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Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations

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Increasing pressure on farming systems due to rapid urbanization and population growth has severely affected soil health and fertility. The need to meet the growing food demands has also led to unsustainable farming practices with the intensive application of chemical fertilizers and pesticides, resulting in significant greenhouse gas emissions. Biochar, a multifunctional carbon material, is being actively explored globally for simultaneously addressing the concerns related to improving soil fertility and mitigating climate change. Reviews on biochar, however, mainly confined to lab-scale studies analyze biochar production and its characteristics, its effects on soil fertility, and carbon sequestration. The present review addresses this gap by focusing on biochar field trials to enhance the current understanding of its actual impact on the field, w.r.t. agriculture and climate change. The review presents an overview of the effects of biochar application as observed in field studies on soil health (soil's physical, chemical, and biological properties), crop productivity, and its potential role in carbon sequestration. General trends from this review indicate that biochar application provides higher benefits in soil properties and crop yield in degraded tropical soils vis-a-vis the temperate regions. The results also reveal diverse observations in soil health properties and crop yields with biochar amendment as different studies consider different crops, biochar feedstocks, and local climatic and soil conditions. Furthermore, it has been observed that the effects of biochar application in lab-scale studies with controlled environments are not always distinctly witnessed in corresponding field-based studies and the effects are not always synchronous across different regions. Hence, there is a need for more data, especially from well-designed long-term field trials, to converge and validate the results on the effectiveness of biochar on diverse soil types and agro-climatic zones to improve crop productivity and mitigate climate change.

Keywords: biochar, sustainable agriculture, soil properties, soil amendment, crop yield, carbon sequestration, climate change mitigation, soil quality and health

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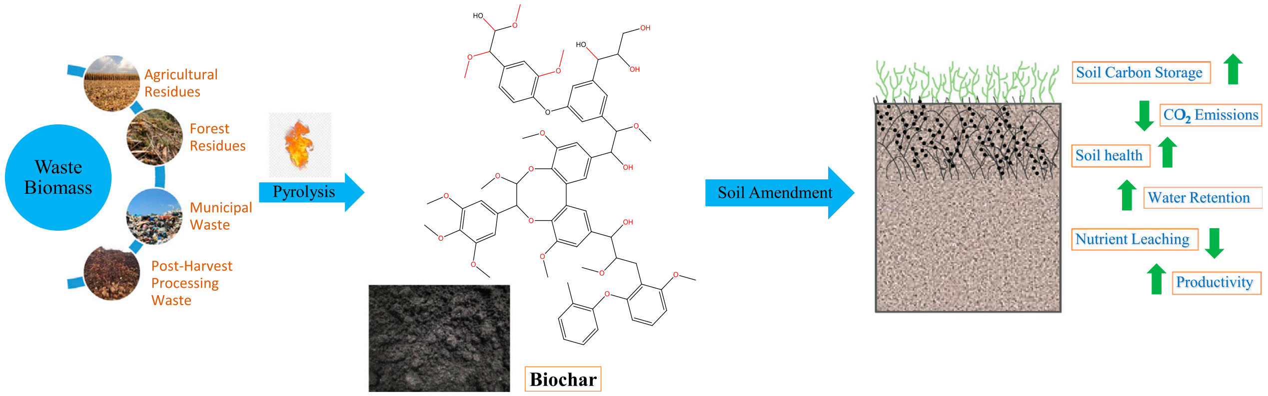

GRAPHICAL ABSTRACT | Biochar application effects on soil amendment and crop yield.

