Use of **Biochar** for Soil Health Enhancement and Greenhouse Gas Mitigation in India:

Potential and Constraints

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FOREWORD

Climate change is threatening food security globally. Countries like India are more vulnerable in view of the tropical monsoon climate and poor coping capacity of the small and marginal farmers. Several agricultural practices like indiscriminate use of agro-chemicals and crop residue burning contribute to emission of greenhouse gasses leading to warming of the atmosphere. Sequestration of carbon both in the vegetation and soil is the most effective means of mitigating GHG emissions. There are several strategies of soil carbon sequestration which can be adopted at farm level. These include: conservation agriculture, biomass recycling, crop rotations and use of organic amendments. One of the recent developments is the conversion of crop residue biomass into biochar and using the char as a soil amendment rather than directly using the crop residues. Several studies show that biochar has a long life in soil and is more effective in sequestering carbon besides improving other soil properties like water holding capacity and nutrient availability.

In Indian conditions, there is an immense scope for converting millions of tonnes of crop residues which are not used as fodder into biochar and use the same for enriching soil carbon. Research program has been initiated under NICRA by different partner institutions on production of biochar, its characterization and the benefits of its application to field crops. However, this being a new subject, there is a need for a bulletin to discuss various issues related to production and use of biochar.

I am happy to note that various institutions of the NARS under the NICRA umbrella have collectively brought out this practical bulletin on biochar. This bulletin provides lucid information on various aspects related to biochar production and its application in agriculture and identifies some future researchable issues. I am sure this bulletin will be highly useful to all the researchers involved in use of biochar in agriculture. I complement the authors for this unique effort.

B.VENKATESWARLU

PREFACE

It is crucial to maintain a threshold level of organic matter in the soil for maintaining physical, chemical and biological integrity of the soil and for sustained agricultural productivity. Efficient use of biomass by converting it as a useful source of soil amendment/nutrients is one way to manage soil health and fertility. The current availability of biomass in India is estimated at about 500 million tons/year. These residues are either partially utilized or un-utilized due to various constraints. It is estimated that about 93 million tons of crop residues are burned in each year in India. Residue burning traditionally provides a fast way to clear the agricultural field of residual biomass, facilitating further land preparation and planting. However, in addition to loss of valuable biomass and nutrients, biomass burning leads to release of toxic gases including GHGs. In this context, biochar, a pyrolysis product of plant biomass offers a significant, multidimensional opportunity to transform large scale agricultural waste streams from a financial and environmental liability to valuable assets. Use of biochar in agricultural systems 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 mitigate GHG emissions from agricultural soils. This has led to renewed interest of agricultural researchers to produce biochar from bioresidues and its use as a soil amendment. Although many countries have prioritized the use of biochar in agricultural systems, studies on biochar production and its utilization as a soil amendment are at a nascent stage in India. In addition to public organizations, many private institutes and NGOs have initiated work on these lines. This bulletin documents the initial outcomes of biochar research being conducted in different parts of the country, and potential benefits of biochar use in improving soil health, crop productivity and in mitigating climate change through reduction in emission of GHGs and carbon sequestration. We firmly believe that this publication will be very useful for researchers, academicians, policy makers and students.

- Authors

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Introduction

Agricultural waste is usually handled as a liability, often because the means to transform it into an asset is lacking. Crop residues in fields can cause considerable crop management problems as they accumulate. The major crop residues produced in India are straws of paddy, wheat, millet, sorghum, pulses (pigeonpea), oilseed crops (castor, mustrad), maize stover and cobs, cotton and jute sticks, sugarcane trash, leaves, fibrous materials, roots, branches and twigs of varying sizes, shapes, forms and densities. Similarly, the agro-industrial residues are rice husk, groundnut shell, cotton waste, coconut shell, coir pith, tamarind shell, mustard husk, coffee husk, cassava peels etc. Some of the common agricultural by-products available in large quantities include bagasse, rice husk, groundnut shell, tea waste, casuarina leaf litter, silk cotton shell, cotton waste, oil palm fibre and shells, cashew nut shell, coconut shell, coir pith etc. (Sugumaran and Sheshadri, 2009).

In India, about 435.98 million tons of agro-residues are produced every year, out of which 313.62 million tons are surplus. These residues are either partially utilized or un-utilized due to various constraints (Murali *et al.*, 2010). Similarly, using different residue to produce ratio values, Koopmans and Koppejan (1997) estimated that about 507,837 thousand tons of field crop residues were generated in India during 1997 of which 43% was rice and 23% wheat. The estimates from Streets *et al.* (2003) reveal that 16% of total crop residues were burnt. The results from Venkataraman *et al.* (2006) suggest that 116 million tons of crop residues were burnt in India in 2001, but with a strong regional variation (Gupta, 2010).

The current availability of biomass in India (2010-2011) is estimated at about 500 million tons/year. Studies sponsored by the Ministry of New and Renewable Energy (MNRE), Govt. of India have estimated surplus biomass availability at about 120–150 million tons/annum (Table 1; MNRE, 2009). Of this, about 93 million tons of crop residues are burned in each year (Table 1; IARI 2012).

Generation of crop residues is highest in Uttar Pradesh (60 million t) followed by Punjab (51 million t) and Maharashtra (46 million t). Maharashtra contributes maximum to the generation of residues of pulses (3 million t) while residues from fibre crop is dominant in Andhra Pradesh (14 million t). Gujarat and Rajasthan generate about 6 million t each of residues from oilseed crops.

Table 1. Generation and surplus of crop residues in different states of India

State	Residue generation (MNRE, 2009)	Residue surplus (MNRE, 2009)	Residue burned (IPCC coeff.)	Residue burned (Pathak et al., 2010)
	Million t/yr			
Andhra Pradesh	43.89	6.96	5.73	2.73
Arunachal Pradesh	0.4	0.07	0.06	0.04
Assam	11.43	2.34	1.42	0.73

State	Residue generation (MNRE, 2009)	Residue surplus (MNRE, 2009)	Residue burned (IPCC coeff.)	Residue burned (Pathak et al., 2010)
	Million t/yr			
Bihar	25.29	5.08	3.77	3.19
Chhattisgarh	11.25	2.12	1.84	0.83
Goa	0.57	0.14	0.08	0.04
Gujarat	28.73	8.9	6.69	3.81
Haryana	27.83	11.22	5.45	9.06
Himachal Pradesh	2.85	1.03	0.20	0.41
Jammu and Kashmir	1.59	0.28	0.35	0.89
Jharkhand	3.61	0.89	1.11	1.10
Karnataka	33.94	8.98	2.85	5.66
Kerala	9.74	5.07	0.40	0.22
Madhya Pradesh	33.18	10.22	3.46	1.91
Maharashtra	46.45	14.67	6.27	7.41
Manipur	0.9	0.11	0.14	0.07
Meghalaya	0.51	0.09	0.10	0.05
Mizoram	0.06	0.01	0.01	0.01
Nagaland	0.49	0.09	0.11	0.08
Orissa	20.07	3.68	2.57	1.34
Punjab	50.75	24.83	8.94	19.62
Rajasthan	29.32	8.52	3.58	1.78
Sikkim	0.15	0.02	0.01	0.01
Tamil Nadu	19.93	7.05	3.55	4.08
Tripura	0.04	0.02	0.22	0.11
Uttarakhand	2.86	0.63	13.34	21.92
Uttar Pradesh	59.97	13.53	0.58	0.78
West Bengal	35.93	4.29	10.82	4.96
India	**501.76**	**140.84**	**83.66**	**92.81**

Source: IARI (2012)

Among different crops, cereals generate maximum residues (352 Mt), followed by fibres (66 Mt), oilseeds (29 Mt), pulses (13 Mt) and sugarcane (12 Mt). The cereal crops (rice, wheat, maize, millets) contribute 70% while rice crop alone contributes 34% to the crop residues (Fig 1).

The surplus residues i.e., total residues generated minus residues used for various purposes, are typically burnt on-farm. Estimated total amount of crop residues surplus in India is 91-141 Mt (IARI, 2012). Cereals and fibre crops contribute 58% and 23%, respectively (Fig 2) and remaining 19% is from sugarcane, pulses, oilseeds and other crops. Out of 82 Mt surplus residues from the cereal crops, 44 Mt is from rice followed by 24.5 Mt from wheat,
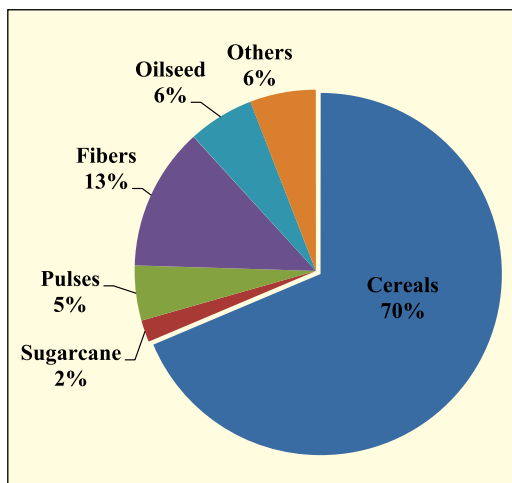
Fig 1. Contribution of various crops to residue generation in India (Calculated from MNRE report, 2009)
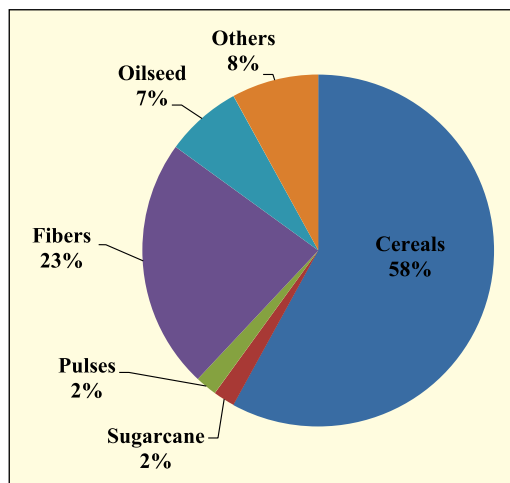

Fig 2. Surplus of various crop residues in India (IARI, 2012)

which is mostly burnt on-farm (Table 1). In case of fibre crops (33 Mt of surplus residue), approximately 80% of the residues are from cotton and are subjected to on-farm burning.

In northeast (NE) Himalayan region, rice and maize are the major cereal crops. Paddy straw is widely used as fodder in this region and hence, burning of paddy straw is uncommon except in few locations in Assam. Maize covers the second largest area after rice and the residue of this crop is burnt in both upland condition and under shifting cultivation. About 9.7 million tons of crop residues are produced annually in this region (Table 2).

Table 2. Estimate of crop residue production in NE India (2009-10)

Crop	Production (000' tons)	Residue: grain ratio	Residue production (000' tons)
Rice	6024	1.5	9036
Maize	263	1.0	263
Pulses	144	1.0	144
Oilseeds	260	1.0	260
Total	6691	-	9703

Source: NEDFI (2013) and Hajarika *et al*. (2006)

Further, forest covers more than 60% of the land in the hill ecosystem of NE and lot of forest waste biomass is readily available for use in agriculture. In addition, a lot of forest biomass is burnt in shifting cultivation (slash-and-burn method).

Residue burning traditionally provides a fast way to clear the agricultural field of residual biomass and facilitating further land preparation and planting. Other reasons for intentional burning include clearing of fields, fertility enhancement, and pest and pasture management. It also provides a fast way of controlling weeds, insects and diseases, by both eliminating them directly or by altering their natural habitat. Further, the time gap between rice harvesting and wheat sowing in northwest India is only 15-20 days. Hence, farmers

prefer burning the rice stalk in the field instead of harvesting it for other uses. Burning is also perceived to boost soil fertility, although burning actually has a differential impact on soil fertility. It increases the short-term availability of some nutrients (e.g. P and K) and reduces soil acidity, but leads to a loss of other nutrients (e.g. N and S), organic matter and microbial activity required for maintaining better soil health.

Among the cereal residues, rice and wheat straws are the dominant and the easiest way to clear the field is burning these in the field itself. For example, 23% of rice straw residue produced is surplus and is either left in the field as uncollected or to a large extent open-field burnt. In Punjab alone, some 70 to 80 million tons of rice and wheat straw are burned annually (Punia *et al*., 2008), releasing approximately 140 million tons of CO_2 to the atmosphere, in addition to methane, nitrous oxide and air pollutants. About three-fourths of greenhouse gas (GHG) emissions from agro-residues burning were CH_4 and the remaining one-fourth was N_2O. Burning of wheat and paddy straws alone contributes to about 42% of GHGs.

On the other hand, 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

Loss of biomass through forest fires (photo by Singh, 2010) and crop residue burning in agricultural fields

to perform its agricultural production and environmental functions (Izaurralde *et al.*, 2001; Srinivasarao *et al.*, 2012, 2013). Hence, 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 (Srinivasarao *et al.*, 2012, 2013). 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 (McHenry, 2009). This has led to renewed interest of agricultural researchers to use charcoal/black carbon/ biochar as a soil amendment for stabilizing soil organic matter (SOM). Converting waste biomass into biochar would transfer very significant amounts of carbon from the active to inactive carbon pool, presenting a compelling opportunity to intervene in the carbon cycle. 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 practiced 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 ((Izaurralde *et al.*, 2001; McHenry, 2009) 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.

1. What is biochar?

Biochar is a fine-grained, carbon-rich, porous product remaining after plant biomass has been subjected to thermo-chemical conversion process (pyrolysis) at low temperatures (~350–600°C) in an environment with little or no oxygen (Amonette and Joseph, 2009). Biochar is not a pure carbon, but rather mix of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in different proportions (Masek, 2009). The central quality of biochar and char that makes it attractive as a soil amendment is its highly porous structure, potentially responsible for improved water retention and increased soil surface area.

