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Biochar and Multiplex Annapurna Active for sustainable agriculture

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ABSTRACT

Soil degradation, declining soil organic carbon (SOC), and climate change have emerged as major constraints to sustainable agricultural production worldwide. Biochar has gained considerable attention as a carbon-rich soil amendment because of its ability to improve soil health, enhance nutrient availability, increase crop productivity, and sequester carbon for extended periods. This review synthesises current knowledge on the production, properties, and mechanisms of biochar, with emphasis on its effects on soil physical, chemical, and biological properties, nutrient cycling, and greenhouse gas mitigation. The review further discusses crop-specific responses to biochar application and highlights the role of biochar in improving fertiliser-use efficiency and restoring degraded soils. In addition, the potential of biochar-enriched formulations, particularly Multiplex Annapurna Active, is examined as an integrated soil amendment that combines biochar with organic amendments, beneficial microorganisms, and plant nutrients to enhance soil organic carbon, microbial activity, and sustainable crop production. Overall, biochar-based soil amendments offer an effective strategy for climate-smart agriculture, long-term soil fertility, and resilient agricultural ecosystems.

Keywords: Biochar, Soil Organic Carbon (SOC), Carbon Sequestration, Soil Health, Nutrient Cycling, Climate-Smart Agriculture, Biochar-Enriched Soil Amendments, Multiplex Annapurna Active

Introduction

Climate change is one of the greatest global challenges affecting agricultural sustainability, environmental quality, and food security. Developing countries such as India are particularly vulnerable because agriculture depends largely on monsoon-driven production systems and supports the livelihoods of millions of small-holder farmers. At the same time, agriculture contributes significantly to greenhouse gas (GHG) emissions through intensive tillage, excessive fertilizer use, livestock production, and crop residue burning, all of which accelerate soil degradation and depletion of soil organic carbon (SOC).

Among these practices, crop residue burning has become a major environmental concern, particularly in the rice-wheat production systems of the Indo-Gangetic Plains. Although burning residues enables rapid land preparation, it releases substantial amounts of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and particulate matter, contributing to air pollution, greenhouse gas emissions, and loss of valuable soil organic matter and nutrients. Converting agricultural residues into biochar offers a sustainable alternative that addresses residue management while improving soil fertility and carbon sequestration.

Soil organic carbon is a key indicator of soil health and agricultural sustainability because it improves soil aggregation, water-holding capacity, nutrient retention, and microbial activity, thereby enhancing soil productivity (Lal, 2004) [1]. However, intensive cultivation, erosion, deforestation, and unsustainable land management have substantially reduced global SOC stocks, leading to declining soil fertility and increased vulnerability to land degradation (Montanarella *et al.*, 2012) [2]. Consequently, restoring soil carbon has become a central component of climate-smart agriculture and sustainable land management.

Carbon farming promotes practices such as conservation tillage, crop rotation, cover cropping, agroforestry, biomass recycling, and the application of organic amendments to increase carbon storage while improving soil health and reducing greenhouse gas emissions (Smith *et al.*, 2008) [3]. Among these approaches, biochar has attracted considerable attention because of its ability to simultaneously improve soil quality and sequester carbon.

Biochar is a stable, carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions, typically at temperatures between 300 and 1000 °C (Lehmann *et al.*, 2009; Lehmann *et al.*, 2015) [4, 5]. Agricultural residues, forestry wastes, animal manures, and other organic materials are commonly used as feedstocks. The physicochemical properties of biochar, including pH, porosity, specific surface area, cation exchange capacity (CEC), nutrient content, and stability, vary depending on feedstock type and pyrolysis conditions.

