# Biochar in agriculture – prospects and related implications

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**Sequestration of atmospheric carbon to the soil is a challenging task for the scientific community to mitigate the rising concentration of atmospheric carbon dioxide ($CO_2$). Biochar, due to its aromatic structure and long mean residence time in the soil (more than 100 years) has the potential for long-term carbon sequestration in the soil. The trend obtained from the meagre published literature raised our hopes of achieving the goal of enhancing the productivity of different crops along with environmental sustainability. According to an estimate, global production of black carbon has been reported between 50 and 270 Tg $yr^{-1}$, with as much as 80% of this remaining as residues in the soil. Biochar decomposition rate is slow in the soil, which indicates that it could be the possible answer to mitigation of elevated atmospheric $CO_2$. It is reported that black carbon can produce significant benefits when applied to agricultural soils in combination with some fertilizers. Increase in crop yield to the tune of 45–250% has been reported by application of biochar along with chemical fertilizers. Soil water retention properties, saturated hydraulic conductivity and nutrients availability increased with the application of biochar. Biochar application reduced $CO_2$ respiration, nitrous oxide and methane production, and decreased dissipation rate of herbicide in the soil.**

**Keywords:** Biochar, carbon sequestration, crop yield, soil amendment, soil attributes.

THE maintenance of a threshold level of organic matter in the soil is crucial for maintaining physical, chemical and biological integrity of the soil and also for the soil to perform its agricultural production and environmental functions[1]. The term 'biochar' denotes black carbon formed by the pyrolysis of biomass, i.e. by heating biomass under oxygen-free or stress environment, so that it is not subject to complete combustion. The global production of black carbon has been estimated to be between 50 and 270 Tg $yr^{-1}$, with as much as 80% of this remaining as residues in the soil[2,3]. Lehmann *et al.*[4] estimated that a total of 9.5 billion tonnes of carbon could potentially be stored in soils by the year 2100 using a wide variety of biochar application programmes. The application of biochar to the soil is proposed as a novel approach to establish a significant long-term sink for atmospheric carbon dioxide ($CO_2$) in terrestrial ecosystems[4]. There is every possibility that atmospheric $CO_2$ concentration will increase in the near future; this further led to increased attention of the scientific community to make the soil a possible sink for atmospheric $CO_2$. $CO_2$ flux plays a vital role in carbon exchange between the biosphere and the atmosphere, but our understanding of the mechanism controlling its temporal and spatial variations is limited. Sollins *et al.*[5] presented a conceptual model by which plant leaf and root litter are converted to soil organic carbon (SOC) and $CO_2$. According to them, stability of the SOC is the result of three general sets of characteristics. (i) Recalcitrance comprises of molecular-level organization of organic substances, which includes elemental composition, presence of functional groups and molecular conformation, that influence their degradation by microbes and enzymes. (ii) Interactions refer to the inter-molecular interactions between organics and either inorganic substances or other organic substances that alter the rate of degradation of those organics or synthesis of new organics. (iii) Accessibility refers to the location of organic substances with respect to microbes and enzymes. For biochar, recalcitrance mechanism is assumed to be the most important phenomenon for sequestering carbon for a longer period of time. The conversion of organic waste to produce biochar using the pyrolysis process is one viable option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality. Biochar has the potential to increase conventional agricultural productivity and enhance the ability of farmers to participate in carbon markets beyond the traditional approach by directly applying carbon into the soil[6]. This led to renewed interest of soil scientists to use charcoal/black carbon/biochar as a soil amendment for stabilizing soil organic matter (SOM).

A schematic sketch of the biochar production technique is shown in Figure 1. Charcoal is a good

