Importance, Properties and Benefits of Biochar

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Biochar can be defined as the carbonaceous product that is obtained when biomass is subjected to heat treatment in an oxygen-limited environment (pyrolysis) and the charred product when applied to soil as an amendment. It is an important and popular carbon sequestration method to mitigate climate change.

biochar carbon sequestration climate change shifting cultivation soil properties

1. Biochar and Its Importance

Biochar can be defined as the carbonaceous product that is obtained when biomass is subjected to heat treatment in an oxygen-limited environment (pyrolysis) and the charred product when applied to soil as an amendment [1]. Pyrolysis is the thermal depolymerization of biomass at elevated temperatures without the participation of oxygen. The end products of pyrolysis are syngas, bio-oil, and char [2][3]. The char can be used as an energy source, and acts as a soil amendment which is called biochar. It can be produced from a wide variety of organic materials including paper mill sludge, forestry and crop residues, and poultry waste [4]. Biochar applications gaining growing interest as a sustainable technology that helps in improving the weathered and degraded soils [5]. It enhances the soil's physical (i.e., bulk density, water holding capacity, permeability, etc.), chemical (i.e., nutrient retention, nutrient availability, etc.") and biological (microbial population, earthworm, enzyme activities, etc.) characteristics which thereby improve plant growth and development [6]. Its recalcitrant nature towards microbial decomposition guarantees a long-term benefit to soil fertility [7]. Apart from this, it also improves the saturated hydraulic conductivity of the topsoil of rice fields and xylem sap which results in higher crop yields and improved response to N and NP chemical fertilizer treatments [8]. They possess a negligible number of heavy metals or toxic elements such as As, Cd, Pb, and polycyclic aromatic hydrocarbons so contamination risk is very low. They have the potential to enhance soil fertility; crop productivity [9][10][11][12]; enhance nutrient and water use efficiencies [13], and mitigate emissions of N_2O [14]. The increasing level of atmospheric CO_2 can be mitigated by the long-term storage of C in soil. In this regard, biochar has emerged as a viable option for sequestering carbon in soil [9].

2. Properties of Biochar

The biochar properties are greatly influenced by the feedstock source and pyrolysis conditions [14][15]. In general, wood biochar has high total C; low ash content; low total N, P, K, S, Ca, Mg, Al, Na, and Cu contents; low potential cation exchange capacity (CEC); and exchangeable cations as compared with manure-based biochar. The increase in pyrolysis temperature increased the ash content, pH, and surface basicity and decreased the surface acidity [15]. In the case of fast pyrolysis, biomass is rapidly heated to 400–550 °C and the main product is bio-oil while in slow pyrolysis, the biomass is slowly heated to the desired peak temperature and the main products are biochar and syngas [16]. Some of the important physicochemical properties of biochar are higher surface area and porosity, low bulk density, higher cation exchange capacity (CEC), neutral to high pH, and higher carbon content [17]. It also contains N, P, and basic cations such asCa, Mg, and K [18] which are essential plant nutrients for crop growth and development. Pyrolysis at low temperature yields higher biochar while biochar with higher C content, large surface area, high adsorption characteristics, greater porosity, and more stable C are obtained at higher temperatures [18]. At high pyrolysis temperature (>600 °C), the functional groups are gradually lost, leaving the material with a high degree of condensation and more recalcitrant with polycyclic aromatic structure [18][19]. The stability of biochar to sustain hundreds to thousands of years in the soil is attributed to a higher proportion of aromatic structures which in turn provides higher resistance against chemical and biological decomposition [20]. The concentrations of C and N for plant-based biochar increase with an increase in pyrolysis temperature while the concentrations of C and N in mineral-rich feedstock decrease with increasing pyrolysis temperature [14]. Some of the properties of biochar from different biomass sources are presented in **Table 1**.

Table 1. Properties of biochar derived from different sources.