The concept of biochar originated from the highly fertile *Terra Preta* soils of the Amazon Basin, where charcoal-rich soils have maintained exceptional fertility for centuries (Harder, 2006) [6]. Due to its highly

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aromatic and recalcitrant carbon structure, biochar is resistant to microbial decomposition and can remain stable in soil for hundreds to thousands of years, thereby transferring carbon from the active carbon cycle into a stable soil carbon pool (Lehmann, 2007) [7]. Large-scale adoption of biochar has therefore been recognised as a promising strategy for long-term carbon sequestration and climate change mitigation (Lehmann *et al.*, 2006) [8].

Soil organic carbon (SOC)

Soil organic carbon (SOC) is a major component of soil organic matter and one of the most important indicators of soil quality, ecosystem functioning, and agricultural sustainability. It consists of carbon derived from decomposed plant and animal residues, microbial biomass, and humified organic compounds. Globally, soils store approximately **1,500–2,400 Pg of organic carbon**, exceeding the combined carbon stored in the atmosphere and terrestrial vegetation, making SOC a critical component of the global carbon cycle (Lal, 2004) [1].

SOC plays a vital role in maintaining the physical, chemical, and biological properties of soils. It improves soil aggregation, porosity, aeration, infiltration, and water-holding capacity, thereby reducing erosion, compaction, and drought stress while enhancing root growth and soil resilience (Lal, 2004) [1]. Chemically, SOC acts as a reservoir of essential plant nutrients and increases the cation exchange capacity (CEC), improving nutrient retention, fertilizer-use efficiency, and sustainable crop production. Biologically, it serves as the primary energy source for soil microorganisms involved in organic matter decomposition, nutrient mineralization, and other biogeochemical processes, thereby enhancing microbial diversity, enzymatic activity, nutrient cycling, and overall soil health (Lehmann *et al.*, 2015) [9].

Beyond its agronomic importance, SOC is a key factor in climate change mitigation because soils function as one of the largest terrestrial carbon sinks. Through photosynthesis, atmospheric carbon dioxide (CO₂) is converted into plant biomass and subsequently incorporated into soil organic matter, promoting long-term carbon sequestration while improving soil fertility (Lal, 2004; Smith *et al.*, 2008) [1, 3]. However, continuous cultivation, intensive tillage, residue removal, deforestation, erosion, and other unsustainable land-use practices have substantially depleted SOC stocks worldwide, leading to reduced soil fertility, poor nutrient cycling, lower water retention, and declining agricultural productivity (Montanarella *et al.*, 2012) [2].

The persistence of SOC depends on stabilization mechanisms including **recalcitrance, mineral interactions, and physical protection within soil aggregates**, which regulate carbon turnover and resistance to microbial decomposition (Sollins *et al.*, 1996) [10]. Consequently, sustainable soil management practices such as conservation agriculture, reduced tillage, residue retention, cover cropping, agroforestry, integrated nutrient management, and the application of organic amendments have been widely recommended to restore SOC, improve soil health, and enhance carbon sequestration (Paustian *et al.*, 2016) [11].

Overall, maintaining and restoring SOC is fundamental for improving soil quality, increasing crop productivity, strengthening ecosystem resilience, and mitigating climate change. Sustainable carbon management practices, particularly biochar-based amendments and carbon farming approaches, will play an increasingly important role in achieving climate-smart and environmentally sustainable agriculture.

Biochar

Biochar is a carbon-rich, porous material produced by the thermochemical conversion of biomass under oxygen-limited conditions, typically through pyrolysis at temperatures ranging from **300–1000 °C** (Lehmann *et al.*, 2009; Lehmann *et al.*, 2015) [4, 5]. It can be produced from a wide range of feedstocks, including agricultural residues, forestry wastes, animal manures, municipal organic wastes, and agro-industrial by-products.

Biochar has gained considerable attention as a sustainable soil amendment because of its dual role in improving soil health and sequester-

ing atmospheric carbon. Unlike fresh organic matter, biochar contains highly stable aromatic carbon structures that resist microbial decomposition, allowing it to persist in soils for hundreds to thousands of years and function as a long-term carbon sink (Lehmann, 2007) [7]. Converting agricultural residues into biochar also provides an environmentally sound alternative to residue burning, thereby reducing greenhouse gas emissions while promoting circular agriculture and sustainable resource utilisation (Kumar *et al.*, 2021) [12].

