The Potential and Promise of Biochar for Sustainable Soil Productivity and Crop Production

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Abstract

Biochar is the carbon-rich solid product resulting from the heating of biomass in an oxygen-limited environment. Due to its highly aromatic structure, it is chemically and biologically more stable compared with the organic material from which it is made. This paper reviews selected pioneering research works done outside Nigeria on the properties and effects of biochars on soil, plant and environment. The review indicates that when biochar is incorporated into the soil, it can, among other things, increase available nutrients and prevent their leaching, stimulate activity of agriculturally important soil micro-organisms, act as effective carbon sink for several hundred years, displace or greatly reduce requirement for mineral fertilizers, sequester atmospheric CO_2 in the soil, suppress emissions of other greenhouse gases (GHGs), eliminate the inefficient slash-and-burn fallow form of agriculture and mitigate off-set effects from agrochemicals. The paper notes that the manifold benefits of biochar technology are anecdotal in Nigeria. It therefore emphasizes the need to initiate systematic biochar research work in the country. The paper concludes by reporting on the research effort being made at Bowen University at producing biochars from different feedstocks and at characterizing them with a view to assessing them for their agronomic effects.

Keywords: *Biochar, biomass, feedstock, sequester, greenhouse gases*

Introduction

Biochar is the carbon-rich product obtained when biomass such as wood, manure or leaves, is heated in a closed container with little or no available air (oxygen) (Lehmann and Joseph 2009a). It has been proposed as a technology which plays a useful role in building soil health and mitigating climate change. Lehmann and Joseph (2009a) and Flannery (2009) describe biochar as the most potent "engine" of atmospheric cleaning, the most single important initiative for humanity's environmental future and an opportunity for sustainable development of agriculture. According to Rosillo-Calle *et al* (2009), it is a technique that could prove particularly relevant in parts of sub-Saharan Africa where increased soil productivity could provide an important dimension of sustainable rural development.

When added to soil, biochar has been reported to increase available nutrients and prevent their leaching, stimulate activity of agriculturally important soil micro-organisms, act as effective carbon sink for several hundred years, displace or greatly reduce requirement for mineral fertilizers, sequester atmospheric CO_2 in soil, suppress emissions of other GHGs,eliminate the inefficient slash-and-burn fallow form of agriculture and mitigate off-sets from agrochemicals (Lehmann 2007b; Yanai *et al* 2007; Chan and Zu 2009; Thies and Rillig 2009; Gaunt and Cowie 2009).

Extensive research results therefore exist in the literature on the multiple positive effects of biochar. But with many potential raw materials (feedstocks) and varying possible conditions of production, properties of biochar vary widely (Lehmann and Joseph 2009a). Consequently, variability is high on the manifold effects of biochar on soil, plant and environment (Lehmann *et al* 2003b; McLaughlin *et al* 2009; Read 2009; Zwieten *et al* 2009).

Because of such non-uniformity, a universal answer to biochar effects on soil, plant and environment has not been, and probably will not be found. Besides, the picture is not so clear, and there are still many knowledge gaps and misconceptions, as to the specific properties of biochar and the mechanisms which are responsible for its many beneficial effects in agriculture and climate change mitigation.

The questions that have been and are still being asked include: What exactly is biochar? What is the precise nature of biochar and extent of its effect? Is biochar a consumable raw material or just a “catalyst” in the soil system? How stable in soil is biochar? What are the long-term effects on soil? How does biochar behave in different soil types? Are the effects of biochar due to its organic carbon, its nutrients, the charring, its ash or to a combination of these? What role does the parent feedstock (biomass) play on the quality of biochar as a sustainable soil organic conditioner? Is the application of biochar to soil economically viable?

There is no pretence in this review to answer definitely all of the questions raised above. But our aim is rather to state our present knowledge in biochar technology in such a way as to stimulate future research work on the potential of biochar as an effective organic soil amendment. The goal of this paper is therefore to review existing key attributes and behaviour of biochar in the soil system and to point to some aspects of the technology that require future research work. We also briefly review the characteristics and production potential constraints of tropical soils using Nigerian soils as an example. This is because the reported manifold benefits of biochar are most evident on the highly weathered tropical soils such as we have in Nigeria. We conclude by mentioning that a modest research effort is being initiated at Bowen University and making a few remarks. The challenge of the work is to promote biochar technology as a viable alternative to the existing farming systems in the country, practicable at farmer’s level and adoptable by the resource-poor peasant farmers that constitute the bulk of food producers in the country.

The Nigerian Soils

The Nigerian soils are highly variable and are capable of supporting a wide range of crops at least in the short run (Babalola 2002). The seven major types of soil are: (i) Entisols – loose sandy soils on the coast and in Chad basin, (ii) Inceptisols – brown and reddish brown soils found commonly under sparsely vegetated northern parts of the Sudan Savannah, (iii)Hydromorphic and alluvial soils (Fadama soils) – soils found in the river valleys and flood plains and the wastal and deltaic swamps, (vi) Ferrallitic soils – these are ultisols which are intensely weathered, highly leached soils with high content of low-activity clay mineral (Kaolinite) (v) Ferrisols – these are mainly Alfisols, (vi) Highly Ferruginous soils – these are mainly Alfisols and patches of Ultisols which cover areas extending from the forest zone to the Sudan savannah, (vii) Vertisols – these are highly clayey soils which have swelling shrinking characteristics, dark coloured, commonly associated with depressions in the Chad Basin area.

