

Review Article

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Role of Biochar in Mitigation of Climate Change through Carbon Sequestration

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ABSTRACT

Biochar is a carbon rich charcoal-like substance created by thermal decomposition biomass (organic matter) in low oxygen conditions at relatively low temperatures (<700°C), a process known as pyrolysis. Biochar is essentially fine-grained charcoal made up of stable organic material and applied to soils in order to achieve net carbon sequestration, which is being promoted primarily for counterbalancing the impact of climate change and for sustaining soil fertility status. Currently, there is a clear cut evidence of large imbalance between carbon emission to the atmosphere and carbon uptake by the plants for the process of photosynthesis which leads to a continued increase in atmospheric CO₂ over long run. Formation of biochar formed through pyrolysis of plant biomass and its application to the in order to achieve higher storage of carbon in soils has been suggested as a means to counterbalance the effect of climate change by sequestering carbon. The principal mechanisms operating in soils through which biochar entering the soil is stabilized and significantly increase its life cycle in soil are its particulate nature, recalcitrance, mean residence time and interaction with mineral surfaces. To derive the maximum possible benefit of carbon sequestration through application of biochar, both yield and stability of the biochar are two important factors and should be optimized. The benefits of carbon sequestration through biochar are more visible in soils lower in carbon than soils relatively higher in carbon. Research evidence suggests that adoption of biochar technology in proper way can address the emerging challenges of agricultural sector and conserve/improve the quality of environment. In this review we evaluate the potential of biochar to reimbursement the current issues related to carbon sequestration.

Keywords

Biochar, Carbon sequestration, Soil organic carbon, Green house gas and Climate change.

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Introduction

Carbon is the most abundant element in living things and accounts for approximately 50% of the total mass of plants and animals. It is well known that the global carbon cycle is closely connected to global climate change largely through anthropogenic emissions of carbon dioxide originating from fossil fuel use and

land use change (IPCC, 2007). Atmospheric concentration of CO₂ has increased from ~ 280 ppm in pre industrial era to ~ 385 ppm in 2008 (+37.5%) and is presently increasing at the rate of ~ 2 ppm yr⁻¹ or 3.5 Pg yr⁻¹ (1Pg = 1billion metric ton) (IPCC, 2007). There exist a strong link between food insecurity and

climate change. The twin crisis of climate change and food insecurity can be addressed by restoring soil organic carbon pool through carbon sequestration in agro-ecosystems, especially in agricultural soils. The global potential of C sequestration in soils of agro-ecosystems is about 2.1 billion tons C year⁻¹ (Lal, 2010). Increase in soil C pool leads to reduction in atmospheric concentration of CO₂ because a part of the photosynthesized biomass is converted into stable humus with a long mean residence time in soil. There are a number of options for carbon sequestration in agro-ecosystems (Lal, 2010) but the modern approach is the soil application of biochar, charcoal created by low-temperature pyrolysis of biomass under anaerobic conditions (Zimmeman, 2010). Biochar is produced by pyrolysis and is dominantly composed of aromatic compounds that are largely resistant to biological degradation (Baldock and Smernik, 2002). Biochar is a highly carbonized material in which the carbon content varies depending on the feedstock and production conditions. It was reported that the total C content was highest in maize biochar (66%) followed by pearl millet biochar (64%), wheat biochar (64%) and rice biochar (60%) (Purakayastha *et al.*, 2015). Due to its relative inertness, biochar application contributes to the soil refractory organic C pool (Glaser *et al.*, 2001; Marris, 2006). Biochar is receiving much attention as a potential tool for mitigating climate change through long-term biological carbon sequestration. The potential of biochar application for soil organic carbon sequestration may be 1 billion tons C year⁻¹ (Sohi *et al.*, 2010) or more (Lehmann *et al.*, 2006).

What is biochar?

Biochar is the product of thermal degradation of organic materials in the absence of oxygen (pyrolysis), and is distinguished from charcoal by its use as a soil amendment.

Biochar is a fine grained, highly carbonaceous, pyrolysed (low temperature) product of biomass. The pyrolysis temperature strongly influences the stability of biochar in soil; the higher the pyrolysis temperature higher would be the stability (Purakayastha *et al.*, 2015). Biochar is charred organic product which made up of biologically recalcitrant carbon that is not easily mineralized by the soil microbes (Chan and Xu, 2009). The carbon present in the biochar is in aromatic form which offer a higher degree of stability and resistant to decomposition, which making it a most important tool for carbon sequestration.

