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Biochar Production and Application in Forest Soils-A Critical Review

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Abstract: The increasing deforestation with an alarming rate is the prime cause of upsetting the balance in the natural ecosystem and the livelihood of local communities. Sustainable forest management and reforestation efforts can equilibrium this destruction and maintain the protected areas. In this regard, soil management strategies for reforestation of the degraded forest land can be helpful. In this review, the potential of using biochar, a solid carbon rich product of biomass thermochemical conversion, as a soil amendment in forest soils has been discussed. The production procedures of biochar, availability of feedstocks and the biochar properties are discussed using the existing knowledge. The positive effects of biochar are soil quality depended and change with varying geographical locations. Therefore, long-term field trials examining a range of biochars, soils, and forest types are required for a better understanding of this issue. Careful planning to match biochar with the soil properties is essential to obtain maximum benefits of biochar as a soil amendment.

Keywords: Sustainable forest management; reforestation; biochar; soil amendment; degraded forest

1 Introduction

Forest ecosystems consist of a complex web of organisms and play an important role in regulating the global climate. About 80% of the world's terrestrial biodiversity is present in forests and the livelihoods of 1.6 billion people depend on this ecosystem. Forests consume CO_2 and thus help to regulate its balance in the environment by retaining a huge volume of atmospheric carbon. Tropical forests can hold more than 210 Gt of carbon [1]. However, the rate of deforestation is increasing during recent years which disrupts the balance in the natural ecosystem. The conversion of forest land to agriculture and livestock areas due to increasing population, not only affects the livelihoods of forest communities, but also the global climatic condition on a much broader scale. Increasing and improving agricultural production without reducing and harming forest area is therefore one of the greatest challenges in recent times.

The net annual rate of forest loss is 0.08% during 2010-2015. In the year 2015, forests made up 30.6% of the world's land areas [2]. Deforestation leads to higher CO_2 contents in the atmosphere contributing to an increase in the global temperature. The average global temperature on earth has increased by about 0.8ºC since 1880 [3]. In the year 2017, the global mean temperature was 1.1 ± 0.1ºC above pre-industrial level [4]. Forests acting as a natural brake sequester and store more carbon than any other terrestrial ecosystem. Carbon sequestration by forests has attracted a huge interest as a mitigation approach. Both afforestation and reforestation, therefore, have been considered an inexpensive way of addressing climate change. Sustainable forest management and reforestation efforts along with food security can balance this destruction and maintain the integrity of protected areas.

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Biochar is a stable form of a carbon-rich compound which is produced by the thermal decomposition of organic material under a limited supply of oxygen (also known as pyrolysis), and at low temperatures typically between 300°C and 700°C [5]. An important defining feature of biochar is the presence of fused aromatic ring structure which is characterized by rings of six carbon atoms linked together. The range of carbon form in biochar depends on various factors including the charring conditions and the process of formation [6]. The chemical composition of the biomass feedstock has a direct impact upon the physical nature of the biochar. Biochar has the capacity to increase soil carbon sequestration leading to improved soil health. Use of biochar as a soil amendment dates back to several thousand years in the Amazon region, known as *terra preta* [6]. According to Lehmann et al. [7] biochar is emerging in conjunction with soil management and carbon sequestration issues. The physiochemical properties of biochar have the potential to increase soil water-holding capacity (WHC), cation exchange capacity (CEC), surface sorption and base saturation when added to soil, leading to improved crop yield [8]. The interaction between biochar, soil, microbes, and plant roots are known to occur after application to the soil and also varies from soil to soil [5]. Types and rates of these complex interactions depend on various factors: (*i*) composition of feedstock materials (*ii*) pyrolysis conditions; (*iii*) physio-chemical properties of biochar and (*iv*) soil characteristics and local environmental conditions [9,10-12].

Research on the application of biochar in forests is limited though much work has been done under field and controlled conditions [13,14]. In this review, the feedstock availability, production procedure, biochar properties, and its potential for restoration of the degraded forest ecosystems is discussed.

