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Biochar for Climate Change Mitigation and Ameliorating Soil Health—A Review

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ABSTRACT

In world about 2.7 billion people use wood, cow dung and crop residue for cooking and house heating. India produces about 120-150 million tons surplus biomass and most them are burn on the field. These agro-residue and biomass are not waste but the resources and can be utilized by meeting the challenge of soil degradation, environmental pollution and energy security. The present paper put light on the potential of the biochar as an agent for mitigating climate change and improving soil health. The biochar has higher calorific value than the raw biomass and is stabilized carbon. Design improvement of cook stove and portable biochar kiln would help in biomass conservation, efficient utilization of biomass as energy source, reduction in greenhouse gases (especially CO_2) emission, black carbon reduction which is responsible for global warming. The biochar embedment in soil improves soil health and carbon sequestration. Therefore, application of biochar needs to be encouraged through the participation of public & private institutions, NGOs and farmers.

Keywords: Biochar, charcoal, pyrolysis, climate change

INTRODUCTION

Biochar is a type of charcoal which is produced by heating organic matter under-limited supply of oxygen. Biochar additions are thought to increase nutrient and water retention in soils, and thereby improving crop yields (Abiven *et al.*, 2014). The concept of biochar came from Terra preta of Amazon basin. Terra preta literally means "black earth", is a type of very dark, fertile anthropogenic soil found in the Basin. The dark colour is attributed by the high char content. Terra preta display elevated soil organic matter enriched with nitrogen, phosphorus, potassium and calcium. The method of producing charcoal as a clean burning fuel is an age old practice and is carried out in traditional kiln. In charcoal production process the burning of biomass is initiated in air and then air supply is restricted. This is suitable for small scale production which is energetically less efficient, time consuming and highly polluting process. The process of producing charcoal is well known as pyrolysis. The thermal conversion of plant and derived biomass in partial and total absence of oxygen is known as pyrolysis. The pyrolysis can be manipulated to yield CO_2, combustible gases (H_2, CO, CH_4), volatile oils and solid carbon rich residue referred as char.

Use of residual biomass from agriculture and agro-processing industry to produce biochar is economically viable solution to manage waste, which is otherwise being used inefficiently. The most favoured feedstock for the production of biochar would be woody and dry biomass, such as nutshells, straw and husk of various farm crops (Parmar *et al.*, 2014). The balance between char and gas, oil and tar products in pyrolysis depends to a considerable extent upon the rate of heating (Table 1). Slow pyrolysis may be deployed as a continuous process, where purged (oxygen-free) feedstock is transported into and through an externally heated kiln (gas flow removing volatiles, char emerging at the other end).The main constrains in incorporating of crop residue is due to delay in decomposition as it contain lignin, however, lignin leads to higher char yield in comparison to cellulose and hemicelluloses.

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The biochar of any feedstock has two times more calorific value than the raw material (Sohi *et al.*, 2009). When pyrolysis is done for subcritical aqueous solution it is termed as hydrothermal carbonization (HTC). Study has been conducted on grains and cereals, fruit, kernels and oilseeds, vegetables, sugarcane and jaggery and manure waste as feedstock for biochar production (Parmar *et al.*, 2014). The characteristics of biochar depends on the feedstock and pyrolysis process related parameters i.e. peak temperature, pressure, heating rate, residence time, rates of heat transfer and solid vapour interaction. In rice straw, increasing charring temperature will increase the aroma of biochar, and might include its recalcitrance (Weixiang *et al.*, 2012).

The design and fabrication of the biochar production stove is based on the pyrolysis process parameters. Biomass used for fuel of cooking stoves can be sourced from various types of plants, and in many forms trunks, branches, sticks, twigs, bark, crop residue, sawdust, wood shavings, rice husk, leaves, grasses, seeds, corncobs, shells (groundnut, coffee, etc.), animal dung, briquettes etc. In semi-arid regions the cooking area is partially ventilated. In traditional stoves the fuel wood feed continuously however, one of the most popular stoves (TLUD) top lit updraft is allowed for batch loading of fuel (Torres, 2011 and Torres *et al.*, 2011). The biomass fuel i.e. wood chips, bunch of sticks, etc. can be loaded once and then ignited at the top. The pyrolysis process moves from the top to bottom and wood gas released which mixes with the secondary air from the bottom of the pot. At the end of combustion biochar gets accumulated at the bottom of the combustion chamber. The batch type is not popular in India and required considerable experience to handle them.

