REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 1S (2024)
http://www.veterinaria.org
Article Received: November 2023, Revised: December 2023, Accepted: January 2024

A Comprehensive Review of Biochar Production Methods and Its Application to Enhance Soil Fertility

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Abstract

A census of the biomass on Earth is key for understanding the structure and dynamics of the biosphere. The overall biomass composition of the biosphere establishes a census of the ≈550 gigatons of carbon (Gt C) of biomass distributed among all of the kingdoms of life. It includes plants (≈450 Gt C, the dominant kingdom) which are primarily terrestrial, whereas animals (≈2 Gt C) are mainly marine, and bacteria (≈70 Gt C) and archaea (≈7 Gt C) are predominantly located in deep subsurface environments.

Biochar plays a crucial role in enhancing crop growth and yield primarily through its effects on soil health and nutrient availability. When incorporated into soil, biochar improves water retention, increases nutrient retention capacity, and promotes microbial activity, thereby enhancing soil fertility. Its porous structure provides a habitat for beneficial microorganisms and promotes aeration, which supports root development and nutrient uptake by plants. Moreover, biochar helps mitigate soil acidity and can bind harmful substances, reducing their availability to plants. These combined benefits contribute to improved crop productivity, resilience to environmental stresses, and sustainable agricultural practices.

In developing countries, the large quantities of agricultural residues are currently utilised either as raw material for paper industry, or as animal feed sources. But generally since the collection and disposal of these residues are becoming more difficult and expensive, it is left unused as waste material or simply burned in the fields, thereby creating significant environmental problems. Pyrolysis of biomass is one of the most efficient technologies used to produce biofuels*)*.The amount of crop residue produced in the world is estimated at 2802×106 Mg/year for cereal crops, 3107×106 Mg/year for 17 cereals and legumes, and 3758×106 Mg/year for 27 food crops.

India alone generates ~500 million metric tonnes (MT) of crop residue annually, of which 100 MT is burned. The practice of residue burning primarily occurs following the wheat and Rice harvest mostly in north western India. This is due to the tight schedule of the harvest-to-sowing transition under the predominant rice-wheat rotation cropping system in north western India has limited the rate of adoption of alternatives. Crop residue burning allows cheap and fast disposal of crop residue and therefore remains a recurring issue, as revealed by a ~60% increase in the number of agricultural fires detected by NASA's Aqua satellite from 2002 to 2016. Several important reasons like short time span for sowing wheat, limited farm mechanisation, scarce manpower and poor acceptability of paddy straw as fodder are the root causes behind this residue burning. The consequences of residue burning leading to respiratory infections are among the leading causes of death and disability globally. Respirable aerosol particles released by agricultural crop-residue burning (ACRB), practiced by farmers in all global regions, are potentially harmful to human health.

Keywords: Biochar, Pyrolysis, Soil fertility, Wheat, Maize

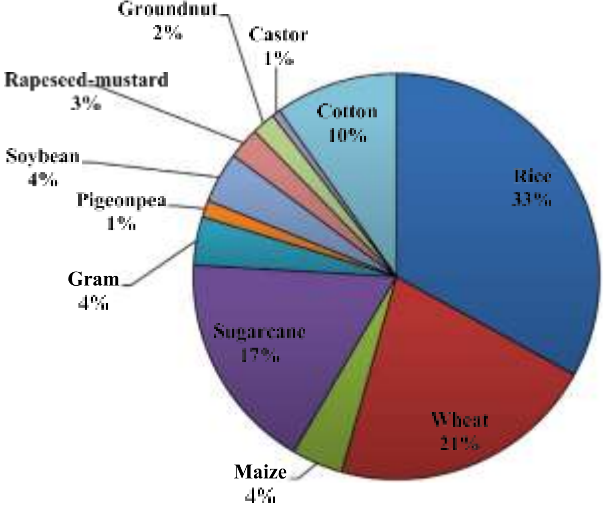
Introduction:

The agricultural industry plays a major role in the overall economic growth of the world. However, there is limited discussion on the management of agricultural waste in the published literature. It could be related to the fact that agriculture industry is not regulated as the municipal solid waste (MSW). The MSW is mainly governed by public entities such as municipalities. Agricultural waste is predominantly handled by the owners of the agricultural land which is predominantly in the private sector, with little public sector involvement *(*Bhuvaneshwari *et al., 2019).* In Haryana state, the Groundwater Act implementation is associated with a concentration of crop residue burning into a narrower window, later in the season, and with a peak intensity that is 39% higher (Balwinder-Singh *et al., 2019).* The Government of India has recently launched a US$157m initiative to discourage burning through agricultural machinery innovations. The current policy environment encourages productivity maximization of cereals and, consequently, very high levels of residue production. If these policies are changed because trade-offs cannot be resolved, companion efforts will be needed to facilitate sustainable intensification in areas such as the Eastern Gangetic Plain, where water resources are relatively abundant and closer coupling of crop-livestock systems provides a diverse set of end uses for crop residues *(*Balwinder-Singh *et al., 2019).*

The Indian Government in the recent past has introduced numerous action plans such as the New National Biogas and Organic Manure Program (NNBOMP) and Sustainable Alternative toward Affordable Transportation (SATAT*)* (Kaushal, 2020)

One alternate suitable option to reduce the burning of crop residues through Biochar production is a sustainable technique that can help to curtail the issue while retaining the nutrients present in the crop residue in the soil (Bhuvaneshwari *et al.,* 2019*).*

Fig-1: Share of selected crops in surplus crop biomass (Information & Tifac)



What is biochar and its importance?
Biochar is a carbon-rich material that is made from biomass through a thermochemical conversion process known as pyrolysis. Biochar is derived from biomass combustion in the presence of a limited oxygen supply and at relatively low temperatures below 700°C (Lehmann S. J. 2009). The earliest known purpose for creating biochar was specifically for soil application such as carbon storage or sequestration in soil; improvement of soil performance such as increase in nutrient availability, reduction of compactness in soil, soil pH improvement; soil water filtration. Recent interest in biochar production from organic waste has been growing in recent years due to its broad applicability, availability, and smoother production (Gabhane *et al.,* 2020).

Biochar production techniques:
Due to increased demand for various purposes like industrial, domestic use and application for soil fertility management is boosting for converting residue into biochar. Thermochemical conversion is a common technology for making biochar. Thermochemical conversion techniques are pyrolysis, hydrothermal carbonization (HCL), gasification, and hydrothermal liquefication (Armah *et al.,* 2022).

2.1: Pyrolysis:
Pyrolysis is a thermal degradation process where biomass is heated under anaerobic conditions or a limited supply of oxygen to produce various gaseous and aqueous products as well as char residues. Agricultural biomass is composed of lignin, cellulose, hemicelluloses, and silica. Generally, the pyrolysis point of cellulose is 350 °C, whereas lignin melts above 350 °C. Thus, the effective temperature range for pyrolysis was found to be 300–700 °C (Lehmann S. J. 2009). Pyrolysis processes have been evolving for decades. Depending upon the process parameters such as temperature, heating rate, and residential time, it is further divided into various modes such as slow and fast pyrolysis. Slow and fast pyrolysis regards to traditional techniques. However, flash pyrolysis, vacuum pyrolysis, and microwave pyrolysis are modern techniques that were modified using modern technologies (Lehmann S. J. 2009). Therefore, slow pyrolysis and fast pyrolysis have been classified and added in the section comprising "traditional approaches". In contrast, flash pyrolysis, vacuum pyrolysis, and microwave pyrolysis have been added in the selection contain modern approaches (Mullen *et.al,* 2009)
Biochar was produced from corn stover using slow pyrolysis at 300, 400 and 500°C, the results shows that, carbon content, ash percent of corn stover biochar increased from 45.5% to 64.5% and decreases biochar yield with increasing pyrolysis temperatures (Rafiq *et al.,* 2016). The biochar produced from all manures behaved similarly with respect to surface area,

ash content, and pH of the biochar increased as temperature increased, while yield decreased with increasing temperature. The biochar was rich in mineral elements such as N, Ca, Mg, and P increased as temperature increased (Cao & Harris, 2010). Greater pyrolysis temperature for low-ash biochar increased fixed carbon, but decreased it for biochars with more than 20% ash (Enders *et al*., 2012*).* High pyrolysis temperature promotes the production of biochar with a strongly developed specific surface area, high porosity, pH as well as content of ash and carbon, but with low values of Cation Exchange Capacity (CEC) and content of volatile matter (Tomczyk *et al.,* 2020a). Biochar produced from animal litter and solid waste feedstocks exhibit lower surface areas, carbon content, volatile matter and high Cation Exchange Capacity (CEC) compared to biochar produced from crop residue and wood biomass, even at higher pyrolysis temperatures. The reason for this difference is considerable variation in lignin and cellulose content as well as in moisture content of biomass (Tomczyk *et al.,* 2020a). In India, about 960 million tonnes of solid waste is being generated annually as by-products during industrial, mining, municipal, agricultural and other processes. Of this 350 million tonnes are organic wastes from agricultural sources (Pappu *et al.,* 2007).

