Biochar production from agro-food industry residues: a sustainable approach for soil and environmental management

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Advance biochar production technique, hydrothermal carbonization (HTC, wet pyrolysis) offers an option to tap the benefits of biomass residues of food industry characterized by high moisture and low calorific value. HTC is more energy efficient due to its low temperature operations and higher biochar recovery rates (up to 90%). Biochar offers multitude of benefits in terms of agronomical and environmental management. It can contribute to climate change mitigation, increase plant productivity and crop yield and remediation of contaminated sites. Limitations and knowledge gaps in the current understanding of biochar along with its properties have been identified. Major hurdles recognized in commercialization of biochar application are permanency, diversity and economic viability.

Keywords: Agro-food industry, biochar production, biomass residues, hydrothermal carbonization.

BIOCHAR in the recent past has grabbed a great deal of attention due to its chemical and physical properties, and has been portrayed as one of the potential drivers of climate change mitigation and sustainable agriculture[1]. Agriculture is one of the biggest sources of greenhouse gases (GHGs), with CO_2 equivalent emission of about 4.7 billion metric tonnes globally in 2010, whereas the share of Indian agriculture is about 609 million metric tonnes[2]. Although fresh food industry dominates in India, food processing is an important and burgeoning sector in terms of production, consumption and export growth potential[3]. Moreover, in the near future, not just India but the developing world as a whole is expected to see an upsurge in growth of agro-processing industry, as a result of rapid urbanization and increase in wealth. As more food processing industries sprout in future, there will be a need to manage the waste generated from these industries in an efficient and sustainable way. The waste generated in agriculture and related agro-industries has the potential to supply feedstock for biochar production. Converting residual biomass from farm and food processing industry into biochar can help in achieving long-term carbon sequestration and other beneficial effects on soils and environmental properties. The concept of biochar production from organic waste and its role in enhancing biomass production by improving soil fertility and contaminant remediation is illustrated in Figure 1.

In this review an effort has been made to collate and discuss recent scientific information regarding availability of feedstock, especially from farm and food processing industry for biochar production, different production techniques and various agronomical and environmental applications of biochar. One of the important objectives of this work was to identify limitations and knowledge gaps in the current understanding of biochar and its properties.

Availability of feedstock for biochar production

Practically all biomass material, unprocessed or processed, can be utilized as feedstock for the pyrolysis.

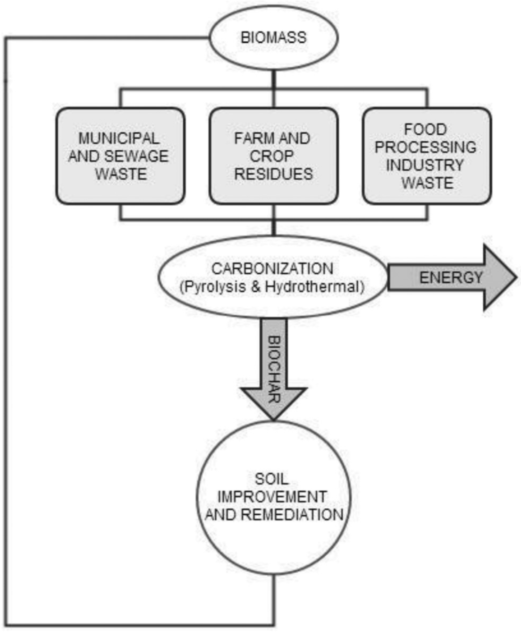

Figure 1. Concept of waste utilization for biochar production and improvement of soil and environment.