Biochar improves soil physical, chemical, and biological properties. Its porous structure reduces bulk density, enhances soil aggregation, increases porosity, improves aeration, and increases water-holding capacity, particularly in degraded and sandy soils (Glaser *et al.*, 2002) [13]. Chemically, biochar increases cation exchange capacity (CEC), improves nutrient retention, minimises nutrient leaching, and enhances the availability of nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. Many biochars also possess alkaline properties that help ameliorate acidic soils and improve nutrient availability (Glaser *et al.*, 2002; Lehmann and Rondon, 2007; Yuan and Xu, 2011) [13, 14]. In addition, biochar can immobilize heavy metals and adsorb organic contaminants, thereby reducing their environmental risks (Zhang *et al.*, 2019) [15].

The porous matrix of biochar provides favorable habitats for beneficial microorganisms, leading to enhanced microbial biomass, enzymatic activity, nutrient cycling, and mycorrhizal colonisation (Gul *et al.*, 2015) [16]. Biochar also enhances biological nitrogen fixation in leguminous crops by improving the soil environment for symbiotic microorganisms (Rondon *et al.*, 2007) [17].

These improvements collectively enhance crop productivity by improving soil fertility, water availability, nutrient-use efficiency, and rhizosphere functioning. The greatest yield responses are generally observed in degraded, nutrient-deficient, and acidic soils (Lehmann *et al.*, 2006; Jeffery *et al.*, 2017) [8, 18]. Furthermore, biochar contributes to climate change mitigation by increasing long-term carbon sequestration and reducing greenhouse gas emissions, particularly nitrous oxide (N₂O), through improved nitrogen retention and altered microbial processes (Taghizadeh-Toosi *et al.*, 2011) [19]. Biochar also enhances plant tolerance to drought and salinity by improving soil moisture retention, nutrient uptake, and physiological responses.

Despite its numerous benefits, the effectiveness of biochar is highly dependent on feedstock type, pyrolysis conditions, application rate, soil properties, climate, and crop management. Inappropriate production conditions may generate contaminants such as polycyclic aromatic hydrocarbons (PAHs), while excessive application rates or unsuitable soil conditions may produce inconsistent agronomic responses (Wardle *et al.*, 2008; Jones *et al.*, 2012) [21, 20]. Therefore, long-term field evaluations are essential to optimize biochar production and application strategies across different agroecosystems.

Overall, biochar is a multifunctional soil amendment that enhances soil organic carbon, improves soil physical, chemical, and biological properties, increases nutrient-use efficiency, recycles agricultural residues, and supports climate-smart agriculture. Furthermore, integrating biochar with organic amendments, beneficial microorganisms, and balanced nutrient sources—as in **Multiplex Annapurna Active**—can further enhance soil fertility, microbial activity, and long-term agricultural sustainability.

Effect of biochar on soil physical properties

Biochar has gained considerable recognition as a multifunctional soil amendment because of its ability to improve soil physical properties while contributing to long-term carbon sequestration. Its highly porous structure, low bulk density, and stable aromatic carbon make it an effective amendment for enhancing soil quality and climate resilience (Lehmann, 2007; Lehmann *et al.*, 2015) [7, 5].

Reduction in soil bulk density

- Biochar decreases soil bulk density due to its low density and porous nature.