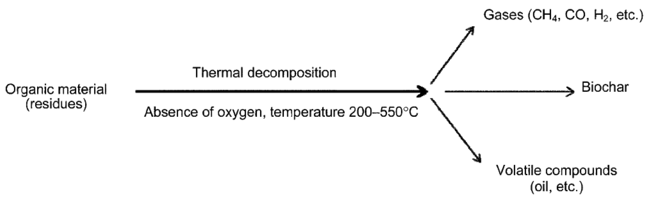

**Figure 1.** Schematic sketch of biochar production technique.

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*For correspondence. (e-mail: jha_iari@yahoo.com) example of biochar produced from woody biomass. However, the term 'biochar' is much broader in perspective than the definition being used and it encompasses black carbon produced from any biomass stock. The use of biochar as soil amendment is proposed as a new approach to mitigate man-induced climate change along with improving soil productivity. The use of biochar in agriculture is not new; in ancient times farmers used it to enhance the production of agricultural crops. One such example is the slash and burn cultivation, which is still being practised in some parts of North East India. In order to sequester carbon, a material must have long residence time and should be resistant to chemical processes such as oxidation to $CO_2$ or reduction to methane. It has been suggested by many authors[4,6] that the use of biochar as soil amendment meets the above requirements; since the biomass is protected from further oxidation from the material that would otherwise have degraded to release $CO_2$ into the atmosphere. Such partially burnt products, more commonly called pyrogenic carbon or black carbon, may act as an important long-term carbon sink because their microbial decomposition and chemical transformation are probably slow. Warnock *et al.*[7] summarized the effect of biochar on mycorrhizal associations. According to them, mycorrhizal fungi use biochar as a habitat. They further reported that ubiquitous symbioses association between biochar and mycorrhizal in terrestrial ecosystems, are potentially important in various ecosystem services provided by soils, contributing to sustainable plant production, ecosystem restoration, soil-carbon sequestration and mitigation of global climate changes. After reviewing other works, they came to the conclusion that the fertile Amazonian dark earths has served as a major inspiration for the use of biochar as a promising soil additive promoting crop growth and carbon storage. Furthermore, they stated that with both biochar addition and mycorrhizal abundance subject to management practices, there are opportunities for exploiting a potential synergism that could positively affect soil quality.

Here, an effort has been made to synthesize information pertaining to biochar characterization, decomposition, impact on crop productivity, soil quality and related environmental implications.

## Recent techniques used for characterization of black carbon

Characterization of any amendments is the first step to understand the mechanism of action. Black carbon derived from different biomass and produced on different timescales has different sets of characteristics. General physico-chemical properties of biochar samples[8–13] prepared from different feedstock are given in Table 1. Biochar pH ranged from 8.2 to 13.0. Total carbon content in biochar materials varied from 33.0% to 82.4%. Biochar in general has low nitrogen content (0.18–2.0%) and C : N ratio varied from 19 to 221. It contains appreciable quantities of Ca, Mg, K and P. Anthrosols from the Brazilian Amazon (ages between 600 and 8700 yrs BP) with high biomass-derived black carbon content had greater potential cation exchange capacity (CEC measured at pH 7) per unit organic carbon than adjacent soils with low black carbon content[14]. Synchrotron-based near-edge X-ray absorption fine structure spectroscopy coupled with scanning transmission X-ray microscopy techniques explained the source of the higher surface charge of black carbon compared with non-black carbon by mapping cross-sectional areas of black carbon particles with diameter 10–50 mm for carbon forms. Spotted and non-continuous distribution patterns of highly oxidized carbon functional groups with distinctly different chemical signatures on black carbon particle surfaces indicate that non-black carbon may be adsorbed on the surfaces of black carbon particles

**Table 1.** Some properties of biochar used in different experiments

| Materials used for producing biochar | pH | Total C (%) | Total N (%) | C : N ratio | Ca (cmol $kg^{-1}$) | Mg (cmol $kg^{-1}$) | P (cmol $kg^{-1}$) | K (cmol $kg^{-1}$) | Cation exchange capacity (cmol $kg^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Papermill waste 1 (waste wood chip) | 9.4 | 50.0 | 0.48 | 104 | 6.2 | 1.20 | – | 0.22 | 9.00 | 8 |
| Papermill waste 2 (waste wood chip) | 8.2 | 52.0 | 0.31 | 168 | 11.0 | 2.60 | – | 1.00 | 18.00 | 8 |
| Greenwaste (grass clippings, cotton trash and plant prunings) | 9.4 | 36.0 | 0.18 | 200 | 0.4 | 0.56 | – | 21.00 | 24.00 | 9 |
| Eucalyptus biochar | | 82.4 | 0.57 | 145 | – | – | 1.87 | – | 4.69 | 10 |
| Cooking biochar | | 72.9 | 0.76 | 96 | – | – | 0.42 | – | 11.19 | 10 |
| Poultry litter (450°C) | 9.9 | 38.0 | 2.00 | 19 | | | 37.42 | | 11 | |
| Poultry litter (550°C) | 13 | 33.0 | 0.85 | 39 | | | 5.81 | | 11 | |
| Wood biochar | 9.2 | 72.9 | 0.76 | 120 | 0.83 | 0.20 | 0.10 | 1.19 | 11.90 | 12 |
| Hardwood sawdust | | 66.5 | 0.3 | 221 | | | | | | 13 |