2 Feedstocks for Biochar Production

Biochar can be produced from a diverse range of feedstocks like forestry wastes and agricultural residues, animal wastes or municipal wastes etc. Biochar feedstock can be categorized into primarily produced biomass and waste biomass (Fig. 1). Different types of perennial grasses, crop residues, wood chips, bagasse, algae etc., are included in the first category [15]. For instance, Konwer et al. [16] reported the conversion of a problematic aquatic weed (*Ipomoea carnea*) to charcoal by pyrolysis. The second category consists of waste biomass produced from various sources like agriculture, forestry, food processing, municipal and household etc. Poultry wastes such as chicken litter, domestic and industrial waste such as sewage sludges and paper mill sludge are also used to produce biochar [16-18]. Organic components present in the feedstock undergo a series of decomposition reactions during the conversion process. High lignin content of the feedstock is responsible for higher yield of biochar [19,20]. At relatively low temperature ~120°C, moisture content within the feedstock is lost. Hemicelluloses degrade at the temperature between 220°C and 315°C; cellulose at 315-400°C; whereas the decomposition of lignin takes place at a wider range of temperature (160-900°C) leading to a higher char yield in a more efficient way [21].

Biochar produced from the waste biomass and weeds helps in achieving twin goal of both carbon sequestration and sustainable waste management without any harmful effect on the environment. Waste generated from different sectors can be collected and used to produce energy and biochar. Switching of residual biomass from land spreading or landfills into biochar would reduce the emission of greenhouse gases (GHGs) related to decomposition.

Biochar yield and its physiochemical properties are influenced by both the feedstock material and the pyrolysis conditions [22]. The carbon content in biochar is more influenced by the type of feedstock rather than the pyrolysis temperature [7]. Biochar produced from different feedstock type may have different concentrations of nutrients. Biochar derived from animal manure can be used as a nutrient source in agricultural systems [23]. Litter biochar has a high concentration of macronutrients due to its high calcium contents [24]. Poultry litter exhibited the highest concentration of nutrients [25]. Sugarcane straw biochars had an intermediate concentration of macronutrient but had high concentration of micronutrients [26]. Rice hull and sawdust biochars also showed a very low concentration of macronutrients and little to no variability in the concentration of the elements with increase in pyrolysis temperature [26]. Scanning electron microscope (SEM) studies indicated the presence of pore alignments or tube-like structures representing a skeletal outline of respective feedstock material in biochar [27]. The feedstock material also influences the yielding capacity of biochar. Both labile and recalcitrant oxygen and hydrogen found in feedstock material affects the biochar yield [28]. For instance, the corn cob converted more than 50% of its mass to biochar [29]. Moreover, the particle size and moisture content of the feedstock material need to be optimized to receive maximum biochar production efficiency [30].

It is essential to study all the aspects of feedstocks prior to any biochar operation. The availability of feedstocks varies with time. The selection of feedstock significantly depends on its availability along with collection, transportation and storage cost. In today's time, the use of biomass energy is a widely accepted strategy towards sustainable development. Biomass is the primary source of energy for nearly 50% of the world's population [31]. The number of countries using biomass as their source of energy is increasing in recent years along with making biomass a much promising option. In developing countries where biomass feedstocks often used for energy purposes, sustainable production of biochar can be a significant subsidy (Fig. 1).

In conclusion, the potential of biochar as a soil amendment depends on the types of biomass used and pyrolysis conditions at which biochar are produced [32]. However, the feedstock property is the major determinant of biochar yield.

3 Techniques for Biochar Production

Thermal decomposition using pyrolysis or gasification produces gas or oil along with the biochar. This energy may be used for other activities, which is relatively inexpensive, easily applicable and quickly scalable or release as heat. Biochar can be produced by dry carbonization, pyrolysis or gasification of biomass, and hydrothermal carbonization (HTC) of biomass under pressure [33]. Different parameters like temperature, heating rate, biomass and vapor residence time distinguish one technique from the other. These technologies involve the heating of biomass material with little or no oxygen environment which drive off the volatile gasses and leave the carbon behind. One of the advantages of these processes is the reduction of the harmful feedstock properties by terminating microorganisms and degrading organic pollutants [34]. Summary of biomass conversion through thermal decomposition is given in Fig. 1.