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Conversion of lignin in comparison to cellulose and hemicellulose has been found more efficient leading to higher char yields[3,4]. The temperature ranges for the conversion of various constituents of feedstock are highly relevant to attain higher conversion rates, hemicellulose generally degrades at temperatures between 220°C and 315°C; cellulose at 315–400°C, and lignin at a wider range 160–900°C (ref. 3). Generally the waste organic matter that does not find any other useful application and has to be discarded can be used as pyrolysis feedstock for waste management purposes. Wood chips, wood pellets, tree bark, crop residues, switch grass, tree cuttings, distillers grain, bagasse, press cakes from oil and juice industry, chicken litter, dairy manure, sewage sludge, paper sludge, municipal organic waste and anaerobic digestates are some of the examples of feedstock which have been used so far. In this article Biochar feedstock has been grouped into three categories, viz. agricultural residues, food processing industry residues and other potential feedstock. Agricultural residues are the one which are by-products of crop production and generated within farm, whereas food processing industry residues are considered as by-products of processing industry and normally produced outside the farm gate.

Agricultural residues

Globally, agriculture has a unique and important place in the economies of most countries, especially India, which has an agriculture-based economy. The country is a major producer of diverse agriculture-based goods, accounting for first in milk, second in fruits and vegetables and third positions in grains production worldwide[5]. Along with this mammoth production of farm products, a large amount of residual biomass is also generated. Countries such as USA and Germany have estimated the total sustainable organic matter which can be harvested from forest and agriculture to be 1.18 and 0.24 billion dry tonnes every year[6]. In developed countries the usage of this biomass may be more efficient than developing countries, where a major portion of this biomass is usually burned on farm or dumped in landfill sites due to lack of investment in waste management technology and bad government policies[5]. Total biomass produced from major crops in India divided into production of crop and residues is displayed in Figure 2. The graph demonstrates that more than 50% of biomass associated with agriculture is residual in nature. The nature/type of these residues produced along with 1 kg of crop production is shown in Figure 3.

Food processing industry residues

Food processing which is a part of manufacturing sector generates residues and by-products which are generally unavoidable (for example, pomace, press cakes, pineapple skin, egg shells, bones, carcasses, etc.). Developed countries like USA and UK generate residues up to 30–40% of the raw materials, treatment and management of which costs billions of dollars[7]. Food waste comprising raw and cooked food constitutes 20–50% of total waste generated in Asian countries like Malaysia, Thailand, etc.[8]. Considering the individual fruit and vegetable processing sectors globally, depending on the processing method, a significant amount of solid waste is generated. Worldwide the amount of residue produced as percentage of raw material in some of the main industries is as follows: apple 25–35%, citrus 50–60%, grapes up to 20%, banana 30–40%, pineapple 40–80% and potato 15–40% (ref. 9). Some of the largest agricultural produce marketing committees (APMCs) in India, including Azadpur, North Delhi, were studied for generation and utilization of waste by the National Institute of Agricultural Marketing (NIMA, Jaipur). Large volumes of residual fruits and vegetables in these marketing committees were found to be unutilized and discarded as garbage in the landfill[10]. Thus as far as biomass availability is concerned, large volumes are available, which could be employed for biochar production to exploit its pronounced potential.

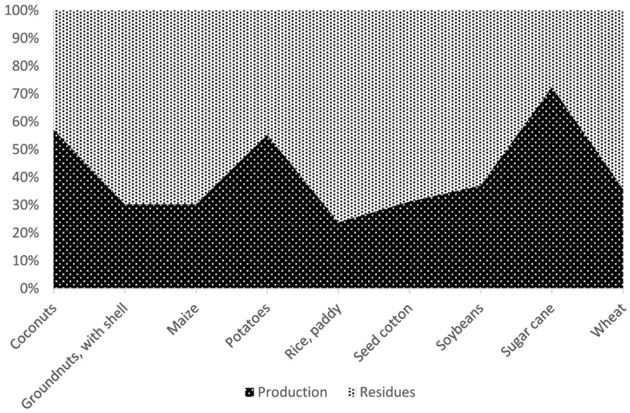

Figure 2. Percentage of total production of some major crops in India and corresponding residual biomass produced (data from IISc, Bangalore, *Biomass Resource Atlas of India*, 2002–2004 and FAOstat).