Materials Used for Producing Biochar	pH	Total C (%)	Total N (%)	C: N Ratio	Ca (cmol kg $^{-1}$)	Mg (cmol kg $^{-1}$)	P (cmol kg $^{-1}$)	K (cmol kg $^{-1}$)	Cation Exchange Capacity (cmol kg $^{-1}$)
Paper mill waste 1 (waste woodchip)	9.4	50.0	0.48	104	6.2	1.20	-	0.22	9.00
Paper mill waste 2 (waste wood chip)	8.2	52.0	0.31	168	11.0	2.60	-	1.00	18.00
Green waste (grass, cotton trash and plant prunings)	9.4	36.0	0.18	200	0.4	0.56	-	21.00	24.00
Eucalyptus biochar	-	82.4	0.57	145	-	-	1.87	-	4.69
Cooking biochar	-	72.9	0.76	96	-	-	0.42	-	11.19
Poultry litter (450 °C)	9.9	38.0	2.00	19	-	-	37.42	-	11
Poultry litter (550 °C)	13	33.0	0.85	39	-	-	5.81	-	11
Wood biochar	9.2	72.9	0.76	120	0.83	0.20	0.10	1.19	11.90
Hardwood sawdust	-	66.5	0.3	221	-	-	-	-	-

3. Benefits of Biochar

3.1. Interaction of Biochar in Soil

Biochar is known to sequester carbon and improve soil functions. Within a short period, the interaction between biochar, soils, microbes, and plant roots occurs after its incorporation into the soil [1]. The factors influencing the types of interactions are (i) feedstock composition, in particular, the total percentage and specific composition of the mineral fraction; (ii) pyrolysis process conditions; (iii) biochar particle size and delivery system; and (iv) soil properties and local environmental conditions. The aging of biochar starts before addition to soils and once incorporated, the rate is partly governed by the soil moisture and temperature condition [21]. Immediately after the application of biochar amendment, the evolution of biochar-derived carbon can be observed within the first 2 weeks and decreases exponentially with time [22]. Water plays a major role in mineral weathering processes such as hydrolysis, dissolution, carbonation and decarbonation, hydration, and redox reactions. The rate of these reactions depends on the type of biochar, nature of reactions, and pedoclimatic conditions. The dissolution and leaching of soluble salts (e.g., K and Na carbonates and oxides) present in the biochar is the first reaction among all the interactions. The dissolution makes the pH increase in the water film around the biochar particles [23]. The biochar converted from biomass is still thermodynamically unstable under the oxidative state of most surface soils [24]. Low-temperature biochar has a considerable fraction of non-aromatic C, which makes the biochar more susceptible to microbial attack [25] and subsequent oxidation than high-temperature biochar [26]. Despite the high stability of aromatic C, it has redox activity and functions as a reducing agent, O_2 being the most common electron-acceptor species. The electron-donating properties of an area with a high density of π-electrons boosted the abiotic reaction and initiated the oxidation of biochar [27]. The number of free radicles in biochar is dependent on the pyrolysis process [28] and thereby increases the reactivity towards the oxidation [29]. Biochar particles can have both acidic and basic properties and are greatly influenced by the moisture condition and the surface retention of ions through electrostatic interactions [30]. They usually co-exist, with the oxidative processes the concentration of basic sites decreases as the biochar particle weathers [31][32]. The biochar which has higher mineral content have interaction with organic matter and clay mineral surfaces depending on the type of clay (2:1, 1:1), distribution of functional groups on the clays (siloxane, OH), and organic matter (COOH, C=O, C–O, CN), the polarity of these compounds and the composition and concentration of cations and anions in solution [33]. There are also complex interactions between biochar with plant roots and microorganisms. Biochar interacts with the soils along with the root hairs. Once the root system encounters the biochar particle, the root hairs can penetrate the water-filled macropores of the particle and the organic compounds (including low- and high-molecular-weight compounds such as free exudates and mucilage); sloughed-out cells and tissues; and lysates from the growing root can be absorbed by biochar surfaces [34]. The fauna (such as worms, termites, larvae, and other insects) present in soil ingest or live inside biochar by breaking it up or coating it with organic compounds. Bioturbation by earthworms plays an important role in the physical mixing of the soil profile with the biochar. Over time, the downward movement of biochar increases within the soil profile where the soil microbial activity is lower [35].

3.2. Role of Biochar in Carbon Sequestration

An increase in ambient temperature has now been unequivocally proven and reported to increase at an unprecedented rate [36]. Since the late nineteenth century, global surface temperatures have increased by 0.88 °C