creating highly oxidized surface. As a consequence of both oxidation of the black carbon particles themselves and adsorption of organic matter to black carbon surfaces, the charge density (potential CEC per unit surface area) was greater in black carbon-rich Anthrosols than adjacent soils. Liang *et al.*[14] corroborated that a high specific surface area was attributable to the presence of black carbon, which may contribute to the high CEC found in soils that are rich in black carbon[14]. Soils with high CEC hold greater amount of nutrients on their exchange sites and will have higher buffering capacity. In such cases leaching loss of nutrients is minimized and availability of nutrients to the plants is enhanced.

The amount and compositional characteristics of black carbon in the soils (mollisol and vertisol), charred biomass (laboratory-produced; rice, chestnut), and soils (southern Spain) affected by forest fire have been studied by Rosa *et al.*[15]. They used a combination of thermogravimetry (TG), TG coupled with isotope ratio mass spectrometry, solid-state $^{13}$C nuclear magnetic resonance (NMR) spectroscopy, and pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS) for characterization of black carbon collected from different sources. Samples affected by fire had higher total organic matter content, and were enriched in aromatic components. Good agreement was observed between the refractory organic matter content determined by TG analysis and the aromatic content measured by $^{13}$C NMR. Py-GC/MS demonstrated the presence of aromatic compounds in samples rich in black carbon. Residues with higher aromatic components could not be easily utilized by soil microbes. This led to slower decomposition of residues in the soil, which in turn helped in further sequestration of carbon in the soil. Rosa *et al.*[15] corroborated that some of the characteristic peaks obtained by analytical pyrolysis in combination with TG analysis and $^{13}$C NMR spectra could be used as markers in the detection of black carbon. Chemical nature of soil and biochar with respect to macro- and micronutrient concentrations, and mobility through SEM images were found to be effective[16].

## Decomposition kinetics of biochar

The stability of biomass-derived black carbon or biochar as a slow cycling pool in the global carbon cycle is an important property and is likely governed by environmental conditions. Because of its macromolecular structure dominated by aromatic carbon, biochar is more recalcitrant to microbial decomposition than uncharred organic matter[17]. Direct estimations of black carbon decomposition rates are absent because the black carbon content changes are too small for any relevant experimental period. Estimations based on $CO_2$ efflux are also unsuitable because the contribution of black carbon to $CO_2$ is too small compared to SOM and other sources. An incubation study[18] was conducted for evaluating the decomposition pattern of $^{14}$C-labelled black carbon (*Lolium perenne*) under external energy source (glucose) and under mechanical disturbance of aggregates for a period of 3.2 years. Addition of external energy source–glucose (20–200% of SOC) did not change the total $CO_2$ efflux from the soil. About 0.5% black carbon was decomposed per year under optimal conditions. The study assumed that if black carbon decomposes 10 times slower under natural conditions, then the mean residence time (MRT) of black carbon was about 2000 years and half-life was about 1400 years. Considering the short duration of incubation and typical decreasing decomposition rates with time, it was concluded that the MRT of black carbon in the soil is in the range of millennia. An increase in black carbon decomposition rate (up to six times) was also observed on adding glucose; the decrease of this stimulation lasted for two weeks (three months in loess) in the soil. The incorporation of black carbon into microorganisms (fumigation/extraction) after 624 days of incubation amounted to 2.6% and 1.5% of $^{14}$C input into the soil and loess respectively. The amount of black carbon in dissolved organic carbon (DOC) was below detection limit (< 0.01%), showing no black carbon decomposition products in water leached from the soil. It was concluded that applying $^{14}$C-labelled black carbon opens new ways for sensitive tracing of black carbon transformation products in releasing $CO_2$, microbial biomass, DOC and SOM pools with various properties.