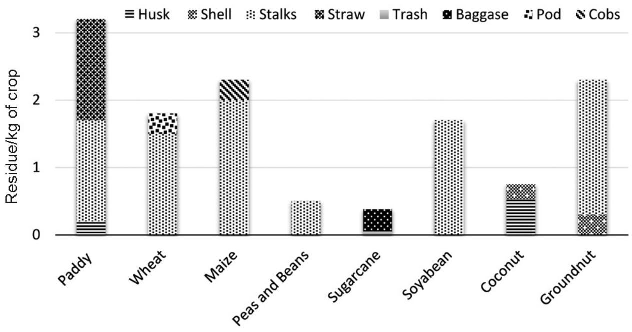

Figure 3. Nature and amount of residual biomass available from some of the main crops of India (per kg). (Source: IISc, Bangalore, *Biomass Resource Atlas of India*, 2002–2004.)

Other potential feedstock

With the increase in pollution and sanitary installations, the amount of human waste (excrements and faecal waste), organic municipal waste and sewage sludge in continuously rising and poses a challenge for handling and treatment. According to an estimate, the European Union alone produces more than 10 million tonnes of dry weight sewage sludge per annum[6]. A holistic approach of ecological sanitation can be applied by converting these wastes into a more stable form of carbon, i.e. biochar. Macroalgae having a rapid growth rate and ability to assimilate nutrients such as nitrogen and phosphorus can serve as biochar feedstock. Many species of freshwater and salt water green algae were studied by Bird *et al.*[11,12], who found potential for biochar production and application from algae. Last but not the least native, fast-growing varieties of trees and shrubs present a potential for biochar; the concept is to produce rapidly growing broadleaf trees and carry out pyrolysis to produce biochar and energy[13]. Tree varieties which are known for rapid growth such as poplar and willow can be utilized for biochar production on large scales.

Biochar production techniques

Utilizing residual biomass from agriculture and agro-processing industry to produce biochar is economically a more viable solution to manage waste from these sectors, which is otherwise being used inefficiently. A list of feedstock and production methods from the recent scientific works is presented in Table 1. It is evident that most favoured feedstock for the production of biochar would be woody and dry biomass, such as nutshells, straw and husk of various farm crops. Pyrolysis is the technique used for the production of high carbon content products like biochar. If this process of thermochemical decomposition is done in subcritical aqueous solution it is termed as hydrothermal carbonization (HTC). In this article dry and wet pyrolysis terms are used to refer to normal pyrolysis and HTC respectively.

Dry pyrolysis

Thermochemical decomposition of organic matter in the absence of oxygen at high temperature is termed as pyrolysis. The main process-related parameters are peak temperature, pressure, heating rate, residence time, heat transfer rates and vapour–solid interaction[6]. Particle size and shape, physical properties, composition (lignin, cellulose, hemicellulose, etc.) and ash content are the most important feedstock properties which influence the properties of the final product[14,15]. Characteristics of biochar which comprises elemental content, structural properties and morphology are greatly influenced by temperature variations, and properties are comparable when similar temperatures are used for thermal degradation. It was found in many studies that biochar produced at higher temperatures had higher surface areas and pore volume[16,17]. Chemical properties such as pH, electrical conductivity (EC) and concentration of unstable and dissolved organic carbon were also modified with temperature variation[14].

Wet pyrolysis

HTC is a thermo-chemical process where organic matter is converted into carbon-rich products called hydrochar under high pressure settings. Distinctive conditions for HTC are high temperature varying from 180°C to 250°C, pressure ranging from 2 to 10 MPa and presence of water as reaction medium[18].

HTC was invented by Friedrich Bergius (1913) and thereafter the technique was refined by Antonietti[19]. Aqueous solution under pressure is the main factor for hydrothermal conversion, which helps in the degradation and carbonization of cellulose, hemicellulose and lignin at relatively low temperature in comparison to other methods such as dry pyrolysis[13]. Chemical processes such as hydrolysis, dehydration, decarboxylation, aromatization and polymerization break down the hydrocarbons into smaller fractions and then rebind them into a final product similar to lignite[13,19]. A range of transitional products are produced during the degradation of cellulose and hemicellulose in this process; some of the chemicals which can be found in the process are acetic acid, glucose, fructose, 5-hydroxymethylfurfural, formic acid, levulinic acid and other organic acids[19,20]. These intermediate products can be valuable for certain industrial applications and processes.