- Lower bulk density reduces soil compaction, improves root penetration, enhances aeration, and facilitates water infiltration.
- A significant negative relationship between biochar application rate and soil bulk density has been reported (Chan *et al.*, 2007; Abel *et al.*, 2013) [23, 22].

b. Improvement in soil aggregation

- Biochar promotes the formation and stabilisation of soil aggregates through interactions with soil minerals, organic matter, and microorganisms.
- It acts as a binding agent, improving soil structure, reducing erosion, and enhancing structural stability.
- These effects are particularly pronounced in coarse-textured soils (Brodowski *et al.*, 2005; Briggs *et al.*, 2012) [25, 24].

c. Enhancement of soil porosity

- The porous structure of biochar increases total soil porosity and pore connectivity.
- Improved porosity enhances aeration, gas exchange, microbial activity, root growth, and water movement within the soil profile.
- The extent of improvement depends on soil type, feedstock, and pyrolysis conditions (Herath *et al.*, 2013; Omondi *et al.*, 2016) [26, 27].

d. Improved water retention

- Biochar increases soil water-holding capacity by storing water within its internal pore network.
- It enhances field capacity, plant-available water, and water-use efficiency, particularly in sandy and drought-prone soils.
- In clay soils, biochar improves hydraulic conductivity and reduces surface runoff (Abel *et al.*, 2013; Edeh *et al.*, 2020) [22, 28].

e. Regulation of soil temperature

- Biochar moderates soil temperature fluctuations by reducing thermal conductivity.
- Stable soil temperatures promote seed germination, root growth, microbial activity, and nutrient mineralization, contributing to better crop establishment.

f. Improved soil resilience

- Biochar enhances resistance to soil degradation by reducing erosion, crust formation, runoff, and compaction.
- Improved soil structure and moisture retention support sustained crop growth under adverse environmental conditions.
- Sandy and degraded soils generally show greater responses than fertile clay soils, while high temperature biochar's are more effective in improving porosity and water retention.

Effect of biochar on nutrient cycling and availability

Biochar improves nutrient cycling and nutrient availability through its high porosity, large surface area, high cation exchange capacity (CEC), and abundance of functional groups. These properties enhance nutrient retention, reduce leaching losses, stimulate microbial activity, and improve soil fertility, resulting in higher nutrient-use efficiency and sustainable crop production (DeLuca *et al.*, 2006) [29].

Nitrogen (N)

- Enhances nitrogen cycling by influencing mineralization, immobilization, nitrification, denitrification, and biological nitrogen fixation (DeLuca *et al.*, 2006) [29].
- Improves microbial activity by providing favourable habitats and increasing soil pH and moisture.

- High-temperature biochar enhances nitrogen retention, while low-temperature biochar may temporarily immobilize nitrogen (Craswell *et al.*, 2021) [30].
- Reduces ammonia volatilization and nitrate leaching by adsorbing NH_4^+ and NH_3 (Taghizadeh-Toosi *et al.*, 2012; Jones *et al.*, 2012) [31, 20].
- Promotes root nodulation and biological nitrogen fixation in legumes, improving nitrogen-use efficiency (Rondon *et al.*, 2007) [17].

Phosphorus (P)

- Increases phosphorus availability by reducing P fixation and enhancing phosphatase activity (Gao *et al.*, 2018) [32].
- Raises soil pH in acidic soils, reducing Fe and Al toxicity and improving phosphate availability (Steiner *et al.*, 2007) [33].
- Stimulates phosphorus-solubilizing microorganisms and phosphatase enzymes (Jin *et al.*, 2016; Zhang *et al.*, 2019) [15].
- Reduces phosphorus leaching and improves phosphorus-use efficiency (Gao *et al.*, 2018) [32].

Potassium (K)

- Acts as a supplementary source of readily available potassium depending on feedstock and pyrolysis conditions (Limwikran *et al.*, 2018; Liu *et al.*, 2019) [34, 35].
- Improves potassium retention through increased cation exchange capacity, reducing leaching losses (Kuo *et al.*, 2020) [36].
- Enhances populations of potassium-solubilizing microorganisms, increasing potassium availability and uptake.