Biochar materials produced from different biomass stocks are supposed to behave (decompose) differently under different water regimes. With this hypothesis, a study on decomposition kinetics of black carbon produced by carbonizing corn residues and oak wood at two temperatures (350°C and 600°C) under three water regimes was conducted[19]. Effects of water regime on carbon loss and potential CEC (CECp at pH 7) were found to significantly depend on biomass type. Corn black carbon was both mineralized (16% carbon loss for the first year) and oxidized (1000 mmol $kg^{-1}$ C) significantly faster under unsaturated conditions than under other water regimes, whereas oak black carbon mineralized most rapidly (12%) under alternating saturated–unsaturated conditions with similar oxidation, irrespective of the water regime. Over one year of saturated incubation, the O : C ratio did not significantly increase even though black carbon was mineralized by 9% and CECp increased by 170 mmol $kg^{-1}$ C, in contrast to unsaturated and alternating saturated–unsaturated conditions. Unsaturated and alternating conditions increased carboxylic and OH functional groups, whereas aliphatic groups were found to decrease. The pH increased by about one unit for corn black carbon, but decreased by 0.2 units for oak black carbon, indicating strong mineral dissolution of corn black carbon. Carbon loss strongly correlated with changes in O : C values of both corn black carbon

**Table 2.** Effect of biochar application on crop yield

| Crops | Soil type | Biochar rate (t ha$^{-1}$) | Fertilizer rate (kg ha$^{-1}$) | Yield/biomass increase over control[a] (%) | Additional information | Reference |
|---|---|---|---|---|---|---|
| Wheat | Ferrosol | 10 | 1.25 g nutricote per 250 g soil (nutricote contains 15.2% N, 4.7% P and 8.9% K)[b] | +250 | Similar response was observed for biomass yield of soybean and radish. Calcarosol (soil type) amended with fertilizer and biochar however gave varied crop responses: Increased soybean biomass, but reduced wheat and radish biomass. No significant effects of biochar were reported in the absence of fertilizer for wheat and soybean, while radish biomass increased significantly. | 8 |
| Radish | Alfisol | 100 | N (100) | +266 (biomass) | In the absence of nitrogen fertilizer, application of biochar did not increase the dry matter production of radish even at the highest rate (100 t/ha).<br>Biochar produced from poultry manure increased the dry matter yield of radish, even at the lowest application rate of 10 t/ha, although N fertilizer was not applied. | 9, 11 |
| Rice | Inceptisol | 30 | Nil | +294 | Sole effect of biochar | 10 |
| | Oxisol | 88 | Nil | +800 | Interaction effect of earthworm and biochar | |
| | Oxisol | 88 | N (40), P (20), K (20) | –21 | Interaction effect of earthworm and biochar | |
| Maize | Oxisol | 20 | N (156–170), P (30–43), K (84–138) | +28 (1st year)<br>+30 (2nd year)<br>+140 (4th year) | In the first year after biochar application, no significant effect on crop yield was observed. | 12 |
| Rice | Ferralsol | 11 | N (30), P (35), K (50) | +29 (stover), +73 (grain) | While charcoal additions alone did not affect crop production, a synergistic effect occurred when both charcoal and inorganic fertilizers were applied. | 22 |

[a]Control means mineral fertilizer alone. + and – signs indicate yield increase and decrease respectively.
[b]Rates are in g nutricote/250 g soil.

and oak black carbon, indicating that oxidation of black carbon was most likely the major mechanism controlling its stability. It was concluded that under saturated conditions, additional mechanisms may govern black carbon degradation and require further study.

## Biochar application and crop yield

Response of crops to biochar application rate is essential for devising suitable strategy for long-term carbon sequestration. Biochar fertilizer is another product being considered to be of relevance to carbon sequestration[20]. It is reported that black carbon can produce significant benefits when applied to agricultural soils in combination with some fertilizers[21,22]. The response of crops to biochar application is summarized in Table 2 (refs 8–12 and 22). Apart from positive effects in both reducing emissions and increasing the sequestration of greenhouse gases, the production of biochar and its application to the soil will deliver immediate benefits through improved soil fertility and increased crop production[4,22].