[37]. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (NO_2) are considered to be the important anthropogenic GHGs, which are released into the atmosphere through the burning of fossil and biomass fuels as well decomposition of above- and belowground organic matter. As per the report, carbon dioxide (CO_2) concentration has increased from 280 ppmv in 1850 to 380 ppmv in 2005 (up to 31% increase) [37]. An increase in the concentrations of methane (CH_4) and nitrous oxide (N_2O) have also been observed over the same period but at a steady rate [36][37][38]. According to Pacala and Socolow [39], approximately 7 $PgCyr^{-1}$ (1 Pg = 10^{15} g) is emitted by fossil fuel combustion and around 1.6 $PgCyr^{-1}$ through deforestation, land-use change, and soil cultivation which in turn plays an important role in contributing to climate change leading to global warming. Thus, there lies a strong quest for mitigating the risks of global warming by stabilizing the GHGs present in the atmosphere [40][41][42]. As per Lal [43], three strategies can be adopted to lower CO_2 emissions *viz.* (i) reducing global energy use, (ii) developing low- or no-carbon fuel, and (iii) sequestering CO_2 from point sources or the atmosphere through natural and engineering techniques [42]. From the view of CO_2 sequestration, there is a wide range of processes and technological options available in agricultural, industrial, and natural ecosystems which include biotic and abiotic sequestration [43]. Studies have considered the potential of bio-based carbon materials for gas capture and storage, and biochar has emerged as one of the important tools among different carbon sequestration techniques [9][44][45]. The application of biochar in the soil poses a novel approach to establishing a significant long-term sink of atmospheric carbon dioxide (CO_2) in terrestrial ecosystems. With the use of a wide variety of biochar application programs, an estimation of 9.5 BTof carbon can be potentially stored in the soils by the year 2100 [9]. About 50% of the carbon can be sequestered during the conversion of biomass carbon to biochar as compared to only 3% carbon retention in soil by burning and less than 10–20% (after 5–10 years) through biological decomposition, thereby giving higher yields of stable soil carbon in soil upon application [9]. The recalcitrance mechanism in biochar is considered to be one of the most important phenomena for sequestering carbon for a longer period [18]. Long-term carbon sinks of biochar are also due to slow microbial decomposition and chemical transformation [20]. Biochar amended at 2, 5, 10, 20, 40, and 60% *w*/*w* levels corresponding to field application rate of 24–720 Mg ha^{-1} has been reported to reduce CO_2 production as well as significant suppression of the ambient CH_4 oxidation and N_2O production at all levels as compared to unamended soils [44]. Thus, biochar can offer both large and long-term C sink in the soil making it one of the desirable choices for carbon sequestration for mitigating climate change. The figure (**Figure 1**) below represents the mechanism through which biochar acts as a carbon sink. Thus, biochar production from biowaste can not only act as a promising precursor for CO_2 sequestration but also has also emerged as a sustainable strategy for solid waste management [45].