Their production potential constraints

Most of the above listed soils have basic physical and chemical limitations which are not always realized by the layman. The soils, like any tropical soils, are inherently infertile. This is largely because they are highly weathered. Consequently, they have high acidity, low cation exchange capacity (CEC) due to dominance of low activity clay minerals and very low organic matter content, especially after the vegetative cover has been removed under cultivation. Low organic matter content makes the soils behave like "sieves", retaining little water during rainfall and irrigation and little nutrients. Also, the very low organic matter content, especially after the vegetative cover has been removed under cultivation. Low organic matter content makes the soils behave like "sieves", retaining little water during rainfall and irrigation and little nutrients. Also, the very low organic matter content confers a weak structure on the soils. Thus, the soils are fragile and their aggregates collapse readily under the impact of raindrops, making them highly susceptible to soil erosion. In the semi-arid parts of the country, many of the soils have a strong liability to surface crusting or sealing which reduces rainfall intake, encourage runoff and soil erosion (Fagbenro 1990, Babalola 2002).

Efforts to remove or minimize the constraints

(i) **Chemical fertilization**

The inherent capacity of the soils to provide plant nutrients is usually supplemented through the application of chemical fertilizer. But the fertilizers have not had desired impact on food production in Nigerian agriculture. Firstly, it has been reported that less chemical fertilizers are being applied per unit land area in Africa than in other regions of the world (FAO 1989; Brady 1993). Secondly, the poorly buffered tropical soils cannot tolerate a high dose of chemical fertilizers unlike their temperate counterparts. Thirdly, although chemical fertilizers can initially raise crop yields, they have been found not sustainable in the long run as their continous application had been known to deplete soil organic matter, without a corresponding application of organic materials (Madeley 1990), leading to reduction in crop yield and serious soil degradation and decline in soil productivity (Parr *et al* 1984; Zake 1993). Figure 1 is a diagrammatical representation of the soil constraints on crop production.

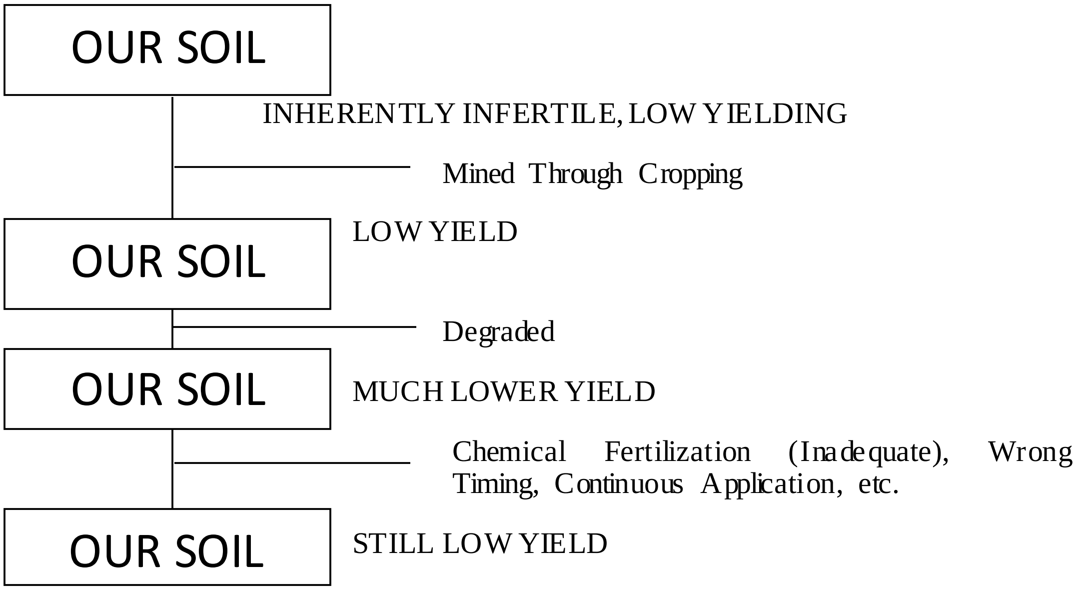

Fig.1. A diagrammatical representation of the soil constraints on crop production
Source: Babalola (2002)

(ii) **Use of Organic input**

Another important mechanism being used in improving the fertility of the tropical soil is through the use of applied organic inputs such as animal manure, green manure and crop residue. But their sole use has also not been found sustainable. Firstly, most of the organic materials are becoming increasingly scarce for use by peasant farmers. For instance, the availability of animal manure can be guaranteed only on farms which are involved in mixed farming (Fagbenro and Olunnga 1989). Secondly, in many tropical cropping systems, enough crop residues are not produced or retained to maintain the fertility of the soil on a sustained basis (Lal 1986; Bouwman 1990b; Aduayi 1991). Thirdly, most organic materials are low in plant nutrients and therefore cannot be used as the sole source of nutrients for optmum crop production (Djokoto and Stephens 1961), except a large quantity is added to soil which may not be feasible in practical situations. Fourthly, these organic materials when added to soil decompose very fast in the humid tropics (Jenkinson and Ayanaba 1977; Tiessen *et al* 1994; Bol *et al* 2000), so that their benefits are often short-lived.

We believe that incorporating biochar into these soils can improve, restore and sustain their productivity in view of the beneficial effects of biochar reported in this review.

What Biochar is

Biochar is a term used to designate a carbon-rich product obtained when a biomass is heated in a closed container with little or no available oxygen (Lehmann and Joseph 2009a). It can therefore be characterized as “thermally-modified biomass” (McLaughlin et al 2009). It is a charcoal or biocarbon destined for addition to soils. According to Wikipedia encyclopedia (2009), biochar is charcoal created by pyrolysis of biomass. Therefore, both charcoal and biochar are carbonaceous residues of pyrolysis. As such, the process of producing biochar is often similar to the production of charcoal (Harris 1999). But biochar is produced specifically for application to soil as part of agronomic or environmental management (Brown 2009). The term biochar also emphasizes biological origin, distinguishing it from charred plastics or other non-biological material (Lehmann and Joseph 2009a).