Sulfur (S)

- Supplies sulfur when produced from sulfur-rich feedstocks and improves sulfur cycling.
- Enhances sulfur mineralization and oxidation by stimulating sulfur-transforming microorganisms (Blum *et al.*, 2013) [37].
- Promotes sulfur-oxidizing bacteria such as *Thiobacillus* spp. and *Pseudomonas* spp., increasing sulfate availability (Wainwright, 1984) [38].
- Adsorbs sulfate ions, reducing sulfur leaching losses.

Micronutrients

- Improves the availability and retention of Fe, Zn, Mn, and Cu through adsorption, cation exchange, and pH-mediated reactions (Tomczyk *et al.*, 2019) [39].
- Reduces copper mobility and toxicity by adsorption and precipitation (Gonzaga *et al.*, 2020) [40].
- Enhances iron availability through microbial and redox-mediated processes.
- Regulates zinc and manganese availability while minimising deficiencies and toxicity (Smider *et al.*, 2014) [41].

Overall influence on nutrient cycling

Overall, biochar enhances nutrient cycling by improving nutrient retention through its high porosity, large surface area, and cation exchange capacity (CEC). It modifies soil pH, stimulates beneficial microbial activity, and promotes nutrient mineralisation, thereby increasing the availability of essential nutrients to plants. Biochar also reduces nutrient losses through volatilisation and leaching, resulting in improved fertiliser-use efficiency, enhanced crop productivity, and sustained soil fertility. These combined benefits make biochar an important component of sustainable agriculture, regenerative farming, and climate-smart nutrient management by improving nutrient cycling while contributing to long-term carbon sequestration (Agegnehu *et al.*, 2017; El-Naggar *et al.*, 2019) [42, 43].

Effect of biochar on crop productivity

Numerous studies have shown that biochar improves crop productivity by enhancing soil fertility, nutrient retention, water-holding capacity, soil organic carbon, cation exchange capacity (CEC), and beneficial microbial activity. However, crop response varies with soil type, crop species, biochar characteristics, application rate, and management practices.

- **Cereal crops:** Biochar increased sorghum yield by improving soil fertility and nutrient retention (Steiner *et al.*, 2007) [33]. Meta-analysis also reported yield increases of approximately **28% in maize** and **13% in wheat**, particularly in nutrient-deficient soils (Jeffery *et al.*, 2017) [18]. In tropical soils, biochar combined with NPK nearly doubled maize yield by improving soil pH, nutrient availability, CEC, and mycorrhizal colonization.
- **Millet:** Acid-modified cow manure biochar improved millet productivity by enhancing soil water-holding capacity, water-use efficiency, and soil organic carbon, especially under moisture-limited conditions.
- **Legumes:** Biochar increased cowpea biomass by **43%** through improved nutrient availability and soil fertility. Combined application of biochar and fertilizers further improved soil fertility and crop growth (Yamato *et al.*, 2006) [44].
- **Oilseed crops:** Biochar enhanced peanut yield by increasing nutrient availability and reducing aluminium toxicity (Yamato *et al.*, 2006) [44]. In rapeseed (mustard), biochar reduced heavy metal availability (Cd, Zn, and Pb), improved soil fertility, and increased biomass production by nearly **threefold** (Beesley *et al.*, 2011) [45].
- **Horticultural crops:** Biochar application (15–30% v/v) improved drought tolerance and establishment of tomato seedlings by increasing soil moisture retention (Mulcahy *et al.*, 2013) [46]. In cotton, biochar combined with organic manure enhanced root growth, nutrient uptake, and seed cotton yield.
- **Perennial crops:** In vineyards, biochar improved soil water availability, hydraulic properties, nutrient retention, and microbial activity, enhancing drought tolerance and long-term soil fertility (Baronti *et al.*, 2014) [47].
- **C3 and C4 plants:** Nutrient-enriched biochar increased biomass production by improving soil moisture, nutrient availability, and labile carbon and nitrogen pools.

