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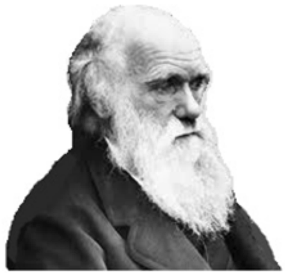

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Biochar: Promoting Crop Yield, Improving Soil Fertility, Mitigating Climate Change and Restoring Polluted Soils

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ABSTRACT

The agricultural and environmental sectors are plagued with challenges. In agriculture, soil infertility and the subsequent quagmire of poor crop yield, has always been a major problem that limits worldwide agricultural productivity. Major environmental concerns, including Climate Change and Soil Pollution, are receiving continual attention from key stakeholders. Efforts are hence being directed at curtailing or mitigating the devastative consequences of these man-made ‘monsters’. Recently, agricultural and environmental research reveals biochar to be a veritable technology that could be used to deal with some of these concerns. Biochar has the ability to have impact upon important soil properties, such as the raising of soil pH and water holding capacity, the attraction of beneficial fungi and microbes, improvement of cation exchange capacity (CEC), induce high carbon sequestration ability and nutrient retention capacity. Moreover, its large surface area makes it a potential remedy to several identified challenges. This review, therefore, critically highlights the importance of biochar, as well as the various ways of harnessing biochar technology towards global food security and environmental sustainability.

Keywords**:** Biochar, agricultural productivity, carbon sequestration, climate change

INTRODUCTION

Biochar is a stable carbon (C) compound created when biomass (feedstock) is heated to temperatures between 300 and 1000 ºC, under low (preferably zero) oxygen concentrations. Though biochar is a relatively new term proposed by Peter Read in 2005, its practice dates back to about 2000 years ago. Soils throughout the world contain biochar deposited through natural events, such as forest and grassland fires. In fact, areas high in naturally occurring biochar, such as the North American Prairie (west of the Mississippi River and east of the Rocky Mountains), are some of the most fertile soils in the world. In the Amazon Basin, evidence of extensive use of biochar can be found in the unusually fertile soils known as Terra Preta and Terra Mulata, which were created by ancient, indigenous cultures.

The modality of biochar in its ability to act as an effective soil amendment is similar to the traditional "slash-and-burn" fertilization method in most shifting cultivation systems, where farmers remove the vegetation and release a pulse of nutrients to fertilize the soil. But the "slash-and-burn" practice has an unfavorable environmental reputation because it is associated with deforestation and air pollution. A 2006 article by soil scientist Johannes Lehmann, Chair of the International Biochar Initiative as a lead author, claims: "Existing slash-and-burn systems cause significant degradation of soil and release of greenhouse gases. Global analysis revealed that up to 12% of the total anthropogenic Carbon emissions by land use change (0.21 Pg C) can be off-set annually in soil, if slash-and-burn is replaced by slash-and-char.

In fact, the charring step fulfills the same requirements as the normal burning except for the absence of oxygen during pyrolysis charring. According to the same study, slash-and-burn farming converts only 3% of the original biomass to charcoal. If this woody aboveground biomass were converted into bio-char by means of simple kiln techniques and applied to soil, more than 50% of this C would be sequestered in a highly stable form.

These characteristics make biochar an exceptional soil amendment for use in sustainable agriculture.

When used as a soil amendment, biochar has been reported to boost soil fertility and improve soil quality by raising soil pH, increasing moisture holding capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity (CEC), and retaining nutrients in soil. While raw organic materials supply nutrients to plants and soil microorganisms, biochar serves as a catalyst that enhances plant uptake of nutrients and water. Compared to other soil amendments, the high surface area and porosity of biochar enable it to adsorb or retain nutrients and water and also provide a habitat for beneficial microorganisms to flourish [1-38].