Biochar production

Biochar is produced from a variety of biomass commonly referred to feedstock. Potential feedstocks include all materials of biological (organic) origin, such as wood, wood chips, saw dust, municipal waste, paper mill wastes, crop residues, forest residues, lignocellulosic dedicated tree crops and animal manures (Amonette & Joseph 2009). These organic materials are plentiful locally in most countries in the humid tropics. But of all these organic materials, lignocellulosic feedstock is an obvious choice as the primary feedstock because it is the most abundant biologically produced material.

A viable and sustainable biochar production is however critically dependent on the quality of feedstock and its sustainable supply (Venuto and Daniel 2010). According to Glover (2009), if biocharand its biofuels and gas are made from intensively farmed foodor wood grade feedstocks, like in the first generation liquid biofuels sector, their overall benefit to sustainability is likely to be limited. Besides, there is currently a controversy on using the limited fertile land resources to produce biomass for bioenergy and for food needs of a growing global human population (Buchmann 2010). Glaser *et al* (2002a) also cautioned that biochar (called charcoal) production for fertilization purposes will only be economically feasible if only organic waste products are charred and applied as fertilizer. This is why Fagbenro *et al* (2011) advocated the use of biomass of shrub and tree legumes and other organic wastes such as municipal waste materials that do not appear to have any higher net resource value in Nigeria than to be converted to biochar and bio-fuels. It is the belief of the authors that the conversion of municipal waste to biochar will afford Nigeria an opportunity to reduce the cost of, or develop income from, management of the wastes that have become environmental pollution and eyesore in her cities and sub-urbans.

Biochar is produced by heating feedstock under limited supply of oxygen, and at relatively low temperatures of below 700^0C (Antal and Gronli 2003; Lehmann and Joseph 2009a). The result is a highly aromatic organic material with carbon concentrations of about 70 to 80% (Lehmann *et al* 2002). Thermal degradation processes that are commonly used to convert biomass to biochar include hydrothermal conversion, torrefaction, fast pyrolysis, slow pyrolysis, gasification and various permutations (Amonette and Joseph 2009). These processes are distinguished chiefly by the presence or absence of free water, feedstock residence time, availability of atmospheric O_2, heating rate, gas environment (e.g. the presence of nitrogen or steam), and the temperatures and pressures used.

The process of producing biochar often mirrors the production of charcoal (Harris 1999). No standard currently prescribes the composition or production of biochar to distinguish it from charcoal produced as fuel (Lehmann and Joseph 2009a) which is the most ancient industrial technology developed by mankind (Harris 1999). According to Brown (2009), the earliest charcoal Kilns consisted of temporary pits or mounds, which have the virtue of simplicity and low cost. These are what we refer to as traditional earthen mound kilns, without energy capture, being used by local charcoal producers. However, conversion of biomass to biochar using this method will more likely range around 30 to 40% as against the use of modern techniques of pyrolysis having temperature, pressure and residence time controls built into the pyrolyser that is likely to give an average recovery of 54% of the initial carbon in the biomass (Lehmann *et al* 2002). According to the authors, improvements in the wood-to-biochar conversion efficiency are feasible with changes in the geometry of the pits or piles and in management of the air supply during the charring process.

Properties of biochar

Structure

According to Lehmann and Joseph (2009a), the question as to what biochar actually is from a chemical point of view rather than from a production point of view is much more difficult to answer due to the wide variety of feedstock and charring conductions used. One of the challenges in characterizing biochar as a class of materials is that it is new and unique in the world of material testing (McLaughlin *et al* 2009).

Nevertheless, the defining property is that the organic portion of biochar has a high C content which mainly comprises so-called aromatic compounds characterized by rings of six C atoms linked together without oxygen (O) or hydrogen (H). Until now, biochar-type materials have largely escaped full characterization due to their complexity and variability (Schmidst and Noack 2000). The structure of biochar-type organic matter was only successfully investigated by Rosalind Franklin in the late 1940s. While efforts to characterize thechemistry ofbiocharare on-going, McLaughlin *et al* (2009) alerted us to the fact that fundamental differences exist between biochars because of the pyrolysis methods, even when the starting feedstock is exactly the same.

Nutrient content

Two factors, feedstock and process conditions, control the amount and distribution of mineral matter in biochars (Amonette and Joseph, 2009). The mineral ash content of feedstocks varies significantly (Table 1).

Table 1. Ash content and elemental composition of representative feedstock

Feedstock	Ash content	Al	Ca	Fe	Mg	Na	k	P	S
	(wt%)	←			(Mgkg^{-1})				→
Coconut shell	0.7	70	1500	120	390	1200	200	90	260
Maize cob	2.8	-[a]	180	20	1700	140	9400	50	9900
Maize stalks	6.8	1900	4700	520	5900	6500	30	2100	13,000
Cotton gin waste	5.4	-	3700	750	4900	1300	7100	740	13,000
Ground nut shell	5.9	3600	13,000	1100	3500	470	18,000	280	11,000
Millet husk	18.1	-6,300	100011,000		1400	3900	1300		150,000
Rice husk	23.5	-1800	530	1600	130	9100	340		220,000
Rice straw	19.8	-	4800	200	6300	5100	5400	750	170,000
Forest residue	1.2	4900	130,000	10,000	19,000	4200	-	-	-
Saw dust	0.44	9,800	170,000	29,000	27,000	10,000	-	-	-
Willow wood	1.1	20	3,900	30	360	150	1400	340	-
Meat and Bone meal	10.4	7600	260,000	4,900	13,000	5,800	23,000	1000,000	-

Note: a = No data reported
Source: Amonette and Joseph (2009).