The cook stove, earth mound kilns and drum kilns are the traditionally used for char and biochar production in India (IBI, 2015). Among these three the cook stove is mostly used. The continuous feed type stove may have blower (Hand operated / electric powered) and the blower supplied the primary air and air duct is fitted underneath the blowers(Verma *et al.*, 2012). The additional air supply creates draft for efficient combustion. In "Good Stove' Avan Series type stove the biomass fuel fed over a raised platform and wood stick do not fall on the combustion pit due to gravity (Reddy, 2012). The primary air for pyrolysis and combustion comes from side to the bottom of the pit. Number of biochar kiln has been designed, developed and used for making biochar from the crop residue and forest biomass (Fig. 1 to 3) in India. However, the uses of these biochar kilns are in laboratory level or small scale.

Biochar for climate change mitigation

The biochar is strongly linked with climate change and renewable energy. Agricultural activities emit greenhouse gases (GHG) and cause 13.5% radiative forcing/climate forcing (Barker *et al.*, 2007). In producing charcoal the traditional kiln liberates greenhouse gases and conserves small proportion of carbon. The slow and control pyrolysis stabilize some carbon in solid form and also collect the energy rich gases and liquids. The pyrolysis may be the more efficient in terms of carbon

Fig. 1: Bio-char kiln (*Source*: Venkatesh *et al.*, 2013)

Fig. 2: Vertical cylinder bio-char reactor equipped with external electrical heating system (Gangil and wakudkar, 2013)

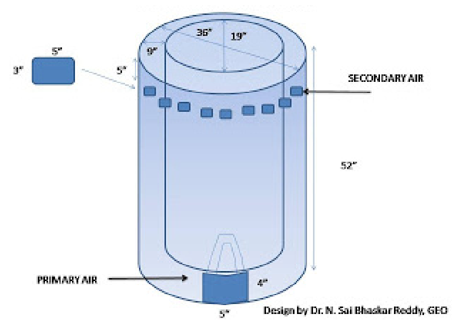

Fig. 3: Holy Mother biochar kiln (Reddy, 2012)

Table1: Effect of pyrolysis parameter on production of biochar

Process	Liquid (bio-oil)	Solid(biochar)(%)	Gas (syngas) (%)
Fast pyrolysis: Moderate temperature (≈500°C), short hot vapour residence time (<2 s)	75% (25% water	12	13
Intermediate pyrolysis: Low to moderate temperature, moderate hot vapour residence time	50% (50% water)	25	25
Slow pyrolysis: Low to moderate temperature, long residence time	30% (70% water)	35	35
Gasification: High temperature (>800°C), long vapour residence time	5% tar (5% water)	10	85

Source: Sohi *et al.*, 2010

emission and production of biochar has greater potential. Biochar and bioenergy co-production from biomass may reduce dependency on fossil fuel, enhance carbon sequestration instable soil carbon pools and drastically reduce the emissions of nitrous oxides (Yanai *et al*., 2007), CH_4 (Rondon *et al*., 2005 & 2006) a more potent greenhouse gas than carbon dioxide and help to combat global climate change. Land application of the 3.5 Mton/yr of biochar (≥63% C) would sequester approximately 2.2 Mton/yr of soil carbon in Zimbabwe alone (Gwenzi *et al*., 2015). Biochar can also be used as an adsorbent for the removal of neutral, anionic and cationic contaminants (Yao *et al*., 2011). The ordinary soil carbon is characterized by high turnover and releases of CO_2 but biochar is more recalcitrant to decomposition (Zimmerman, 2010). Reduction of up to 50% in N_2O emission was recorded from animal urine-added Templeton silt loam soil with biochar application rate of 30 tonnes/ha in New Zealand (Taghizadeh-Toosi *et al*., 2011). In a two-year consecutive study of paddy cultivation cycle in China, apart from positive effects on soil properties after biochar amendment, N_2O emissions from paddy fields reduced significantly in both crop cycles (Zhang *et al*., 2012). Therefore biochar diverts the carbon from the rapid biological cycle into slower biochar cycle. Converting biomass to biochar reduce the methane and CO_2 from the landfill and waste dump.