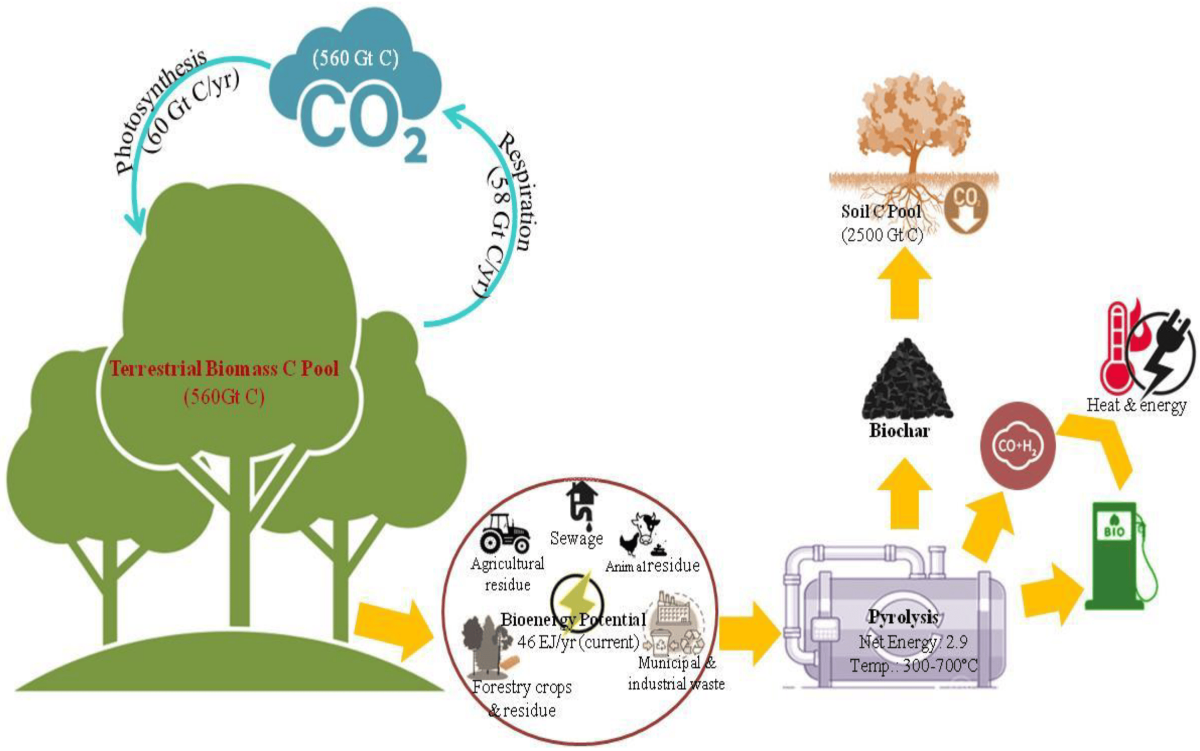

Figure 1. Schematic diagram of biochar-induced carbon sequestration.

3.3. Impact of Biochar on Soil Physical, Chemical, and Microbial Properties

Improved soil physical, chemical, and biological properties are desirable for optimum plant growth and development. Applications of biochar in soil are known to have a significant impact on various properties of soil [46][47][48]. The high porosity of biochar tends to improve a wide range of soil physical properties such as total porosity, soil density, soil moisture content, water holding capacity, and hydraulic conductivity [46][49][50]. Improvement in water retention capacity of the soil is mainly attributed to improved soil texture and aggregation posed by higher surface area and porosity of biochar [8][51][52]. Biochar applications at higher rates significantly increase the field capacity of the soil [53]. The effects can be more pronounced in non-irrigated regions with an increase in available water for crop growth as well as reducing the occurrence of water stress in between the events of rainfall. Addition of biochar decreases soil bulk density [48][54] which affects the infiltration rate in soil. Improved bulk density due to increased soil porosity will have a positive impact on soil aeration which is desirable for root and microbial respiration. Higher organic carbon content [55], as well as surface charge [56] in biochar, is another aspect that plays a crucial role in enhancing soil aggregation and its stability [55]. The stable soil aggregates change the structure of soil and thus improve soil moisture retaining capacity, infiltration, run-off reduction, and erosion [55].

Biochar plays a significant role in improving soil's chemical properties which includes raising pH, organic carbon, and exchangeable cations [10]. Most studies reported an increase in soil pH upon biochar additions [48][51]. An increase in cation exchange capacity (CEC) is confirmed by Lehmann et al. [57] which is an important property to prevent leaching loss of nutrients and thus can increase the fertilizer use efficiency (FUE). The higher CEC of biochar is reported to possibly enhance soil aggregation by aiding in forming certain complexes between organic matter and other minerals with that biochar [56]. However, it is observed that the effective cation exchange capacity is reported to increase with time after being incorporated into the soil [56]. This is so because the surfaces of biochar tend to get oxidized after getting in contact with moisture (water) and air [31][56][58]. The advantages of an increase in pH value on biochar application are more pronounced, especially in acidic soils that are associated with heavy metal toxicity or nutrient deficiencies. Depending on the pH-buffering capacity of the soil, biochar is reported with typical high liming equivalence in raising the pH value in acidic soils [59]. The increase in pH due to liming effect of biochar can play a significant role in the availability of essential nutrients in the soil. Important macro (N, P, K, Ca, Mg) and micro-nutrients (Cu, Fe, Mn, Zn,) which are essential for plant growth and development are reported to increase upon application of biochar in soil [10][12][60][61]. Apart from this, biochar due to its high affinity to hold nutrients reduces nutrient loss through leaching which in turn increases fertilizer use efficiency by the plant [57]. Several investigations have confirmed that volatilization of NH_4^- decreases significantly with a high biochar application rate (10% or 20%, *w*/*w*) due to high CEC [57] however, biochar with high N content may lead to a higher leaching of NO_3^- [14]. Biochar particles are assumed to act like clay and thus hold large amounts of immobile water even at increased matric potentials. Several other studies also reveal that the addition of biochar significantly increases the nodulations of rhizobia [62] thereby confirming the improvement in nitrogen fixation [63]. As per Biederman and Harpole [62], the increase in N-fixation following biochar application was reported to be 72%. In terrestrial ecosystems, biochar is also observed to act as a habitat for mycorrhizal fungi. The porous structure of biochar provides a habitat for microbes in soil and protects them from predation [47]. The habitat leads to a ubiquitous symbiotic association between them and favors the soils to carry out various ecosystem services in contributing to sustainable plant production and ecosystem restoration [47].