Woody feedstocks generally have low (<1 percent by weight) ash contents, whereas grass, straw and grain husks, which have high silica contents, may have as much as 24 percent by weight ash (Raveendran *et al*, 1995). Much of the mineral content in the feedstock is carried over into the biochar where it is concentrated due to loss of C, H and O during pyrolysis.

Biochars from manures and other high quality organic materials (in terms of their N content) typically have very high ash contents (Table 2).

Table 2. Elemental composition of some biochars

Biochar Feedstocks	**pH**	**C**	**N**	**P**	**K**	**C/N**	**Production conditions**	**References**
	←		**gkg^{-1}**			→		
Poultry litter	9.9^b	380	20	25.2	22.1	19	450^{0}C	Chan *et al* (2007)
Sewage sludge	a	470	64	56	-	7	450^{0}C	Bridle and Pritchard (2004)
Broiler litter	-	258	7.5	48	30	34	700^{0}C and activated	Lima and Marshall (2005)
Bark of Acacia Mangium	7.4^C	398	10.4	-	-	38	260^{0}C-360^{0}C	Yamato *et al* (2006)
Rice straw	-	490	13.2	-	-	37	500^{0}C	Tsai *et al* (2006)
Coconut shell	-	690	9.4	-	-	74	500^{0}C	Tsai *et al* (2006)
Soybean cake	-	590	78.2	-	-	7.5	550^{0}C	Uzun *et al* (2006)
Eucalyptus deglupta	7.0^d	824	5.74	0.6	-	144	350^{0}C	Rondon *et al* (2007)
Unknown	9.6^c	905	56.4	2.7	51	16	Unknown	Topoliantz *et al* (2005)

Note: a = Data not available
b = pH measured in 0.01M cacl$_2$
c = pH measured in 1MKCl
d = pH measured in de-ionized water

Chicken-litter biochars, for example, can have up to 45 percent mineral matter (Koutcheiko *et al* 2007), and bone biochars may have as much as 84 percent mineral matter (Purevsuren *et al* 2004). But the question is: does biochar serve as a significant source of nutrients irrespective of other inputs?

It is important to note that biochar is somewhat depleted in a number of essential nutrients occasioned by the nature of the pyrolysis or oxidation process that generates it (DeLuca *et al* 2009). Heating causes some nutrients to volatize, especially at the surface of the material while other nutrients become concentrated in the remaining biochar. Individual elements are potentially lost to the atmosphere, fixed into recalcitrant forms or liberated as soluble oxides during the heating process. In the case of wood-based biochar formed under natural conditions, carbon (C) begins to volatize around 100^{0}C, N above 200^{0}C, S above 375^{o}C, and K and P between 700^{o}C and 800^{o}C. The volatization of magnesium (Mg), calcium (Ca) and manganese (Mn) occurs at temperature above 1000^{o}C (Neary *et al* 1999; Knoepp *et al* 2005). Biochar produced from sewage sludge pyrolysed at 450^{o}C contained over 50 percent of the original N (although not in a readily bioavailable form) and all of the original P (Bridle and Pritchard 2004). As noted above, N is the most sensitive of all macronutrients to heating, thus the N content of high-temperature biochar is extremely low (Tyron 1948). Nevertheless, biochar additions to soil do provide a modest contribution of nutrients depending, in part, upon the nature of the feedstock (wood versus manure) and upon the temperature under which the material is formed (Bridle and Pritchard 2004; Gundale and DeLuca 2006).

As a measure of the direct nutrient value of biochars, it is not the total content but, rather, the availability of the nutrient that is an important consideration (Chan and Zu 2009). But considering the long residence time of a typical biochar in the soil system, because of its aromatic structure that makes the compound resistant to microbial degradation (Goldberg 1985), biochar is probably more important as an organic soil conditioner and driver of nutrient transformations and less so as a primary source of nutrients (Glaser *et al* 2002; Lehmann *et al* 2003b).

Biochars can be produced at almost any pH between 4 and 12 (Lehmann 2007b) and can decrease to a pH value of 2.5 after short-term incubation of four months at 70ºC (Cheng *et al*, 2006). The higher the pyrolysis temperature of biochar production, the higher the pH of the biochar. Carbon contents in biochars range between 17.2 and 90.5% (coefficient of variation, CV = 106.5percent). The ranges are even larger in the case of total N (0.18 to 5.64%), total P (0.27 to 48.0%) and total K (0.1 to 5.8%), all with CV≥100 percent (Chan and Xu, 2009).

Changes and stability of biochar in soil

Much of the current understanding of the properties of biochar is derived from studies centred on the phenomenon known as "Terra Preta". Terra preta (literally black earth in Portuguese) refers to expanses of very dark, fertile anthropogenic soils mostly found in the Amazon Basin in Brazil. It is characterized by the presence of low-temperature charcoal (biochar) in high concentrations (Wikipedia encyclopedia 2009). The majority of the biochar applied and incorporated within the soil in this region of the Amazon over centuries underwent various changes and became macroscopically unrecognizable, while enriching the soil with nutrients and changing soil properties (Hammes and Schmidst 2009). This implies that biochar, when added to soil, undergoes changes slowly but surely, over the years. Changes in soil properties have been recorded for different soils to which biochar was added and include increasing the cation exchange capacity and pH of the soil (Liang *et al* 2006; Cheng *et al* 2008).