It is important to note that there is a wide variety of char products produced industrially. For applications such as activated carbon, char may be produced at high temperature, under long heating times and with controlled supply of oxygen. In contrast, basic techniques for manufacture of charcoal (such as clay kilns) tend to function at a lower temperature, and reaction does not proceed under tightly controlled conditions. Traditional charcoal production should be more accurately described as 'carbonization', which involves smothering of biomass with soil prior to ignition or combustion of biomass whilst wet. Drying and roasting of biomass at even lower temperatures is known as 'torrefaction' (Arias *et al.*, 2008). Biochar from pyrolysis, and conventional charcoal and char share key characteristics which are related to carbon sequestration (long residence time) and soil fertility (soil conditioning effect). Intensive study of biochar-rich dark earths in the Amazon (*terra preta*), has led to a wider appreciation of biochar's unique properties as a soil enhancer.

2. Preparation of Biochar

For as long as human history has been recorded, heating or carbonizing wood for the purp0se of manufacturing biochar has been practiced (Emrich, 1985). Carbonization is as old as civilization itself (Brown, 1917). There are different ways to make biochar, but all of them involve heating biomass with little or no oxygen to drive off volatile gasses, leaving carbon behind. This simple process is called thermal decomposition usually achieved from pyrolysis or gasification. Pyrolysis is the temperature driven chemical decomposition of biomass without combustion (Demirbas, 2004). In commercial biochar pyrolysis systems, the process occurs in three steps: first, moisture and some volatiles are lost; second, unreacted residues are converted to volatiles, gasses and biochar, and third, there is a slow chemical rearrangement of the biochar (Demirbas, 2004). A summary of biomass conversion processes is presented in Fig 3.
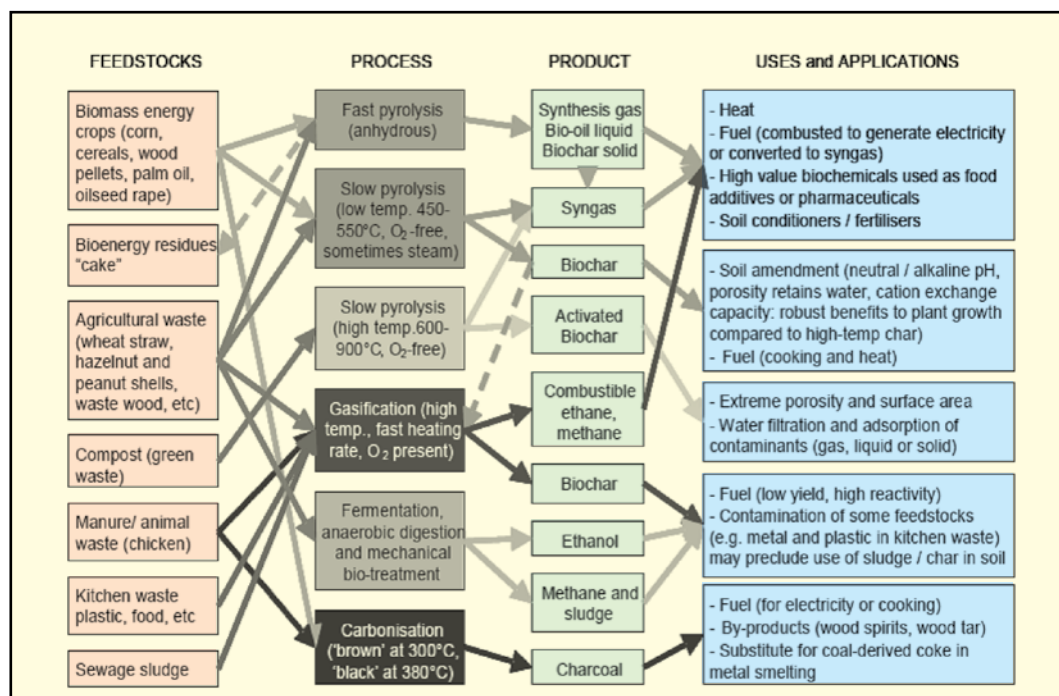
Fig 3. Summary of pyrolysis processes in relation to their common feed stocks, typical products, and the applications and uses of these products (Sohi et al., 2009)

At the instant of burning, the biomass carbon exposed to fire has three possible fates. The first, and least possible fate of biomass exposed to fire is that it remains un-burnt. The other two possible fates are that it is either volatized to carbon dioxide or numerous other minor gas species, or it is pyrolised to biochar (Graetz and Skjemstad, 2003). These methods can produce clean energy in the form of gas or oil along with biochar. This energy may be recoverable for another use, or it may simply be burned and released as heat. It is one of the few technologies that are relatively inexpensive, widely applicable and quickly scalable.

To differentiate between the different pyrolysis reactors, nomenclature recommended by Emrich (1985) is given below.

Kiln: Kilns are used in traditional biochar making, solely to produce biochar

Retorts and converters: industrial reactors that are capable of recovering and refining not only the biochar but also products from volatile fractions (liquid condensates and syngases) are referred to as retorts or converters

Retort: The term retort refers to a reactor that has the ability to pyrolyzepile-wood, or wood log over 30 cm long and over 18 cm in diameter (Emrich, 1985).

Converters: produce biochar by carbonizing small particles of biomass such as chipped or pelletized wood.

Slow pyrolysis: refers to a process in which large biomass particles are heated slowly in the absence of oxygen to produce biochar.

Fast pyrolysis: refers to reactors designed to maximise the yields of bio-oil and typically use powdery biomass as feedstock.

The major criteria to consider are the targeted final products: (1) biochar and heat, (2) biochar, bio-oil and gases, (3) biochar, carbon black, and syngas (gas mixtures that contain varying amounts of CO and H), and (4) syngas (Pelez-Samaniego et al., 2008). Depending upon the requirement, suitable procedure is followed for production of biochar alone or combination with other useful co-products. But biochar production technology is more than just the equipment needed to produce biochar. It necessarily includes entire integrated systems that can contain various components that may or may not be part of any particular system. Brazil is by far the largest biochar producer in the world producing 9.9 million tons/year. Other important biochar producing countries are: Thiland (3.9 million tons/year), Ethiopia (3.2 million tons/year), Tanzania (2.5 million tons/year), India (1.7 million tons/year) and Democratic Republic of Congo (1.7 million tons/year).

Biochar can be produced at scales ranging from large industrial facilities down to the individual farm (Lehmann and Joseph, 2009), and even at the domestic level (Whitman and Lehmann, 2009), making it applicable to a variety of socioeconomic situations. Various pyrolysis technologies are commercially available that yield different proportions of biochar and bio-energy products, such as bio-oil and syngas. The gaseous bio-energy products are typically used to generate electricity; the bio-oil may be used directly for low-grade heating applications and, potentially, as a diesel substitute after suitable treatment (Elliott, 2007). To make biochar technology popular among the farmers, it is imperative to develop low cost biochar kiln at community level or low cost biochar stove at individual farmer's family level.

2.1 Heap Method

Charcoal making is one of the traditional practices to generate income in various parts of India. In traditional method, a heap of pyramid like structure (earth kiln) is prepared by keeping wood logs and roots of plants for making charcoal (Fig 4). To allow the combustion products to escape, vents are opened starting from the top and working downwards. When smoke production is stopped, the cooling process is started by covering stack with a layer of moist earth. The cooling process takes several days before the earth is removed and the biochar produced is separated from the surrounding carbonized portions. Earth-mound kilns equipped with a chimney are most advanced among earth kilns. The ability to alter the chimney diameter according to the oxygen demand, and precise control of the draft of

the chimney, which is dependent on height, results in better control of the pyrolysis process (Emrich, 1985).

Biochar making from *Prosopis julifera* is practiced in the rain-fed tracts of Ramanathapuram district of Tamil Nadu during off-season. Generally, people use the heap method of charcoal production as it is easy and cost involved in char production is very low. Mostly fibre wastes of coconut, paddy straw or any available agriculture waste are used to prepare paste mixed with clay soil to cover the heap structure containing wood logs. Finally, it is covered with sand from outside and water is applied over it. Entire wood logs are converted into charcoal after burning inside the heap for 3-4 days. The charcoal is transported to various districts of Tamil Nadu and also certain states like Maharashtra and Gujarat for industrial purpose.
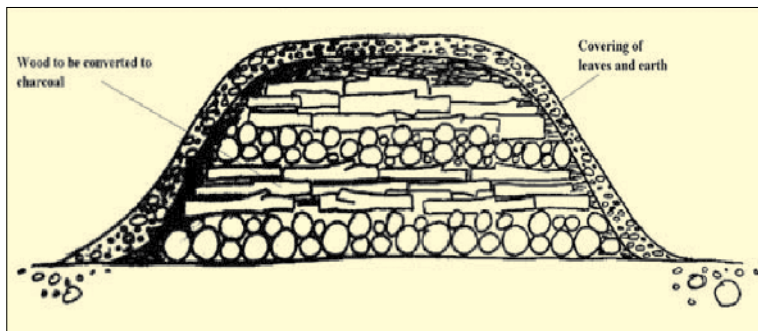
Fig 4. Traditional earth kiln (Source: http://en.howtopedia.org/wiki/Biomass_(Technical_Brief)

Similarly, a very simple biochar kiln 'Holy Mother Biochar Kiln' has been designed by Sarada Matt (Holy Mother) at Almora, Uttarakhand, India (Fig 5). Bricks and clay are used in the construction. The biomass is added continuously as the fire continuous. The primary air source at the bottom will be kept open as long as biomass is added. It is convenient to operate the kiln during less windy days. As the biomass reaches the level just below the secondary air vents, further addition of biomass should be stopped and the primary air inlet is closed. After some time, water is sprinkled to extinguish the embers (quench). The biochar can be collected immediately or after some time.
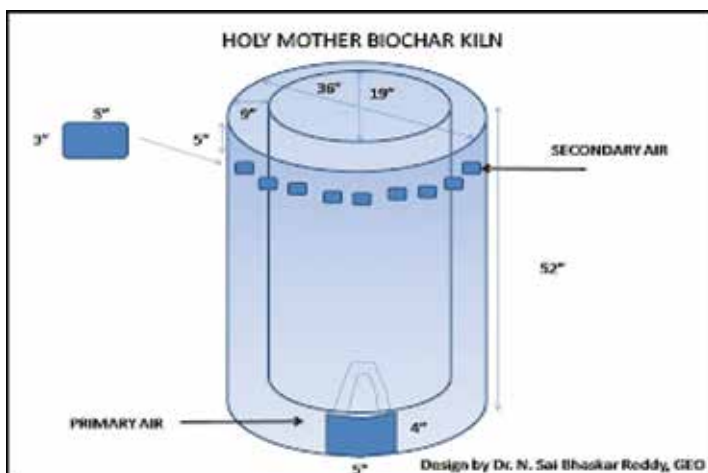
Fig 5. Holy Mother Biochar Kiln (Source: http://biocharklin.blogspot.in/)

Heap method of biochar preparation in Tamil Nadu (Source: Jeyaraman, TNAU)

2.2 Drum Method

Kilns that are built in place, typically are constructed from soil or other local materials, are located close to biomass resources and are small. They are economically viable if the cost of construction and transportation of biochar is lower than the cost of transporting and processing of biomass. In a modified method, char production is done by pyrolysis kiln. Venkatesh *et al*. (2010) developed a low-cost charring kiln by modifying oil drums at CRIDA, Hyderabad. A cylindrical metal oil drum (200 L capacity) with both sides intact was procured from local market and was modified for use as charring kiln. A square shaped hole of 16 cm x 16 cm was made on the centre of top side of the drum for loading the crop residues. On the opposite side (bottom) of the oil drum, a total of 36 holes each measuring 4 cm^2 were made in concentric circles with a 5 cm^2 hole at the center covering 20% of the total surface area of the bottom portion of the oil drum to facilitate uniform circulation of air from below.

A view of bottom side of the charring kiln

After making sufficient modifications, inner sides of the charring kiln were cleaned by burning some waste jute bags so as to make free from residual hydrocarbon. Another metal sheet measuring 20 cm x 20 cm was made ready to cover the top square hole at the end of burning process to stop the circulation of air. Sufficient amount of clay soil was collected for sealing purpose. Later, preliminary trials were conducted by using the charring kiln to study the conversion efficiency of maize stalks into biochar at different loading rates and partial combustion time. The details of the study and major findings are presented below.

Loading the charring kiln: Before loading the modified kiln with the maize stalks, initial weight of the charring kiln was recorded using a platform balance. The dried maize stalks were loaded through top square hole, by holding a big wooden stick of 5-8 cm diameter at the center of the kiln to create a central vent. While loading, few stalks were smeared with diesel and placed at the bottom to aid initial ignition. Maize stalks were loaded in the kiln at five different quantities viz. 6.7, 8.2, 8.7, 9.7 and 10 kg. After loading the maize stalks,

the wooden stick was carefully removed leaving a central vent in the drum. Weight of the loaded kiln was recorded using platform balance.

Firing and sealing of the charring kiln: Before initiating the burning process, the loaded kiln was placed on three stones (about 15 cm height) to facilitate air flow through the holes at the bottom. The stalks were ignited through the bottom holes. After the reduction in thickness of smoke, the metal sheet was placed partially on the top hole of the kiln to slow down the flow of air into the drum. This was to reduce the flow of oxygen so that the stalks were not burnt to ashes. Whenever the amount of smoke increased, the cover was opened to allow more air flow. The maize stalks were subjected to three different periods of partial combustion viz. 13, 15 and 16 minutes. The kiln was allowed to burn until the fire became clear and produced a very thin blue smoke. At this stage, the kiln was ready to be sealed with clay. The metal sheet was placed over the top hole. Later, the kiln was transferred to a leveled surface. Clay was used to seal the bottom edges of the drum and also along the edges of the metal sheet used for covering the top hole. It was ensured that no smoke was escaping from the drum. The drum was left for cooling. After cooling, the sealed clay was removed and the biochar was taken out from the kiln and weighed.