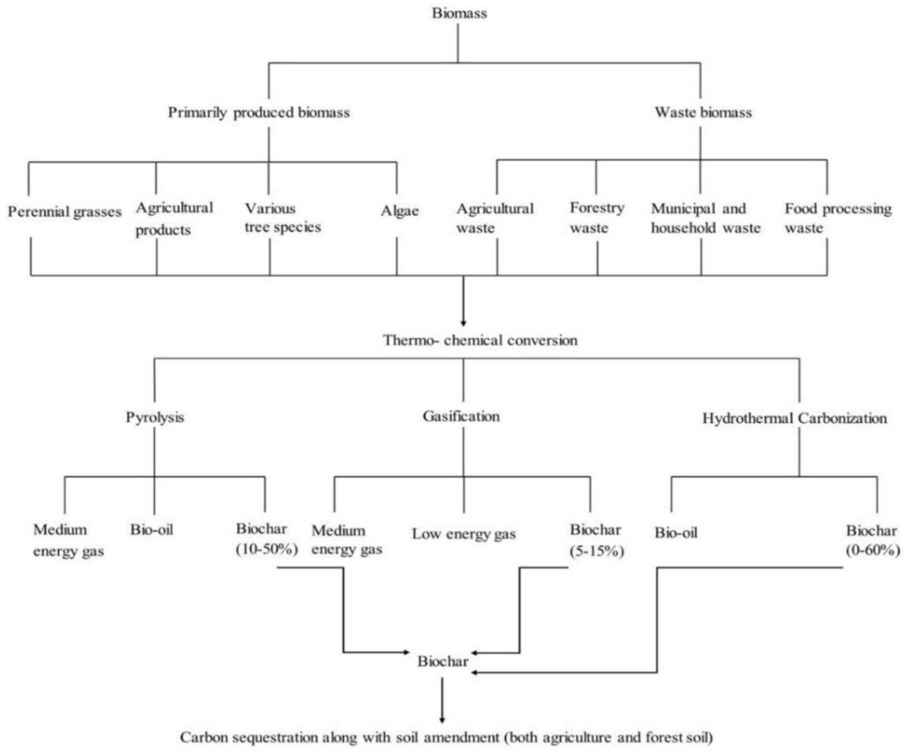

Figure 1: Process of biochar production

3.1 Pyrolysis

It is the most widely used technique to produce high carbon content products like biochar. During pyrolysis, the thermo-chemical decomposition of organic matter takes place at high-temperature in an oxygen-free environment. Depending on the heating rate and residence time, pyrolysis can be slow pyrolysis or fast pyrolysis. Fast pyrolysis favors higher yield of bio-oil while in case of slow pyrolysis, a high amount of biochar is generated [33]. Slow pyrolysis is the conventional carbonization method used in char production purposes for centuries. In slow pyrolysis, the typical heating rate varies between 1 and 30 °C min^{-1} [35] whereas fast pyrolysis achieves high heating rate (in the order of several hundred °C sec^{-1}) [36]. Higher yield is generated from biochar produced at low operating temperatures and low heating rates [37]. Biochar yield commonly decreases with increasing temperature but the carbon concentration in the produced biochar increases at the same time [38]. Biochar produced at high-temperature has larger surface area and porosity which help to improve soil water retention and sorption capacity upon addition into the soil [8,39,40]. However, with the increase in pyrolysis temperature, biochar density, extractable PO_4^-, and NH_4^+ are decreased [41].

3.2 Gasification

In gasification, biomass is exposed to a relatively high temperature along with an oxidative environment and therefore, partially combusted. Gasification is the thermo-chemical conversion of biomass at high temperatures under a controlled amount of oxidizing agent that converts biomass into a gaseous mixture consisting of carbon monoxide, hydrogen, carbon dioxide and traces of methane. Biochar is a co-product of the gasification process. About 10% (by weight) of biomass is converted to biochar through gasification [42,43]. In this case, biochars exhibit a higher degree of carbonization as indicated by its low H/C ratio than the biochars produced at lower pyrolysis temperatures [44].

3.3 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is a thermo-chemical process in which organic matter is converted into carbon-rich products under a high-pressure environment. In case of HTC, damp biomass is preferred as the reaction takes place in an aqueous condition. About 30 to 60% char yield is reported during HTC reaction [45]. Processing temperature for HTC varies from 180°C to 250°C and pressure ranges from 2-10 MPa [46]. Higher pressure is required to prevent the boiling of water when the reaction temperature increases. Temperature and mean residence time are the most important parameters which affect the hydrochar properties for its further use as an amendment. Like the biochar, the yield of hydrochar is decreased with increase in temperature. The biomass thermochemical conversion technologies and product distribution are given in Tab. 1. In crux, various processing parameters that distinguish one technique from the other, also affect the yield and properties of produced biochar.