Biochar Production

In many agricultural and forestry production systems, waste is produced in significant amounts from crop residues such as (i) forest residues (logging residues, dead wood, excess saplings, pole trees); (ii) mill residues (lumber, pulp, veneers); (iii) field crop residues; or, (iv) urban wastes (yard trimmings, site clearing, pallets, wood packaging). In many cases, these waste materials have little value and their disposal incurs costs, of which they can be made useful in a sustainable manner by converting them into biochar feedstocks. The most suitable materials have high lignin concentration yielding the most bio-char such as residues from sawmills, forest residues, or nut shells.

There are several thermochemical technologies to produce biochar such as pyrolysis, gasification, and hydrothermal conversion. However, pyrolysis is by far the most common method for producing biochar. Pyrolysis involves the heating of organic materials in the absence of oxygen to yield a series of bioproducts: biochar, bio-oil, and syngas. Pyrolysis is a simple and inexpensive process which has been used to produce charcoal for thousands of years. However, traditional earthen and brick kilns used to produce charcoal usually vent a large amount of volatiles to the atmosphere, which causes air pollution.

Gasification is a thermochemical process where biomass is heated with a small amount of air to produce a main product—syngas and a byproduct—biochar. Gasification leaves behind at most 10% of the biomass carbon as charcoal and there are no studies which look at the properties of biochar made that way and how it impacts on soils. Another technique is called Hydro-thermal carbonization or HTC and it involves steaming biomass together with different types of acid which act as a catalyst. Hydrothermal conversion primarily focuses on using wet biomass to generate bio-oil. Biochar is a byproduct of that process as well.

Fate of Biochar in the Soil

Studies on soils amended with biochar have shown that when incorporated into the soil, biochar becomes "charged" with nutrients, covered with microbes, and pH-balanced, and its mobile matter content is decomposed into plant nutrient. Evidence also suggests that components of the carbon in biochar are highly recalcitrant in soils, with reported residence times for wood biochar being in the range of 100s to 1,000s of years, i.e. approximately 10-1,000 times longer than residence times of most soil organic matter (SOM) and this is due to its resistance to microbial decomposition and mineralization.

Feedstocks for Biochar production

Despite many different materials having been proposed as biomass feedstock for biochar (including wood, crop residues and manures), the suitability of each feedstock for such an application is dependent on a number of chemical, physical, environmental, as well as economic and logistical factors. The type of organic matter (or feedstock) that is used and the conditions under which a biochar is produced greatly affect its relative quality as a soil amendment. Different types of charred biomass have very different properties and chemical structures, depending on the temperature and the length of time for which they were charred and the type of biomass used.

Effect of Temperature variation on Biochar

Studies have also shown that Biochars generated under different pyrolysis temperatures have varying effects on their sorption capacity for nutrients. This may be attributed to the alteration of biochar surface properties with pyrolysis temperature. Reported that the particular heat treatment of organic biomass used to produce biochar contributes to its large surface area and its characteristic ability to persist in soils with very little biological decay.

Hemicellulose, cellulose, and lignin are three main components in most biomass. Previous research has shown that hemicellulose decomposition occurs at 180-240 °C while cellulose begins decomposing between 230-310 °C. Lignin starts to decompose at low temperatures (160-170 °C) and continues decomposition at a low rate until 900 °C. The greatest decomposition in the biomass pyrolysis process usually occurs within a narrow temperature interval from about 200-400 °C.

When evaluating biochar's properties, elemental composition is another important parameter to consider. As shown in Table 1, the carbon content of biochar generated from corn cob increased while the oxygen and hydrogen contents decreased with increasing temperature. This indicates an increasing degree of carbonization. The degree of carbonization is described by the H/C ratio, because H is primarily associated with plant organic matter. By increasing pyrolysis temperature from 250 to 550 °C, the H/C ratio of biochar produced from corn cob decreased greatly (Table 1). The low value of H/C ratio at 550 °C indicates that the biochar is highly carbonized. By contrast, a high H/C ratio suggests that the sample contains a good amount of original organic residues, such as polymeric CH_2 and fatty acid, lignin (aromatic core), and some cellulose (polar factions). Also, the O/C ratio of biochar produced from corn cob decreased with increasing pyrolysis temperature (Table 1), indicating the surface of the biochar produced under high temperature becomes less hydrophilic. The decrease of the polarity index (O+N)/C with the pyrolysis temperature (Table 1) indicates a reduction in the content of polar functional groups.