HTC avoids energy-intensive drying processes for wet biomass and offers recovery rates of up to 90% generating minimal amounts of co-products[21]. Maximum yields of hydrochar are obtained up to temperature of 220°C and pressure of 2 MPa. Further increase in temperature (up to 400°C) results in more liquid fraction known as hydrothermal liquidification; at very high temperatures super critical state of water can be reached, where hydrothermal gasification occurs with minimal amount of solid fractions[6]. Temperature and mean residence time were found to be the most important parameters affecting hydrochar properties and recovery rates. It is clear that the process condition has higher effect on characteristics of hydrochar than feedstock differences[21]. Liu and Balasubramanian[22] observed a sharp decline from 90% to 28% in hydrochar yields for temperature ranging from 150°C to 375°C. Anaerobically digested maize silage was converted into hydrochar at 190°C, 230°C and 270°C, where again temperature was the most important parameter in governing the physical and chemical properties; highest surface area was detected at 190°C (ref. 18). However, there are some

Table 1. Feedstock from different farm and agro-processing industries and the corresponding biochar production method

Industry	Feedstock	Production method	Reference
Grains and cereals	Kentucky bluegrass seed screenings[a], Corn cobs and stover[b], Wheat straw[c], Soya bean stover[d], anaerobically digested maize silage[e]	Gasification[a], pyrolysis[b–d], hydrothermal carbonization[e]	(58)[a], (59)[b], (60)[c], (17)[d], (18)[e]
Fruit, kernels and oilseeds	Walnut shell[a], peanut hull[b], rapeseed cake[c], palm oil press waste[d]	Pyrolysis[a–c], hydrothermal carbonization[d]	(61)[a], (17)[b], (62)[c], (63)[d]
Fruit and vegetables	Tamarind seed[a], cassava waste[b], orange peel[c]	Pyrolysis[a–c]	(64)[a], (65)[b], (50)[c]
Sugarcane and jaggery	Baggase[a], anaerobically digested baggase[b]	Pyrolysis[a,b]	(59, 32)[a], (66, 27)[b]
Livestock	Dairy manure[a], swine solids[b], turkey litter[c]	Pyrolysis[a–c]	(67)[a–c]

fundamental differences in the properties of hydrochar like lower carbon content, reduced aromaticity and lower recalcitrant properties in comparison to biochar[6]. High moisture feedstock such as wet manure, municipal organic waste, faecal sludge, sewage sludge and aquaculture residues and algae, can be subjected to hydrothermal degradation directly without major pretreatment. Another advantage of this process is that it is known to reduce the harmful characteristics of feedstock by terminating microorganisms and degrading organic pollutants[23]. Cellular structures of organic matter are completely degraded and hydrochar can be easily separated from the process water, which enables the specific energy for sewage sludge to increase four times[19]. In a study by Roman *et al.*[20], the heating values were enhanced by 1.75 and 1.5 times for sunflower stem and walnut shell respectively. Therefore, hydrochar provides a product which has energy-producing capacities similar to lignite[24]. Various studies have been carried out where hydrochar was found useful as soil amendments, for energy production, for soil remediation and also development of nanoparticles[25,26]. There have been reports about biochar produced from anaerobically digested feedstock having better surface area and soil remediation properties[27,28]. Utilizing anaerobic digestates for producing hydrochar would not only help in using the waste twice, but also provide a final product with better qualities.

Applications of biochar

Ample literature is available to prove the potential of biochar in achieving environmental and agronomical benefits. These constitute climate change mitigation, enhanced crop productivity, contaminant remediation and increased soil microbial biomass.

Climate change mitigation

Carbon sequestration and reduction of GHGs are the two major aspects of climate change mitigation where the role of biochar has been examined.