Table 1: Biomass thermochemical conversion technologies and product distribution

Thermochemical	Temperature (°C)	Residence time	Heating rate	Defining parameter	Char yield (%)	Reference
Slow pyrolysis	400-600	Min to days	1-30°C min^{-1}	Low-moderate temperature, Long residence time.	20-50	[36,47,48]
Fast pyrolysis	400-600	<2 sec	In the order of several hundred °C sec^{-1}	Moderate temperature, Short residence time, High heating rates.	10-25	[37,49,50]
Gasification	500-1500	5-20 s	-	High temperature, Long vapor residence time.	5-15	[51]
Hydrothermal carbonization	180-250	1-12 h	-	Elevated pressure.	0-60	[45,52]

4 Characteristics of Biochars

4.1 Stability

Due to the occurrence of the condensed aromatic structure, biochar is chemically more stable than other carbon forms. The stability of biochar in nature depends on various factors, including the biomass, production procedure, soil physiochemical properties, and climatic conditions [7]. Along with the aromatic ring structure, a considerable fraction of non-aromatic carbon is formed during the process of conversion which may mineralize more rapidly over a relatively short period of time [53-55]. This portion of biochar becomes susceptible to microbial attack and oxidation [32]. Biochar produced at low temperature has a considerable amount of non-aromatic carbon and is, therefore, more vulnerable to such conditions than the biochar produced at high-temperature [11]. Some biochars may decompose rapidly in soils while others persist for a longer period [56]. For instance, the residence time of the stable portion of biochar has been predicted to be greater than 1000 years [57-59]. The deposits from Amazonia, Guyana and Costa Rica have been reported as up to 6000 years, 9500 years and 23,000 years old charcoals, respectively [60-62].

4.2 Nutrient Retention and Absorption Capacity

Biochar has a higher sorption affinity towards a range of compounds and high nutrient retention ability than the other forms of soil organic matter [63-67] due to its greater surface area [68,53]. Presence of a range of reactive functional groups in biochar surfaces make them highly reactive in soil [69,70] and increases base saturation [8,71,72]. The porous structure of biochar also can increase soil water-holding capacity and cation exchange capacity (CEC) [5,7]. Higher nutrient retention and nutrient availability have been reported upon addition of charcoal to the soil [8]. Freshly produced biochars have lower ability to retain cations, resulting in minimal CEC [6,68] compared to the aged biochar [53]. These results support higher CEC value as observed in Amazonian Anthrosols [68]. Uchimiya et al. [73] observed a higher uptake of heavy metals from the soil when biochar with high oxygen content is added. The high reactivity of the biochar surfaces is partly attributed to the presence of a range of reactive functional groups. Moreover, the availability of nutrients in biochar is related to the association of bonds in their elemental level. The addition of biochar to forest soils has been found to influence nitrogen transformations [41,74-77], phosphorus availability, and also sorption of alkaline and some trace metals [8,9,78]. The capacity of biochar to absorb a wide variety of chemicals makes it an environment-friendly and cost-effective amendment for the remediation of contaminated soil and water.

In soils, the majority of nitrogen present in complex organic forms which needs to be converted to simpler form prior to plant uptake. Application of biochar changes the soil pH, which favors the autotrophic nitrifying bacteria and ultimately influences the nitrogen transformations in soil [79,80]. Biochar may also act as a habitat for soil microorganisms involving nitrogen, phosphorus, or sulfur transformations [81]. The high surface area, porous and often hydrophobic nature of biochar makes it an ideal surface for the sorption of hydrophobic organic compounds. A reduction in soluble or free phenolic compounds is found when activated carbon is added to soils [41,75-77,82]. The physical properties of biochar make it an ideal surface for sorption of such organic compounds [83,84] which may otherwise affect and reduce the nutrient transformation by inhibiting microbes like nitrifying bacteria [85,86]. Phosphorus uptake is also found to increase in presence of biochar but very little work has done on the mechanisms that lead to these changes. Some of the mechanisms suggested are i) biochar itself as a source of soluble phosphorus salts ii) changes of pH due to biochar addition helps to increase the microbial activity and phosphorus mineralization.