The effect of pyrolysis temperature on biochar quantity and quality:

There are three stages of biochar production process: pre-pyrolysis; main-pyrolysis and formation of carbonaceous soil products (Lee *et al.* 2017). The first stage (from ambient temperature to 200 °C) is attributed to evaporation of moisture and light volatiles (Cárdenas- Aguiar *et al*., 2017). The second stage (from 200 to 500 °C) was a devolatilized and decomposed of hemicelluloses and cellulose at a fast rate (Ding *et al.* 2014). The last stage (above 500 °C) is degradation of lignin and other organic matter with stronger chemical bonds (Cárdenas-Aguiar *et al.* 2017). The pyrolysis temperature is strongly correlated with changes in the structure and physicochemical properties of biochar (Chen *et al.,* 2017*);* (Tomczyk *et al.,* 2020a); (Ghodake *et al.,* 2021). The experimental results suggested that the biochar obtained at 400 and 500 °C in fast pyrolysis was composed of a highly ordered aromatic carbon structure and the degree of carbonization for biochar increases (Kim *et al.,* 2012). The yield of biochar decreases and carbon increases as pyrolysis temperature increases (Kim *et al*., 2012); (Rafiq *et al*., 2016). The exponential increase of ash content and pH with increased pyrolysis temperature resulting in biochar's that are more alkaline in nature probably due to the concomitant decrease in acidic functional groups and increase in ash content (Rafiq *et al.,* 2016).

Table 1: Pyrolysis classification

Pyrolysis Type	Heating Rate (ºC/Sec^{-1})	Temperature º C	Gas and Solid residence time (minutes)
Slow	0.1-1	300-500	More than 30 minute
Fast	1-100	500-900	10-20 S
Flash	>1000	500-900	1 S

Source: Aysu & Kuciik, 2014

Biochar production methods:

The biochar quantity extracted during the pyrolytic is based on the type and composition of the biomass utilized, pyrolysis conditions and temperature. Temperature is the major operational process condition that results the efficiency of the product (Kumar *et al.,* 2020). When the temperature of the pyrolysis process rises, the yield of biochar decreases, and also significant change on the composition and physical properties of biochar yield (Noor *et al.,* 2019). Pyrolysis generally classify into three broad categories based on the operating conditions (heating rate, temperature, residence time, and pressure): (i) slow pyrolysis with temperature of 300°C (Noor *et al.,* 2019), (ii) intermediate pyrolysis at temperatures ranging from 400-650° C (Kazawadi *et al.,* 2021), and (iii) fast pyrolysis with heating rate is relatively more than 500 °C (Ivanova *et al.,* 2016). The biochar conversion efficiency of the drum method 29.3% biochar at holding time 15minitus for maize starver (G Venkatesh *et. al,* 2013).

Physiochemical Properties of biochar:

Functional groups:

The essential functional groups present at surface of biochar that increase its adsorption properties include carboxylic (-COOH), hydroxyl (-OH), amine, amide and lactonic groups. The main factors that influence surface functional groups of biochar are biomass and temperature (Li *et al.*, 2017). In addition, when other properties such as pH, surface area and porosity are increased there is a chance of reduction in biochar functional groups. The surface functional groups are characterized using Fourier Transform Infrared Spectroscopy (FTIR). The biochar produced at different temperatures showed a significant difference in their surface functional groups. Apart from FTIR, NMR (Nuclear Magnetic Resonance) can also be used for determining surface functional groups present in biochar (Li *et al.*, 2017).