Carbon sequestration: Many studies on the chemical properties of biochar have shown that it has a potential for long-term carbon sequestration because of its recalcitrant nature. The incubation studies on a mixture of biochar and soils have revealed that the average soil residence time for biochar can be up to thousands of years[29,30]. Henceforth, recalcitrant nature of biochar makes organic matter unavailable for microorganisms and other decomposers as substrate, which subsequently helps in long-term storage of carbon in soils. Matovic[31] studied the feasibility of the entire biochar process on a global and Canadian scale and concluded that enough biomass and land are available to obtain significant levels of carbon sequestration. A life cycle assessment for CO_2 sequestration potential of sugarcane bagasse was conducted at Miyako Island, Japan, and it was found that 50–70% of the bagasse carbon can be stabilized as biochar[32]. It was realized that if all the available bagasse in Miyako Island, Japan (12,000 tonnes/year) is utilized for biochar production, a total of 1200–1800 tCO_2 can be sequestrated yearly, considering the life cycle of biochar, including processes like transportation, pyrolysis and farmland application.

GHG emissions: Biochar has been found beneficial in increasing soil organic matter and reducing the emission of highly potent GHGs such as CH_4 and N_2O (refs 33, 34). Reduction of up to 50% in N_2O emission was recorded from animal urine-added Templeton silt loam soil with biochar application rate of 30 tonnes/ha in New Zealand[35]. Earlier, Zhang *et al.*[36] found similar results of 40–51% reduction of N_2O with N fertilization and 21–28% without N fertilization in paddy soils from China. In a two-year consecutive study of paddy cultivation cycle in China, apart from positive effects on soil properties after biochar amendment, N_2O emissions from paddy fields reduced significantly in both crop cycles, whereas CO_2 remained unchanged and CH_4 was reduced in the second cycle only[36]. In one of the studies it was found that reduced CH_4 emissions from paddy fields were not due to the deficiency of methanogenic archaea (microbes which are responsible for CH_4 production), but because of overabundance of methanotrophic proteobacteria (these microbes are responsible for oxidation of methane)[37]. All these positive results reflect that enough evidences are available to suggest that biochar has the unique ability to reduce the emission of GHGs and in turn mitigate climate change.

Table 2. Effect of biochar addition on soil, plant and environmental systems, corresponding biochar property and possible mechanisms

Property	Effect	Biochar property	Mechanism	Reference
Soil				
Organic matter	Increased	High C content	Increased carbon concentration	68
Water-holding capacity	Increased	Porous structure	Increased macroporosity and hydrophilicity; enhanced water adsorption rate	69, 70
Porosity	Increased	Porous structure	Dilution effect and formation of macro aggregates	69, 38
pH	Increased	Alkaline nature	High ash content	38, 68
Cation exchange capacity (CEC)	Increased	Specific surface area	High specific surface area of biochar; increased carboxylic group	38
Plant				
Crop yield	Increased	Soil organic matter, pH, bulk density, CEC, high porosity	Due to the positive effect of soil quality; chemical, physical and microbial; nutrient availability, mulching effect of BC	68
Plant productivity	Increased	Colour, P and K cycling	Black colour of BC influences thermal dynamics and facilitates fast germination	71
Environment				
CH_4 emissions	Decreased	Porous structure, pH	Abundance of methanotrophic proteobacterial, methenogenic bacteria reduced at too high or too low pH	37
N_2O emissions	Decreased	Recalcitrant, porous structure	Enhanced aeration and stable carbon, increased microbial activity and immobilization of N	68, 33
Carbon sequestration	Increased	Recalcitrant or stable C; black carbon (BC) resists decomposition	Long-term storage of stable carbon in soils	32, 31
Nutrient leaching	Decreased	Porous structure, surface area and negative surface charge	Enhanced CEC facilitates retention of nutrients	71

Agronomic benefits

Several studies have been made on various soil, plant and environmental benefits of biochar addition to soil. Many of these effects are shown in Table 2, with possible mechanisms and the biochar property behind these effects.