5 Biochar Application in Forest Ecosystem

Forest soils are usually more shallow and rocky than the agricultural soils and tend to be more variable in their physical and chemical properties compared to agricultural soils. These soils mainly contain undisturbed organic layers and soil horizons [87]. The structure of the forest soil is directly or indirectly dependent on various factors controlling the forest environment. Forest soils contain a high population of both micro and macro-organisms which helps to improve the soil structure [88].

5.1 Climate Change Mitigation

Negative emission strategy includes obtaining energy from biomass and storage of carbon in soil through application of biochar [89]. The global potential of carbon sequestration of biocher lies between 0.3-2 Gt CO2 yr-1 [91]. It is reported that 90 to 135 Pg of carbon lost in soil ecosystem due to conversation of land [91,92]. This soil carbon pool and its dynamics directly influence the global carbon cycle. These changes lead to an urgent need for developing a strategy of net negative emissions. It is reported that biochar has potential for delivering negative emissions and comparing the biophysical, energy and cost impacts, it has advantages over other negative emission technologies [93,94]. During conversion of biomass to biochar, about 50% of the carbon present in biomass is converted and trapped in the new stable form and thereby reduces CO_2 emission from the soil due to decomposition [7]. Improvement in soil fertility due to the addition of biochar also stimulates plant growth which helps in additional CO_2 consumption. Plants consume 120 Gt CO_2-C annually through photosynthesis [95] which is 8 times greater than anthropogenic emissions of GHG [5]. Annually, 4-8 Gt of aboveground biomass is exposed to fire from which 1.3-7.5 Gt is released to the atmosphere and 0.5-1.7 Gt is converted to the charcoal [96]. In a laboratory incubation study, a higher microbial flux was recorded from a forest soil receiving maple wood biochar than the soil which was applied with spruce feedstock biochar [97]. The effect of biochar application on soil CO_2 fluxes in forest ecosystems varies considerably [98]. Studies on the application of biochar on forest soils revealed increasing, decreasing or negligible effects on CO_2 emission. For instance, Mitchell et al. [99] reported that CO_2 emissions increased due to the application of sugar maple biochar in a temperate forest soil. Similar cases were reported by Hawthorne et al. [100] where CO_2 fluxes from a Douglas-fir forest soil treated with 10% biochar significantly increased than the soil treated with 1% biochar. Increased soil carbon mineralization in response to the addition of char was also documented [101]. In some studies, the application of biochar reduced CO_2 emissions up to 31.5% from pine forest soils [102]. Contrary to this, in an incubation experiment; biochar application documented no influence on CO_2 emission from the forest soil [103]. Several other studies also reported similar results indicating no influence of applied biochar in soil CO_2 fluxes from forest soils [104-106].

In case of CH_4, most studies confirmed a reduction in emission or no influence from biochar-amended soils. This may be due to the application of biochar which increases the soil pH and favors the growth of methanotrophs [107]. The increasing soil porosity favors CH_4 oxidation and uptake activity by soil bacteria [108]. Application of chicken manure biochar (10%, w/w) significantly increased CH_4 uptake in forest soils [109]. It is [110] also reported that, regardless of the application rate, biochar treatment reduced the soil CH_4 emission from Chinese chestnut plantation. However, in some studies, no significant effect of biochar application on CH_4 emissions from deciduous, temperate hardwood and subtropic acidic forest soils was noted [103,105,111].

However, Biochar application in forest soils has been reported to reduce N_2O emission significantly [103,102,110]. Application of biochar (30 t ha^{-1}) to a pine forest soil significantly decreased (25.5%) the cumulative N_2O emissions [102]. Similarly, application of corn silage biochar (1% w/w) to deciduous forest, significantly reduced N_2O emissions [103]. Biochar application at 5 t ha^{-1} to a Chinese chestnut forest reduced the annual average flux and annual cumulative total soil N_2O emissions by 27.4 and 20.5% respectively [110]. Yanai et al. [112] also found a reduction in N_2O emission from loam to clay loam soil when municipal biowaste biochar was added. The increased soil aeration due to biochar application reduces the anaerobic micro-sites and consequently may result in decreasing N_2O emissions through a reduction in denitrification rate [112,113]. However, in some studies, no effect of biochar application on N_2O emission was also noted. For example, Sackett et al. [105] reported that the application of 5 t ha^{-1} biochar in a temperate hardwood forest did not alter the soil N_2O emission. The effects of biochar on GHG emission is also biochar, soil, and plant specific. Researchers tested sixteen different biochars on three diverse types of soils (agricultural, forest, and landfill) and reported that changes in GHGs were dependent on both soil and biochar types [114].