However, changes in soil properties as discussed above depend on biochar application rate, type of feedstock, soil type, pyrolysis parameters, and various other conditions prevailed [10][64][65]. Several studies revealed that biochar, when applied at sufficiently high rates tends to improve soil's physical properties [10][59][66][67]. Chan et al. [11] reported that the increasing rate of biochar application tends to increase the field capacity but, the significant changes could only be observed at higher rates of biochar application, i.e., 50 and 100 Mg ha^{-1}. Soil amended with biochar made from green waste with application rates of 50 and 100 Mg ha^{-1} to an alfisol has shown significant retention of water at field capacity compared to control [10]. In another case, the addition of mixed hardwood biochar at 1 and 2% (*w*/*w*) to a mollisol, did not detect any effect on moisture retention at soil water potential of −0.33 bars and −15 bar however, significant increases in moisture retention were observed at −1 and −5 bars soil water potential compared to control [48]. An increase in pH value after application of biochar is reported to be higher in sandy and loamy soils as compared to clayey soils [68] however; buffering capacity is reported to be higher in finely textured soil compared to that of coarse-textured soil. Nutrient retention capacity is found to be higher in aged biochar when compared to fresh biochar [31], which suggests that CEC increases in soil over time following biochar application. It can act as an alternative to fertilizer. Thus, biochar can be effectively used as a soil amendment to improve its overall quality in a sustainable, economic, and environmentally friendly way. The overall effect of biochar on various soil properties has been represented in **Figure 2**.

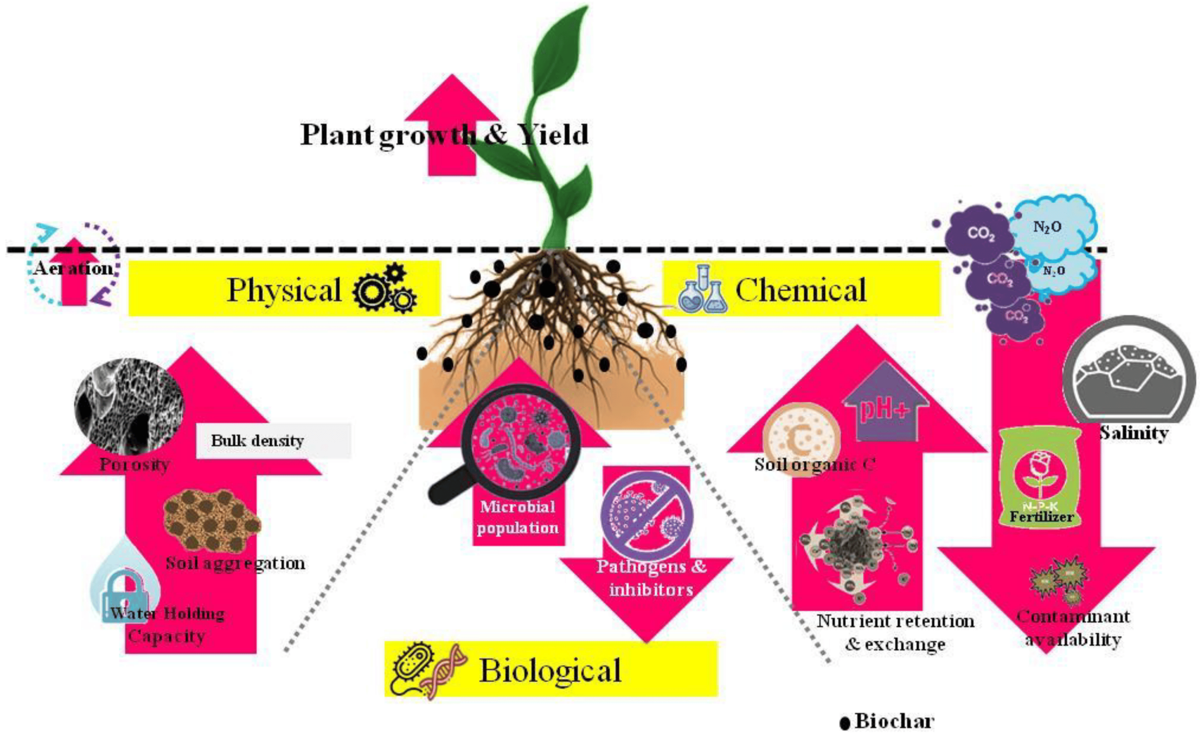

Figure 2. Graphical representation of the overall effect of Biochar after soil application.

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