The chemical properties of wheat biochar and corn biochar, such as pH and infrared spectra, were studied with the increase of temperature. It was found that the pH of biochar from wheat straw and corn straw combustion increased with the increase of temperature. It may be related to the content of functional groups in the biochar's themselves (Zhang et al., 2022). With the increase of temperature, the functional groups of the two biochar's, such as hydroxyl and carboxyl chemical bonds of these functional groups are broken with the increase of temperature. Resulting in a decrease in the number of acidic functional groups and an increase in the alkalinity of the biochar (Zhang *et al.*, 2022). Biochar changes the physical and chemical properties of soil, which in turn, it effect the characteristics and behaviour of the soil biota (Thies & Rillig, 2012)

Surface area and porosity:

Usually, biochar with increased surface area and high porosity will possess high adsorption property. The porous surface in biochar is formed during pyrolysis process when there is an increase in water loss during dehydration process. According to the International Union of Pure and Applied Chemistry, the pores present in biochar may be micro (<2 nm), meso (2_50 nm) and macro (>50 nm). The biochar with less pore size cannot adsorb the pesticide molecules despite their polarity or charges. The pore size of biochar can be characterized using SEM (Scanning Electron Microscopy). The surface area is the keynote for determining biochar sorption capacity while temperature plays a major role in biochar formation. The surface area may vary between treated and untreated raw materials. Commercially, activated carbon possesses more surface area. The biochar produced without activation process possesses a low surface area and is less porous(Kim *et al*., 2012). Hence during biochar production, activation process is involved to increase porosity and surface area of biochar. The physical and chemical activation process may be involved in activation process.

Estimates of the resulting surface area of different biochar's range from 10 to several hundred square metres per gram (m^2 g^{-1}). The biochar having more porosity, it to retain water, provide surfaces for microbes to colonize, and for various elements and compounds to become adsorbed will also likely increase over time. Smaller pores will attract and retain capillary soil water much longer than larger pores (larger than 10 µm to 20µm) (Thies & Rillig, 2012).

Wheat and maize are significant in biochar production due to their abundance and the substantial biomass residues generated by them. These residues such as straw and stalks, are often underutilized and can be converted into biochar through pyrolysis, providing an effective means of waste management. Biochar produced from wheat and maize residues improves soil health by enhancing nutrient retention, increasing soil organic matter and improving water retention. Additionally, biochar can sequester carbon, thus contributing to climate change mitigation. Utilizing wheat and maize residue in biochar also supports sustainable agriculture by recycling nutrients and reducing the need for synthetic fertilizers.

Maize straw biochar:

The Maize corn cob is generally wasted b farmers after harvest of the crop subjected to improper burning, which creates pollution. The Corn cob has a potential material for biochar production and its application. The hypothesis is that if the available corn cob is used for biochar production, it will reduce the carbon dioxide (CO_2) emission by 0.13 Gt per year (Adekanye *et al.,* 2022).

The biochar yield decreases with an increasing temperature for the maize cob biochar at 300, 400 and 500 °C. The biochar produced at 300 °C has the highest fixed carbon content of 60.5% and largest surface area was (281.8 m2 ·g–1) at 500 °C. At low temperature (400 ºC), the char yield is positively corelated to heating rate. But at higher temperature (500 to 700 ºC), the char yield rate decreases as heating rate increases(Li *et al.,* 2016) (Zhang *et al.*, 2022). The studies on conventional biomass were carried out in fixed bed reactor at different temperatures 300, 350, 400 and 450 °C. The optimum temperature required to produce Corn cob and Wheat biochar are 450, 400°C respectively (Biswas *et al*., 2017).

Table 2: Biochar produced form Corn straw:

BF	PT	PY %	pH	SSA (m2/g) VM	VM (%)	A (%)	C%	References
Corn cobs	500	18.9	7.8	0	-	13.3	77.6	(Mullen *et al*., 2010)
Corn stover	300	66.2	7.7	3.2	54	5.7	45.5	(Rafiq *et al*., 2016)
	400	37.1	8.8	3.2	45.5	12.5	64.0	(Rafiq *et al*., 2016)
	500	17.0	7.2	3.1	-	32.8	57.3	(Mullen *et al*., 2010)
		29.2	9.8	4.6	33.8	18.7	64.5	(Rafiq *et al.,* 2016)

Biochar Feedstock (BF), Pyrolysis Temperature (PT), Specific Surface Area (SSA), Volatile Matter: (VM), Ash (A), Product Yield (PY), Total Carbon Content (C)

Table 3. Yield and Physico-Chemical Properties of Biochar's produced through Corn stover