The initial weight of the modified oil drum (charring kiln) was 18.8 Kg. The average length and girth of the chopped maize stalks were 15.93 cm and 5.8 cm, respectively and the moisture content after air drying for 20 days was 14%. The results revealed that at a loading rate of 6.7 kg and partial combustion time of 13 minutes, about 50% of maize stalks remained un-burnt. Upon extending the partial combustion time to 15 minutes, the conversion rate was 29.3 and 23.7% for loading rates of 8.2 and 9.7 kg, respectively. At a partial combustion time of 16 minutes, the conversion rate was 27.6, 23.7 and 23.0% for loading rates of 8.7, 9.7 and 10 kg maize stalk, respectively. The preliminary results of the study indicate that a partial combustion time of 15

Biochar of maize stalks

minutes was found optimum for production of biochar from chopped maize stalks. It was also found that the biochar conversion efficiency did not differ significantly due to different loading rates of maize stalks (8.7-10 kg/kiln). However, the highest conversion efficiency was obtained at a loading rate of 8.2 kg and a partial combustion time of 15 minutes. Biochar yield decreased with increase in time of partial combustion. This may be due increased exposure to oxygen supply which might have contributed to volatilization of carbon.

Similarly, Purakayastha *et al*. (2012) developed a cylindrical low-cost pyrolysis kiln made from fire brick at IARI, New Delhi. The gap between the two fire brick wall is filled with perlite which acts as insulator to check the heat loss through dissipation. The used oil drum was placed on a stand inside the brick kiln for heating. The drum is filled with agricultural residues with not too tight packing and the drum is closed from the top with a metal lid having provision for escape of syngas. Heating is provided by wood log externally at the bottom of the drum until the desired temperature (300 – 400°C) is reached. This method requires two hours for complete preparation of good quality biochar with biochar yield

Biochar preparation at IARI: Drum used for preparation of biochar (A); Drum filled with maize stover (B); Drum covered with lid (C); Drum placed inside the firebrick kiln heating provide at the base of drum externally (D); Biochar removed from drum (F); and Biochar the final product with little percentage of ash (F)

of approximately 50%. The cost of fabrication of pyrolysis kiln is approximately Rs. 50,000. Biochar could also be prepared in oil drum without construction of fire brick kiln.

Researchers at CIAE, Bhopal have developed a 'CIAE Portable Charring Kiln'. It converts crop-residues into char through pyrolysis process for smokeless kitchen fuel (briquettes) production. It can be used for different bioresidues including soybean straw, pigeonpea and cotton stalks etc as input material. It consists of M.S. drum, handle and a door (Table 3).

Table 3. Specifications and working features of CIAE charring kiln

Overall dimension (mm)		Weight (kg)	Input (crop residues) (kg/day)	Output (char) (kg/ day)	Labour requirement (man-h/q)	Operating cost (Rs/q)
Length	Diameter					
1100	800	45	200	80	16	225

CIAE Charring Kiln

Similarly, a modified portable metallic kiln was used at ICAR Research Complex for NEH Region to make biochar from waste of plywood factory and weed biomass. The kiln was made from 200 litre used oil-drum. It had a conical grate at the bottom extended to the top of the drum by a cylinder of 120 mm diameter. The cylinder was further extended

Portable metallic kiln (a) charring drum, (b) charring drum with lid and chimney, (c) burning of biomass during charring and (d) charred biomass after cooling
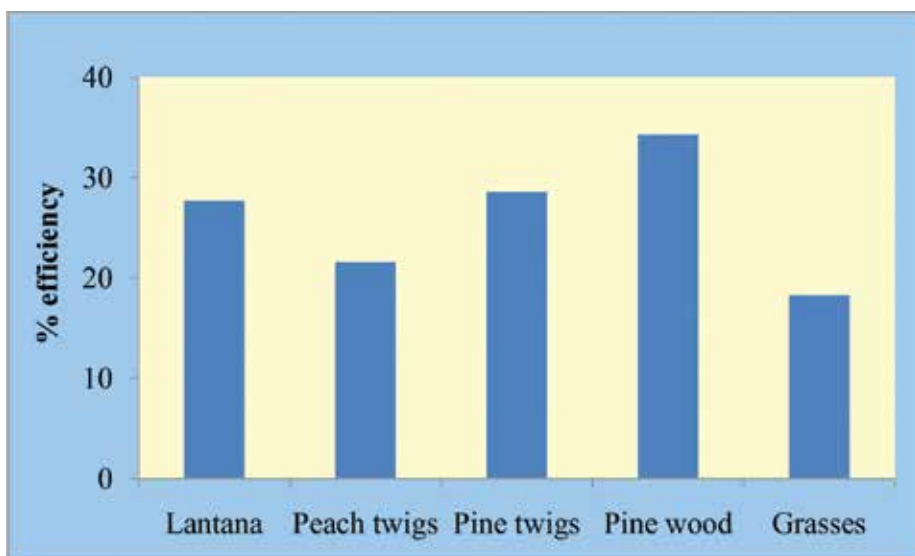
Fig 6. Charring efficiency of portable metallic kiln for different organic materials

to a chimney of same diameter up to a height of 1200 mm. A pipe of 60 mm diameter was provided below the drum to supply air by a blower. After putting a small charge of dry biomass, it is ignited at the top and air is blown from bottom of the drum. Once the biomass catches sufficient fire, addition of charge in small quantities is continued till the drum is filled. The chimney is put on the conical grate extension after ignition. Initially a lot of black smoke comes out but it reduces after 20-30 minutes. When the colour of smoke fades, the chimney is taken out and a lid is put over the drum which completely seals the smoke. Blower is taken out and the bottom pipe is closed by using mud. Where an electric blower is not available, a hand operated blower can be used similar to one used in foundry artisans. In one batch, 30-40 kg biomass can be converted to biochar within two hours with a conversion efficiency of 25-35% depending on the type of biomass (Fig 6). The cost of the kiln excluding the blower is approximately Rs. 4000.

Biochar was also made from pine needles, maize stalk and weed biomass using a hot air oven at 350°C for 4 hours. The weed species were *Lantana camara*, *Ageratum*, *Setaria*, *Gynura sp.* and *Avena fatua*. Each biomass was oven dried at a temperature of 65°C for 24 hours before charring. Then the biomass was crushed to < 25 mm size and placed in stainless steel containers of 100 mm diameter and 150 mm height and were further pyrolysed. The yield of biochar varied from 23.2 to 47.7%. The highest biochar recovery was obtained from pine needles compared to other types of biomass.

In Tamil Nadu the biochar is prepared from various crop residues. The dried leaves of banana, chickpea stover, outer shells of the Jatropha pods, millet cones and dust, shells of palm fruits, and sugarcane wastes are collected and tightly packed in a oil drum (this is available from hardware shops) by placing a PVC tube of 6 inch diameter at the centre of the drum. At the top of the drum agriculture wastes are loaded, loose packs of the same is burnt and closed for a while to undergo pyrolysis process. During this process the drum is closed completely until the pyrolysis process come to an end. Sugumaran and Seshadri (2010) designed large-sized charring kiln or cylindrical drum like structure with top cut

out to place the chimney. Above the firing portion an iron perforated sheet with holes is fixed. The bottom side of the drum is closed with iron sheets and provided with four legs. For carbonization, the kiln is loosely packed with about 100 kg dry biomass. After loading biomass, the kiln is closed with a metal lid attached to a conical chimney. Little amount of biomass in the firing portion is ignited in the kiln and the door is closed tightly to start the pyrolysis process. In the absence of air, the burning process is slow and the fire slowly spreads to the biomass through the holes in the perforated sheets. This method takes 1-2 h to prepare biochar with biochar yield of 30-45% depending on the biomass type. The cost of charcoal kiln with chimney is approximately Rs. 20000.

Recently, IIT, Mumbai has developed a biochar unit for bamboo waste and it can be used for charring of other biomass (non-powdery) with minor modifications. The uniqueness of this biochar unit lies in the fact that otherwise called "polluting gases are all driven out from a central channel, the bottom of the channel ends with a perforated chimney like structure kept inside the drum. The drum is loosely packed with residues and these are ignited and the smoke stars coming out through the chimney. Initially the residues are ignited in presence of oxygen and later, the oxygen supply is cut-off slowly by covering the upper side of the drum with a perforated lid. The cost of the whole set up is around Rs. 35000.

As part of the *terra preta* trials at Odam, Tiruchuli, Tamil Nadu a special oil drum kiln was developed. Several holes are made at the back side of the drum and a large square hole was cut in the other side to be used for filling the kiln (this is the top). Another piece of metal was needed to cover the square hole. Before filling the agricultural biomass into the kiln, oil residue in the drum is cleaned and further residue is removed by burning. The biomass should not be packed too tightly as it would have poor flow of air, neither should it be packed too loosely as it would allow too much air to flow. After filling the biomass, the 6 inch dia PVC tube is carefully removed to leave a hole up to the bottom of the drum. Before burning the waste, the drum is placed on three bricks or stones, to allow air flow into the holes at the bottom. The material at the bottom of the hole is ignited by lighting a piece of paper or cloth and pushing it to the bottom of the drum with a stick. At first, the waste burns with a thick, yellow smoke. The kiln is allowed to burn until the fire becomes clear and produces a very thin blue smoke. The drum is ready to be sealed when it burns well with almost no smoke and the drum is very hot. The cover is placed over the hole and the stones are removed from under the drum by supporting the drum with a large stick. Mud is used to seal the bottom edge of the drum and any gaps at the top. It should be ensured that no holes are left for the smoke to escape. The drum is then left for cooling. After 2-4 h, the mud is brushed off and the charcoal is removed.

Carbon Zero Experimental Biochar Kiln: It is simple closed retort kiln having an insulated firebrick enclosure designed for a 200 litre steel barrel as a retort. A small hole in the centre of barrel (12 mm diameter), vents the evolving gases to an afterburner positioned above the barrel. Depending on the moisture content of the feedstock, a small support flame may be needed to keep the gases ignited. A generous supply of air to the afterburner is important in this kiln. A squirrel cage blower is mounted so that it injects a tangential stream of air into the top of the afterburner and a stainless steel mesh or firebrick plate is positioned about $3/4^{th}$ of the way up the afterburner barrel to deflect the gas stream so that it mixes well with the air and keep it ignited. Thermocouple probes extend into the retort at top and bottom to monitor the temperature. It can take as little as 15 minutes to bring temperatures to 300 °C to initiate pyrolysis if the feedstock is bone dry, and as much as 2 hours or more if it is somewhat moist.

Continuous biochar production unit: ICAR Research Complex for NEH Region has procured the unit for biochar production. The unit is capable of converting up to 300 kg/h of woody biomass into biochar. Shredded biomass is introduced to the partial-oxidation reactor, a controlled aerobic (O_2 limited) environment that contains some limited atmospheric air, where it is carbonized at 300-550°C for 2-30 minutes. Feedstock introduction rate and residence time in the reactor are process dependent and can vary widely depending on operating conditions. Air and gases are motivated by a suction blower, which controls rates of production. Temperatures are controlled by managing the ratio of available air to biomass and ensuring that it is well below the complete combustion ratio. This management of air to biomass allows for the preservation of solid carbon through the process and drives off nitrogen, oxygen, hydrogen, and other biomass constituent components.

Carbonized material and pyrolysis gases are moved into the secondary reactor, or drop box. In the secondary reactor, coarse particles of carbonized material are separated from the gas stream and continue to be heated at 250-550°C for 2-10 minutes. The pyrolysis gas produced during the first stage is used as sweep gas for the second stage, and is primarily composed of N_2, H_2, CO, CH_4, and other higher VOCs and trace gases. No oxygen should be available in this stage of the process. Incorrect running procedures can introduce oxygen, which can be very dangerous (i.e. unintentional combustion of process gases; explosion). The coarse char particles that are removed from the gas stream by a baffle, into the secondary reactor, are augured out of the secondary reactor into a clean 55-gal steel drum. Materials must remain in the steel drum or other fire proof container until cooled. Cooling will take a minimum of 2 days if cooling agents such as water are not used. Pyrolysis gases are burned in a flare at a temperature between 500-1500°C. This flare can be lit with a "weed burner" torch once wood gas is produced in reaction. Wood gas will be yellow once it can light, this can take 15-35 minutes after starting the process.

Biochar preparation using continuous biochar production unit at ICAR RC NEH, Barapani: wood chips collected in drums (A); continuous biochar production unit (B); feeding the biochar unit with wood chips (C); Firing the smoke with a torch (D); initial smoke from biochar unit (F); and wood chips burning inside main reactor (F)

2.3 Biochar Stove

More than two billion people in developing world still cook and heat their homes with primitive stoves or open fires by burning wood, straw, dung, or coal. These inefficient technologies cause air pollution that can harm respiratory and cardiac health, and exacerbate global warming. New stove technologies can produce both heat for cooking and biochar for carbon sequestration and soil building. Limited testing indicates that these stoves are much more efficient and emit less gas. The UN Environment Program now recognizes that Atmospheric Brown Clouds (ABCs) are a major contributor to climate change (UNEP, 2008). ABCs are caused by particulate emissions from inefficient combustion of biomass

and fossil fuels and they include both black particles (soot) that heat the atmosphere by absorbing sunlight, and white particles that reflect sunlight and contribute to cooling. Black carbon has a significant effect on global warming, second only to carbon dioxide (CO_2) (Ramanathan and Carmichael, 2008). Unfortunately, even some improved (non-biochar making) cook stoves that are otherwise efficient users of wood still emit large amounts of black carbon. One study comparing improved cook stoves showed that a common design, the rocket stove, had black carbon emissions equal to those of an open fire (MacCarty *et al.*, 2008). The study found that gasifier stoves, both natural draft and fan-assisted, had very low black carbon emissions. There are two basic types of stoves that can be used to produce charcoal and heat, the Top-Lit Updraft Gasifier (TLUD) and the Anila stove. There are many variations on the TLUD, but the biggest distinction is between natural draft TLUDs and fan-forced TLUDs. The TLUD operates as a gasifier by creating a stratified pyrolysis/combustion regime with four basic zones: raw biomass, flaming pyrolysis, gas combustion and charcoal combustion (Anderson and Reed, 2004). The charcoal can be retained if it is removed at the proper time and quenched. Biomass fuel is placed between the two cylinders and a fire is ignited in the centre. Heat from the central fire pyrolyzes the concentric ring of fuel. The gases escape to the centre where they add to the cooking flame as the ring of biomass turns to char. The centre combustion chamber can be configured as either a rocket stove design (with a side opening door) or as a TLUD with primary combustion air entering from the bottom.