INTRODUCTION

In the present times of unprecedented climate change, it is crucial to investigate techniques that can significantly reduce emissions of greenhouse gases (Pachauri and Meyer, 2015). Soils constitute the largest terrestrial reservoir of organic carbon (OC) (Van Der Voort et al., 2016). The top 1 m alone is estimated to contain 1,500–1,600 Pg of OC (1 Pg C = 1,015 g C), roughly double the amount held in the atmosphere (Jobbágy and Jackson, 2000). Converting land under natural or unmanaged vegetation to crop production releases large amounts of carbon from standing biomass and soil (Banwart, 2011). As a result, there are ongoing global initiatives to restore and increase organic carbon content in soils, e.g., the "4 per 1,000" initiative (4p1000). In addition to their importance for global biogeochemical cycles, soil productivity and health are crucial in sustaining agriculture. Increased pressure on the agricultural sector from increasing population has adversely affected soil fertility and led to a decline in agricultural yield, particularly in the tropical regions (Lal, 2015). Reduction in per-capita landholding and deteriorating soil quality has also resulted in an increase in inorganic fertilizers application rates to sustain crop productivity. The global demand for nitrogen, phosphorus, potassium fertilizers was 191 MT in 2019 and is forecasted to grow to around 200 MT by 2022 (FAO, 2019). Excessive usage of chemical fertilizers can result in soil fertility depletion, nutrient imbalance, and global warming due to the rapid soil organic matter mineralization and subsequent decline in the soil carbon content (Foley et al., 2005). This impact is especially acute in tropical regions as only a small portion of the added organic materials get stabilized in soil in the long-term, and the remaining carbon gets released to the atmosphere as carbon dioxide (CO_2) (Glaser et al., 2002; Agegnehu et al., 2016). Loss of soil carbon induced by agriculture is reported to be the second-highest anthropogenic source of global carbon emissions after the energy sector, with a 20% contribution to the total greenhouse gas (GHG) emissions (FAO, 2017). As a result, sustainable, environment-friendly, and economical crop management practices that can potentially enhance the soil organic matter (SOM) while simultaneously mitigating climate change by sequestering carbon and decreasing GHG emissions are of great importance (Lehmann et al., 2015).

Sustainable agricultural intensification and enhancing production per unit land area is a promising approach for ensuring food security for the growing world population (Tilman et al., 2011). Biochar is seen as a viable option for addressing these problems and is being researched across the globe for its potential benefits (Shackley et al., 2012; Vijay et al., 2015; Nair et al., 2017). Biochar is a carbonaceous material with unique physicochemical properties (Jeyasubramanian et al., 2021). It has received significant attention in the last decade due to its multifaceted benefits related to the broader fields of climate change, agriculture, wastewater treatment, and soil health (Yu et al., 2019). Biochar is reported to significantly enhance the soil quality and crop yield, carbon sequestration, and GHG emissions (CO_2, N_2O, and CH_4) reduction (Curaqueo et al., 2014; Agegnehu et al., 2017; Sahota et al., 2018). A previous investigation revealed that around 12% of the total anthropogenic carbon emissions (0.21 Pg C) by change in land-use could be offset annually in soil, if slash-and-burn is substituted by slash-and-char practice (Lehmann et al., 2006). Several investigations have reported that biochar application may enhance soil microbial activity and physico-chemical properties such as pH, cation exchange capacity (CEC), pore size distribution, bulk density, soil structure, soil organic carbon (SOC), and water holding capacity (WHC) (Atkinson et al., 2010; Omondi et al., 2016; Godlewska et al., 2021). Additionally, biochar can enhance soil nutrient bioavailability, reduce leaching of nutrients, and immobilize toxic elements in contaminated soils (Igalavithana et al., 2017; Chen P. et al., 2021).