Biochar-enriched formulations: Multiplex Annapurna Active

Recent advances in biochar technology have led to the development of nutrient-enriched biochar formulations that combine biochar with plant nutrients, organic amendments, and beneficial microorganisms. These formulations act as slow-release nutrient carriers, improving nutrient availability while reducing nutrient losses through leaching and volatilization (Atkinson *et al.*, 2010; Lehmann *et al.*, 2015) [48, 5]. Multiplex Annapurna Active is an advanced biochar-based soil amendment formulated with biochar, organic carbon sources, macro- and micronutrients, beneficial microorganisms, neem cake, pongamia cake, castor cake, vermicompost, and coir pith. This integrated formulation enhances soil fertility, restores soil organic carbon, and improves long-term soil health.

Key benefits of Multiplex Annapurna Active

- **Improves Soil Organic Carbon (SOC):** Supplies stable carbon that enhances carbon sequestration, soil aggregation, and long-term soil fertility.

- **Enhances Microbial Activity:** Biochar provides a protective habitat for beneficial microorganisms, promoting nutrient mineralization, biological nitrogen fixation, and phosphorus solubilization (El-Naggar *et al.*, 2019) [43].
- **Improves Nutrient Availability:** Supplies balanced macro- and micronutrients while reducing nutrient losses and improving fertilizer-use efficiency (Glaser *et al.*, 2002) [13].
- **Enhances Soil Physical Properties:** Increases cation exchange capacity (CEC), improves water-holding capacity, and promotes better soil structure.
- **Corrects Soil pH:** Improves nutrient availability, enhances biological nitrogen fixation, and reduces heavy metal uptake (Rees *et al.*, 2015) [49].
- **Supports Sustainable Agriculture:** Restores degraded soils, improves crop productivity, and contributes to climate-smart and regenerative farming.

Studies also indicate that moderate biochar application rates provide the greatest improvements in nutrient uptake, plant-water relations, and disease suppression, whereas excessive application may reduce these benefits (Jaiswal *et al.*, 2016) [50].

Conclusion

Biochar has emerged as a promising climate-smart soil amendment that enhances soil health, improves crop productivity, and supports long-term carbon sequestration. Its unique physical, chemical, and biological properties improve soil structure, water-holding capacity, nutrient retention, microbial activity, and fertilizer-use efficiency, leading to sustainable improvements in soil fertility and agricultural productivity. In addition to recycling agricultural residues, biochar contributes to greenhouse gas mitigation and the restoration of degraded soils, making it an important component of sustainable and regenerative agriculture.

The integration of biochar with organic amendments, balanced nutrients, and beneficial microorganisms, as demonstrated by **Multiplex Annapurna Active**, further enhances its agronomic benefits by improving soil organic carbon, nutrient availability, microbial diversity, and long-term soil fertility. Such biochar-enriched formulations provide a holistic approach to sustainable soil management while reducing dependence on chemical fertilizers.

Although the effectiveness of biochar varies with feedstock, production conditions, soil type, climate, and crop management, continued long-term field research will help optimize its application across diverse agroecosystems. Overall, biochar and biochar-based formulations offer an effective strategy for improving soil health, enhancing crop productivity, increasing carbon sequestration, and supporting climate-resilient agriculture and global food security.

References

1. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science*. 2004;304:1623–1627.
2. Montanarella L, Vargas R. Global governance of soil resources. *Current Opinion in Environmental Sustainability*. 2012;4:559–564.
3. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2008;363(1492):789–813.
4. Lehmann J, Joseph S. *Biochar for Environmental Management: Science and Technology*. Earthscan; 2009.
5. Lehmann J, Joseph S. *Biochar for Environmental Management: Science, Technology and Implementation* (2nd ed.). Routledge; 2015.
6. Harder B. The charcoal vision. *Science News*. 2006;169:218–220.