The modern Anila stove was developed by U.N. Ravikumar, an environmentalist and engineer with the Centre for Appropriate Rural Technology (CART) at India's National Institute of Engineering. The key aims of the design are to reduce the indoor air pollution that results from cooking and to take advantage of the abundance of bio-residues found in rural areas in developing countries. The engineering principle the underlines the Anila stove is top lit updraft gasification, which essentially means that the hardwood fuel burns from the top down and simultaneously combusts the syngas that is released by the biomass (Fig 7). The stove is made from steel and weighs about 10 kg (Iliffe, 2009).
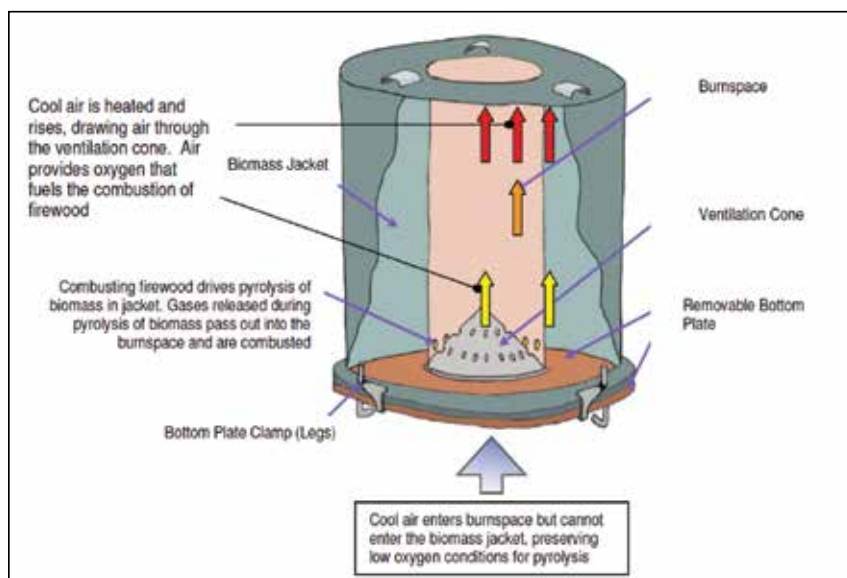

Fig 7. Labelled diagram of the Anila stove (Source: Iliffe, 2009)

Reddy (2011) from Hyderabad has developed a fan-assisted and non-fan assisted biochar cooking stove. In this process, energy liberated from residue during controlled burning is used for cooking purpose and biochar is produced as left out material. However, the yield of biochar is less in this method as compared to other methods of biochar preparation.

3. Characteristics of biochar

Characterization of any amendment is the first step to understand the mechanism of action. The properties of biochar are governed by its physical and chemical constituents. The form and size of the feedstock and pyrolysis product may affect the quality and potential uses of biochar (Sohi *et al.*, 2010). The importance of biochar depends on its physical and chemical characteristics, although the relationship of char properties to these applications is not well understood. To understand the mechanism of action of biochar in soil, its proper characterization is the first step towards unraveling the beneficial effect of biochar. Sohi *et al*. (2010) reported that biogeochemical characterization of biochar helps in determining the agronomic importance as well as impact on soil process. It further helps in preparation of particular kind of biochar which may have higher agronomic significance. It has been documented by several authors that biochar produced from different feedstock and on different temperature and time scales has altogether different characteristics.

Some workers have reported seven key properties for the evaluation of biochar i.e. pH, content of volatile compounds, ash content, water-holding capacity, bulk density, pore volume, and specific surface area (Okimori, *et al.*, 2003, Sohi *et al.*, 2010). All these properties are governed by the quality of the feed stock that is used for the biochar production. In addition, pyrolysis temperature and duration of pyrolysis are the other two most significant processes that affect the physico-chemical quality of biochar.

Several techniques are used for characterization of biochar/black carbon. Physical structure of biochar is generally characterized by scanning electron microscopy (SEM). Sohi *et al.* (2010) reported that the macroporous structure (pores of approximately 1 mm diameter) of biochar produced from cellulosic plant material inherits the architecture of the feedstock, and is potentially important to water holding and adsorption capacity of soil (Day *et al.*, 2005; Ogawa *et al.*, 2006; Yu *et al.*, 2006). The pore structure of biochar seen under SEM provided physical refuge, resulting in increased abundances of beneficial microorganisms (Purakayastha *et al.*, 2013b). However, surface area measured by gas adsorption is influenced by micropores that are not relevant to plant roots, microbes, or to the mobile soil solution. Recently, with the technological advancement, the characterization of biochar is done more precisely. Liang *et al.*, (2006) demonstrated higher surface charge of biochar by mapping cross sectional areas of biochar particles with diameters of 10 to 50 mm for C forms by using Synchrotron-based near edge X-ray absorption fine structure (NEXAFS) spectroscopy in combination with scanning transmission X-ray microscopy (STXM) techniques. Spotted and non-continuous distribution patterns of highly oxidized C functional groups with distinctly different chemical signatures on biochar particle surfaces indicated that non-biochar material may be adsorbed on the surfaces of biochar particles creating highly oxidized surface. Elemental ratios of O: C,O:H and C:H have been found to provide a reliable measure of both the extent of pyrolysis and the level of oxidative alteration of biochar in the soil, and are relatively easier to determine (Sohi *et al.*, 2010). Apart from

elemental composition other techniques such as diffuse reflectance infrared Fourier transform spectroscopy (FTIR), X–ray photoelectron spectroscopy (XPS), energy dispersive X–ray spectroscopy (EDX), NEXAFS spectroscopy (Baldock and Smernik, 2002; Fernandes and Brooks, 2003; Lehmann *et al.*, 2006) have also been extensively used to examine surface chemistry, functional groups and to obtain information on ageing mechanism of biochar. FTIR analysis of biochar exhibited very weak absorbance in the IR spectrum with the major occurring at about 1600 and 1430 cm^{-1} denoting aromatic ring carbon C=C stretching, and a weaker band at about 1700 cm^{-1} indicative of aromatic carbonyl/carboxyl C=O stretching (Purakayastha *et al.*, 2013b).

Rosa *et al.* (2007) studied the amount and compositional characteristics of black carbon in soils (Mollisol and Vertisol), formed due to forest fire. They used a combination of thermo-gravimetry (TG), TG coupled with isotope ratio mass spectrometry (IRMS), 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. Similarly, Brewer *et al.*, (2009) characterized the biochar, produced from fast pyrolysis and gasification of switch grass and corn stover, by proximate analysis, CHNS elemental analysis, Brunauer-Emmet-Teller (BET) surface area, particle density, higher heating value (HHV), scanning electron microscopy, X-ray fluorescence ash content analysis, Fourier transform infrared spectroscopy using a photo-acoustic detector (FTIR-PAS), and quantitative ^{13}C nuclear magnetic resonance spectroscopy (NMR) using direct polarization and magic angle spinning.

3.1 Physical characterization

Pyrolysis temperature is the main regulating factor which governs surface area of biochar. It was reported that increase in temperature from 400 to 900°C increased surface area of biochar from 120 to 460 m^2/g (Day *et al.*, 2005). The importance of temperature leads to the suggestion that biochar created at low temperature may be suitable for controlling release of nutrients (Day *et al.*, 2005), while high temperatures would lead to a material analogous to activated carbon (Ogawa *et al.*, 2006). It is also noted that the surfaces of low temperature biochar can be hydrophobic, and this may limit the capacity to store water in soil. Initially, the ratio of exposed to total surface area of biochar will be affected by its particle size. However, although low temperature biochar is stronger than high temperature products, it is brittle and prone to abrade into fine fractions once incorporated into the mineral soil. It may be proposed that the surface area over the long term, that is, of weathered biochar, is not greatly affected by temperature (Sohi *et al.*, 2010).

Increase in pyrolysis temperature from 400°C to 600°C decreased the volatile and N component of biochar, while it increased ash and fixed carbon content (Purakayastha *et al.*, 2012). Thus biochar prepared at 60°C had wider C:N ratio making it more stable in soil. Purakayastha *et al.* (2013a) reported that the bulk density of rice and wheat biochar prepared at 400°C was comparatively lower than the maize and pearl millet biochar. The water holding capacity of wheat biochar was highest (561%) followed by maize biochar (456%).

3.2 Chemical characterization

General chemical properties of biochar samples prepared from different feed stocks are given in Table 4 (Jha *et al.*, 2010). Biochar produced from different feed stock had pH ranged from 8.2-13.0. Invariably, total carbon content of biochar increased with the increase in

pyrolysis temperature (Fig 8). Total carbon content in biochar materials produced from different feedstock varied from 33.0 to 82.4%. Maximum heating temperature and heating rate have a strong influence on the retention of nutrients as does the original composition of the feedstock. N and S compound tends to volatize at a temperature above 200 and 375°C, respectively. So, biochar produced at higher temperature shows depletion of N (Fig 9) and S. Whereas, K and P volatilize between 700 and 800°C (DeLuca *et al.*, 2009). High-temperature biochars (800°C) tend to have a higher pH, electrical conductivity (EC), and extractable NO_3^-, while low-temperature biochars (350°C) have greater amounts of extractable P, NH4 $^+$, and phenols (DeLuca *et al.*, 2009).

Table 5. Some properties of biochar used in different experiments

Materials used for producing biochar	pH	Total C	Total N	C:N	Ca	Mg	P	K	CEC	Reference
		(%)			(cmol/kg)					
Paper mill waste 1- (waste wood chip)	9.4	50.0	0.48	104	6.2	1.20	-	0.22	9.00	Zwieten et al. (2010)
Paper mill waste 2- (waste wood chip)	8.2	52.0	0.31	168	11.0	2.60	-	1.00	18.00	Zwieten et al. (2010)
Green waste (grass clippings, cotton trash, and plant prunings)	9.4	36.0	0.18	200	0.4	0.56	-	21.00	24.00	Chan et al. (2007)
Eucalyptus biochar	-	82.4	0.57	145	-	-	1.87	-	4.69	Noguera et al. (2010)
Cooking biochar	-	72.9	0.76	96	-	-	0.42	-	11.19	Noguera et al. (2010)
Poultry litter (450°C)	9.9	38.0	2.00	19	-	-	37.42	-	-	Chan et al. (2008)
Poultry litter (550°C)	13	33.0	0.85	39	-	-	5.81	-	-	Chan et al. (2008)
Wood biochar	9.2	72.9	0.76	120	0.83	0.20	0.10	1.19	11.90	Major et al. (2010)
Hardwood sawdust	-	66.5	0.3	221	-	-	-	-	-	Spokas et al. (2010)

Adapted from Jha *et al.* (2010)

The ratios of H/C and O/C decreased with increasing temperature and the lower ratio was found good in terms of aromaticity and stability (Baldock and Smernik, 2002). There was wide variation in nitrogen content of biochar material produced from different biomass. Biochar in general had low nitrogen content (0.18-2.0%) and C:N ratio varied from as low as 19 to 221. Except N, the concentration of other elements in biochar increased with the increase in pyrolysis temperature (Fig 10 & 11). Biochar contains appreciable quantity of Ca, Mg, K and P. Due to its high pH and appreciable amount of Ca and Mg, biochar acts as liming material (amendment) in acid soils. Lakaria *et al.* (2012) also observed variations in nutrient composition of biochars formed under varying pyrolitic temperature and duration.

