). Biochar pH was determined in a 1:2 biochar-water suspension using the Dwyer model WPH1 waterproof pH tester. Carbon content was determined using wet digestion dichromate method. Total Nitrogen was determined using the macro-Kjeldahl method. The available phosphorus in the biochar was determined using the Bray P1 method. Calcium ions, Mg^{2+}, Na^{+} and K^{+} were determined using 1 M ammonium acetate buffered at pH 7.0 as the extractant. The Ca^{2+} and Mg^{2+} concentrations in soil extracts were measured using a Perkin-Elmer Model 403 (Shelton, Connecticut, USA) Atomic Absorption Spectrophotometer (AAS) and the Na^{+} and K^{+} concentrations were measured using a Gallenkamp Flame photometer. The exchangeable acidity was extracted with 1 M KCl and the extract was titrated with 0.05 M NaOH using phenolphthalein as the indicator.

Results and Discussion

Yield of biochar

Maize cobs, maize stovers and cocoa pod husks were slow pyrolysed at 332°C, 361°C and 500°C respectively using a local charcoal-fired reactor to produce different biochars. The biochar yield is shown in Table 1. Maize cobs, maize stovers and cocoa pod husks gave 27.6%, 26.0% and 22.3 % respectively of biochar production. The mass of uncharred materials was also recorded as 107.4 g for maize stovers and 568.4 g for maize cobs while there was no uncharred cocoa pod husk. These yields were higher when compared to results obtained by Mullen et al. (2010) who produced bio-oil and biochar from maize cobs and stovers by fast pyrolysis and found that biochar yield was 18.9% and 17.0% (mass/mass) from maize cobs and maize stovers respectively. Yao et al. (2011) however obtained higher biochar yields of 45.5% and 36.3% of initial dry weight with digested and undigested sugar beet tailings. This difference may not be unconnected with the inherent properties in different farm wastes for biochar productions. Enders et al. (2012) observed that animal litter and solid waste generated a high yield of biochar compared to that from crop residues and wood biomasses.

The high yield of biochar is related to the higher inorganic constituents of the feedstock materials, as indicated by their relatively high ash content (Enders *et al.*, 2012). Pyrolysis temperature plays a significant role in changing biochar characteristics (Antal and Gronli, 2003). The high temperature at which cocoa pod husk was pyrolysed might be responsible for its low yield when compared to the other raw materials and the fact that there were no uncharred materials. The high yield of biochar at low temperatures indicated that the material had been only partially pyrolysed (Katyal et al., 2003). Therefore, the decrease in biochar yields at higher temperature was probably because more organic matter decomposed when the temperature increased. Angin (2003) also observed reduced yields of biochar with increase of pyrolysis temperature and heating rate using safflower seed press cake as organic waste. The decrease in the biochar yields with increasing temperature could either be due to greater primary decomposition or through secondary decomposition of char residues.

Table 1: Yield of biochar produced from different sources

Farm waste	Farm waste Quantity (g)	Biochar Fresh Wt (g)	Biochar Dry Wt (g)	Uncharred Material (g)	Material Produced (%)
CPH	9,850.0	3,285.5	2,194.8	-	22.3
MAS	10,940.0	6,382.0	2,842.3	107.4	26.0
MAC	17,660.0	9,761.1	4,870.7	568.4	27.6

Legend: CPH = Cocoa Pod Husks, MAS = Maize Stovers, MAC = Maize Cobs, Qty = Quantity, Wt = Weight

However, a contrary opinion was reported by Uchimiya *et al*. (2011) who converted cottonseed hulls into biochar at various pyrolysis temperatures ranging from 200 to 800 °C. A rapid decrease in biochar yield was observed at □ 400 °C due to the loss of volatile matter and non-condensable gases such as CO_2, CO, H_2, and CH_4, whereas at > 400 °C, a steady biochar yield was observed. The biochar yield at > 400 °C was fairly consistent because of the low lignin content in cottonseed hulls. A comprehensive comparison among different biochars derived from grass and wood biomass based on pyrolysis temperature was made by Keiluweit et al. (2010). Rapid decline in biochar yield at < 300 °C was reported due to initial dehydration reactions. Relatively lower lignin contents in grass compared to wood caused an earlier thermal breakdown at low pyrolysis temperatures (200–400 °C).