Many studies on the chemical properties of biochar have shown that it has a potential for long-term carbon sequestration because of its resistive nature. The incubation studies on a mixture of biochar and soils have revealed that the average soil residence time for biochar can be up to thousands of years (Kumar *et al*., 2013 and Xu *et al*., 2012). Resistive nature of biochar makes organic matter unavailable for microorganisms and other decomposers as substrate, which helps in long-term storage of carbon in soils.

Biochar for ameliorating soil health

The soil has capacity to accommodate biochar at large scale, biochar can improve the soil function and productivity (Glaser, 2002), suppress the emission of the methane and nitrous oxide. Biochar addition to soil will proceed only where sufficient improvements in soil performance and productivity are perceived or assured. The changes in the soil physical properties and increase water holding capacity (Gaskin *et al*., 2008). The biochar has important properties such as high surface area and cation exchange capacity (CEC), high carbon content, higher aggregate stability (Mukherjee and Lal, 2013) and nutrient content, low bulk density and neutral to alkaline pH makes depend on the pyrolysis process and feedstock (Hass *et al*., 2012). It is used as soil conditioner also (Steiner *et al*., 2007). Biochar with low bulk density and stable organic carbon reduces the penetration resistance and increase total soil porosity (Zhang *et al*., 2011). Application of biochar enhances the CEC (Liang *et al*., 2006; Lehmann, 2007 and Verheijen *et al*., 2010), nutrient retention (Shenbagavalli and Mahimairaja, 2012 and Nagori, 2012) and bioavailability of soil (Hass *et al*., 2012 and Uzoma *et al*., 2011). The porous space of biochar provides habitat for soil organism and protect from predators (Rillig *et al*., 2010). In sandy and loamy soil the leaching of nutrient can be checked by the use of biochar. The neutral or alkaline biochar has the potential to ameliorate acid soil (Gaskin *et al*., 2008 and Zwieten *et al*., 2010) and improve nutritional availability as it contains nitrogen as well as phosphorus (Major *et al*., 2010 & Sika and Hardie, 2014) . The high stable carbon of biochar may play critical role in improving soil aggregate and aggregate stability. The changes in soil structure because of biochar may enhance the moisture retention capacity (Karhu *et al*., 2011), infiltration and reduce runoff and erosion. Several authors have reported the improvement of soil health due to biochar amendment given in Table 2.

Table 2: Effect of biochar on different soil properties

Factors	Impact	Source
Cation exchange capacity	50% increase	Glaser *et al*., 2002
Fertilizer use efficiency	10-30% increase	Gaunt and Cowie, 2009
Soil moisture retention	Up to 18% increase	Tryon, 1948
Methane emission	100% decrease	Rondon *et al*., 2005
Nitrous oxide emission	50% decrease	Yanai *et al*., 2007
Bulk density	Soil dependent	Laird, 2008
Mycorrhizal fungi	40% increase	Warncock *et al*., 2007
Biological nitrogen fixation	50-72% increase	Lehman and Rondon, 2006
Leaching N and dissolved P	11% and 69% reduced	Laird *et al*., 2010

(*Source*: Srivivasarao *et al*., 2013)

It has been observed that application of biochar enhances crop emergence (Solaiman *et al*., 2012), the crop yield (Cornelissen *et al*., 2013), and reduces GHG emission (Mukome *et al*., 2013). Increase in yield of crops reported by several authors as listed in Table 3.