Asai *et al.*[23] studied the effect of biochar application on grain yield of upland rice (*Oryza sativa* L.) in northern Laos (Table 2). Three different experiments were conducted under upland conditions at 10 sites, combining variations in biochar application (0–16 t ha$^{-1}$), fertilizer application rates (N and P) and rice cultivars (improved and traditional). Biochar application resulted in higher grain yields at sites with low P availability and improved the response to N and NP chemical fertilizer treatments. However, biochar application reduced leaf chlorophyll concentration, possibly through a reduction of the availability of soil nitrogen, indicating that biochar application without additional N fertilizer application could reduce grain yields in soils with a low indigenous N supply. They concluded that biochar application has the potential to improve soil productivity of upland rice production in Laos, but the effect of biochar application is highly dependent on soil fertility and fertilizer management.

A pot trial was carried out to study the effect of biochar produced from green waste by pyrolysis on the yield of radish (*Raphanus sativus* var. Long Scarlet)[9]. Three rates of biochar (10, 50 and 100 t $ha^{-1}$) with and without additional nitrogen application (100 kg N $ha^{-1}$) were studied. The soil used in the pot trial was a hardsetting alfisol (Chromosol) (0–0.1 m) with a long history of cropping. In the absence of N fertilizer, application of biochar to the soil did not increase radish yield even at the highest rate of 100 t $ha^{-1}$. However, a significant biochar × N fertilizer interaction was observed, in that higher yield increases were observed with increasing rates of biochar application in the presence of N fertilizer, highlighting the role of biochar in improving N fertilizer use efficiency of the plant. For example, additional increase in dry matter of radish in the presence of N fertilizer varied from 95% in the control to 266% in the 100 t $ha^{-1}$ biochar-amended soils. A slight but significant reduction in dry matter production of radish was observed when biochar was applied at 10 t $ha^{-1}$; this requires further study.

Chan *et al.*[11] evaluated two biochars produced from poultry litter under different conditions in a pot experiment by assessing the yield of radish (*R. sativus* var. Long Scarlet). The non-activated poultry litter biochar produced at lower temperature (450°C) was more effective in terms of dry matter production than the activated biochar produced at higher temperature (550°C), probably due to higher available P content. They studied four rates of biochar (0, 10, 25 and 50 t $ha^{-1}$), with and without nitrogen application (100 kg N $ha^{-1}$). Both biochars, without N fertilizer, produced similar increase in dry matter yield of radish, which was detectable at the lowest application rate of 10 t $ha^{-1}$. The yield increase (%), compared with the unamended control rose from 42% at 10 t $ha^{-1}$ to 96% at 50 t $ha^{-1}$ of biochar application. The yield increases can be attributed largely to the ability of these biochars to increase N availability. Significant additional yield increases, in excess of that due to N fertilizer alone, were observed when N fertilizer was applied together with the biochars, highlighting the other beneficial effects of these biochars.

In a greenhouse study, two soil types (sandy loam and silt loam) with different combinations of biochar, cattle manure and N fertilizer were evaluated for soil productivity, with maize as the test crop[24]. Highest shoot dry weight of maize was recorded from the 3 t $ha^{-1}$ biochar + 120 kg N $ha^{-1}$ treatment, possibly due to improved nutrient retention from the biochar. Shoot dry weight ranged from 41 to 45 g $pot^{-1}$ for the sandy loam soil and 28 to 35 g $pot^{-1}$ for the silt loam soil. Soil pH declined in both cases. Biochar resulted in N recovery of 4% and 5% in maize shoot and root respectively, for the sandy loam soil but caused less N recovery for the silt loam soil. The results showed that N recovery can be improved by biochar application to sandy loam soil but not silt loam soil, suggesting the effect of soil texture on biochar application for soil productivity.

Other studies have shown that charcoal amendments can, in the short term, either increase or decrease plant yield, depending amongst other things on the quantity of charcoal added, soil type and crop tested (Table 2). There are no long-term field studies and so it is not known whether the increased plant growth sometimes observed with the addition of charcoal would be sustained over the longer term.