Table 1. Selected physicochemical properties of a commercial activated carbon (AC) and biochars prepared under different conditions from selected feedstocks.

Feedstock	Pyrolysis Temp.	SSA (m^2/g)	% C	% H	% N	% O	% Ash
Corn cob	250 °C	1.86	61.16	4.96	0.82	27.82	3.92
Corn cob	300 °C	2.42	70.54	4.19	0.81	19.06	4.1
Corn cob	350 °C	3.36	72.92	3.79	0.79	16.86	4.35
Corn cob	400 °C	4.70	75.23	3.37	0.82	14.11	5.12
Corn cob	450 °C	7.79	77.84	2.95	0.86	11.45	5.55
Corn cob	500 °C	17.08	80.85	2.5	0.97	8.87	5.56
Corn cob	550 °C	30.57	82.62	2.25	0.84	7.43	5.58
Wood pellet*	750 °C	105.3	81.99	1.14	0.52	3.04	8.75
Wood chip	450 °C	12.96	70.44	2.67	1.11	13.86	10.23
Defatted DDG	400 °C	1.98	64.43	3.76	7.44	10.14	12.78
Corn stover	400 °C	4.69	55.98	3.4	0.43	18.16	20.75
Pine cone	400 °C	17.92	73.88	3.21	1.33	15.31	4.95

Abbreviations: SSA-specific surface area; C-carbon; H-hydrogen; N-nitrogen, and O-oxygen. (O+N)/C: atomic ratio of sum of nitrogen and oxygen to carbon. O/C: atomic ratio of oxygen to carbon. H/C: atomic ratio of hydrogen to carbon.

* The biochar provided by Chip Energy Inc. from a gasification system.

Effect of Biochar on Soil Physicochemical Properties

Reported that after harvest, the soil organic matter, soil pH, available phosphorus P1 and P2, and CEC generally increased in the field plots treated with biochar. The increase in soil organic matter and CEC showed that fairly large amounts of carbon and exchangeable cations were introduced by biochar application. The high level of available phosphorus P_1 and P_2 after biochar application indicated that the use of biochar as a soil amendment led to a high retention of nutrients in the soil. By contrast, the contents of nitrate-N in these biochar-amended plots were significantly reduced even when undergoing nitrogen fertilizer application. This further confirms that biochar can sorb nitrogen fertilizers and inhibit their nitrification and thus the concentrations of nitrate in the fields with biochar addition were largely decreased. Biochar properties have also been reported with cation exchange capacities (CECs) from negligible to approximately 40 $cmolcg^{-1}$, C:N ratios from 7 to 500 (or more).

Biochar often can have an initially high (alkaline) pH, which is desirable when used with acidic, degraded soils; however, if soil pH becomes too alkaline, plants may suffer nutrient deficiencies. One could expect less positive results from adding an alkaline biochar to an alkaline soil.

Effect of Biochar on Crop Growth and Yield

Nutrients are retained in soil and remain available to crops mainly by adsorption to minerals and soil organic matter. Usually, the addition of organic matter such as compost and manure into soil can help retain nutrients. Biochar is considered much more effective than other organic amendment in retaining and making nutrients available to plants. Its surface area and micro-pore structure are favorable to bacteria and fungi that are needed by plants to absorb nutrients from the soil. Most of the results of deliberate biochar additions to soil showed increasing crop yields with increasing additions up to very high loadings of 140 $MgCha^{-1}$.

Conducted a meta-analysis of biochar application to a range of soil types across a range of different climates (although chiefly tropical) on soils and plant productivity. Their results showed a small overall, but statistically significant, positive effect of biochar application to soils on plant productivity in the majority of cases. The greatest positive effects were seen on acidic free-draining soils with other soil types, specifically calcarosols showing no significant effect (either positive or negative). There was also a general trend for concurrent increases in crop productivity with increases in pH up on biochar addition to soils. This suggests that one of the main mechanisms behind the reported positive effects of biochar application to soils on plant productivity may be a liming effect.