Physico-chemical properties of biochar produced

The selected physical and chemical characteristics of the biochar used in the study are shown in Table 2. Previous studies have suggested that the chemical constituents, such as cellulose, lignin, and hemicellulose contents, of the feedstock may control the yield as well as quality of the biochars (Basta et al., 2009; 2011). The biochars' pH in 1:2 biochar-water suspension ranged from 10.77 to 11.98 indicating their alkaline nature. Biochars made from all the three sources were alkaline in nature, with CPH biochar having the highest value. According to Van Zwieten et al. (2010), the pH of biochar can vary but it is often above 9, and biochar can have a liming value in the order of several tens of percent. In cases where the soil pH is below optimal for its intended use, a rise in pH can provide range of benefits in terms of soil quality, notably by chemically improving availability of plant nutrients, and in some cases by reducing the availability of detrimental elements such as Al (Brady and Weil, 2008). Biochar pH is mostly neutral to basic and the pH of soils has been shown to change to a more neutral pH, especially in acidic soils (Fowles, 2007) after biochar application.

Table 2: Physico-chemical properties of biochars produced

Property	**Value**		
	CPH	**MAC**	**MAS**
pH	11.98	10.77	11.10
Ash (%)	15.69	17.59	16.75
Moisture content (%)	14.00	6.00	2.60
Carbon content (g kg^{-1})	436.10	483.50	511.00
Total Nitrogen (g kg^{-1})	7.40	10.90	12.10
C/N Ratio	58.93	44.35	42.23
Total Phosphorus (mg kg^{-1})	1150.00	700.00	620.00
Na^{+} (%)	0.024	0.018	0.016
K^{+} (%)	0.44	0.36	1.33
Ca^{2+} (%)	0.56	0.16	0.27
Mg^{2+} (%)	0.18	0.10	0.11

Cocoa pod husks were pyrolysed at the highest temperature of 500°C among the farm wastes compared and had highest pH value (11.98) and highest Ca^{2+} concentration. The high pH values of the biochar samples suggest their potential for use as amendments to reduce soil acidity (Verheijen et al., 2009). This agreed with Schneider et al. (2010) who observed increased pH, C content, degree of condensation, specific surface area and sorption capacity of the biochar produced with increased pyrolysis temperatures.

Total phosphorus in the biochars ranged from 620.00 to 1150.00 mg kg^{-1}, moisture contents ranged from 2.6 to 14.0% while ash contents ranged from 15.69 to 17.59%. Mullen et al. (2010) produced biochar from corn cobs and stovers by fast pyrolysis and found that overall ash content of the bio-char was 13.1% for the corn cob bio-char and 32.4% for the corn stover bio-char. Yaman (2004) observed that feedstocks such as soft woods have low ash contents of less than one percent, whereas herbaceous biomass (e.g. grasses and cereals) and manures have higher ash contents of up to 15%. Our findings are not in agreement with the report of Spokas et al. (2012), Wu et al. (2012) and (Ronsse et al., 2013) who stated that increased pyrolysis temperature for biochar production was associated with the increase in ash content and oxygen functional groups occurring during the thermo-chemical conversion of the biomass (Ronsse et al., 2013). Variations in our results with Mullen et al. (2010) may not be unconnected with varietal differences in the maize from which the wastes used for biochar production came from and from the temperature at which pyrolysis took place.

Cocoa pod husk biochar had relatively high values for exchangeable cations, though dominated by Ca^{2+} and K^{+}. Lower pH values in soils (greater acidity) often reduce the CEC and thereby the nutrient availability to plants. Additions of biochar to soil have shown increases in cation exchange capacity and pH (Topoliantz et al., 2002). Increase in CEC results in plants taking up nutrients more easily (Fowles, 2007). The carbon content ranged from 436.1 to 511.0 g kg^{-1}. These values were higher than 308.1 g kg^{-1} obtained by Yao et al. (2011) from the digested sugar beet tailings biochar. The relatively higher carbon contents (400 to 900 g kg^{-1}) of biochars were obtained by Antal and Gronli (2003), Chan and Xu (2009) and Gaskin et al. (2010) from different feedstocks. A low total C content could also indicate that part of the original plant structures remain in the biochar in the form of carbohydrates (cellulose and hemicellulose).

Corresponding increase in the nitrogen content of the biochar produced was obtained. Maize stovers biochar (12.1 g kg^{-1}) had the highest value, while cocoa pod husks (7.4 g kg^{-1}) had the least. Depending on feedstock, the content of total nitrogen may range from almost none in wood-based biochar up to 64 g kg^{-1} in biochar made from sewage sludge (Bridle and Pritchard, 2004; Chan and Xu, 2009). In general, high nitrogen content of biochar can provide nutrients to soil and improve crop productivity (Sanna et al., 2011). A wide range of nutrient concentrations has been detected within different biochars; hitherto, mainly depending on the feedstock that it is derived from (Chan et al., 2009).

Conclusion

We concluded that cocoa pod husks, maize cobs and maize stovers are potential feedstocks for making biochars of different physical forms and properties for the improvement of soil health and crop productivity. The biochars are valuable soil amendments as they contain most of the mineral nutrients needed for enhanced crop growth, and may sequester C due to their high organic carbon content. However, the quantity and quality of the biochar produced highly depends on the nature of the feedstock used.

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