Parameters	**Pyrolysis Temperature**		
	300°C	**400°C**	**500°C**
Yield [%]	66±2a	37±1 b	29.2±0.3 c
pH [H_2O]	7.70±0.08 c	8.8±0.2 b	9.775±0.005 a
Ash [%]	5.7±0.2 c	12.5±0.2 b	18.7±0.3 a
Volatile matter (%)	54.0±0.6 a	45.5±0.5b	33.8±0.5 c
C [%]	45.5±0.5 b	64±1 a	64.5± 1 a
H [%]	5.4±0.6 a	3.9±0.3 b	2.7±0.1 c
O [%]	42±1a	32±1 b	33.1±0.4 b
N [%]	0.63±0.04 a	0.42±0.04 b	0.25±0.01 c
P [mg L^{-1}]	3.4±0.1 c	7.2±0.3 a	5.54±0.10 b
K [mg L^{-1}]	60.1±0.2 c	102± 2 b	224±2 a
Ca [mg L^{-1}]	21.0±0.3 c	24.1±0.2 b	29.7±0.1 a
Mg [mg L^{-1}]	18.8±0.6 c	22.6±0.7 b	30.3±0.4 a
Na [mg L^{-1}]	1.78±0.02 b	2.03±0.04 b	3.3±0.4 a
Total Cation Base [mg L^{-1}]	101.7±0.5 c	151±2 b	288±2 a

Source: Rafiq *et al.*, 2016

The fixed carbon content is an important index for the biochar's quality and it is depend on the heating rate and the holding time. The study in wheat straw showed the temperature rise provoked higher values of carbon fixation in the biochar (Velichkova *et al.,* 2022).

Use of Biochar:

The potential biochar application- cations include: (1) pollution remediation due to high CEC and specific surface area; (2) soil fertility improvement on the way of liming effect, enrichment in volatile matter and increase of pore volume, (3) carbon sequestration due to carbon and ash content, etc. (Tomczyk *et al.,* 2020b*)*. The application of biochar in black soil increases the pH, organic matter and the C/N ratio also shows an overall upward trend. It promotes the transfer of carbon and nitrogen nutrients to the soil aggregate in the black soil, and effectively improving the soil carbon fixation capacity of the aggregates and also reduces soil bulk density(Jiang *et al*., 2022).

The two aspects that make biochar amendment superior to other organic materials are high stability against decay, so that it can remain in soil for longer times providing long time benefit to soil and secondly it is having more capability to retain the nutrients. Biochar helps to improve soil pH, Moisture holding capacity, cation-exchange capacity and microflora. It was indicated that the biochar use also help for control of pathogens farm land. It is effective both air-born (e.g. *Botrytis cinerea* and powderly mildow) and soil borne pathogens (e.g. *Rhizoctonia solani* and *Fusarium*, *Phytophthora)* (Jyoti Rawat, 2019).

The application of biochar in acidic soil (pH 4.7) had a more remarkable effect on the growth performance of maize varieties grown and also biochar useful tool to improve crop yield in nutrient-poor and acidic soil. The Biochar reduces the N_2O emissions and ammonium leaching over time was due to increased adsorption capacity of biochar's through oxidative reactions on the biochar surfaces with ageing (Singh *et al*., 2010).

Rate of application of Biochar:

Many studies have shown a positive effect of using biochar on crop yield with rate of 5-50tonnes per hector with appropriate nutrient management.

Several studies have reported a positive effect of using biochar on crop yields with rates of 5–50 tonnes per hectare with appropriate nutrient management. Nimbalkar *et.al.* 2023, concluded that in (T3) the application of microbial-enriched Biochar @ 7.5 t ha^{-1} + 75 % GRDF has given significantly higher grain yield (Soybean: 25.89 qha^{-1} and Wheat: 43.19 qha^{-1}) and straw yield (Soybean: 27.49 qha^{-1} and wheat: 45.78 qha^{-1}) over the GRDF in both Soybean and Wheat cropping sequence.

Enhancement of Microflora and plant growth:

The porous structure of biochar, its high internal surface area and its ability to adsorb soluble organic matter, gases and inorganic nutrients are likely to provide a highly suitable habitat for microbes to colonize, grow and reproduce, particularly for *bacteria, actinomycetes* and *arbuscular mycorrhizal fungi* (Thies & Rillig, 2012).