SCIENTIFIC GAPS

Some of the scientific gaps which were identified during this review and need further research are as follows:

1. Feedstock availability and supply of biochar for its production is full of uncertainties.
2. Application rate of biochar for specific soils and crop combination has not been standardised.

Table 3: Summary of experiments assessing the impact of biochar addition on crop yield

Study outline	Results summary	Authors
Pea, India	Char at 0.5 t/ha increased biomass by 160%	Iswaran *et al.*, 1980
Mung bean, India	Char at 0.5 t/ha increased biomass by 122%	
Soybean on volcanic ash loam, Japan	Char at 0.5 t/ha increased yield by 151%, Char at 5 t/ha decreased yield by 63%, and Char at 15 t/ha decreased yield by 29%	Kishimoto & Sugiura, 1985
Sugi trees on clay loam, Japan	Wood charcoal, bark charcoal and activated charcoal at 0.5 t/ha increased biomass by 249, 324 and 244%, respectively	
Bauhinia trees on alfisol/ultisol	Charcoal application increased biomass yield by 13% and height by 24%	Chidumayo, 1994
Cowpea on xanthic ferralsol	Char at 67 t/ha increased biomass by 150% Char at 135 t/ha increased biomass by 200%	Glaser *et al.*, 2002
Soil fertility and nutrient retention. Cowpea was planted in pots and rice crops in lysimeters at the Embrapa Amazonia Ocidental, Manaus, Brazil	Biochar additions significantly increased biomass production by 38 to 45% (no yield reported)	Lehmann *et al.*, 2003
Comparison of maize yields between disused charcoal production sites and adjacent fields, Kotokosu watershed, Ghana	Grain and biomass yield was 91 and 44% higher on charcoal site than control.	Oguntunde *et al.* , 2004
Maize, cowpea and peanut trial in area of low soil fertility	Acacia bark charcoal plus fertilizer increased maize and peanut yields (but not cowpea)	Yamamoto *et al.*, 2006
Pot trial on radish yield in heavy soil using commercial green waste biochar (three rates) with and without N	Biochar at 100 t/ha increased yield x3; linear increase 10 to 50 t/ha, but no effect without added N	Chan *et al.*, 2007
Enhanced biological N-2 fixation (BNF) by common beans through bio- char additions. Colombia	Bean yield increased by 46% and biomass production by 39% compared to control at 90 and 60 g biochar/kg, respectively	Rondon *et al.*, 2007
Four cropping cycles with rice (Oryza sativa L.) and sorghum (Sorghum bicolor L.)	Charcoal amended with chicken manure amendments resulted in the highest cumulative crop yield (12.4 t/ ha)	Steiner *et al.*, 2007
Mitigation of soil degradation with biochar. Comparison of maize yields in degradation gradient cultivated soils in Kenya.	Doubling of maize grain yield in the highly degraded soils from about 3 to 6 t/ha	Kimetu *et al.*, 2008

(*Source*: Sohi *et al.*, 2009, Woolf 2008 and Srinivasarao *et al.*, 2013)

3. Long-term studies are required to understand nature of biochar interaction with soil.
4. Scarce data is available on biochar-induced toxicity on soil organisms and plants.

CONCLUSION

Disposal of large amount of biomass waste from the crop production, food processing and other allied industry is creating problem. The higher labour wages, collection and treatment process and space are the major constraint. The biochar technologies is an important method for utilizing these waste to source of nutrient and energy and can be recycled to the soil, meet the energy requirement at household level and reduce emission. Future of biochar depends on the studying its long-term effects and risks. The awareness of the technologies and hand on training to the potential user may popularise it. The participation of the farmers, villagers and the scientific community would make it possible to sensitize the people about climate change and soil health deterioration due to uncontrolled burning of the biomass. The knowledge about the production process and application of biochar can ameliorate the soil heath, reduces the emission of GHG and particulate, smoke and ultimately helps in mitigating climate changes.

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