Biochar and Soil Micro-organisms

Research indicates that both biological nitrogen fixation and beneficial mycorrhizal relationships are enhanced by biochar applications.

Biochar and Carbon Sequestration

Biochar can be a simple yet powerful tool to combat climate change. According to the International Biochar Initiative, biochar can sequester up to 2.2 billion tonnes of carbon every year by 2050 and this carbon will remain in soil for thousands of years. As organic materials decay, greenhouse gases, such as carbon dioxide and methane (which is 21 times more potent as a greenhouse gas than CO_2), are released into the atmosphere. By charring the organic material, much of the carbon becomes "fixed" into a more stable form, and when the resulting biochar is applied to soils, the carbon is effectively sequestered. It is estimated that the use of this method to "tie up" carbon has the potential to reduce current global carbon emissions by as much as 10 percent.

The evidence for these claims is largely based on short term laboratory studies or on observations of terra preta or charcoal from wildfires in soils, and on modelling that extrapolates from such studies. The main basis for the belief that biochar can help reduce climate change is the apparent high stability of black carbon, i.e. the carbon it contains.

Biochar and other GHGs Sequestration

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O) are important drivers of the anthropogenic greenhouse effect, which are released both through burning of fossil and biomass fuel as well as decomposition of above- and belowground organic matter. Apart from the beneficial effects of drawing CO_2 from the atmosphere, biochar applications to soil are also able to reduce the emissions of other greenhouse gases. Found a virtually complete suppression of methane emissions at biochar additions of 20 g kg^{-1} soil. Nitrous oxide emissions were reduced by up to 50% when biochar was applied to soybean and by 80% in grass stands. These low emissions may be explained by better aeration (less frequent occurrence of anaerobic conditions) and possibly by greater stabilization of C. The lower nitrous oxide evolution may also be an effect of slower N cycling (possibly due to a higher C/N ratio).

Biochar and Environmental Pollution

In addition to reducing greenhouse gas emissions, biochar applications to soil have the potential to decrease environmental pollution. Black Carbon in soil similar to biochars efficiently adsorbs ammonia (NH_3) and acts as a buffer for ammonia in soil, therefore having the potential to decrease ammonia volatilization from agricultural fields. Biological immobilization of inorganic N also aids in retaining N and in decreasing ammonia volatilization, due to the low N concentrations and high C/N ratios of biochars. Bio-chars are very efficient adsorbers for dissolved ammonium, nitrate, phosphate, and other ionic solutes as well as hydrophobic organic pollutants. Whereas this behavior may greatly mitigate toxicity and transport of common pollutants in soils through reducing their bioavailability, it might also result in their localized accumulation, although the extent and implications of this have not been fully assessed experimentally.

Biochar and Heavy Metal Remediation

Similar to activated carbon, biochar can serve as a sorbent in some respects. Biochar usually has greater sorption ability than natural soil organic matter due to its greater surface area, negative surface charge, and charge density. Furthermore, soils containing biochar have a strong affinity for organic contaminants. For example, one study revealed that unmodified biochar pyrolyzed from waste biomass could effectively sorb two triazine pesticides, effectively retarding their transport through the soil. In a nickel contaminated soil, observed a decrease in Nickel concentrations in root and shoot of spinach with the application of cotton-sticks-derived biochar as compared to the control.

CONCLUSION

The potential benefits of biochar seem to be enormous as evident in this review. It is apparent that a bioenergy strategy that includes the use of biochar in soil not only leads to a net sequestration of CO_2, but also may decrease emissions of other more potent greenhouse gases such as N_2O and CH_4. As well, they claim that soil fertility will be dramatically improved, fertilizer demand lessened and that nitrous oxide emissions from soils will be reduced.

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