Biochar is a carbon rich charcoal-like substance created by thermal decomposition biomass (organic matter) in low oxygen conditions at relatively low temperatures (<700°C), a process known as pyrolysis. Almost half of dry biomass weight is pure carbon. If biomass is left to decompose in air, almost all of the carbon is lost into the atmosphere within a few years. During pyrolysis, around 50% of biomass carbon is converted into biochar. Of the other 50%, around two thirds can be released as useful energy. Thus 1 Mt of dry biomass sequesters (locks away) 0.3 MT of carbon, equivalent to 1.2 MT CO₂ (Bajiyia *et al.*, 2017). Thus, biochar could play an important role in helping to sequester carbon from the atmosphere. Its high stability in the environment relative to other types of organic C substances is one of the important distinguishing properties of biochar. It has been estimated that biochar can persist up to 13,900 and 10,000 years sea and soils environments, respectively (Masiello and Druffel, 1998) However, long-term simulations show biochar-C can reside for 100 to 2000 years which may varies based on the location, soil, agro-climate and various agronomic management factors employed for crop production. Therefore, biochar addition to soil can provide a potential sink for C and

known to reduce the CO₂ release back to the atmosphere.

Carbon sequestration

Carbon sequestration is the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide (Sedjo *et al.*, 2012). Carbon sequestration involves long-term storage of carbon dioxide or other forms of carbon to mitigate or defer global warming. It has been proposed as a way to slow the atmospheric and marine accumulation of greenhouse gases, which are released by burning fossil fuels. Carbon dioxide (CO₂) is naturally captured from the atmosphere through biological, chemical, and physical processes. Artificial processes have been devised to produce similar effects, including large-scale, artificial capture and sequestration of industrially produced CO₂ using subsurface saline aquifers, reservoirs, ocean water, aging oil fields, or other carbon sinks. Soils are the largest terrestrial sink for carbon on the planet. World soils constitute the third largest global C pool, comprising of two distinct components: (i) soil organic C (SOC) estimated at 1550 Pg, and (ii) soil inorganic C (SIC) pool estimated at 950 Pg, both to one meter depth (Lal, 2004). The soil carbon sequestration is the long-term storage of carbon in soil which could well be accomplished by the application of biochar as a soil amendment (Purakayastha *et al.*, 2015).

Role of biochar in carbon sequestration

Declining fertility status of cultivated lands due to declining level of SOC is a major anxiety especially in Asian and African countries left their soils with lower crop productivity and resource use efficiency. SOC being keystone to soil quality also reported to an important indicator of agricultural sustainability. Restoring SOC is important not only to achieve food security and soil quality but also to offset the negative impact of

agricultural related climate change (Lal, 2004). Addition of biochar to soils has been recognized as one of the important strategy to counterbalance the impact of climate change through sequestering the carbondioxide (CO₂) into the soils so the load of excess atmospheric CO₂ will reduced (Lehmann *et al.*, 2006). To fulfill this purpose of carbon sequestration under wider agro-climatic situations we have to keep care of following two points. First, we have to convince the growers to cultivate the plants and suitable crops as they are being charred because the actual step of sequestering atmospheric CO₂ with the help of biochar is solely depends on photosynthesis in plants. It is widely reported that the plant biomass synthesized in the plants through the process of photosynthesis on an annual basis can emit their carbon rapidly in the atmosphere due to faster decomposition. Decomposition of plant biomass contradictory to the biochar process and play a crucial role in the process of climate change as it release the bulk of carbon in the atmosphere that is fixed by the plants through photosynthesis. In contrast to decomposition, the process of transforming the photo synthetically fixed plant biomass into biochar that decomposes much more slowly (conversion of rapid biological cycle of C into a much slower biochar mediated C cycle) (Lehmann, 2007). Second, the finally charred material (biochar) should be more stable than the plant biomass from which it was formed. As the degree of stability of biochar is one of the important parameters that can widely use to evaluate its potential for carbon sequestration. The pyrolysis process through which the conversion of organic matter in biochar take place has significantly influences on the stability of the final product thus increases the recalcitrance of C in the biomass. The pyrolysis process may result into complete destruction of cellulose and lignin and the appearance of aromatic structures in the charred product that

leading to significantly change in composition. These changes in the composition of organic materials through pyrolysis also have significant effect on the stability of biochar. To estimate the carbon sequestration potential and scaling out the quantity of atmospheric CO₂ carbon sequestered through biochar several approaches have been identified and taken into consideration to provide first estimates of the large-scale potential of biochar sequestration and therefore its benefit in terms of higher crop productivity (Lehmann *et al.*, 2006; Laird, 2008), but these approaches need to be perfected against economic and ecological constraints and extended to include a full emission balance of carbon. For example, the full balance of carbon emission require a comparison to a baseline scenario and at the same time showing what emissions of carbon have been reduced by changing of the product from plant material that utilizes biochar. Therefore, still more locations based depth studies that add in information density required to extrapolate to the global scale and at the same time simple comparison between global carbon fluxes emission in the atmosphere may need to suffice to demonstrate the potential of sequestration of carbon using biochar. It has been estimated that Earth's soils is stored around four times more organic C than in atmospheric CO₂ (Lehmann, 2007). Likewise, the annual uptake of CO₂ by plants for the process of photosynthesis is around eight times greater than today's anthropogenic CO₂ emissions in the atmosphere. Therefore, there is clear cut evidence that a huge amount of CO₂ are cycling between atmosphere and plants annually and soil is one of the most important source where most of the world's organic C is already stored in soil. So, if we are going to divert a very small proportion of this huge amount of cycling C into the soil with the help of biochar cycle would make a large difference to atmospheric CO₂ concentrations