## Effect of biochar application on soil quality attributes

It is well corroborated that biomass-derived black carbon (biochar) affects microbial populations and soil biogeochemistry. Both biochar and mycorrhizal association, a symbiotic association in terrestrial ecosystems, are potentially important in various ecosystem services provided by the soil, contributing to sustainable plant production, ecosystem restoration, soil-carbon sequestration and hence mitigation of global climate changes[7]. Biochar is an excellent soil amendment for sequestering carbon (increasing SOC content) and water retention as well as providing a habitat for microbes[16]. Biochar also adds some macro- (P, K, N, Ca, Mg) and micronutrients (Cu, Zn, Fe, Mn) which are needed for sustainable agriculture[8–12,22]. Black carbon may significantly affect nutrient retention and play a key role in a wide range of biogeochemical processes in the soil, especially for nutrient cycling. Chan *et al.*[9] studied the influence of rate and type of biochar produced from poultry litter under different conditions on soil quality parameters. Biochar addition to the hard-setting soil resulted in significant but different changes in soil chemical and physical properties, including increase in C, N, pH and available P, and reduction in soil strength. The different effects of the two biochars (one produced at 450°C and the other at 550°C) could be related to their different characteristics. Significantly different changes in soil biology in terms of microbial biomass and earthworm preference properties were observed between the two biochars; however, the underlying mechanism needs to be assessed. Similarly, Asai *et al.*[23] studied the effect of biochar application on soil physical properties and grain yield of upland rice (*O. sativa* L.) in northern Laos. Biochar application improved the saturated hydraulic conductivity of the top soil and xylem sap flow of the rice plant.

Lehmann *et al.*[25] studied the soil fertility and leaching losses of nutrients from Fimic Anthrosol and a Xanthic Ferralsol from Central Amazônia. The Anthrosol is a relict soil from pre-Columbian settlements with high organic carbon containing large proportions of black carbon. They tested whether charcoal addition among other organic and inorganic applications could produce fertile soils similar to the Anthrosols. In the first experiment, cowpea (*Vigna unguiculata* L.) was planted in pots, whereas in the second experiment lysimeters were used to quantify water and nutrient leaching from soil cropped to rice (*O. sativa* L.). The Anthrosol showed significantly higher P, Ca, Mn and Zn availability than the Ferralsol and biomass production of both cowpea and rice increased by 38–45% without fertilization. The soil N contents were also higher in the Anthrosol but the wide C : N ratios due to high soil carbon content led to immobilization of N. Despite the generally high nutrient availability, nutrient leaching was minimal in the Anthrosols, providing an explanation for their sustainable fertility. However, when inorganic nutrients were applied to the Anthrosol, nutrient leaching exceeded that in the fertilized Ferralsol. Charcoal additions significantly increased plant growth and nutrition. Leaching of applied N fertilizer was significantly reduced by charcoal, and Ca and Mg leaching was delayed. In both the Ferralsol with added charcoal and the Anthrosol, nutrient availability was elevated with the exception of N, whereas nutrient leaching was comparatively low.

Significant changes in soil quality, including increase in pH, organic carbon and exchangeable cations as well as reduction in tensile strength were observed at higher rates of biochar application, i.e. > 50 t ha$^{-1}$. Reduction in tensile strength and increase in field capacity of hard-setting soil were the most significant findings[9].

After reviewing the experimental evidence for symbiotic association between biochar and mycorrhizal association, Warnock *et al.*[7] critically examined the hypotheses pertaining to four mechanisms by which biochar could influence mycorrhizal abundance and/or functioning. These are (in decreasing order of currently available evidence supporting them): (i) alteration of soil physico-chemical properties; (ii) indirect effects on mycorrhizae through effects on other soil microbes; (iii) plant–fungus signalling interference, and (iv) detoxification of allele-chemicals on biochar.

## Use of biochar and environmental implication

A potential abatement to increasing levels of $CO_2$ in the atmosphere is the use of pyrolysis to convert vegetative biomass into a more stable form of carbon (biochar) that could then be applied to the soil. However, the impacts of pyrolysis biochar on the soil system need to be assessed before initiating large-scale biochar applications to agricultural fields. Sohi *et al.*[26] raised certain pertinent questions regarding biochar application to the soil. According to them, in short-term experiments ranging from months to a few years, biochar addition seems to generally enhance plant growth and soil nutrient status and decrease nitrous oxide ($N_2O$) emissions. Surprisingly, little is yet published concerning how these benefits occur, or particularly why the effects are quantitatively so variable according to crop, soil and application rate. Therefore, despite the recent interest in biochar as soil amendment for improving soil quality and soil-carbon sequestration, implications of long-term biochar application on environmental conditions need to be assessed.