There are several reports which show that biochar has the capability to stimulate the soil microflora, which results in a greater accumulation of carbon in soil. Besides adsorbing organic substances, nutrients, and gases, biochar's are likely to offer a habitat for bacteria, actinomycetes and fungi. It has been suggested that faster heating of biomass (fast pyrolysis) will lead to the formation of biochar with fewer microorganisms, smaller pore size, and more liquid and gas components. The enhancement of water retention after biochar application in soil has been well established, and this may affect the soil microbial populations. Biochar provides a suitable habitat for a large and diverse group of soil microorganisms, although the interaction of biochar with soil microorganisms is a complex phenomenon. Many studies reported that addition of biochar along with phosphate solubilizing fungal strains promoted growth and yield of *Vigna radiata* and *Glycine max* plants, with better performances than control or those observed when the strains and biochar are used separately. The use of biochar increased *mycorrhizal* growth in clover bioassay plants by providing the suitable conditions for colonization of plant roots .Summarized four mechanisms by which biochar can affect functioning of mycorrhizal fungi: (i) changes in the physical and chemical properties of soil, (ii) indirect effects on mycorrhizae through exposure to other soil microbes, (iii) plant- fungus signalling interference and detoxification of toxic chemicals on biochar, and (iv) providing shelter from mushroom browsers. Carrots and legumes grown on steep slopes and in soils with less than 5.2 pH showed significantly improved growth by the addition of biochar. It was found that biochar increased the biological N2 fixation (BNF) of Phaseolus vulgaris mainly due to the greater availability of micro- nutrients after application of biochar.(Lehmann *et al., 2012)* reported that biochar reduced the leaching of $NH4^+$ by supporting it in the surface soil where it was available for plant uptake. *Mycorrhizal* fungi were often included in crop management strategies as they were widely used as supplements for soil inoculum. When using both biochar and *mycorrhizal fungi* in accordance with management practices, it is obviously possible to use potential synergism that can positively affect soil quality. The fungal hyphae and bacteria that colonize the biochar particles (or other porous materials) may be protected from soil predators such as mites, *Collembola* and larger (>16 µm in diameter) *protozoans* and *nematodes*. Biochar can increase the value of non-harvested agricultural products and promote the plant growth. A single application of 20 t ha^{-1} biochar to a *Colombian savanna* soil resulted in an increase in maize yield by 28–140% as com- pared with the unamended control in the 2nd to 4th years after application. With the addition of biochar at the rate of 90 g kg−1 to tropical, low-fertile ferralsol, not only the proportion of N fixed by bean plants (*Phaseolus vulgaris*) increased from 50% (without biochar) to 72%, but also the production of biomass and bean yield were improved significantly. When biochar was applied to the soil, a higher grain yield of upland rice (*Oryza sativa*) was obtained in northern Laos's sites with low P availability. Many of these effects are interrelated and may act synergistically to improve crop productivity. Often there has been a reported increase in yields, which is directly related to the addition of biochar as compared to the control (without biochar).

Increase in the yield of soybean with the application of RDF + Biochar over the yield obtained with the application of RDF alone as increase in the yield was 5, 19 and 24 per cent due to co-application of 2, 3.5 and 5 t ha^{-1} Biochar. Similar trend was observed with the yield of biomass. (Oak *et.al,* 2020).

Application of sole biochar had no significant effect on grain yield. However combined application of BMS 60 m^3 ha^{-1} and biochar 2.5 tha^{-1} and recorded significantly higher grain yield (39.3 %) as compared to RDF. (Oak *et.al,* 2021)

Conclusion:

The direct beneficial effects of biochar addition for the availability of nutrients are largely due to the higher content of potassium, phosphorus, and zinc availability and, to a lesser extent, calcium and copper. Few studies have examined the potential for amending biochar in soil to impact plant resistance to pathogens. Concerning soil pathogens principally concerned with the effect of AM fungal inoculations on asparagus tolerance to the soil-borne root rot pathogen *Fusarium*, demonstrated that charcoal amendments had a suppressive effect on pathogens. One more study that supported these earlier findings stated that biochar made from ground hardwood added to asparagus field soil led to a decrease in root lesions caused by *Fusarium oxysporum*, *F. asparagi, and F. proliferatum* compared to the non-amended control. Biochar reduces the need for fertilizer, which results in reduction in emissions from fertilizer production, and turning the agricultural waste into biochar also reduces the level of methane emission.

Acknowledgement

The authors are thankful to the Research Coordination Committee (RCC), BAIF Development Research Foundation, Pune, for providing technical and financial support to publish this review article and thankful to the scientists at BAIF Central Research Station, Urulikanchan, Ta. Haveli, Dist. Pune 412 202 M.S. (India) for cooperation and guidance.

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