but a very small difference to the global soil C storage. It has been already estimated that by diverting merely one per cent of annual net plant uptake into biochar would mitigate almost 10 per cent of current anthropogenic C emissions to the atmosphere in the form of carbon (Laird, 2008).

While evaluating for carbon sequestration potential stability of biochar is an important parameter since only a long half-life will ensure a relevant sequestration potential by offering a wider resistance towards decomposition of biochar through soil microbial communities. Stability of biochar simply determines how long carbon held in the soil in the form of biochar will remain sequestered in soil system and at the same time how long it may influence emissions of greenhouse gas from the soil system and help in the counterbalancing the effect of climate change. It has been found that conversion of plant biomass to biochar using pyrolysis process followed by its application to the soil increases the residence time of carbon (C) in the soil as compare to when same plant biomass applied directly to the soil (Lehmann, 2007). The benefits of biochar in terms of higher carbon sequestration have been found significantly greater with increase in the stability of charred product.

Influence of biochar on native soil organic carbon

It has been widely reported fact that application of biochar contributes to the soil recalcitrant C pool (Glaser *et al.*, 2001; Marris, 2006). Therefore, it's a promising alternative tool for sequester more C compared to traditional agricultural practices involving direct incorporation of plant biomass in the form of crop residues that results in rapid mineralization carbon leading to larger CO₂ release in the atmosphere (Bruun *et al.*, 2011). However, the results of

many studies have been suggested both suppression and stimulation of native SOC decomposition with the application of biochar (Liang *et al.*, 2010; Cross and Sohi, 2011; Luo *et al.*, 2011). The differences in the nature of material used for biochar formation and soil, and incubation conditions and agronomic factors of different studies leads to inconsistent results (Jones *et al.*, 2011). The higher rates of mineralization than predicted indicate positive priming of a specific C source, whereas lower than that predicted indicate negative priming. In general, at low temperature (250 and 400°C) biochar-C mineralization was positively primed during early incubation stage (Zimmerman *et al.*, 2011).

Biochar is a stable product when applied to soil, it remains in soil for centuries and securely store C for long-term C sequestration due to more resistance towards decomposition by soil microbes. It has been estimated that in India about 309 million tons of biochar (eqv. to 154 MT of biochar C) could be produced annually by using the plant residues, the application of which might offset about 50% of C emission (292 Tg C yr⁻¹) from fossil fuel (Lal, 2004). Additionally both heat and gases can be captured during production of biochar by pyrolysis to produce energy carriers such as electricity, bio-oil, or hydrogen and certain other valuable co-products.

Carbon sequestration and greenhouse gas emission

Long term application of biochar to soil may result in net removal of carbon from the atmosphere particularly over time. With the use of biochar the mitigation of carbon emissions is obtained not only through its application and long term storage in the soil, but also from substitution of fossil fuel by the produced bio-oil that also one of the major

source of green house gas emission in the atmosphere (Cross and Sohi, 2011). The stability of charred biochar is one of the basic and important criteria that will decide its half life in the soil system. The one approach which may employ to increases the stability of biochar is by raising the pyrolysis temperature, but this will be at the expense of the quantity produced (Luo *et al.*, 2011). Interestingly, the highest biochar carbon sequestration is achieved at 500 °C, despite the fact that biochar made at higher temperatures is relatively more recalcitrant than low temperature biochars. As biochar is highly resistant to microbial decomposition and application of biochar to the agricultural soils has a significant potential to mitigate greenhouse gases emissions. For example, Liang *et al.*, 2014 reported that CH₄ emissions from the paddy field were significantly decreased with the application of corn stalk biochar.

PCR study of the same experiment further revealed that biochar amendments (1) increased methanotrophic bacterial abundances significantly, and (2) decreased the ratios of methanogenic to methanotrophic abundances greatly that untimely resulted into lower down the emission of methane with biochar application.

Likewise, application of biochar to soil in-conjugation with mineral fertilisers can reduce N₂O emissions without suppressing the mineralisation or nitrification processes. For example, application of biochar decreased not only the cumulative N₂O (52-84%) but also the NO (47-67%) emissions compared to control or mineral fertilizer application (Nelissen *et al.*, 2014). Further it has been reported that N₂O emissions were more decreased at high compared to low pyrolysis temperature. According to a recent estimation the maximum carbon sequestration potential of biochar in the world is 2.27 Pg C year⁻¹.