Spokas *et al.*[27] compared $CO_2$ respiration, $N_2O$ production, methane ($CH_4$) oxidation, and herbicide retention and transformation through laboratory incubations at field capacity in a Minnesota soil (Waukegan silt loam), with and without added biochar. $CO_2$ originating from the biochar needs to be subtracted from the soil–biochar combination in order to elucidate the impact of biochar on soil respiration. After this correction, biochar amendment reduced $CO_2$ production for all amendment levels tested (2%, 5%, 10%, 20%, 40% and 60% w/w; corresponding to 24–720 t ha$^{-1}$ field application rates). In addition, biochar additions suppressed $N_2O$ production at all levels. However, these reductions were only significant at biochar amendment levels >20% w/w. Biochar additions also significantly suppressed ambient $CH_4$ oxidation at all levels compared to unamended soil. The addition of biochar (5% w/w) to the soil increased the sorption of atrazine and acetochlor compared to non-amended soils, resulting in decreased dissipation rates of these herbicides. The recalcitrance of the biochar suggested that it could be a viable carbon sequestration strategy, and might provide substantial net greenhouse gas benefits if the reductions in $N_2O$ production are long-lasting.

Conversion of biomass carbon to biochar carbon leads to sequestration of about 50% of the initial carbon compared to the low amounts retained after burning (3%) and biological decomposition (< 10–20% after 5–10 years), therefore yielding more stable soil carbon than burning or direct land application of biomass[4]. This efficiency of carbon conversion of biomass to biochar is highly dependent on the type of feedstock, but is not significantly affected by the pyrolysis temperature (within 350–500°C common for pyrolysis). The existing slash-and-burn system causes significant degradation of the soil and release of greenhouse gases. However, it also provides opportunities for improvement by conversion of the slash-and-burn system to the slash-and-char system. The analysis revealed that up to 12% of the total anthropogenic carbon emissions by land-use change (0.21 Pg C) can be offset annually in the soil, if the slash-and-burn system is replaced by the slash-and-char system. Agricultural and forestry wastes such as forest residues, mill residues, field crop residues or urban wastes add a conservatively estimated 0.16 Pg C yr$^{-1}$. Biochar soil management systems can deliver tradable carbon emissions reduction, and the carbon sequestered is easily accountable, and verifiable[4].

Biochar produced from agricultural crop residues has proven effective in sorbing organic contaminants. Cao *et al.*[28] evaluated the ability of dairy manure-derived biochar to sorb heavy metal, Pb and organic contaminant, atrazine. They prepared two biochar samples by heating dairy manure at low temperature of 200°C (BC200) and 350°C (BC350). The untreated manure (BC25) and commercial activated carbon (AC) were included as controls. They reported that sorption of Pb by biochar followed a dual Langmuir–Langmuir model, attributing to Pb precipitation (84–87%) and surface sorption (13–16%). Chemical speciation, X-ray diffraction, and infrared spectroscopy indicated that Pb was precipitated as beta-$Pb_9(PO_4)_6$ in BC25 and BC200 treatments, and as $Pb_3(CO_3)_2(OH)_2$ in BC350 treatment. Lead sorption by AC followed a single Langmuir model, attributed mainly to surface sorption probably via coordination of Pb *d*-electron to C=C (pi-electron) and –O–Pb bonds. The biochar was six times more effective in Pb sorption than AC, with BC200 being the most effective (up to 680 mmol Pb $kg^{-1}$). The biochar also effectively sorbed atrazine where atrazine was partitioned into its organic phase, whereas atrazine uptake by AC occurred via surface sorption. When Pb and atrazine coexisted, little competition occurred between the two for sorption on biochar, whereas strong competition was observed on AC. Results from this study indicated that dairy manure can be converted into value-added biochar as effective sorbent for metal and/or organic contaminants.