Purakayastha *et al.* (2013a) characterized the chemical composition of biochar prepared from various crop residues at 400°C. The biochar prepared from rice residues showed highest CEC and pH of maize (10.7) and pearl millet (10.6) biochar was higher than that in wheat (8.8) and rice (8.6) biochar. Total carbon content was highest in pearl millet biochar (61%) followed by wheat (52%) and rice biochar (49%) whereas maize biochar had lowest carbon content (37%). However, maize biochar was richer in major (N, P, K), secondary (Ca, Mg) and micronutrient (Fe, Mn, Zn and Cu) contents. Wheat biochar ranked second with respect to all the above nutrients except sulphur for which it ranked first.
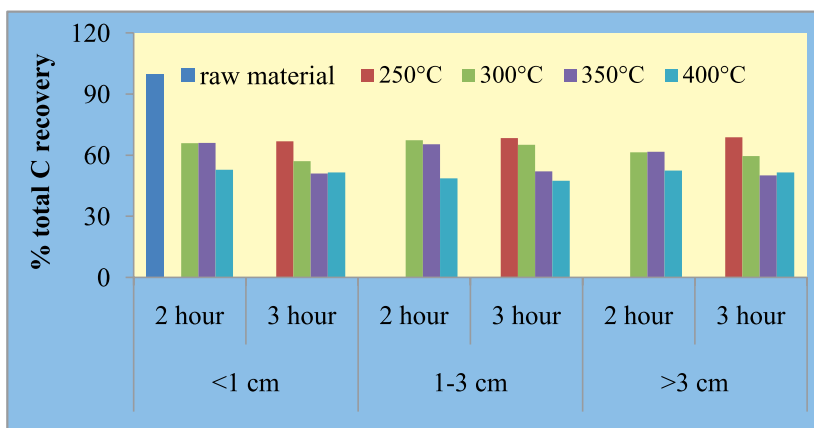
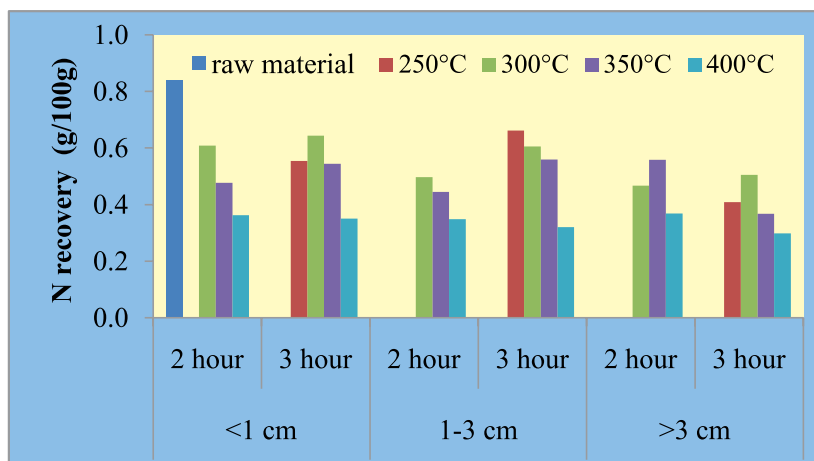Fig 8. Carbon recovery in subabool (*Leucaena leucocephala*) biochar

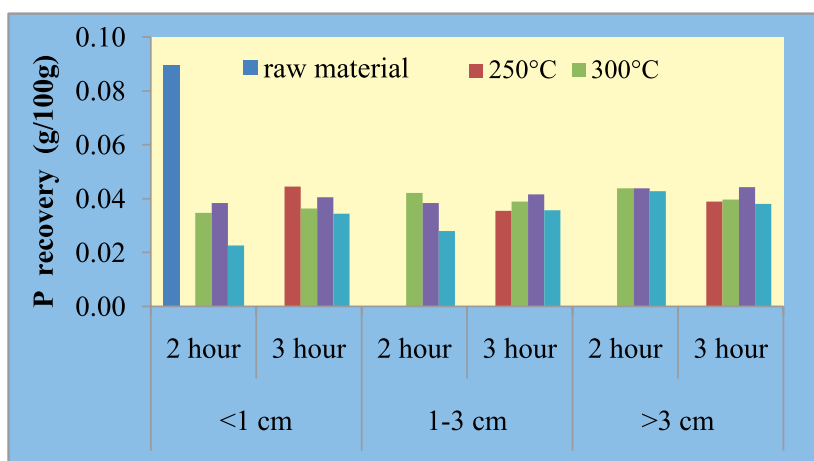Fig 9. Nitrogen recovery in subabool (*Leucaena leucocephala*) biochar

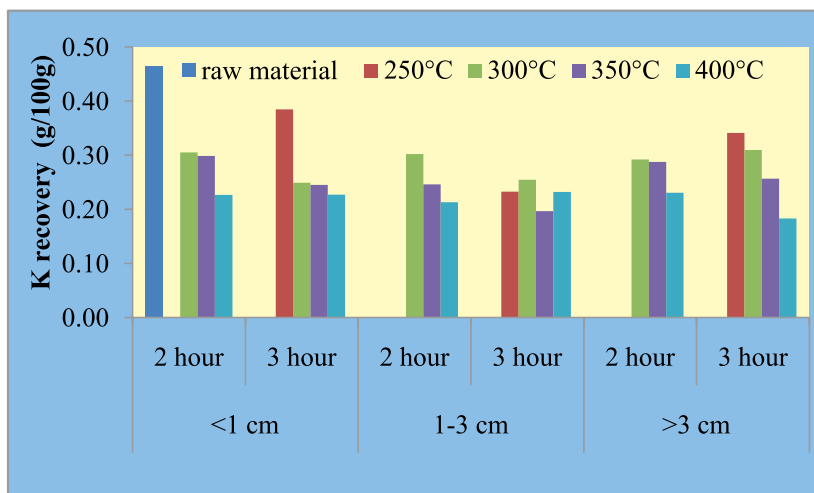Fig 10. Phosphorus recovery in subabool (*Leucaena leucocephala*) biochar

Fig 11. Potassium recovery in subabool (*Leucaena leucocephala*) biochar

4. Biochar for climate change mitigation

4.1 C sequestration

Soil C sequestration is the removal of atmospheric CO_2 through photosynthesis to form organic matter, which is ultimately stored in the soil as long-lived, stable forms of C. The global carbon cycle is made up of flows and pools of carbon in the Earth's system. The important pools of carbon are terrestrial, atmospheric, ocean, and geological. The carbon within these pools has varying lifetimes, and flows take place between them all. Carbon in the active carbon pool moves rapidly between pools (Lehmann, 2007b). In order to decrease carbon in the atmosphere, it is necessary to move it into a passive pool containing stable or inert carbon. Biochar provides a facile flow of carbon from the active pool to the passive pool. In comparison to burning, controlled carbonization converts even larger quantities of biomass organic matter into stable C pools which are assumed to persist in the environment over centuries (Glaser *et al.* 1998; Schmidt and Noack 2000; Glaser *et al.* 2001). The conversion of biomass carbon to biochar leads to sequestration of about 50% of the initial carbon compared to the low amounts retained after burning (3%) and biological decomposition (less than 10-20% after 5-10 years) (Lehmann *et al.* 2006). 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).

According to Gaunt and Lehmann (2008), *terra preta* soils suggest that biochar can have carbon storage permanence in the soil for many hundreds to thousands of years. Large amounts of carbon in biochar may be sequestered in the soil for long periods estimated to be hundreds to thousands of years (Lehmann *et al.* 2006; Ogawa *et al.* 2006; Woolf, 2008; Bracmort, 2010). While biochar mineralizes in soils, a fraction of it remains in a very stable form (Schmidt and Noack, 2000); this property of biochar provides it the potential to be a major carbon sink. Compared with other terrestrial sequestration strategies, such as afforestation or re-forestation, carbon sequestration in biochar increases its storage time (Ogawa *et al.* 2006 and Sohi *et al.* 2010). 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. About 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.

The principal mechanisms operating in soils through which biochar entering the soil is stabilized and significantly increase its residence time in soil are intrinsic recalcitrance, spatial separation of decomposers and substrate, and formation of interactions between mineral surfaces (Sollins *et al.*, 1996). In a fifteen weeks biochar carbon stability study, Purakayastha *et al.* (2013a) reported that the carbon loss ranged from 2.34% in maize biochar to 4.49% in rice biochar. Among the biochars, maize biochar showed lowest carbon mineralization suggesting its greater potential for long-term carbon sequestration. Application of biochar showed highest amount of carbon in soil under wheat-pearl millet cropping system.

The findings of a recent modeling study (Woolf *et al.*, 2010) reported that biochar amendments to soil, when carried out sustainably, may annually sequester an amount of C equal to 12% the current anthropogenic CO_2 emissions. They estimate that the maximum sustainable technical potential for carbon abatement from biochar is 1-1.8 giga ton (Gt) C per year by 2050. Technical estimates of the potential for biomass pyrolysis coupled with soil storage to sequester carbon suggest that several hundred gigatons of carbon emissions could be sequestered or offset by 2100, which is a large fraction of the total needed to mitigate global climate disruption. Furthermore, it is relatively simple to verify the benefits that can be derived from the application of biochar as soil amendment. It is also easy to monitor carbon sequestration as a climate change mitigation measure for national carbon accounting (Glaser *et al.*, 2002; Lehmann *et al.* 2006; Gaunt and Cowie, 2009; Yeboah *et al.* 2009). This can be done by using the income generated and the quantity of carbon that has been sequestered (Gaunt and Cowie, 2009). Production and application of biochar to farm soils can tackle many global and domestic policy issues. Nevertheless, the application of biochar at the farm level is discouragingly slow, largely due to financial constraints.

4.2 Mitigation of greenhouse gas emissions

Burning of residues emits a significant amount GHGs. For example, 70, 7 and 0.66% of C present in rice straw is emitted as CO_2, CO and CH_4, respectively, while 2.09% of N in straw is emitted as N_2O upon burning. One ton straw on burning releases 3 kg particulate matter, 60 kg CO, 1460 kg CO_2, 199 kg ash and 2 kg SO_2. This change in composition of the atmosphere may have a direct or indirect effect on the radiation balance. Besides other light hydrocarbons, volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) and SOx, NOx are also emitted. These gases are important for their global impact and may lead to a regional increase in the levels of aerosols, acid deposition, increase in tropospheric ozone and depletion of the stratospheric ozone layer.

Apart from carbon sequestration, there are other environmental benefits that can be derived from the application of biochar in soils which include reduction in the emission of non-CO_2 GHGs by soils (Fig 12). Soil is a significant source of nitrous oxide (N_2O) and both a source and sink of methane (CH_4). These gases are 23 and 298 times more potent than carbon dioxide (CO_2) as greenhouse gases in the atmosphere. Biochar is reported to reduce N_2O emission could be due to inhibition of either stage of nitrification and/or inhibition of denitrification, or promotion of the reduction of N_2O, and these impacts could occur simultaneously in a soil (Berglund *et al.*, 2004; DeLuca *et al.*, 2006). Increased soil aeration

from biochar addition reduces denitrification and increases sink capacity for CH_4. Biochar addition induces microbial immobilization of available N in soil, thereby decreasing N_2O source capacity of soil. Increased pH from biochar addition drives N_2 formation from N_2O. When applied to the soil, biochar can lower GHG emissions of cropland soils by substantially reducing the release of N_2O (Lehmann *et al.*, 2003). Reduction of N_2O and CH_4 emission as a result of biochar application is seen to attract considerable attention due to the much higher global warming potentials of these gases compared to CO_2 (Steiner, 2010). Rondon *et al.* (2005) reported a 50% reduction in N_2O emissions from soybean plots and almost complete suppression of CH_4 emissions from biochar amended acidic soils in the Eastern Colombian Plains. Yanai *et al.* (2007), however, reported an 85% reduction in N_2O emission from re-wetted soils containing 10% biochar, compared to soils without biochar. Biochar from municipal biowaste also caused a decrease in emissions of nitrous oxide in laboratory soil chambers (Yanai *et al.* 2007). Spokas *et al.* (2009) also found a significant reduction in N_2O emission in agricultural soils in Minnesota; while Sohi *et al.* (2010) found an emission suppression of only 15%. Additions of 15 g biochar/kg of soil to a grass and 30 g/kg of soil to a soil cropped with soybeans completely suppressed methane emissions (Rondon *et al.* 2005).

An assumption of net carbon abatement of between 0.5 and 1 t CO_2 abatement per ton of feedstock used in pyrolysis biochar system (PBS) as reported by number of published life cycle studies, then this could represent between 35 to 70 million tons of CO_2 abatement per year in India. This assumes however, that all feedstock would be used in PBS, where as in reality there will be many competing uses for the same feedstock and use of biochar might necessitate substitution of residues by a different source of biomass, potentially with attendant greenhouse gas emission that would need to be accounted for. As per the estimates in 2009, the greenhouse gas emission in India was 1,900 million t CO_2 per annum, hence it can be seen that biochar could contribute between 2-4% reduction (Priyadarshini and Prabhune, 2009). More research is needed to understand the interactions between biochar, site specific soil, climatic conditions, and management practices that alter the sink capacity of soils.
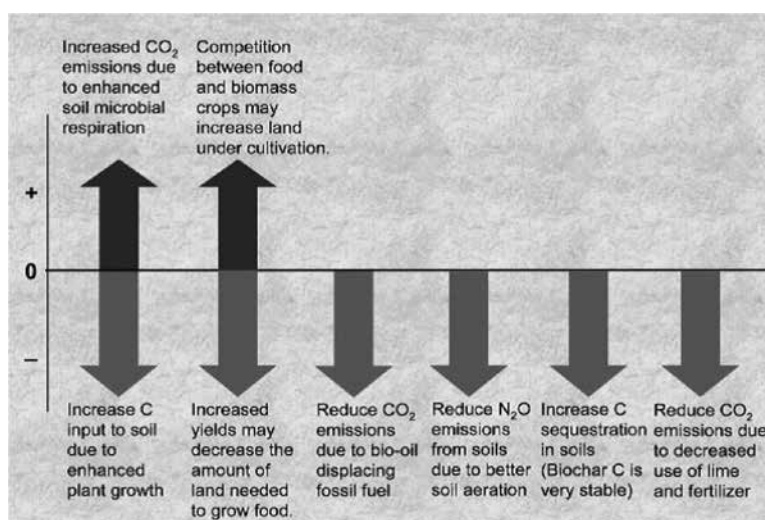

Fig 12. Net impact of biochar applications in soil on greenhouse gas emissions. (Adapted with changes from Rogovska *et al.*, 2008).

5. Biochar as soil amendment

5.1 Method of application

Like any other organic amendments, Biochar can be applied to soil by different methods including broadcasting, band application, spot placement, deep banding etc. However, the method of biochar application in soil depends on the farming system, available machinery and labor. Application of biochar by hand is well known, but is not viable on large-scale because of labor intensity and human health concerns due to prolonged contact with airborne biochar particulates. In developed countries, several large scale biochar trials have been conducted using a tractor propelled lime spreader. While the technology lends itself to careful calibration of output and uniform application, there are significant concerns surrounding environmental air quality and product loss due to wind and water erosion. Similarly, deep banding of biochar has been successfully implemented in several wheat fields in Western Australia. This low-impact application method deposits biochar directly into the rhizosphere, and may be viable for previously established crops, and perennial cropping systems. However, relatively low rates of application are technically possible with one pass (3 t/ha), and the process is relatively labour intensive. Additionally, issues with pneumatic clogging due to biochar particle size distribution and air quality remain.