5.2 Soil Quality Improvement

Use of biochar as a soil amendment dates back to several thousand years in the Amazon region, known as *terra preta* [8]. Biochar improves soil fertility by improving its physicochemical and microbial properties [115]. The observed effects on soil fertility have been explained mainly by an increase in pH or improved nutrient retention capacity through cation adsorption. Glaser et al. [8] reported that biochar acts as liming agent resulting in increased pH and nutrient availability for some soil types and may be best considered as a substitute for lime and expected to reduce soil acidity for a long period of time. Mbagwu and Piccolo [116] reported an increase of 1.2 unit pH in various soils with the addition of biochar. Application of biochar at a high rate (50-100 t ha^{-1}) increased soil pH from 4 to 4.8 in *Eucalyptus* forestry plantation [117]. Later, Rhoades et al. [118] also noted an increase in pH from 5.7 to 6.4 in lodgepole pine (*Pinus contorta*) forest soil under the joint application of biochar and mulch. Brady and Weil [119] claimed that biochar has a low bulk density; that can reduce the overall total bulk density of the soil after application. A significantly low bulk density was reported in mesic woodlands where plots were treated with green waste biochar at a rate of 20 t ha^{-1} [120]. The author also reported an increase in soil moisture content after application of the biochar. Because of the porous structure, biochar can absorb water which is held in its pore spaces, voids and in the spaces between soil particles [121].

Biochar contains nutrients such as nitrogen, phosphorus, and sodium depending on its feedstock and char making conditions; thus, it can supply nutrients to the soil but in varied amounts. An initial increase of available potassium followed by calcium and magnesium was reported when biochar was applied to hardwood forest soil [97]. The combination of ash and char is very effective in retaining soil nutrients [122]. Yamato et al. [123] reported that application of bark charcoal on soil increased the soil pH, total nitrogen, available P_2O_5, CEC, amounts of exchangeable cations and base saturation, but decreased the exchangeable Al^{3+} in forest soils. The increased base saturation in forest soils is considered a function of ash deposition [71]. Tryon [124] studied the effects of 15, 30, and 45% charcoal by volume on soil properties and observed an increase of phosphoric acid, potash, calcium, and magnesium. Application of rice husk biochar increased plant diameter than the control. The height of the sapling was also affected due to the application of biochar and varied significantly among species [125]. Various factors including inherent differences in the soil, biochar type, and differences in responses among plant species influenced these inconsistencies. An average of 41% increase in biomass was reported from a recent meta-analysis of tree responses to biochar [126]. The biochar can improve the initial seedling growth of tree species. However, the effects were less significant in temperate forests than in tropical or boreal forests [126].

Lima et al. [127] reported that the relation between biochar, soil, microbes, and plant roots are generally biochar and site-specific, that controls its efficiency as a soil amendment. Due to its physio-chemical composition, biochar provides a suitable habitat for microorganisms. Therefore, the population of soil microorganisms increases with the addition of biochar, though this effect of biochar disappears in the long run. Biochar properties like high internal surface and adsorbing capacity make a potential niche for the soil microbes which catalyze the processes that reduce nutrient loss and ultimately help in plant growth [128]. While working on the forest soil of sub-boreal spruce, Robertson et al. [129] noted the highest abundance of some individual morphotypes at 5% biochar when amended with fertilizer. Perotti and Verona [130] reported that addition of both animal and vegetable charcoal to cultures was beneficial for the growth of microorganisms. In their experiment, charcoal at the rate of 0.01 to 1.0% by weight was added to the cultures. A slight increase in microbial weight was found when 0.5 to 0.75% of charcoal was used; but above 0.75%, the microbial weight was reduced. Wildfire-produced charcoal enhances nitrogen mineralization and nitrification in the temperate ecosystem [41,77] by creating a suitable territory for microbes [81,131]. Ogawa [132] reported the growth of fungi from within the pores of biochar out into the soil. These microbes might decompose organic matter adsorbed on the biochar surface and within pores [133]. Soil biological activity and soil respiration increased by 1.9 times with the application of biochar produced from a water hyacinth [134]. Application of rice straw biochar (5%) significantly increased the activity of soil enzymes urease-the key enzyme in the transformation of soil nitrogen [74]. Net nitrification rate is also increased in char amended temperate and boreal forest soils that otherwise demonstrate little or no net nitrification [74,77]. However, there has been little evidence for such an effect in grassland [74] or agricultural soils [135,136], which might be due to the presence of an active nitrifying community in those ecosystems. Gross nitrification rates in char-amended forest soils were nearly four times that in the untreated forest soil, demonstrating the stimulatory effect of char on the nitrifying community rather than reduced immobilization [74]. Changes in properties of the soil ecosystem due to biochar application and the associated possible mechanisms are summarized in Tab. 2. In conclusion, application of biochar, with its unique characteristics, to forest soil alters the soil physicochemical properties, directly or indirectly, that affect the soil microbial abundance, composition and function. The forest soil showed the heterogeneous results of positive, negative, or no significant change when biochar was added [128].