Knoblauch *et al.*[29] studied the degradability of charred rice husk under aerobic and anerobic conditions in a laboratory incubation study. They observed that only 4.4% and 8.5% of the black carbon added was mineralized to $CO_2$ under aerobic and anaerobic conditions respectively, after an incubation period of three years. They further reported that application of black carbon had no significant effect on soil respiration, but significantly enhanced $CH_4$ emissions in the first rice crop season. The additional $CH_4$ released accounted for only 0.14% of black carbon added. If the same amount of organic carbon was added as untreated rice husk, 34% of the applied carbon was released as $CO_2$ and $CH_4$ in the first season.

The effect of biochar application on biological nitrogen fixation was studied by Rondon *et al.*[30]. They studied the potential, magnitude and causes of enhanced biological $N_2$ fixation (BNF) by common beans (*Phaseolus vulgaris* L.) through biochar additions. Biochar was added at 0, 30, 60, and 90 g $kg^{-1}$ soil, and BNF was determined using the isotope dilution method after adding $^{15}N$-enriched ammonium sulphate to a Typic Haplustox cropped to a potentially nodulating bean variety in comparison to its non-nodulating isoline, both inoculated with effective *Rhizobium* strains. The proportion of fixed N increased from 50% without biochar additions to 72% with 90 g $kg^{-1}$ biochar added. Although total N derived from the atmosphere (NdfA) was significantly increased by 49% and 78% with 30 and 60 g $kg^{-1}$ biochar added to soil respectively, NdfA decreased to 30% above the control with 90 g $kg^{-1}$ due to low total biomass production and N uptake. It was reported that the higher BNF with biochar additions was due to greater B and Mo availability. Increase in K, Ca and P availability, as well as higher pH and lower N availability and Al saturation, might also have contributed to a lesser extent. Enhanced mycorrhizal infections of roots did not contribute to better nutrient uptake and BNF. Bean yield increased by 46% and biomass production by 39% over the control at 30 and 60 g $kg^{-1}$ biochar respectively. However, biomass production and total N uptake decreased when the biochar applications were increased to 90 g $kg^{-1}$. Results demonstrate the potential of biochar applications to improve N input into agro-ecosystems while pointing out the need for long-term field studies to better understand the effects of biochar on BNF.

## Issues for future research interventions

The fundamental mechanisms by which biochar could provide beneficial functions to the soil and the wider function of the agro-ecosystem are poorly described in terms of providing the predictive capacity that is required. We must answer certain questions before recommending large-scale use of biochar for agriculture purposes.

- Does producing biochar involve large-scale fossil-fuel burning?

  The amount of carbon sequestered in the biochar biomass must take into account of net carbon balance, i.e. the amount of $CO_2$ evolved for producing biochar must be considerably less than the amount of carbon sequestered in charcoal. There must be positive carbon balance for producing biochar biomass.
- How will the soil microbial community, particularly the soil heterotrophs, behave under the presence of a non-degrading carbon source?

  As we know the decomposers present in the soils derive energy from the breakdown of SOM, particularly the soil heterotrophs. Thus their dynamics under the presence of non-degrading carbon source must be fully understood. Otherwise it may have some adverse effect on the soil ecological settings.
- Since the decomposition of biochar is extremely slow, what is the mechanism that operates for nutrients release/availability?
- What will be the enzymatic activity under the influence of a non-degrading substrate?
- What should be the optimum rate of biochar application?
- What will be the impact of long-term application of biochar on crop yield and soil quality?

  Although biochar as soil amendment for improving soil quality and soil-carbon sequestration has attracted

global attention, there is inadequate knowledge on the long-term application of soil amendment properties of these materials produced from different feedstocks and under different pyrolysis conditions.
- Is there any proven technology for large-scale production of biochar on a small farm scale?
- Are there any environmental implications related with biochar application?
- What will be the effect of biochar on problematic soils?

## Conclusion

Although there are contradictory reports on the beneficial use of biochar in agriculture, biochar could be the panacea to mitigate the increasing $CO_2$ concentration in the environment provided its rate of application and mechanism of action are fully understood. There is need to monitor the changes in physical, chemical, hydrological and ecological settings of the soil under the long-term application of biochar. Also, the response of different crops to biochar application under the different agro-ecological regions must be ascertained.

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