Broadcast application of biochar (Source: Jeyaraman, TNAU)

Mixing of biochar with composts and manures may reduce odors, and improve nutrient performance over time due to slower leaching rates. Mixtures may be applied for uniform topsoil mixing, or top-dressed in tree plantations without incorporation. Although the airborne dust fraction would be minimized, the tonnages of biochar application may be relatively low per ha, and additional equipment would be needed to incorporate applied compost into top soils thereby increasing costs and carbon footprint. Line trenching and backfilling may lend itself to high biochar application rates in soil for carbon sequestration while still increasing the agronomic performance of soils. Though labor and carbon intensive, the combination of high saturation rates and improved agronomic productivity may make the practice viable. However, like deep banding, it is unknown how well biochar migrates vertically through the soil profile.

5.2 Rate of application

It depends on many factors including the type of biomass used, the degree of metal contamination in the biomass, the types and proportions of various nutrients (N, P, etc.),

and also on edaphic, climatic and topographic factors of the land where the biochar is to be applied. Given the variability in biochar materials, nature of crop and soils, users of biochar should consider testing several rates of biochar application on a small scale before setting out to apply it on large areas. Experiments have found that rates between 5-50 t/ha (0.5-5 kg/m^2) have often been used successfully. While no recommended application rates for biochar can be given, biochar should be applied in moderate amounts to soil. Rates around 1% by weight or less have been used successfully so far in field crops (Major, 2013). Research suggests that even low rates of biochar application can significantly increase crop productivity assuming that the biochar is rich in nutrients which that soil lacks (Winsley, 2007). In the case of piggery and poultry manure biochar, the biochar works both as an organic fertilizer and soil conditioner with agronomic benefits observed at low application rates (10 t/ha) (Chan *et al.* 2007). Application to soils of higher amounts of biochar may increase the carbon credit benefit; but, in nitrogen-limiting soils it could fail to assist crop productivity as a high C/N ratio leads to low N availability (Lehmann and Rondon, 2006). Crop productivity benefits of higher biochar application rates can be maximized only if the soil is rich in nitrogen, or if the crops are nitrogen-fixing legumes. Therefore, application of biochar to soils in a legume-based (e.g. peanut and maize) rotational cropping system, clovers and lucernes is more beneficial. Biochar application rates also depend on the amount of dangerous metals present in the original biomass. The chance of bio-magnification also depends on the amount of a given metal in the soil.

5.3 Soil quality and fertility improvement

Biochar is a high carbon containing material (more than 50%) produced by heating of biomass in absence of oxygen. Biochar application to soil leads to several interactions mainly with soil matrix, soil microbes, and plant roots (Lehmann and Joseph, 2009). The types and rates of interactions depend on different factors like composition of biomass as well as biochar, methods of biochar preparation, physical aspect of biochar and soil environmental condition mainly soil temperature and moisture. Biochar can act as a soil conditioner by improving the physical and biological properties of soils such as water holding capacity and soil nutrients retention, and also enhancing plant growth (Sohi *et al.,* 2010).

The application of biochar in soils is based on its properties such as: (i) agricultural value from enhanced soils nutrient retention and water holding capacity, (ii) permanent carbon sequestration, and (iii) reduced GHG emissions, particularly nitrous oxide (N_2O) and methane (CH_4) release (Bracmort, 2010; Brown, 2009; Glaser *et al.* 2002; Kammen and Lew, 2005; Lehmann *et al.* 2006; Steiner, 2010; Steiner *et al.,* 2008). Farmers will be motivated to apply biochar on their farms if these benefits can be demonstrated explicitly. At the local scale, soil organic carbon levels shape agro-ecosystem function and influence soil fertility and physical properties, such as aggregate stability, water holding capacity and cation exchange capacity (CEC) (Milne *et al.,* 2007). The ability of soils to retain nutrients in cation form that are available to plants can be increased using biochar. The addition of biochar to agricultural soils is receiving considerable interest due to the agronomic benefits it may provide (Quayle, 2010).

Several authors have reported that biochar has the potential to: (i) increase soil pH, (ii) decrease aluminum toxicity, (iii) decrease soil tensile strength, (iv) improve soil conditions for earthworm populations, and (v) improve fertilizer use efficiency (Table 6).

Table 6. Effect of biochar on different soil properties

Factor	Impact	Source
Cation exchange capacity	50% increase	(Glaser *et al.*, 2002)
Fertilizer use efficiency	10-30 % increase	(Gaunt and Cowie, 2009)
Liming agent	1 point pH increase	(Lehman and Rondon, 2006)
Soil moisture retention	Up to 18 % increase	(Tryon, 1948)
Crop productivity	20-120% increase	(Lehman and Rondon, 2006)
Methane emission	100% decrease	(Rondon *et al*, 2005)
Nitrous oxide emissions	50 % decrease	(Yanai *et al.*, 2007)
Bulk density	Soil dependent	(Laird, 2008)
Mycorrhizal fungi	40 % increase	(Warnock *et al.*, 2007)
Biological nitrogen fixation	50-72% increase	(Lehman and Rondon, 2006)

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*. (2007) 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. Similarly, Asai *et al*. (2009) 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.

Mankasingh et al. (2011) conducted a plot-scale evaluation of biochar application to agricultural soils in Tirunelveli, Tamil Nadu, India, to investigate the potential of biochar to improve soil fertility and moisture content. Several locally available feedstocks (rice husk, cassia stems, palm leaves and sawdust) were analysed as proposed soil amendments so that no single biomass material is depleted. The biochars from different biomass feedstock contained >20% C and were high in macro- and micronutrients. The results suggest that an application rate of 6.6 metric tons cassia biochar/ha was enough to initiate C-accumulation, which is reflected in an increase in organic matter and a net reduction in soil bulk density.

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. Reduction in tensile strength and increase in field capacity of hard-setting soil were the most significant findings (Chan *et al*., 2007). Biochars can potentially increase the cation exchange capacity (CEC) of soils especially for highly weathered, nutrient-poor sandy soils; however, this is dependent on biochar properties and aging of applied biochar in the soil. The published data suggest that biochars from woody materials tend to provide low CEC values, while non-woody plant materials such as sugarcane trash (leaf) or tree bark tend to have higher CEC values (Yamamoto *et al.*, 2006; Chan *et al.*, 2007; Major et al., 2009; Singh and Gu, 2010; Van Zwieten *et al.*, 2010).

Biochar can be used by farmers to control the pH of soil and also to reduce lime applications (Rodriguez *et al.,* 2002). Rodriguez *et al.* (2009) used biochar produced from sugarcane bagasse to increase the pH of soil from 4.0-4.5 to 6.0-6.5 in a maize trial in Colombia. The pH increase in sandy and loamy soils has been reported to be larger than in clayey soils (De Gryze *et al.,* 2010). In a study on the effects of charcoal production on soil physical and hydrological properties in Ghana, Oguntunde *et al.* (2008) reported that the saturated hydraulic conductivity of soils under charcoal kilns increased significantly. When mixed with organic matter, biochar can result in enhanced retention of soil water as a result of its pore structure which contributes to nutrient retention because of its ability to trap nutrient-rich water within the pores (Oguntunde *et al.,* 2008; Major *et al.,* 2009; De Gryze *et al.,* 2010). Biochar has an even greater ability than other soil organic matter to adsorb cations per unit carbon (Sombroek *et al.,* 1993), due to its greater surface area, greater negative surface charge, and greater charge density (Liang *et al.,* 2006). In contrast to other organic matter in soil, biochar also appears to be able to strongly adsorb phosphate, even though it is an anion, although the mechanism for this process is not fully understood.

After reviewing the experimental evidence for symbiotic association between biochar and mycorrhizal association, Warnock *et al.* (2007) 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 signaling interference, and (iv) detoxification of allelechemicals on biochar. Purakayastha et al. (2012) also reported that microbial activities measured in terms of dehydrogenase activity and microbial biomass carbon were enhanced due to biochar application in soils; rice biochar showed greater microbial activities than other biochar because of its higher lability than the others.

Rondon *et al.* (2007) 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 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 biochar added. Although total N derived from the atmosphere (NdfA) was significantly increased by 49% and 78% with 30 and 60 g/kg biochar added to soil respectively, NdfA decreased to 30% above the control with 90 g/kg 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 biochar respectively. However, biomass production and total N uptake decreased when the biochar applications were increased to 90 g/kg. 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.

These properties make biochar a unique substance, retaining exchangeable and therefore plant available nutrients in the soil, and offering the possibility of improving crop yields

while decreasing environmental pollution by nutrients. Thus, biochar application could provide a new technology for both soil fertility and crop productivity improvement, with potential positive and quantifiable environmental benefits, such as carbon trading (Bracmort, 2010 and Yeboah *et al.* 2009).

5.4 Remediation

Carbonaceous materials such as char and activated carbon have received considerable attention in recent years as soil amendment for both sequestering heavy metal contaminants and releasing essential nutrients like sulfur. Information is currently lacking in how aging impacts the integrity of biochars as soil amendment for both agricultural and environmental remediation purposes. Biochar has a relatively structured carbon matrix with a medium-to-high surface area, suggesting that it may act as a surface sorbent which is similar in some aspects to AC. Black carbon surfaces are porous with apolar and aromatic surfaces. They have a high surface to volume ratio and a strong affinity to non-polar substances such as polycyclic aromatic hydrocarbons (PAHs), dioxins, furans (PCDD/Fs), PCBs, and PBDEs. Biochar can be used by farmers to control the pH of soil and also to reduce lime applications (Rodriguez *et al.,* 2002). Rodriguez *et al.* (2009) used biochar produced from sugarcane bagasse to increase the pH of soil from 4.0-4.5 to 6.0-6.5 in a maize trial in Colombia. The pH increase in sandy and loamy soils has been reported to be larger than in clayey soils (De Gryze *et al.,* 2010).

5.5 Carrier for inoculum

Saranya et al. (2011) developed carrier based preparations of *Azospirillum lipoferum* (AZ 204) inoculant, using two different sources of biochar (acacia wood and coconut shell) and were evaluated for their suitability as a best alternate to lignite for commercial biofertilizer production. The survival of the microbial inoculant was estimated over a period of 180 days. Among the different carriers, coconut shell based biochar recorded a maximum population of log 10.79 cfu/g of carrier 180 days after inoculation with a maximum moisture content of 25.2%. It was also found that seedling vigour index of green gram was paramount in response to coconut shell based biochar. In addition, coconut shell based biochar was found to increase the survival of *Azospirillum lipoferum* up to 180 days (6 months) of storage period at a required population compared to acacia wood based biochar and lignite.

5.6 Crop productivity

The application of biochar (biomass-derived black carbon) to soil has been shown to improve crop yields which could be due to direct or indirect effect. The direct effect is explained by the fact that biochar being concentrated during pyrolysis contains higher amount of nutrients than the biomass from which they are prepared. The indirect effect is due to improvement in soil physical, chemical and biological properties due to biochar application.

Several workers have reported that biochar applications to soils have shown positive responses for net primary crop production, grain yield and dry matter (Chan *et al.* 2008; Chan and Xu,2009; Major *et al.* 2009 and Spokas *et al.* 2009). Purakayastha (2010) reported that application of biochar prepared from wheat straw @ 1.9 t/ha along with recommended doses of NPK (NPK::180:80:80) significantly increased the yield of maize in Inceptisol of IARI farm and this treatment was superior to either crop residue incorporation (CRI) or

crop residue burning (CRB). In the case of pearl millet and rice, the yields with biochar were on par with those obtained either with CRI or CRB fertilizer.

Biochar prepared from different feedstocks (pigeonpea, castor and cotton) was evaluated for its effect on pigeonpea yield at CRIDA, Hyderabad. Biochar was applied at different rates (3 and 6 t/ha) along with recommended NPK. Highest grain yield (1685 kg/ha) of pigeonpea was recorded with alternate year application of cotton stalk biochar @ 3 t/ha supplemented with NPK. In case of castor stalk biochar experiment, application of biochar at 6.0 t/ha either every year or alternate year+NPK gave marginally higher yield than other treatments. However, in another experiment, application of pigeon pea stalk biochar+RDF and RDF alone in every year gave similar but significantly higher yield compared to all other treatments (CRIDA, 2012). Similarly, application of biochar at different rates had no appreciable negative effect on crop yield. The grain yield in biochar treated plots was significantly higher than in unamended control plots, but no differences were observed between biochar application rates at 3.0 and 6.0 t/ha+RDF. Further, higher agronomic nitrogen use efficiency (91.0 kg grain/kg N) was recorded with application of biochar at 6.0 t/ha+NPK followed by biochar at 3.0 t/ha+NPK (52 kg grain/kg N) (Venkatesh *et al.*, 2012).

In another experiment at CRIDA, effect of biochar produced from maize, castor, cotton and pigeonpea stalks was evaluated on maize yield. Different sources of biochar were applied at 2 and 4 t/ha alone and in combination with mineral fertilizers and organic manures. Maize performed better in the plots under application of castor stalk biochar at 4 t/ha in combination with RDF (120:60:60) + FYM (5 t/ha) and recorded 34% higher grain yield than that of RDF (CRIDA, 2012). Similarly, application of maize stalk biochar at 2 t/ha + RDF + FYM gave 23% higher yield whereas pigeonpea and cotton stalk biochar gave 14% higher yield compared to RDF (Fig 13).