Potential and role of biochar in enhancing carbon sequestration

According to an estimate approximately 500-550 MT of crop residues are produced per year in India. It consist of 93.9 MT of wheat, 104.6 MT of rice, 21.6 MT of maize, 20.7 MT of millets, 357.7 MT of sugarcane, 8.1 MT of fiber crops, 17.2 MT of pulses and 30.0 MT of oilseeds crops, in the year 2011-12 (MOA, 2012). Disposal of this crop residue remains a key issue in rural farm areas and city organic waste in urban societies. Most wastes are either burnt or end up in landfill, which degrade the environment and also produce large amounts of GHGs. The production of biochar from farm wastes and their application in farm soils offer multiple environmental and financial benefits. Biochar use has a very promising potential for global climate change mitigation. There is significant availability of non-feed biomass resources in the country as potential feedstock for biochar production. Biochar having high pH value can be a good remedy for acid soil amelioration. If only 1% of this biomass is converted to biochar, about 74 thousand tons of carbon can be sequestered annually. The sequestration potential depends on climate, soil type and site specific management. Soil organic carbon of crop land increases only if either soil organic carbon additions are enhanced or decomposition rates reduced. Reduced decomposition is an advantage of charcoal (biochar). As the soil organic carbon pool declines due to cultivation, the more resistant charcoal fraction increases as a portion of the total carbon pool and may constitute up to 35% of the total soil organic carbon pool in ecosystems (Skjemstad *et al.*, 2002). Only 2-20% of the carbon added as above ground residues and root biomass enters the soil organic carbon pool by humification. The rest is converted to CO₂ due to oxidation (Lal, 2004).

About 50% of the carbon can be captured if biomass is converted to biochar (Lehmann *et al.*, 2006). Globally, soil is estimated to hold more organic carbon (1,100 GT; 1 GT=1,000,000,000 tonnes) than the atmosphere (750 GT) and the terrestrial biosphere (560 GT) (Post *et al.*, 1990). The global flux of CO₂ from soils to the atmosphere is in the region of 60 GT of carbon per year due to microbial respiration and decomposition of soil organic matter (SOM). Biochar are considerably more recalcitrant than soil organic matter and decomposes very slowly, over a time frame. Thus, biochar allows more carbon input as compared to the carbon output and this is the basis behind biochar's possible carbon negativity and hence it's potential for climate change mitigation. It is highly stable against microbial decomposition and hence reduces GHG emissions. Agricultural waste containing high silica are not suitable for biochar, because silica entrapping carbon during combustion (Raveendran *et al.*, 1995). Further, studies showed that the highest biochar carbon sequestration is achieved at 500° C, despite the fact that biochar made at higher temperatures is relatively more recalcitrant than low temperature biochars. However, CO₂ is also emitted during the process of pyrolysis, transportation and application. Therefore, estimating the net carbon sequestration potential should consider these CO₂ emissions. Kameyama *et al.*, 2010 estimated the net carbon sequestration potential of farmland application of bagasse charcoal produced by the pilot plant and it was estimated that 0.3 and 0.2 ton CO₂ t⁻¹ dry weight for dry feedstock (MC 20%) and wet feedstock (MC 50%), respectively. These values corresponded to 70% and 50% of the carbon stabilized as bagasse charcoal in Japan. Lehmann *et al.*, 2006 predicted that the biochar storage capacity of global crop land and temperate grassland is ~400 GT C, which

would be equivalent to a ~25% increase in global soil carbon. Lenton and Vaughan, 2009 calculated a reduction in atmospheric carbon of up to 22 GT C (equivalent to a reduction of 10 ppm CO₂) by 2050. Continuing the trend forward, they predicted 3.15 GT C yr⁻¹ could be sequestered by 2100. Thus conversion of crop residue to biochar and its utilization in agricultural land has showed a very high potential in sequestering C in soil and mitigating the adverse effect of climate change.

In conclusion, biochar is a novel approach for establishing a sink for soil carbon sequestration and reported to increase the SOC over time. The interaction mechanisms with different soil constituents and fate in different soil types, agro-ecologies and agronomic and soil management practices especially under long-term condition, its yield and stability should be studied to have a better understanding of biochar in soil systems. So, wide-scale dissemination of biochar technology for carbon sequestration and climate change mitigation needs intensive investigation. To derive the maximum possible benefit of carbon sequestration through application of biochar, both yield and stability of the biochar are two important factors and should be optimized. The benefits of carbon sequestration through biochar are more visible in soils lower in carbon than soils relatively higher in carbon. The knowledge on mechanism of biochar induced reduction in greenhouse gas emission can be applied to develop a more effective greenhouse gas mitigation process for paddy fields.

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