Table 2: Effect of biochar application on soil properties, seed germination, plant behavior and the emission of greenhouse gases

Property	Result	Soil type/Vegetation	Biochar feedstock	Biochar rate	Mechanism	Reference
pH	Increase	Sandy-loam Alfisols -	Lodgepole pine chips -	20 t ha^{-1} biochar 50-100 t ha^{-1}	Biochar acts as a liming agent. The initial dissolution of soluble salts increases pH around the biochar particles.	[117]
Bulk density	Reduce	Temperate grassy eucalypt woodlands	Green waste	20 t ha^{-1}	Large surface area and presence of micropores in biochar.	[120]
Cation Exchange Capacity	Increase	Farmland	Bark charcoal	10 L m^{-2}	Due to greater surface area and higher negative surface charge of biochar.	[123]
Nutrient content	Increase	Hardwood forests Hardwood forest/sandy loam texture	Sawdust Forest fire	5 t ha^{-1}	Biochar carbon content increases the soil organic matter. Biochar contain mineral ash which is a source of nutrients.	[97]
Nitrification	Increase	Subsoil samples from a ponderosa pine forest	Ponderosa pine and Douglas-fir	1000 mg charcoal kg^{-1} soil	Biochar produces a suitable territory for microbes	[74]
Soil microbial activity	Increase	Boreal forest	Forest fire	-	Biochar properties like high internal surface and adsorbing capacity make a potential niche for the soil microbes.	[128]
Seed germination	Increase	Silty loam pine forest soil/ Sandy loam alder forest soil	Softwood chips	5 t ha^{-1}/ 10 t ha^{-1}	Biochar adsorbs salts, heavy metals and organic compounds which otherwise inhibit plant germination and growth.	[129]
Plant growth	Increase	Swidden fallows	Rice husk	4 Mg ha$^{-1.}$	Reduces the overall bulk density which is desirable for plant growth.	[125]
CH_4 emission	Reduce	Forest loam soil	Chicken manure	10% w/w	Increasing the abundance of the microbes that are responsible for oxidation of methane.	[109]
N_2O emission	Reduce	Deciduous forest Forest loam soil Pine forest soil Loam to clay loam grassland soil	Corn silage Chicken manure Wheat straw Municipal biowaste	1% w/w 5 t ha^{-1} 30 t ha^{-1} 10 wt%	The increase in soil aeration reduces anaerobic micro-sites and consequently may result in decrease in N_2O emissions by minimizing denitrification.	[103] [110] [102] [112]

6 Limitation in Biochar Application in Forest Soils

Apart from the advantages of biochar addition in the soil, some studies showed insignificant or sometimes negative effects of large-scale and long-term soil application. Long-term field studies are required to understand the interaction of biochar where various natural dimensions are active. Some of the possible limitations and negative impacts regarding the field application of biochar are listed in Tab. 3. With the substantial increase in the soil fauna, charcoal may decompose the organic carbon already present in the soil [101]. Long-term soil contamination problem may also occur due to the presence of organic or inorganic contaminants in the feedstock material [32,137]. Biochars produced at lower temperatures (350-500°C) for shorter times contain higher PAH concentration [138]. Presence of polyaromatic hydrocarbons (PAHs), toxic metals, and other organic and inorganic contaminants have also been noted in biochar. These phytotoxic substances (PAHs, phenolic compounds, formic or acetic acid) may be released from the fresh biochar, which later may affect the seed germination [139]. However, application of biochar produced at high pyrolysis temperature may increase the soil salinity due to its high electrical conductivity and may subsequently provide undesirable impacts on the plant growth [140]. Some issues related to biochar application are yet unclear which require further investigation. The ecotoxicological effects of biochar application and their mechanisms on the forest ecosystem should be given proper attention.