Pigeonpea stalk at 6 t/ha + RDF

Recommended dose of fertilizer (RDF)

Recommended dose of fertilizer (RDF)

Unamended control

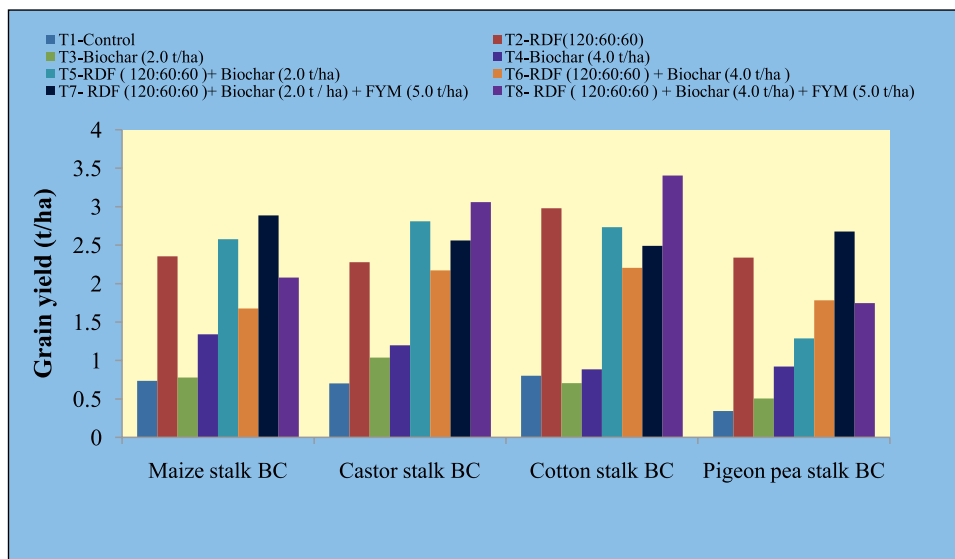**Effect of pigeonpea stalk biochar application on growth of pigeonpea**

Fig 13. Effect of different sources and rates of biochar application on maize yield

In Tamil Nadu, biochars produced from different feed stocks (Prosopis, maize stover, cotton stalk, pigeonpea stalk and rice husk) were evaluated for their effect on soil properties and yields of field crops including maize, cotton, groundnut and green gram. Field experiments were conducted at different locations in Tamil Nadu to evaluate biochar prepared from prosopis, rice husk, cotton, maize and pigeonpea stalks at different application rates on field crops.

At Vagarai (Dindigul district), application of FYM @ 12.5 t/ha produced significantly higher maize yield (8.11 t/ha) than prosopis biochar treatments. Among the biochar treatments, application of prosopis biochar @ 5 t/ha gave significantly higher maize yield (7.34 t/ha) but further increase in application rate of biochar (10 and 15 t/ha) resulted in lower maize yields. Similarly, in another experiment at the same location, maize straw biochar produced marginally higher yield of maize than the pigeonpea biochar at all application rates. Similar to prosopis biochar, higher application rates of both maize straw biochar and pigeonpea biochar had advers effect on maize grain yields (Fig 14).

In a similar experiment on maize at Kovilpatti (Tuticorin district), however, different application rates (5, 10 and 15 t/ha) of prosopis biochar and rice husk biochar produced similar yields (3.34-3.48 t/ha) of maize and all the treatments were at par with application of FYM @ 12.5 t/ha (3.45 t/ha). Similarly, in another experiment at Kovilpatti, different biochars (maize, cotton and pigeonpea) and their application rates (5, 10 and 15 t/ha) produced similar yields (3.13-3.34 t/ha) of maize.

On contrary, higher application rate of prosopis biochar (15 t/ha) gave higher grain yield of black gram compared to its application at lower doses at Kumulur (Trichy district). Further, prosopis biochar was found better than rice husk biochar at all application rates in improving black gram yield. In another experiment, application of cotton-stalk biochar @ 10 t/ha produced significantly higher yield of black gram closely followed by pigeonpea-stalk biochar @ 10 t/ha. However, further increase in application rate of these biochars marginally reduced the black gram yield (Fig 15).
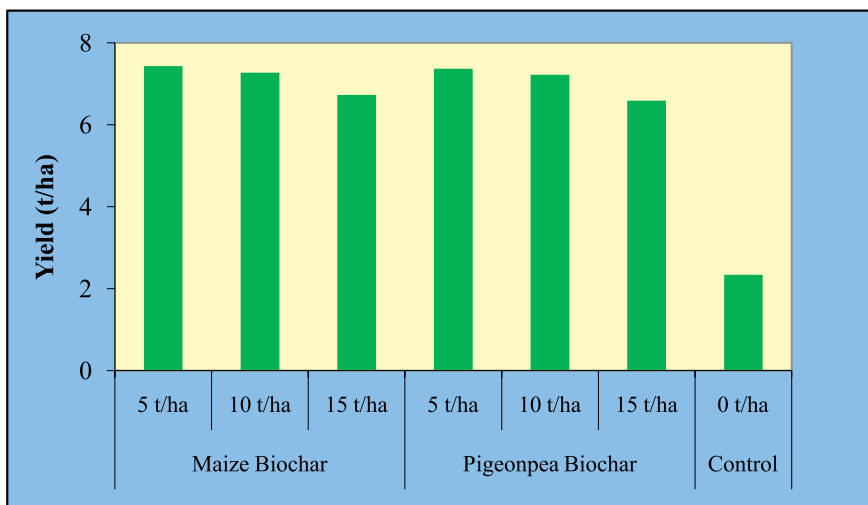
Fig 14. Effect of different biochars and their application rates on maize yield
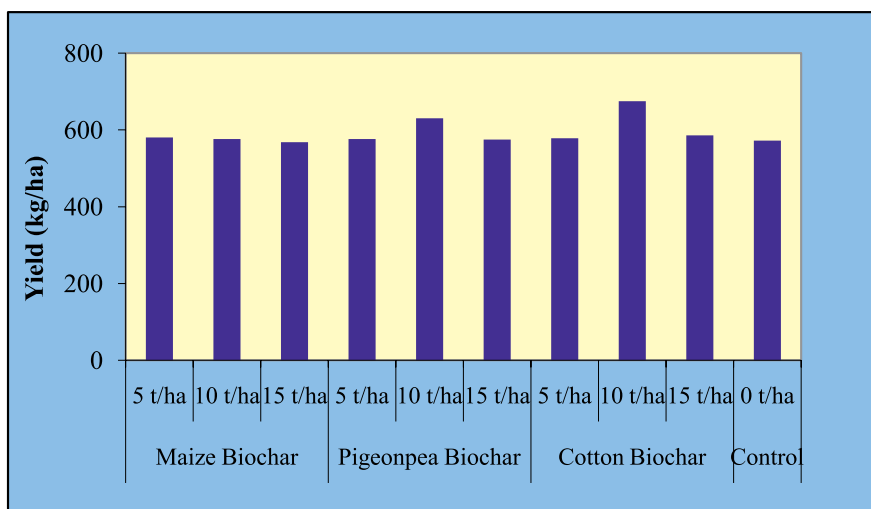
Fig 15. Effect of different biochars and their application rates on black gram yield

In cotton, prosopis biochar and rice-husk biochar applied at different doses (5, 10 and 15 t/ha) produced similar seed cotton yield (918-929 kg/ha) as that of FYM @ 12.5 t/ha (936 kg/ha) at Kovilpatti. Similarly, in another experiment at the same location, different biochars (maize, cotton and pigeonpea) and their application rates (5, 10 and 15 t/ha) had no significant effect on seed cotton yield (904-937 kg/ha). Among the three biochars, pigeonpea biochar gave marginally higher seed cotton yield followed by cotton biochar at all application rates. Similar results were reported from a field experiment on rainfed cotton at Aruppukottai (Virudhunagar district).

The combined application of biochar and inorganic fertilizer has the potential to increase crop productivity, thus providing additional incomes, and reducing the quantity of inorganic fertilizer use and importation (De Gryze *et al.*, 2010; Quayle, 2010). Steiner *et al.* (2008) reported that application rate of biochar @ 5 t/ha decreased fertilizer needs by 7%. The impact of biochar application is seen most in highly degraded acidic or nutrient

depleted soils. Low charcoal additions (0.5 t/ha) have shown marked impact on various plant species, whereas higher rates seemed to inhibit plant growth (Glaser *et al.*, 2001; Ogawa *et al.*, 2006). Crop yields, particularly on tropical soils can be increased if biochar is applied in combination with inorganic or organic fertilizers (Schmidt and Noack, 2000; Glaser *et al.*, 2002; Woolf, 2008). Oguntunde *et al.* (2004) reported that grain and biomass yield of maize increased by 91 and 44%, respectively on charcoal site soils compared to adjacent field soils.

Glaser *et al.* (2001) reviewed a number of early studies conducted during the 1980s and 1990s. These tended to show marked impacts of low charcoal additions (0.5 t/ha) on various plant species. Higher rates seemed to inhibit plant growth. In later experiments, combination of higher biochar application rates alongside NPK fertilizer increased crop yield on tropical Amazonian soils (Steiner *et al.*, 2007) and semi-arid soils in Australia (Ogawa *et al.*, 2006). Table 7 shows yield responses of different crops to biochar.

Table 7. Summary of experiments assessing the impact of biochar addition on crop yield

Authors	Study outline	Results summary
Iswaran *et al.* (1980)	Pea, India	Char at 0.5 t/ha increased biomass by 160%
Iswaran *et al.* (1980)	Mungbean, India	Char at 0.5 t/ha increased biomass by 122%
Kishimoto & Sugiura (1985)	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
Chidumayo, (1994)	Bauhinia trees on Alfisol/Ultisol	Charcoal application increased biomass yield by 13% and height by 24%
Glaser *et al.* (2002)	Cowpea on xanthic ferralsol	Char at 67 t/ha increased biomass by 150% Char at 135 t/ha increased biomass by 200%
Lehmann *et al.* (2003)	Soil fertility and nutrient retention. Cowpea was planted in pots and rice crops in lysimeters, Brazil	Biochar additions significantly increased biomass production by 38 to 45% (no yield reported)
Oguntunde *et al.* (2004)	Comparison of maize yields between disused charcoal production sites and adjacent fields, Ghana	Grain and biomass yield was 91 and 44% higher on charcoal site than control.
Yamamoto *et al.* (2006)	Maize, cowpea and peanut trial in area of low soil fertility	*Acacia* bark charcoal plus fertilizer increased maize and peanut yields (but not cowpea)
Chan *et al.* (2007)	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

Authors	Study outline	Results summary
Rondon *et al.* (2007)	Enhanced biological N$_2$ fixation (BNF) by common beans through biochar additions, Colombia	Bean yield increased by 46% and biomass production by 39% compared to control at 90 and 60 g biochar/kg, respectively
Steiner *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)
Kimetu *et al.* (2008)	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

On the other hand, large additions of charcoal or coal-derived humic acids may also have detrimental effects on crop growth. Yield declines of soybeans and maize were observed with an addition of 5 Mg charcoal/ha and 15 Mg charcoal/ha (Kishimoto and Sugiura, 1985) The reason for these reductions can be attributed to an increase in pH for pH-sensitive plants, such as observed for pine (Tryon 1948) or due to pH-induced micro-nutrient deficiencies (Kishimoto and Sugiura, 1985). However, crop yields did not generally decline after additions of large amounts of charcoal. From the few data available, no general optimum range can be deduced. Instead, for optimum plant growth, the amount of added charcoal may have to be determined for each type of soil and plant. Additionally, some investigations showed that crop yields can be enhanced even more compared to control soils if charcoal amendments are applied together with inorganic or organic fertilizers (Glaser *et al.*, 2002; Lehmann *et al.*, 2003).

Most of the currently published studies assessing the effect of biochar on crop yield are generally small scale, almost all short-term, and sometimes conducted in pots where environmental fluctuation is removed. These limitations are compounded by a lack of methodological consistency in nutrient management and pH control, biochar type and origin. It is not therefore possible at this stage to draw any quantitative conclusion, certainly not to project or compare the impact of a particular one-time addition of biochar on long-term crop yield. Nonetheless, evidence suggests that at least for some crop and soil combinations, moderate additions of biochar are usually beneficial, and in very few cases negative.

6. Critical factors for maximizing the benefits from biochar
6.1 Quality of feedstock biomass

Different types of biomass can be used for producing biochar: crops and forest residues, municipal green waste, paper mill waste, saw-mill waste, piggery waste, poultry waste and even human waste. All biochar types are reported to be beneficial. In situations such as desertified land, or even the degraded agricultural lands of India, South Africa and Australia, the benefits of biochar application in soils can be transforming. But, all types of feedstock biomasses are not equally good for various types of soils. Nutrient types and amounts vary with the biomass used. For instance, when wood based feedstocks are pyrolyzed, coarse and resistant biochars are generated with high carbon contents (up to 80%), as the rigid

ligninolytic nature of the source material is retained in the biochar residue (Winsley, 2007). The higher the amounts of nutrients in a feedstock biomass, the richer in nutrients are the biochar. A study conducted in Australia by Chan *et al.* (2007) shows that biochar produced from poultry manure had higher electrical conductivity, N, P and pH values than that from garden organic waste (Table 8). These analyses highlight the fact that the more nutrient-rich the organic waste, the greater the benefits from the biochar.

Table 8. Impacts of different biochar on soil properties

Feedstock	Acti-vated	pH	EC (dS/m)	C (%)	Total (N%)	Total (P%)	Mineral (N) (mg/kg)	Extractable P (mg/kg)
Garden organic	Yes	9.4	3.2	36	0.18	0.07	<0.5	400
Poultry manure	Yes	13	14	33	0.9	3.6	2.5	1800
Poultry manure	No	9.9	5.6	38	2.0	2.5	2.4	11600

Source: Chan *et al.* (2007)

6.2 Optimum temperature for biochar production

High cation exchange capacity (CEC), carbon levels and higher soil surface areas are some of the properties of better quality biochar. The higher the temperatures of the pyrolysis, the greater are the CEC and surface area of biochar. But, this outcome is compromised in two ways: 1) low carbon levels; and 2) additional handling costs of small-sized biochar (Lehmann, 2007a; Desmond and Kingston, 2007). High-temperature pyrolysis reduces the carbon percentage of biochar, which results in lower carbon sequestration and the other benefits of biochar are also reduced. Similarly, small-sized biochar (<1 mm size), produced by high temperature pyrolysis, is difficult to handle as either pelletisation or slurrying is necessary, which incurs additional costs. Consequently, the optimum temperature for biochar production is around 500°C (Lehmann, 2007a).