The macro-molecular structure of biochar is dominated by aromatic C, thus making biochar more recalcitrant to microbial decomposition than the parent organic materials (Baldock and Smernik 2002). But when a fresh biochar is added to soil, the labile fraction of C in the biochar (ca 25%) is mineralized abiotically or biotically to CO_2 within a short period of time (Joseph *et al* 2009). The mineralization of biochar typically shows a two-phased dynamic: a rapid mineralization followed by a slow mineralization. This initial rapid mineralization occurs within a few weeks to a few months for incubations at 20ºC to 30ºC. The mineralization (oxidation) produces carboxylic groups on the edges of the aromatic backbone, which increases the nutrient retention capacity of the biochar (Glaser *et al* 2002a). The abiotic and biotic mineralization of the remaining 75% portion is extremely slow in natural environments hence the long residence time of biochar in the soil (Shneour 1966). However, an increasing number of studies confirm that significant microbial-induced changes take place in biochar in the long term and that the initial abiotic oxidation could actually facilitate further microbial oxidation (Hammes and Schmidt 2009). Therefore, biochar is mineralized in soil and there is no doubt that biochar is not a permanent sink of atmospheric CO_2. Otherwise the earth's surface would be converted into charcoal within a period of time of <100,000 years.

Manifold Benefits of Biochar

Biochar has the potential to deliver a variety of sustainability outcomes, including carbon sequestration, improved soil fertility, mitigation of off-site effects from agrochemicals and renewable energy (Lehmann 2007b). However, the benefits of biochar need to be viewed from a systems perspective in order to fully capture the economic benefits and costs, environmental complexity and energy of the technology.

Biochar systems can be different from each other. Choices are guided by the availability of biomass, the need for soil improvement or the demand for energy. For example, if biochar is added to soil, there are at least four possible outcomes, namely improvements of soils and crop production, mitigation of climate change, reduction of off-site pollution and waste management on an economically viable basis. When a choice of outcome is made, that outcome will be the main objective while others become secondary and biochar production is mainly optimized for that outcome.

In this review, the focus is on using biochar to improve soil productivity and crop production. Therefore, what follows is based on this outcome.

On soil physical property

Our understanding of the influence of biochar on soil physical properties is still incomplete (Gaunt and Cowie 2009). However, recent evidence shows that biochar can influence soil structural properties affecting soil strength, increase soil specific surface area, improve soil surface drainage, soil moisture-holding capacity and infiltration. Chan *et al* (2007) reported that the incorporation of biochar at 50 t ha^{-1} improved soil moisture-holding capacity and reduced tensile strength of soil. However, the extent of changes recorded will depend upon the porosity characteristics of different biochars and application rates (Zweiten et al 2009). Besides, an important disadvantage of using organic residues is that large amounts, between 50 and 200 t ha^{-1}, were required to obtain substantial improvements in both soil water retention capacity and structural stability. For practical field applications, these rates are not realistic (Piccolo et al, 1996). Soil water retention increased by 18% over the control upon addition of 45% (by volume) charcoal to a sandy soil (Tryon 1948). Only in sandy soil did the addition of charcoal increase the available moisture (Table 3).

Table 3. Effect of charcoal on percentage of available moisture in soils on volume basis

Soil	0% Charcoal	15% Charcoal	30% Charcoal	45% Charcoal
Sand	6.7	7.1	7.5	7.9
Loam	10.6	10.6	10.6	10.6
Clay	17.8	16.6	15.4	14.2

Source: Tryon (1948)

In loamy soil, no changes were observed, and in clayey soil, the available soil moisture even decreased with increasing coal additions, probably due to hydrophobicity of the charcoal. Therefore, improvements of soil water retention by charcoal additions may only be expected in coarse-textured soils or soils with large amounts of macropores (Glaser *et al* 2002a).

However, Lehmann *et al* (2003b) reported that biochar can indirectly reduce water mobility in clay soils through increased plant biomass and evaporative surfaces. Biochar addition to soil has been reported to reduce soil bulk density in line with application rates (Watts *et al* 2005) and favour soil aggregation (Warnock *et al* 2007; Cheng *et al* 2006).

Influences of biochar on soil chemical properties and nutrient availability and transformation

Direct influence

Additions of biochar to soil have shown definite increases in the availability of major cations and phosphorus as well as in total nitrogen concentrations (Glaser *et al* 2002; Lehmann *et al*, 2003a). Both CEC and pH are also frequently increased through such applications by up to 40% of initial CEC and by one pH unit respectively (Tryon 1948; Topoliantz *et al* 2005). Higher nutrient availability for plants is the result of both the direct nutrient additions by the biochar and greater nutrient retention (Lehmann *et al* 2003a).

Application of biochar may, indeed, lead to N immobilization (Lehmann *et al* 2003b; Rondon *et al* 2007) due to the presence of a small portion of the freshly produced biochar that is relatively easily mineralizable because of its high C/N ratio. However, the bulk of the remaining organic C (with even higher C/N) does not cause mineralization-immobilization reactions because of its high degree of biological recalcitrance. The application of biochar can decrease the Al saturation of acid soils which often is a major constraint for productive cropping in highly weathered soils of the humid tropics (Cochrane and Sanchez 1980). Based on several studies, biochar is effective in reducing the leaching of all essential nutrients, at least in the short term (Lehmann *et al* 2003b).

Indirect influence

Review of literature has shown that biochar has the potential to modify N, P and S in mineral soils. Its addition to soil has been reported to increase net nitrification in acid forest soils that otherwise demonstrate little or no nitrification (Berglund *et al* 2004). Gundale and DeLuca (2006) reported that biochar addition to soil caused reduced ammonification compared to the control. This is possibly due to NH_4^+ adsorption to biochar (Berglund *et al* 2004). There have been no studies that have directly evaluated the influence of biochar on NH_3 volatization.