The stability of added biochar in soil remains a contentious topic. Research shows that it can range widely from a few years to thousands of years (Lehmann, 2007). Biochar's stability in soil depends on the production process (including types of feedstock and pyrolysis conditions), climatic conditions, soil structure, and other environmental factors (Pandit et al., 2018). Its application may not uniformly affect carbon stability and soil fertility across different regions. Many of the studies, including laboratory studies, concluded positive effects of biochar application on crop productivity (Jeffery et al., 2011; Zhang et al., 2012;

Biederman and Stanley, 2013; Shareef and Zhao, 2017). On the contrary, some studies in temperate regions have reported no effect or negative effects on crop productivity (Hussain et al., 2017; Sänger et al., 2017; Cornelissen et al., 2018; Zhang et al., 2020). Moreover, the majority of literature available on biochar production, its characterization, and effects on soils are based on lab scale (pot or plot) studies; the field scale studies being very limited. Another challenge in biochar research is harmonizing data from trials covering an expansive spatial heterogeneity, such as different soil types, climate, and land-use. This impedes effective cross-comparisons of the various approaches. Furthermore, tropical regions still remain underrepresented in studies, even though there is a lot of pressure on natural resources in these regions.

Currently, the two main areas of large field biochar application include agriculture and developing strategies to mitigate climate change. Biochar is a desired soil conditioner that impacts plant growth, soil productivity and addresses climate change (Galinato et al., 2011). This review summarizes the field trial-based knowledge obtained in the last decade on the role of biochar on soil properties (physical, chemical, and biological), crop production, and climate change. It also aims to present the differences observed in the effects of biochar application in tropical and temperate regions. It further highlights the need for long-term biochar field trials to validate the effects of biochar application and the prominence of effects in tropical regions vis-a-vis temperate regions.

PRODUCTION OF BIOCHAR

Pyrolysis is a thermo-chemical process for conversion of biomass (namely tree and crop residues, grasses, manures, agricultural wastes, and wastewater sludge, etc.) in oxygen limited conditions to produce high energy density solid (biochar), high energy density liquid (bio-oil), and relatively low energy density gas (non-condensable) (Kapoor et al., 2020). The long-chain polymers such as cellulose, hemicellulose, fat, starch, and lignin break down and form gases (e.g., CO_2, CO, CH_4, and H_2) during the pyrolysis process. Some molecules combine and form condensable gases, yield liquid fuel and aromatics compounds that produce char via repolymerization or aromatization. The aromatic framework of biochar without cellular structure provides resistance to decay, whereas its porous structure provides additional advantages in various soil applications, making them stable and recalcitrant for more than 100 years (Lehmann et al., 2006; Zimmerman and Gao, 2011; Purakayastha et al., 2019).

There are three main categories of pyrolysis technologies: slow pyrolysis, flash pyrolysis, and fast pyrolysis (Kan et al., 2016). Slow pyrolysis is a batch reactor or a continuous system that slowly heats the biomass to >350˚C. It is the most widely used pyrolysis system due to ease, and this pyrolyzer yields around 35% biochar, 30% bio-oil, and 35% gas by mass. The slow pyrolysis systems known as “charcoal kilns” are less controlled, where the bio-oil and the gas are not separated. Therefore, the biochar yield in slow pyrolysis can vary between 25–60% (El-Naggar et al., 2019). In the flash pyrolysis process, biomass is heated in batches under moderate to high pressure in a distillation system. It is specifically designed to maximize the bio-oil production, where the yields are typically 60% bio-oil and 40% biochar and gas. Gasification maximizes the production of syngas at temperatures 800–1,200˚C, where a controlled quantity of oxygen is injected into the chamber to produce minimal biochar and bio-oil. This system, if optimized, can produce a mixture of biochar and traces of bio-oil (tar) at 5–15%. In a fast pyrolysis system, temperature is raised up to 700˚C within a few minutes, and it produces more gases and gives lower carbon yield. The products are 50–70% bio-oil, 10–30% biochar, and 15–20% gas. In general, the solid product gives higher yield when the material is heated at a slow heating rate of 10–20˚C/min from 300–750˚C (Lee et al., 2013). Pyrolysis is also a part of biomass gasification process in which the biomass is oxidized in a controlled supply of oxygen to maximize the yield of combustible syngas (Basu, 2010). Furthermore, the yield of different pyrolysis products and the biochar performance are based on the parent feedstock, temperature, time of reaction, and pyrolysis system.