6.3 Soil carbon level

The soil carbon level of the area where biochar is to be applied is another serious concern. A 10-year study where charcoal was prepared, mixed into the soil and left undisturbed under three contrasting forest stands in northern Sweden, found a substantial increase in soil bacteria and fungi. As a result, there was mineralization (decomposition) of native soil organic matter with accelerated emissions of CO_2 (Wardle *et al.,* 1998). This revealed that biochar application in carbon-rich soils could partially offset the GHG benefits. Therefore, to maximize the overall benefits of biochar, it should be applied to carbon-poor soils. Biochar application on Indian and South African agricultural soils could be more promising as 25% of South Africa and 45% of India's cultivated lands are degraded (FAO, 2008; Hatrack, 2008).

6.4 Soil types and soil moisture

A major attraction of biochar is that it increases water quality and plant available water capacity (PAWC). In dry countries such as Australia and India, where water quantity and quality is extremely variable, this would be a significant benefit. The soil type, anyway, will ultimately determine the soil water benefits of biochar. Soil type has a significant influence on PAWC. Although biochar addition increases the water holding capacity and plant available moisture in sandy soils, there is no guarantee that it will increase the available water in loam and clay soils (Table 9). Because it is so porous, charcoal has a high surface

area with increased micro-pores and improves the water holding properties of sandy soils. But, in loamy soils, no changes were observed; and in clayey soil, the available soil moisture decreased with increasing charcoal additions, probably through the hydrophobicity of the charcoal (Glaser *et al.*, 2002). Therefore, biochar soil water benefits are maximized in sandy soils and thus there are enormous benefits of biochar in cropping areas where the opportunity cost of water is very high such as the sandy soils of the Western Australian wheat belt and water scarce soils of India.

Table.9. Effects of biomass derived char on percentage of available moisture in soils on a volume basis

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

Source: Glaser *et al.* (2002)

6.5 Soil pH and soil contamination

Soil pH is an important factor for plant growth for various reasons: some plants and soil micro-biota prefer either alkaline or acidic conditions; some soil-borne diseases are more common when the soil is alkaline or acidic; and, nutrient availability in soils depends on soil pH. Most macronutrients are available in neutral soils. But, inappropriate use of nitrogenous fertilizers, removal of crop residues, leaching of N and the presence of calcium sulphate ($CaSO_4$) parent material, has resulted in soil acidity being a major soil problem worldwide. Acid soils enhance soil contamination, as they increase concentrations of Al and Fe cations in the soil, which decrease the available symbiotic micro-organisms needed for effective tree growth (Shuj *et al.* 2007). In order to neutralize acidic soils, farmers apply thousands of tons of lime to farm soils at great expense. In addition to this direct cost, the production, packaging, transportation and application of lime emits significant amounts of GHGs (Maraseni, 2008). Application of biochar to acidic soils can avoid significant amounts of direct and indirect (such as avoiding GHG emissions) costs.

7. Implications of biochar use

7.1 Economic implications

The economic cost of implementing biochar production and use is important not just because it determines how readily and rapidly we might deploy the technology, but also because it must compete for finance and resources with other technologies that may likewise be aimed at climate change abatement and soil quality improvement (Woolf, 2008).

Using the highest carbon content of the wood-based biochar (i.e. 80%) and the CO_2 offset price range, the approximate value of biochar C sequestration is $2.93-$90.83 per metric ton of biochar. The potential economic returns to farmers if they utilize biochar as a substitute for agricultural lime under three price scenarios: (a) $114.05 per metric ton based on the energy content of a wood-based biochar; (b) $87 per metric ton; and (c) $350.74 per metric ton. The first value represents the opportunity cost of the foregone use of biochar as energy source. A wood-based biochar has an average energy content

of 12,500-12,500 BTU/lb (Dynamotive Energy Systems, 2007). The energy content of the Central Appalachian coal is 12,500 BTU/lb and its price is $116.38 per metric ton as of 2008 (EIA, 2009). Using the energy content as basis, the combustion value of biochar is 98% that of Central Appalachian coal, or $114.05/metric ton. The latter two prices are adopted from the estimated break-even prices of biochar in Granatstein et al. (2009). If the market price of biochar is low enough so that a farmer will earn a profit after applying biochar to the crop field (i.e. in one case study, lower than $12.05/MT and $100.52/MT when the price of carbon offset if $1/MT CO_2 and $31/MT CO_2, respectively) (Galianto et al. 2010).

Transportation distance has significant effects on costs, whereas ramifications for GHG emissions are low. Even transporting the feedstock and biochar each 200 km, the net CO_2 emission reductions decrease by only 5% of the baseline (15 km). At 1000 km, the net GHG emission reductions decrease by 28% to -626 kg CO_{2e}. The net energy is more sensitive than the GHG emissions to the transport distance. At 200 km the net energy decreases by 15%, and at 1000 km, the net energy decreases by 79% to 863 MJ. Costs are the most sensitive to transportation distance, where costs increase by $0.80 to 1 for every 10 km. Therefore, biochar systems are most economically viable as distributed systems with low transportation requirements (Roberts et al., 2010).

7.2 Environmental implications

The temperature rise is predominantly because of increases in atmospheric greenhouse gas emissions, dominated by carbon dioxide (CO_2). Eleven of the last 12 years rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The 100-year linear trend (1906–2005) is 0.74°C (0.56–0.92). Globally, soils contain about 1500 Pg (1 Pg =1 Gt) of organic carbon (Batjes, 1996), about three times the amount of carbon in vegetation and twice the amount in the atmosphere (IPCC WGI, 2001). Smith et al. (2008) suggested that technologies, which promote soil carbon sequestration, will also help to mitigate climate change itself (by reducing atmospheric CO_2 concentrations) and are cost competitive with mitigation options available in other sectors.

Sohi et al. (2009) 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 (Jha et al., 2010).

8. Potentials of biochar use in India

With a production of 93.9 million tons (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 fibre crops (jute, mesta, cotton), 17.2 Mt of pulses and 30.0 Mt of oilseeds crops, in the year 2011-12 (MoA, 2012), it is but natural that a huge volume of crop residues are produced both on-farm and off-farm. It is estimated that approximately 500-550 Mt of crop residues are produced per year in the country (IARI,

2012). Efficient and sustainable disposal of organic waste remains a key issue in rural farm areas and 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 the development of sustainable agricultural systems in India, and also for global climate change mitigation. There is significant availability of non-feed biomass resources in the country as potential feedstock for biochar production. The current availability of biomass in India (2010-2011) is estimated at about 500 million metric tons/year. Studies sponsored by the Ministry of New and Renewable Energy, Govt. of India have estimated surplus biomass availability at about 120–150 million metric tons/annum. Biochar having high pH value can be a good remedy for acid soil amelioration. North-East India has the potentiality of producing 37 million tons of agricultural waste biomass. If only 1% of this biomass is converted to biochar, about 74 thousand tons of carbon can be sequestered annually. Out of this, if 1% of the process of producing biochar is carried out through modern equipments, about 1300 and 900 tons of bio-oil and biogas can be produced, respectively which is equivalent to 31 terra joule of energy.

Moreover, in rural India, women cook their food with biomass (mostly wood and charcoal) in highly polluting stoves, which represent a number of problems including deforestation, lots of time spent on wood collection and on cooking, back pains and other life-threatening risks. Furthermore, charcoal is inefficiently produced in the earth-mound kiln releasing a considerable amount of methane emissions. Therefore, the establishment of the commercialization chain of highly-efficient biochar-making cook stoves, diffusion of improved small-scale kilns, pyrolysis of agricultural residues that are burnt otherwise, offer an opportunity to enhance the living conditions of rural families, counteract deforestation, protect biodiversity, increase crop production, improve agricultural waste management and remove carbon from the atmosphere as a carbon-negative strategy to fight global warming (Anon, 2012).

9. Constraints of biochar use in India

One factor determining how much biochar may be produced is the existence of competing demands for biomass feedstock. Production of biochar is, of course, not the only use that can be made of biomass. Numerous other applications for various types of biomass have been used in the past, are in current demand, and may become popular in the future. The crop residues and other biomass are used for animal feeding, soil mulching, biomanure making, thatching for rural homes and fuel for domestic and industrial use. Once environmental costs of carbon-based greenhouse gas emissions have been suitably internalised, we can expect market forces and the price mechanism to be the dominant factor in apportioning use of biomass resources between competing demands (Woolf, 2008). Other constraints on biochar production methods arise because emissions of CH_4, N_2O, soot or volatile organic compounds combined with low biochar yields (for example, from traditional charcoal kilns or smouldering slash piles) may negate some or all of the carbon-sequestration benefits, cause excessive carbon-payback times or be detrimental to health (Woolf *et al.*, 2010). However, to promote the application of biochar as a soil amendment, and also as a climate change abatement option, research, development and demonstration on biochar production and application is very vital.

10. Future research, development and policy needs for promoting use of biochar

10.1 Research needs

Research information on biochar in agricultural use in India is scanty. Very few reports are available on production, characterization and use of biochar as soil amendment. Biochar research in the world as a whole is decade old and lot of advancement has already been made in this direction. A baseline study comprising compilation of data on non-feed biomass resources in India needs to be conducted. Similarly, a review of current non-feed biomass utilization and thermo-chemical conversion technologies, particularly slow pyrolysis also has to be carried out. Further, we must answer certain questions before recommending large-scale use of biochar for agriculture purposes (Jha *et al.*, 2010).

- 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?

10.2 Development needs

- Installation of Biochar production units in places where bio-waste generation is abundant.

- Create awareness among the various biochar stakeholders such as farmers, agricultural extension officers, researchers etc and to build their capacities in biochar production and application technologies through the development and implementation of training programmes.

- Familiarizing biochar production and application technologies at KVKs and state agricultural departments for awareness generation among the farmers.

- Establishing self-help groups and encouraging unemployed youths to take up biochar production as a profession

- Each university, research institute and NGO committed to sustainable development of agriculture should start working with some selected farmers. Their experience should be used for improving the biochar production and application technology.

10.3 Policy needs

The way crop residues are used and managed by millions of farmers depends on their individual perceptions about the benefits, largely economic, both short- and long-term and the opportunities available (IARI, 2012). The current policy instruments, if any, draw from the need to control air pollution resulting from the negative impacts of burning of crop residues and not from the benefits of biochar use in achieving goals of sustainable agriculture. The benefits of biochar use in agriculture relate to soil health improvement, C sequestration, reduced GHGs emissions and improved use-efficiency of inputs. There is a need to undertake policy-related research to quantify the benefits under a range of situations to aid policy level decisions. Some of the policy needs to promote biochar use in agriculture are:

- Developing a crop residues/biomass management policy for each state defining clearly various competing uses.

- Developing and implementing appropriate legislation on prevention and monitoring of on-farm crop residues burnings through incentives and punishment.

Conclusions

Crop residues in fields can cause considerable crop management problems as they accumulate. In India, about 435.98 million tons of agro-residues are produced every year, out of which 313.62 million tons are surplus. These residues are either partially utilized or un-utilized due to various constraints. Efficient use of biomass by converting it as a useful source of soil amendment/nutrients is one way to manage soil health and fertility. One of the approaches for efficient utilization of biomass involves carbonization of biomass to highly stable carbon compound known as biochar and its use as a soil amendment. Use of biochar in agricultural systems is one viable option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality. Further, several studies across the world have established that biochar application increases conventional agricultural productivity and mitigate GHG emissions from agricultural soils. This has led to renewed interest of agricultural researchers particularly in India to produce biochar and its use as a soil amendment. Recently, many ICAR institutes and SAUs have initiated work on biochar production from different bio-residues and its use as a soil amendment. The initial outcomes reveal that biochar application helps in improving soil health and crop productivity. However, to promote the application of biochar as a soil amendment and also as a climate change abatement option, research, development and demonstration on biochar production and application is very vital. It is necessary to develop low-cost biochar kilns to make the technology affordable to small and marginal farmers. Further, inter-disciplinary and location-specific research has to be taken up for studying the long-term impact of biochar application on soil physical properties, nutrient availability, soil microbial activities, carbon sequestration potential, crop productivity, and greenhouse gas mitigation.

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Acronyms/Abbreviations

BC	Biochar
BNF	Biological Nitrogen Fixation
CART	Centre for Appropriate Rural Technology
CEC	Cation Exchange Capacity
CIAE	Central Institute of Agricultural Engineering
CRIDA	Central Research Insitute for Dryland Agriculture
EC	Electrical Conductivity
EDX	Energy Dispersive X–ray Spectroscopy
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
IARI	Indian Agricultural Research Institute
ICAR RC NEH	ICAR Research Complex for NEH Region
IISS	Indian Institute of Soil Science
IIT	Indian Institute of Technology
IPCC	Intergovernmental Panel on Climate Change
MNRE	Ministry of New and Renewable Energy
MoA	Ministry of Agriculture
NEDFI	North Eastern Development and Finance Corporation
NEXAFS	Near Edge X-ray Absorption Fine Structure
PAHs	Polycyclic Aromatic Hydrocarbons
PAWC	Plant Available Water Capacity
PBS	Pyrolysis Biochar System
PCBs	Polychlorinated Biphenyls
PVC	Polyvinyl Chloride
RDF	Recommended Dose of Fertilizers
SEM	Scanning Electron Microscopy
SOM	Soil Organic Matter
STXM	Scanning Transmission X-ray Microscopy
SVOCs	Semi-Volatile Organic Compounds
TLUD	Top-Lit Updraft Gasifier
UNEP	United Nations Environment Programme
VOCs	Volatile Organic Compounds
XPS	X–ray Photoelectron Spectroscopy