Soil improvement: The major physio-chemical properties which were modified after biochar addition to the soils are bulk density (BD), porosity, surface area, electrical conductivity, pH/liming, surface chemistry, etc. (Table 2). These properties play an important role in determining the soil organic matter, moisture availability, fertilizer use efficiency, nutrient uptake and leaching. Significant changes have been observed in physical and chemical properties of highly weather soils of humid Asia, where pH levels increased from 3.9 to 5.1, cation exchange capacity (CEC) from 7.41 to 10.8 cmol/kg, base cation percentage from 6.4 to 26 and BD was reduced from 1.4 to 1.1 mg/m^3 (ref. 38). A comprehensive study of specifically targeting a wide range of climates and soil types in China[39], reported that key indicators of soil quality such as soil organic carbon (SOC), pH, total nitrogen (TN) and agronomic N-use efficiency (AE$_n$) increased by 33%, 6%, 10% and 43% respectively. A reduction in soil erosion potential has also been reported due to formation of macro aggregates in the biochar amended soils[38]. On account of the ability of biochar to retain water and nutrient, a positive effect on treating aridity of sandy soils in USA and Italy and enhanced productivity of tomato seedling in these soils was recorded[40].

Crop productivity: Various studies showing positive effects of biochar on crop yield and plant productivity have been compiled in Table 2. Enhanced nitrogen uptake efficiency due to biochar amendment in Chinese paddy fields was reported by Huang *et al.*[39], which had a progressive effect on the yields of rice. A three times increase in biomass production of rapeseed crop with an addition of 10% biochar mass fraction in a heavy metal contaminated soils was reported by Houben *et al.*[41]. In a low C and low inherent fertility soil in the coastal plains of the southeastern United States, Gaskin *et al.*[42] observed that peanut hull biochar increased the concentration of nutrients (N, P, K, Mg and Ca) and pH. In the same study, the changes in corn tissue nutrient (N, P, S and Mg) status with the application were analysed, which showed little response, whereas yield of corn has significantly responded to biochar application during the course of the two-year study. Yield of cherry tomatoes during a pot experiment was 64% higher than control pots, along with significant changes in nutrient uptake (P and K) and chemical properties of soil[43]. The importance of biochar presence in the root zone of crop was identified by Jones *et al.*[44]. It was observed in the study that deep rooting (>1 m) was responsible for insignificant productivity

Table 3. Effects of biochar on various organic and inorganic contaminants concentrations in soil and water

Pollutant	Study	Tests	Results	Reference
As, Cd, Zn	Soil sediments	Column leaching test and scanning electron micro analysis	300 times reduction in Cd and 45 times in Zn; as leachate concentration did not decline	46
Cd, Zn, Pb	Bioavailability in rapeseed crop	ICP–AES; bio-concentration factor = Concentration of plant tissue/Concentration of soil	Adding 10% biochar led to a reduction of 71%, 87% and 92% for Cd, Zn and Pb respectively	41
Pb, Cu, Ni, Cd	Removal from aqueous solutions	ICP–AES	Significant amount of sorption took place ranging from 57% to 97%	27
Polycyclic aromatic hydrocarbons (PAHs)	Total and bioavailable	GC-MS analysis	Up to 40–50% reduction in PAH concentrations, reduced both concentrations	45, 48
Hydrophobic organic compounds (HOC) (naphthalene and p-nitrotoluene) and phosphate	In aqueous solution	UV-spectrophotometer, HPLC with UV detector, ICS	Sorption potential by biochars for HOC and phosphate	50
Trichloroethylene	Levels in groundwater	Batch adsorption tests, HPLC with UV–Vis detector	Biochar produced at higher temperature was more effective in TCE adsorption from water	17
Pentachlorophenol	Soil sediments and seed germination ecotoxicity	HPLC with UV detector; seed germination assay	Levels in extractable liquid decreased to 0.17 from 4.53 mg/l; enhanced seed germination in the presence of 2% biochar	72
Pb and atrazine	Sorption on biochar surface; levels in soils	AAS for Pb HPLC for atrazine	Significant sorption of Pb and atrazine on biochar surfaces; effective immobilization obtained with biochar	73, 74
Chlorantraniliprole	In earthworms and soil	LC-MS/MS	Bioavailability of pesticide reduced significantly	49
Simazine	Sorption on biochar surface	C^{14}-labelled spatial imaging	Significant sorption potential, with 100 t/ha biochar ~ 97%; simazine was sorbed in 24 h	44
Glyphosate	Levels in water leachates	LC-MS	Leaching of herbicide glyphosate reduced with the addition of biochar	75
Phosphate	In aqueous solutions	Ascorbic acid method with spectrophotometer	Elimination rates of up to 73% were achieved with digested sugar beet tailing biochar	28