But biochar has the potential to catalyze the denitrification process in the soil (DeLuca *et al* 2009). This is because an increase in net nitrification in acid forest soils when biochar is added would be expected to increase its potential for denitrification under anaerobic conditions where available C is high. Biochar addition to soil also significantly increased N_2 fixation compared to a control (Rondon *et al*, 2007). The study further indicates that biochar may stimulate N_2 fixation as the result of increased availability of trace metals such as nickel (Ni), iron (Fe), boron (B), titanium (Ti) and molybdenum (Mo). Phosphorus is as well transformed in the soil in the presence of biochar. Gundale and DeLuca (2006) demonstrated this with an increased extractable PO_4^{3-} from soil amended with biochar made from bark and bole samples of Douglas-fir and ponderosa pine trees. In addition to directly releasing soluble P, biochar can have a high ion exchange capacity (Liang *et al* 2006), and may alter P availability by providing anion exchange capacity or by influencing the activity of cations that interact with P. Furthermore, biochar additions to mineral soils may directly or indirectly affect S sorption reactions and S reduction (Stevenson and Cole 1999). Organic matter additions to soil are known to reduce the extent of SO_4^{2-} sorption in acid forest soils (Johnson 1984). Therefore, biochar amendments may act to increase solution concentrations of P and S in acid iron-rich soils common in the humid tropics.

Effects on soil micro-organisms

Decades of research have shown that biochar stimulates the activity of a variety of agriculturally important soil micro-organisms (Ogawa *et al* 1983). The presence and size distribution of pores in biochar provides a suitable habitat for many microorganisms by protecting them from predation and desiccation and by providing many of their diverse carbon (C), energy and mineral nutrient needs (Warnock *et al* 2007). However, the biochar particles themselves do not appear to act as significant substrates for microbial metabolism as a result of their stability in the soil which ranges from hundreds to thousands of years. Instead, the residual bio-oils on the biochar surface appear to be the only substrates available -in the short term- to support microbial growth and metabolism (Steiner *et al* 2008).

In the Amazonian Dark Earths, which are rich in biochar, microbial community activity, biomass and composition are significantly different from those in adjacent unamended soils (Liang 2008). Jin *et al* (2008), in field studies where mineral soil was amended with varying rates of maize stover derived biochar (0, 1, 3, 12 and 30t ha^{-1}), reported that total microbial respiration and the respiratory rate decreased with increasing biochar added. According to Thies and Rillig (2009), the observed decreased respiratory activity in response to adding biochar to soil could indicate that the biochar is inhibiting the activity of biochar–colonizing microorganisms, changing bacterial to fungal ratio (or population structure), increasing C-use efficiency, and decreasing population abundance or some combination of these responses. Changes may also result from chemisorption of respired CO_2 to the biochar surface. Which of these scenarios is the primary driving mechanism for reduced CO_2 release from biochar amended soils is yet to be resolved. Nevertheless, available research evidence suggests that microbial abundance increases in soils rich in biochar; thus, decreased abundance is not among the driving mechanisms (Zackrisson *et al* 1996). Besides, biochar additions to mineral soil enhance N_2 fixation by rhizobia-nodulating *Phaseolus Vulgaris* and colonization of *arbuscular mycorrhizal* fungi (Rondon *et al* 2007).

Effects on plant growth and development

Positive and, to a lesser extent, negative plant responses as a result of biochar application to soils have been reported for a wide range of crops and plants in different parts of the world (Chan and Xu 2009) (Table 4).

Positive yield responses

Positive responses by plant to biochar addition to mineral soil can be very significant and can be in terms of increase in seed germination, plant growth and crop yields (Glaser *et al* 2002). Chidumayo (1994) reported generally better seed germination (30% enhancement), shoot heights (24%) and biomass production (13%) among seven indigenous woody plants on soils under charcoal kilns compared to the undisturbed soils. Crop yield responses as related to relevant biochar properties are indicated in Table 4.

Table 4. Crop yield responses as related to relevant biochar properties

Feedstock for Biochar and Rate of application	**Crops/ Plants**	**Reponses**	**Reasons for responses given by the authors**	**References**
Unknown wood (0.5t ha^{-1})	Soybean	Biomass increased by 51%	Water-holding capacity and black colour on temperature	Iswaran *et al*,1980
Unknown wood (5t ha-1 and 15 t ha^{-1})	Soybean	Yield reduced by 37 and 71% Respectively	pH-induced micronutrient deficiency	Kishimoto and Sugiura, 1985
Wood for charcoal Production (unknown rates)	Vegetation in charcoal hearth and non-hearth areas compared after 110 years	Tree density and basal area was reduced by 40%	Negative responses due to changes in soil properties	Mikan and Abrams, 1995
Secondary Forest Wood (68t C ha^{-1}) 13t C ha^{-1})	Rice, Cowpea and oats	Biomass of rice increased by 17% cowpea by 43%	Improved P,k and possibly Cu	Lehmann *et al*, 2003b; Glaser *et al*, 2002
Bark of *Acacia mangium* (37t ha^{-1})	Maize, Cowpea and peanut at two sites	Response only at one site (less fertile) with200% increase (fertilized)	Increase in P and N and reduction of exchangeable Al^{3+}, arbuscular mycorrhizal (AM) fungal Colonization	Yamato *et al*, 2006
Secondary forest Wood (11 t ha^{-1})	Rice and Sorghum	Little response with biochar alone, but with a combination of biochar and inorganic fertilizer yielded as much as 880% more than plots with fertilizer alone.	Not stated	Steiner *et al*, 2007
Rice husk (10t ha^{-1})	Maize, Soybean	10 – 40% yield increases	Not clearly understood, dependent upon soil, crop and other nutrients	FFTC, 2007