Properties of Biochar and Its Effect on Soil

The impacts of biochar on soil are associated with the material’s porosity, water holding capacity, sorption capacity, redox properties, liming capacity, and nutrient retention (Guo et al., 2020). Typically, pore-size distribution, surface area, surface structure, water holding capacity, and particle density are determined to assess the physical properties of biochar (Yi et al., 2020). For example, larger macropores (pore diameter > 50 μm) on biochar surfaces and biochar sizes can aid changes in soil gas transport, hydrology, particle size distribution, and habitat for microbes. Chemical characteristics of interest include sorption, pH, CEC, total C/N, nutrients (Mukherjee et al., 2014; Al-Wabel et al., 2019), electrical conductivity (Cantrell et al., 2012), elemental composition, surface molecules, and organic coatings on biochar surfaces (Song and Guo, 2012; Yi et al., 2015). Biochar often promotes plant growth and microbial activity, but there are reports where biochar can leach harmful substances that can lead to biochar toxicity (Godlewska et al., 2021). Biochar toxicity is caused by the feedstock and production temperature that transforms biochar pH, electrical conductivity, polycyclic aromatic hydrocarbons, and heavy metals, which can leach into the ecosystem and have toxic effects on organisms. In each field, biochar has its specific property for particular performance based on its physicochemical properties. Hence, it is essential to characterize biochar properties before any soil application.

Chemical constraints which affect plants are acidity, alkalinity, salinity, and nutrient deficiency. High pH > 8 reduces bioavailability of nutrients to the plants. Salinity comes from the high salt concentration in soil, and sodicity refers to a high proportion of sodium ions compared to Mg, Ca, and K ions. Salinity reduces plant growth by osmotic stress, and sodicity reduces root growth, collectively affecting the whole crop production (Ramrez-Rodrguez et al., 2007). The charge density per unit surface of organic matter increases the cation exchange capacity. Biochar has a unique adsorption and desorption mechanism that can regulate the leaching of nutrients (Xiao et al., 2018) and enhance crop productivity, especially when combined with other organic materials such as manure and compost (Wang et al., 2019). As biochar is produced from biomass, it also contains nutrients and elemental composition from its parent material. Hence, it can act like an organic fertilizer for crops while minimizing nutrient runoff by utilizing the nutrient storage capacity on biochar pores (Hagemann et al., 2017).

Soil texture is also influenced by biochar incorporation into agricultural soil. Bulk density of soil decreases and its porous structure is modified resulting in changes in water retention capacity (Al-Wabel et al., 2019). Reduced permeability favours anaerobic conditions, enhances N_2O, CH_4 emissions, and suppresses the rhizosphere microbial activity. Decrease in the productivity of soybean and corn has been found due to compacted soil (Yu et al., 2019).

Thus, the biochar properties make it a suitable candidate for improving soil health. The upcoming section presents the biochar application effects on soil health and its various physico-chemical and biological properties as reported in field trials.

Soil Health

Soil health with reference to agriculture refers to the capability of soil to support and sustain crop production and plant growth (Doran and Zeiss, 2000). Soil is fertile if it has the adequate capability to deliver vital nutrients and water supply to promote growth of plants without the presence of toxic elements, which can hinder plant development (Voltr, 2012). Soil fertility is governed by physical, chemical, and biological properties of soils (Igalavithana et al., 2015). Low fertility of soil is a common issue in several areas of the world (FAO, 2019). For instance, arid and semi-arid area soils generally have lower water holding capacity and insufficient nutrient supply levels for most crops (Khalifa and Yousef, 2015). For tropical rainforest regions, it is particularly challenging to sustain agricultural production as vital plant nutrients are quickly leached from topsoil due to heavy rainfall in combination with low cation binding capacity. Furthermore, relatively higher temperatures and decomposer' abundance lead to higher mineralization rates of soil organic matter (SOM) (Bruun et al., 2015). Thus, having adequate levels of SOM and biological nutrient recycling is critical for the success of soil management systems. Improvement in soil health is a major objective for biochar application. It is reported that biochar application on problematic soils can improve physical, chemical, and biological properties of soil as discussed in the upcoming sections.