response in maize crop in contrast to pasture grass crop with shallow rooting (<30 cm) zones.

Contaminated soil remediation

Eco-toxicological significance of pollutants in soil systems is normally gauged by their bioavailability and water solubility, rather than total concentration in soils. Encouraging results concerning retention of both organic and inorganic pollutants on biochar surfaces have been found in many studies and are summarized in Table 3. There are many sites available globally which had been exposed to heavy industrialization during previous centuries and are abandoned due to contamination risks. Kidsgrove, Stafforshire, UK is one of such site, chosen by Beesley *et al.*[45] for a 60-day study for inorganic and organic contaminant remediation on biochar surfaces. A significant reduction in total and bioavailable Cd, Zn and polycyclic aromatic hydrocarbon (PAH) concentrations in the pore waters was reported after addition of biochar derived from hardwood[45]. In another study, Beesley and Marmiroli[46] recorded the sorption of water-soluble inorganic pollutants (As, Cd, Zn) on biochar surfaces and claimed a significant reduction in their leachate concentrations. Copper toxicity was significantly reduced in quinoa plants (*Chenopodium quinoa*) in a sandy soil, as 50 mg/g Cu in soil showed major stress symptoms on plants which died at 200 mg/g Cu. With the application of 4% biochar with maximum amount of Cu concentration, quinoa plants showed the same biomass as in control samples[7]. Buss *et al.*[47] also reported the reduced concentration of Cu in roots, shoots and leaves of these plants. Bioaccumulation of PAH significantly reduced in the earthworm tissue (*Eisemia fetida*) which was incubated in biochar amended soils for 28 and 56 days[48], to prevent these toxins from entering into food chains. In another study on the bioavailability of pesticide (chlorantraniliprole) in earthworms, with concentrations of 10 mg/kg of soil, the penetration in earthworm tissues was 9.65 mg/kg in control samples, which was reduced to

Table 4. Results from recent studies showing no positive effects of biochar application on soil, plant and environmental systems

Type of biochar	Properties studied	Results/effects	Reference
Wood-derived	pH, organic carbon (OC), microbial biomass (MB)	pH, OC and MB were enhanced in three months, but after 14 months no significant changes were observed in OC and MB	76
Rice husk	Biochar dynamics	Established that rice husk biochar was mobile in poor sandy soils, moved below 0.3 m in 4 years	77
Wood-derived	Colonization of biochar pores by microorganisms for 3 years	Found no heavy colonization	78
Wheat straw	Effect on CH_4 and N_2O emissions from paddy fields	CH_4 emissions increased	36
By-product of birch charcoal	Emissions of CO_2, N_2O and CH_4 from wheat cultivation	No significant reduction in N_2O and CO_2	34
Wood-derived	Concentration of trace elements As and Cu	Increased 30 times after the addition of biochar	45
Hard wood-derived	Biodegradability of simazine	Reduced biodegradability	44

Table 5. Practical limitations in large-scale long-term application of biochar in agricultural and environmental management