It should be noted that the effect of biochar on plant productivity depends on a number of factors which include the properties and quantity of biochar added, soil properties, concurrent nutrient and organic matter additions, and plant species (Lehmann and Rondon 2006). Legumes appear to thrive under greater biochar additions more than do gramineae species. Amongst the studies presented in Table 4, Lehmann *et al* (2003b) reported that using wood biochar at rates of 68t C ha^{-1} to 135t C ha^{-1} increased rice biomass by 17 per cent and cowpea by 43 per cent in a pot experiment (in the absence of leaching). As to which attribute of biochar is responsible for the observed plant positive response is yet to be fully resolved. For example, out of the authors of studies reported in Table 3, only one group of authors (Lehmann *et al* 2003b) attributed some of the positive crop response to nutrients supplied directly by the biochar. The authors attributed the positive growth responses to improved P and K and, possibly. Cu nutrition provided by the biochar applied. A few studies attributed the positive plant responses to other effects of biochar on nutrient availability rather than simply as a direct supplier of nutrients (Iswaran *et al* 1980; Lehmann *et al* 2003b; Chan *et al* 2007c; Van Zwieten *et al* 2007) or to increasing or maintaining the soil pH (Hoshi, 2001; Yamato *et al*, 2006; Rondon *et al* 2007; Van Zwieten *et al* 2007 or to improved soil physical properties (Iswaran *et al* 1980) or to reduction in leaching of applied fertilizer N by biochar addition (Lehmann *et al* 2008). Addition of nutrients from using inorganic or organic fertilizers is usually essential for high productivity and increase the positive response of the biochar amendment (Glaser *et al* 2002a; Lehmann *et al* 2002). Chan *et al* (2007C) reported a dry matter increase of up to 266 per cent in radish when 100t ha^{-1} biochar was applied with 100kg N ha^{-1} compared to a control that received the same amount of N but no biochar.

Negative yield responses

Kishimoto and Sugiura (1985) reported yield reductions of soybean by 37 and 71 per cent when biochar was applied at 5t ha^{-1} and 15t ha^{-1}, respectively, and they attributed this to micronutrient deficiency induced by the resulting pH increases. Such pH – induced adverse effect was also reported by Mikan and Abrams (1995), who observed significant retardation of calcifuge plant species in charcoal hearth areas even after 110 years and attributed this to the elevated pH and Ca levels remaining from past charcoal production activities. Therefore, while the alkaline nature and liming value of the biochar might be beneficial for the amelioration of acid soils, with resulting increases in crop production, the same properties might be deleterious to certain plant species (Chan and Xu 2009). These observations highlight the specific nature of some of the soil amendment values of biochars, the limitation of the value of some biochars under certain soil conditions, and importance of a better understanding of the properties of different biochars.

Potential of Biochar in Eradicating Slash-and – Burn Form of Agriculture

The centuries-old slash-and-burn fallow system of agriculture which returns soil organic matter naturally is no longer efficient in maintaining soil fertility in the humid tropics due to increase in human population which allows little, if at all, any potential for bringing new land under cultivation (Lal *et al* 2005). Both from an ecological and economic point of view, it seems most promising to replace slash-and-burn systems by slash-and-char techniques (Glaser *et al*, 2002a). Slash-and-char is an improvement over slash-and-burn system as the former has a reduced negative effect on the environment. It is the practice of charring the biomass (e.g. slash materials, crop residues, etc) resulting from the slashing or cropping instead of burning it as in the slash-and-burn practice.

According to Wikipedia Encyclopedia (2009), slash-and-char offers considerable benefits to the environment, when compared to slash-and-burn: It results in the creation of biochar, which can then be mixzed with other biomass such as crop residues, food wastes, manure and/or other materials, and buried in the soil to bring about the formation of Terra preta which is one of the richest soils on planet earth (Glaser *et al* 2000; 2001a). Fallow periods on Oxisols usually last 8-10 years, whereas fallow periods, if at all, on Terra Preta soils which lead to the effective restoration of their fertility can be as short as 6 months.

Biochar (charcoal) can be easily produced by local farmers under slash-and-char system. The procedures of charcoal production are well known and the required tools and resources (organic materials) are readily available. However, charcoal is a valuable cash product in most countries in the humid tropics (Coomes and Burt 2001). Therefore, it should be emphasized that charcoal (biochar) production for soil fertilization purposes will only be economically feasible if only organic waste products or slash materials/crop residues obtained from the site are charred. Charcoal amendments under slash-and-char systems may not be feasible for large scale farming but is certainly suitable for high-value crops, subsistence farming common in the humid tropics and for horticultural and tree crop nurseries (Jaenick 1999).

Need for Further Biochar Research

Extensive research results on biochar technology exist as reviewed in this paper, but being a new technology, variability is high on the beneficial properties and effects of biochar on soil, plant and environment (Lehmann *et al* 2003b; McLaughlin *et al* 2009; Read 2009; Zwieten *et al* 2009). Besides, much of the knowledge on the manifold benefits of biochar technology is anecdotal in Africa and truer for Nigeria where systematic research is yet to commence. Therefore, there is an urgent need to extend the frontier of scientific knowledge on biochar technology in the humid tropics where there is a compelling need to increase food production per unit area of land in view of increasing human population.

The following are some of the identified areas where further studies are required:

- Effect of biomass feedstock types, pyrolysis conditions, feedstock pre-treatment and particle size on biochar quality and yield.
- The agronomic efficiency of raw and nutrient-enhanced biochar and their long term effects on SOM, plant growth and nutrient-uptake as related to biochar application method, soil type and climatic condition.
- Effect of abiotic and biotic aging on properties of biochar, nutrient leaching and agronomic effectiveness.
- Effect of different types of binder and pelletization on the handling, transportation, storability, application and effectiveness of biochar as a soil conditioner.
- Effect of type and particle size of biochar on soil biota population, type and succession.
- Investigation of effect of moisture, temperature, N fertilization and biochar particle size on the mineralization of applied biochar.
- Demonstration of the economic viability of slash-and-char form of agriculture over slash-and-burn form in different agro-ecological zones and the development of logistics for the adoption of the former by rural farming communities.
- Identification of conditions for co-pyrolysing different feedstock with high quality organic materials and inorganic fertilizers for the production of nutrient-rich biochars having high bioavailability to suit different crops and soils.
- Determination of effect of biochar on mycorrhizal symbioses, mycorrhizal response variables and explanation for mechanism involved.
- Interaction of high mineral contents with C structures in biochar and the implications on biochar stability.
- The mechanisms by which biochar affects N mineralization and immobilization in different ecosystems.
- Biochar effects on nutrient leaching in soil-biocahr and soil-biochar-plant systems in the laboratory and field.