7. Lehmann J. A handful of carbon. *Nature*. 2007;447:143–144.
8. Lehmann J, Rondon M. Biochar soil management on highly weathered soils in the humid tropics. In *Biological Approaches to Sustainable Soil Systems*. CRC Press; 2006.
9. Lehmann J, Kleber M. The contentious nature of soil organic matter. *Nature*. 2015;528:60–68.
10. Sollins P, Homann P, Caldwell BA. Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma*. 1996;74:65–105.
11. Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. *Nature*. 2016;532:49–57.
12. Kumar A, Bhattacharya T. Biochar: A sustainable solution for improving soil health and mitigating climate change. *Environmental Challenges*. 2021;5:100344.
13. Glaser B, Lehmann J, Zech W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: A review. *Biology and Fertility of Soils*. 2002;35:219–230.
14. Yuan JH, Xu RK. The amelioration effects of biochar on acidic soils. *Soil Use and Management*. 2011;27:110–115.
15. Zhang X, Wang H, He L, Lu K, Sarmah A, Li J, Bolan NS, Pei J, Huang H. Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental Science and Pollution Research*. 2019;20:8472–8483.
16. Gul S, Whalen JK, Thomas BW, Sachdeva V, Deng H. Physicochemical properties and microbial responses in biochar-amended soils. *Biology and Fertility of Soils*. 2015;51:1–15.
17. Rondon MA, Lehmann J, Ramírez J, Hurtado M. Biological nitrogen fixation by common beans increased with biochar additions. *Biology and Fertility of Soils*. 2007;43:699–708.
18. Jeffery S, Abalos D, Prodana M, Bastos AC, van Groenigen JW, Hungate BA, Verheijen F. Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*. 2017;12:053001.
19. Taghizadeh-Toosi A, Clough TJ, Condon LM, Sherlock RR, Anderson CR, Craigie RA. Biochar incorporation into pasture soil suppresses nitrous oxide emissions. *Journal of Environmental Quality*. 2011;40:468–476.
20. Jones DL, Rousk J, Edwards-Jones G, DeLuca TH, Murphy DV. Biochar-mediated changes in soil quality and plant growth. *Biology and Fertility of Soils*. 2012;48:939–951.
21. Wardle DA, Nilsson MC, Zackrisson O. Fire-derived charcoal causes loss of forest humus. *Science*. 2008;320:629.
22. Abel S, Peters A, Trinks S, Schonsky H, Facklam M, Wessolek G. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma*. 2013;202–203:183–191.
23. Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S. Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*. 2007;45:629–634.
24. Briggs C, Breiner J, Graham R. Physical and chemical properties of soil amended with biochar. *Soil Science Society of America Journal*. 2012.
25. Brodowski S, Amelung W, Haumaier L, Abetz C, Zech W. Morphological and chemical properties of black carbon in physical soil fractions. *Geoderma*. 2005;128:116–129.
26. Herath HMSK, Camps-Arbestain M, Hedley M. Effect of biochar on soil physical properties in two contrasting soils. *Geoderma*. 2013;209–210:188–197.
27. Omondi MO, Xia X, Nahayo A, Liu X, Korai PK, Pan G. Quantification of biochar effects on soil hydrological properties using meta-analysis. *Geoderma*. 2016;274:28–34.
28. Edeh IG, Mašek O, Buss W. A meta-analysis on biochar's effects on soil hydraulic properties. *Geoderma*. 2020;373:114444.
29. DeLuca TH, MacKenzie MD, Gundale MJ. Biochar effects on soil nutrient transformations. *Plant and Soil*. 2006;289:1–18.
30. Craswell ET, Lefroy RDB, Hansen EH. The role of biochar in nitrogen cycling and fertilizer efficiency. 2021.
31. Taghizadeh-Toosi A, Clough TJ, Condon LM, *et al.* Biochar incorporation into pasture soil suppresses ammonia volatilization. *Journal of Environmental Quality*. 2012;41:210–219.