Limitations	Reason	Risks	Reference
Permanency	Once applied cannot be removed from the soil	Loss of native organic matter; introduction of xenobiotics such as PAHs and dioxins	79
Availability	Enough biochar may not be available to obtain significant positive results	Use of virgin biomass for biochar production which would prove uneconomical	80
Wind erosion	While applying dry biochar on fields	Human inhalation of fine biochar particles	44
Diversity	Every biochar and each soil is different	Wrong combination can induce negative effects	44
Legal issues	Response of local communities	Opposition of large-scale application and production of biochar	81

0.59 mg/kg with the application of biochar produced at 850°C (ref. 49). A novel magnetic biochar was proposed by Chen *et al.*[50], where magnetic component was added during the production of biochar from fruit waste (orange peel). This was found to be efficient in removing hydrophobic organic compounds (naphthalene and p-nitrotoluene) and phosphate from wastewater.

Many theories and assumptions have been made regarding the mechanism of biochar interface with pollutants. Electrostatic interaction and precipitation in the case of heavy metals, whereas surface adsorption, partition and sequestration in case of organic contaminants were the possible mechanisms behind the remediation potential of biochar[51]. All the traditionally available treatment technologies such as precipitation, ion exchange, electrocoagulation, membrane filtration and packed bed filtration attract higher operational cost in comparison to biochar production and application[27].

Effects of biochar application on soil microorganisms

Terra preta soils in Amazonia are rich in biochar-like substance and possess a typical soil biota which could be one of the reasons for their high fertility[52]. These soils have been found to have an increased microbial biomass and diversity in comparison of neighbouring infertile soils. In many studies it was hypothesized that fungi and bacterial growth may enhance after biochar application as these microorganisms invent pore habitats in biochar, which could be protection against competetors or predators[1,53]. Along with safe habitats, biochar can also sometimes provide substrate to these microorganisms[54]. Large fungal colonies were observed on the roots of plant in biochar amended soils in contrast to control pots[55]. In a study in Dhanbad, India[56], biochar produced from a water hyacinth (*Eichornia crasipes*) significantly increased soil biological activity (three times in active biomass) and soil respiration by 1.9 times. An interesting observation was made by Elad *et al.*[57], who proposed disease and pest management in crops with biochar application. In this study on tomato and pepper, significant reduction of two foliar fungal pathogens and a pest was observed with biochar application rates of 3–5%. The fungal pathogens were grey mold (*Botrytis cinerea*) and powdery mildew (*Leveillula taurica*), whereas the pest which was studied was broad mite (*Polyphagotarsonemus latus* Banks).

Apprehensions and limitations related to biochar application

In many studies variable results showing insignificant or sometimes negative effects of biochar production were found which give rise to some apprehensions regarding its large-scale long-terms application. Results from some of the recent studies with no positive effects on large-scale biochar application are summarized in Table 4. Major hurdles in the commercial application of biochar on large scale for soil and environmental management are listed in Table 5. Unless there are clear answers and mechanisms which can prove that we can overcome these limitations the future of biochar may be uncertain.

Knowledge gaps

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

1. Cost of biochar production, feedstock availability and economics of supply and demand of biochar is full of uncertainties.
2. Lack of long-term studies limits the understanding of biochar interaction in a real world scenario where various natural dimensions are active.
3. Multiple assumptions have been made to explain the mechanisms behind various soil and environmental effects of biochar application.
4. No standard application rate of biochar for specific soils and crop combination to get maximum positive results is available.
5. Effect of ageing process on biochar properties has not been studied in detail; for example, adsorption capacities of biochar changes with time.
6. Limited knowledge is available on biochar-induced toxicity on soil organisms and plants.

Conclusion

It is evident that feedstock and production technologies are available for large-scale manufacturing of biochar. However, in spite of positive results of biochar on soil and environment, sufficient scientific and socio-economic apprehensions exists as far as large-scale and long-term application of biochar is concerned. Future of biochar depends on the critical assessment and mitigation of its long-term risks and challenges. Immediate steps are required to comprehend and fill existing gaps in the knowledge as far as commercialized production and large-scale application of biochar are concerned.

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