- Determination of biochar optimal application rate for different soils, plant species and biochar types.
- Evaluation of the agronomic effectiveness and the economic viability of biochar as a soil amendment under field conditions.

Biochar Research at Bowen University, Nigeria

Background and Primary objective

The biochar research project was begun in January 2010. The on-going project is being funded by Bowen University. The main focus of the project is on the provision of a cleaner environment and enhancement of soil productivity and food security hence the title of the project, "Utilization of saw dust, municipal organic wastes and selected wooden biomass materials as soil conditioners and fertilizers for plant growth". The stimulus for the project emanates from the fact that saw dust and municipal wastes are two major sources of environmental pollution in our cities and sub-urbans. In addition, our environment is blessed with a variety of other biomass materials such as wood, wood chips, paper mill wastes, forest residues, crop residues, lignocellulosic tree crops and so on. So, the primary objective of the project is to explore different ways of producing biochar from these selected organic materials to overcome soil constraint of SOM depletion which is militating against sustainable soil productivity and crop production in the country. The challenge of the project is to make the production of biochar sustainable with respect to biomass supply and practicability at farmer's level and to accomplish the widest possible adoption of the slash-and-char form of agriculture by peasant farmers, first in Iwo land and later throughout the country, with a view to improving their livelihood.

The journey so far

Sourcing for feedstocks

Assessment of pattern of refuse disposal and type of wastes generated had been completed in four urban centres, namely Iwo, Ile-Ogbo, Ede and Ilesha and two sub-urban centres of Ikonifin and Telemu in Osun State. In each sampling centre, four refuse dumping sites were purposively selected (SW, SE, NW, NE), assessed, sampled and sorted. Saw dust samples were also collected in each of the centres. Data emanating from the survey are being analyzed chemically and statistically.

Biochar production and characterization

We have succeeded in producing and characterizing ten biochar types using the traditional earthen mound kiln method without energy capture. The temperature of production is about 350^0C.

The feedstocks used are as follows:

(i) Saw dust
(ii) Sorted municipal organic wastes
(iii) Swine dung
(iv) Leucaena leucocephala
(v) Gliricidia sepium
(vi) Moringa oleifera

The choice of the feedstocks is based on their abundance in the landscape so as to ensure their sustainability of supply. According to National Academy of Sciencess (NAS 1979), nitrogen fixing trees are lignocellulosic plants that grow abundantly in the wild over the entire tropical and subtropical land mass. They have also been reported to have strategic sustainability advantages of biomass supply since they can be grown in a fallow as a short-rotation dedicated crop (Crucible Carbon 2008), produce N-rich biomass, are perennial rather than seasonal crops, do not require prime agricultural land, and do not appear to have any higher net resource value in Nigeria than to be converted to biochar and bio-fuels (Fagbenro *et al* 2011). Moringa is selected in view of its multi-purpose nature and its reported high nutrient concentration in the biomass (Fahey 2005). This feedstock was either used singly or in combination (1:1, w/w) to give the following ten biochar types:

(i) Saw dust biochar
(ii) Leucaena biochar
(iii) Gliricidia biochar
(iv) Moringa biochar
(v) Municipal waste biochar
(vi) Municipal waste/Leucaena biochar
(vii) Saw dust/Gliricidia biochar
(viii) Municipal waste/Moringa biochar
(ix) Saw dust / Leucaena biochar
(x) Saw dust/Swine durng biochar

Plates 1 and 2 show two of the biochars in picture.

Plate 1

Plate 2

Establishment of slash-and-burn/slash-and-char research farm

The project has also established a research farm which we choose to call slash-and-burn/slash-and-char research farm. The farm was established at the beginning of year 2010 planting season. It was planted to maize. The farm, as shown in Plates 3 and 4 in picture, has twelve treatments and five replications, making a total of 4 by 4m 60 plots.

Plate 3

Plate 4

The main purpose is to assess effects of twelve different forms of farming systems common in the humid tropics on the growth and yield of crops and to investigate how applications of biochar can be integrated into working farm's cultivation practices to improve crop output and growth, especially by incorporating the material as an effective soil amendment in Iwo's marginal sandy soils. As its name implies, the treatments include burning and not burning, charring and not charring, biochar addition, inorganic fertilization and so on. More information on the farm will emerge later as the studies progress. The farm is established to be a permanent one, similar to the Rothamsted International Research Farm in the United Kingdom.

Recommendation and Conclusion

Using biochar as a tool for improving soil fertility while at the same time increasing C sequestration in soil is far from being a well-recognized technology in Nigeria. Both the wide variations in feedstock properties and production conditions have significant effects on biochar properties. The high number of possible combinations of both feedstock and production types make it very difficult to predict and compare biochar properties and its effects. Because of such non-uniformity, a universal answer to biochar effects on soil, plant and environment has not been, and probably will not be, found.

Nevertheless, this review has indicated positive and negative effects of biochar additions on soil properties and crop productivity and has demonstrated its potential in eradicating the now inefficient centuries-old slash-and-burn form of agriculture. However, there is an urgent need to conduct further site-speccific systematic research to annex the full potential of biochar technology particularly in Nigeria where very little, if at all, biochar research has been carried out. It is our utmost hope and desire to put biochar research on a sound footing in Nigeria as it is being done in different parts of the world. We must always remember that tropical farming is organic farming; biochar farming?

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