32. Gao S, DeLuca TH. Wood biochar impacts soil phosphorus dynamics and microbial communities in organically managed croplands. *Soil Biology and Biochemistry*. 2018;126:144–150.
33. Steiner C, Glaser B, Teixeira WG, *et al.* Long-term effects of manure, charcoal and mineral fertilization on crop production and soil fertility. *Plant and Soil*. 2007;291:275–290.
34. Limwikran T, Kheoruenromne I, Suddhiprakarn A, Prakongkep N, Gilkes RJ. Dissolution of K, Ca, and P from biochar grains in tropical soils. *Geoderma*. 2018;312:139–150.
35. Liu X, Liu C, Gao W, Xue C, Guo Z, Jiang L, Li F, Liu Y. Impact of biochar amendment on the abundance and structure of diazotrophic community in an alkaline soil. *Science of the Total Environment*. 2019;688:944–951.
36. Kuo YL, Lee CH, Jien SH. Reduction of nutrient leaching potential in coarse-textured soil by using biochar. *Water*. 2020;12(7):2012.
37. Blum SC, Lehmann J, Solomon D, Caires EF, Alleoni LRF. Sulfur forms in organic substrates affecting S mineralization in soil. *Geoderma*. 2013;200:156–164.
38. Wainwright M. Sulfur oxidation in soils. *Advances in Agronomy*. 1984;37:349–396.
39. Tomczyk A, Sokołowska Z, Boguta P. Biochar physicochemical properties and their influence on soil nutrient dynamics. *Reviews in Environmental Science and Bio/Technology*. 2019;18:191–220.
40. Gonzaga MIS, Matias MIDA S, Andrade KR, de Jesus AN, da Costa Cunha G, de Andrade RS, de Jesus Santos JC. Aged biochar changed copper availability and distribution among soil fractions and influenced corn seed germination in a copper-contaminated soil. *Chemosphere*. 2020;240:124828.
41. Smider B, Singh B. Agronomic performance of a high ash biochar in two contrasting soils. *Agriculture, Ecosystems & Environment*. 2014;191:99–107.
42. Agegnehu G, Srivastava AK, Bird MI. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*. 2017;119:156–170.
43. El-Naggar A, Lee SS, Awad YM, *et al.* Biochar influences on nutrient cycling and soil fertility: A review. *Critical Reviews in Environmental Science and Technology*. 2019;49:1–44.
44. Yamato M, Okimori Y, Wibowo IF, Anshori S, Ogawa M. Effects of biochar on crop productivity in tropical soils. *Soil Science and Plant Nutrition*. 2006;52:489–495.
45. Beesley L, Moreno-Jiménez E, Gomez-Eyles JL. Effects of biochar on metal availability and plant growth. *Environmental Pollution*. 2011;159:3269–3282.
46. Mulcahy DN, Mulcahy DL, Dietz D. Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *Journal of Arid Environments*. 2013;88:222–225.
47. Baronti S, Vaccari FP, Miglietta F, *et al.* Biochar application improves soil water availability in vineyards. *Agricultural Water Management*. 2014;132:34–41.
48. Atkinson CJ, Fitzgerald JD, Hipps NA. Potential mechanisms for achieving agricultural benefits from biochar application. *Plant and Soil*. 2010;337:1–18.
49. Rees F, Germain C, Sterckeman T, Morel JL. Plant growth and metal uptake by a non-hyperaccumulating species (*Lolium perenne*) and a Cd-Zn hyperaccumulator (*Nocca caerulea*) in contaminated soils amended with biochar. *Plant and Soil*. 2015;395:57–73.

50. Jaiswal AK, Elad Y, Graber ER, Cytryn E, Frenkel O. Soil-borne disease suppression and plant growth promotion by biochar soil amendments and possible mode of action. In V International Symposium on Tomato Diseases: Perspectives and Future Directions in Tomato Protection. 2016;1207:69–76.
51. Kappler A, Wuestner ML, Ruecker A, *et al.* Biochar interactions with iron cycling microorganisms. 2014.

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