Table 3: Possible limitations regarding large scale application of biochar on field

Limitations	Explanation	Reference
Effect of biochar remains for many years	Although several studies have recognized the potential of black carbon for enhancing ecosystem carbon sequestration, the experiment on Boreal forest sites in northern Sweden indicated that biochar can stimulate loss of native soil carbon.	[101]
High electrical conductivity (EC) of biochar	Biochar produced at high pyrolysis temperature may increase soil salinity and subsequently provide undesirable impacts on the plant growth due to its high EC.	[138]
Biochars may contain undesirable compounds (such as polyaromatic hydrocarbons, dioxin, phenolic compounds etc.)	i) The concentration of toxic compounds can sometimes be very high and may create a threat to living organisms. ii) These compounds present in biochar may inhibit seed germination and seedling growth and may harmful to plants and soil microbes.	[140,137,139]
Interaction between biochar and soil	Various factors including inherent differences in the soil, biochar type, and differences in responses among plant species influence the variability.	[141]
Biochar production technology and feedstock availability	The required amount of biochar may not be easily available at the appropriate time for the large scale field application.	[142]
Variability of cost of production	Where virgin feedstocks are utilized, production costs can be very high.	[142]

7 Economics of Biochar Application

The economic viability of biochar production systems depends on various parameters including the feedstocks used, the production technologies, and subsidies through carbon sequestration [143-147]. The size and scale of the biochar system also affect the cost and economic feasibility of biochar. Study of the economic feasibility of biochar produced from three different types of feedstocks: forest harvest residue, sawmill residue and underutilized trees of Northwestern Ontario, Canada, revealed that feedstock collection cost (12%) is higher as compared to transportation cost (9%) [148]. However, in other studies, the transportation cost is found to be more than feedstock collection cost where the feedstock is mainly agriculture or municipal waste [149,150-152]. Corn fodder feedstock shows a moderate potential (costs $26

Mg^{-1}) for economic feasibility as compared to forest residue [153]. For energy subsidies and inclusion in the global carbon market, more emphasis should be given on waste products. There is a wide variation in the specific capital costs for biochar production system where pyrolysis is considered as one of the most energy/resource expensive investments [149]. Advance and efficient technologies not necessarily cost significantly more per unit of installed capacity than conventional technologies [154]. The demand for bioenergy production is increasing with time due to its positive impacts on the environment and so more emphasis should be given to the development of highly efficient and cost-effective system. Therefore, the best prospect is to establish a methodology for biochar which meets the requirements of the Verified Carbon Market. The idea of customizing into the local production system is more profitable for the biochar [149]. Land application of biochar returns the carbon back to the soil which reduces the net withdrawal of GHGs that ultimately offsets the other costs in long run. The economic viability of biochar application to soils can be quantified with a high degree of certainty based on biochar characteristics and environmental conditions. The economic assessment regarding the cost and revenue contribution from biochar life cycle reveals that the main costs arise from the collection of feedstock material, its production technologies, and transportation, while the revenues are generated from the value of the biochar to reduce GHG emissions.

Therefore, for large-scale and long-term biochar application proper scientific and socio-economic understanding is required. Land variability, production technology, and distance from the production area to application site and rate of application affect the cost of biochar for land application.

8 Conclusion

Compared to agricultural soil, information on the distribution of natural chars and their effects in forest soil is limited. Though strong evidences of positive effects of biochar application on the growth of woody plants are available, the responses vary among tree species, soil types, and rate of applied biochar. Soil quality plays an important role as the effect of biochar changes depending on the soil of the specific site. Therefore, long-term field trials examining a range of biochars (produced from different feedstocks), soils, and forest types are required for eliminating the uncertainties. The basic characterization of biochar, its phytotoxic potentiality and a total environmental risk assessment including the possible health impacts are essential prior to its application on a large commercial scale. Careful planning to match biochar with the soil properties is essential to obtain maximum benefits of biochar as a soil amendment.

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