Effects of Biochar on Soil Physical Properties

Bulk Density and Soil Compaction

Soil bulk and particle density directly affect the soil properties to a great extent. Soil compaction is also a major physical constraint affecting root growth, typically occurring in soil up to depths of around 30 cm. Poor aeration and physical resistance have been reported to hamper root growth for bulk density $>1.7\ \mathrm{Mg\ m^{-3}}$ (Bruand and Gilkes, 2002). Roots are unable to penetrate soil pores that are lesser than the root cap diameter, and the root growth is hindered by the reduction in soil pore sizes (Xiang et al., 2017). Compressed soils have a low pore space and lower oxygen diffusivity resulting in anaerobic conditions that decreases plant growth considerably (Havlin, 2014). A reduction of 45 and 14% was observed in the yield of soybean and corn, respectively, when cultivated in compacted soils compared to normal soil (Ramazan et al., 2012). Biochar application can reduce these effects and enhance the physical properties of nutrient-depleted or degraded soils. Peake et al. (2014) stated that application of biochar reduced soil compaction by over 10% (Peake et al., 2014). Earlier investigations have also reported that the addition of biochar to infertile soils reduces the soil bulk density (Agegnehu et al., 2017; El-Naggar et al., 2019) as the soil gets loosened physically. A recent study that incorporated 4% biochar into highly weathered tropical soils (sandy clay loam) *in-situ* for 1 year revealed that wood-based biochar could reduce soil bulk density by 5% and increase porosity by 5%. When this biochar at 4% was applied with 1% compost, the bulk density further reduced by 16% and porosity increased by 8%. Higher biochar application (6%) with compost (1%) lowered the bulk density and increased porosity even more at 16 and 22%, respectively, (Jien et al., 2021). Blanco-Canqui (2017) analyzed studies from 22 different soils and revealed that biochar amendment decreased soil bulk density by 3–31% (average 12%) and improved porosity by 14–64% (Blanco-Canqui, 2017). The reduced bulk density and improved soil porosity enhance transport of water, gases, and heat in soils (Lehmann et al., 2003; Liang et al., 2006). As shown, the degree of changes in physical properties depends on the application amount of biochar and on the soil type.

Porosity and Water Holding Capacity

Changes in soil porosity are mainly caused by the porous internal structure (intrapores), the shapes and application rates of biochar, pores between biochar and soil particles (interpores), particle size distribution of the amended soil, and adsorption/absorption properties of biochars (Zhang and You, 2013; Yi et al., 2020). These factors determine the increased/decreased porosity, water retention, hydraulic conductivity, and air permeability in biochar amended soils. Biochar application improves the soil porosity and water holding capacity as reported in several field studies (Rogovska et al., 2011; Randolph et al., 2017). Omondi et al. (2016), with a meta-analysis (74 publications), showed that biochar application enhanced soil porosity, water holding capacity, and saturated hydraulic conductivity by 8.4, 15.1, and 25.2%, respectively, (Omondi et al., 2016). Biochar's ability to retain soil water depends upon its internal porosity (biochar pore size <10 μm) as once the moisture drains down gravitationally, biochar gets filled up, upholding water in its pores, thus reducing hydraulic conductivity, increasing water retention (Suliman et al., 2017), and thereby potentially reducing air permeability, as observed for carbonate-rich sandy soils (Kumari et al., 2014). For clays, Wong et al. (2016) showed that the effect of biochar addition on the air permeability of clayey soils depended on the degree of compaction, where in more compacted soil, permeability decreased with increasing share of biochar while at a lower degree of compaction, permeability was not influenced by the share of added biochar (Wong et al., 2016). These studies show that the effect of biochar addition on properties and processes that are strongly affected by the structure of the pore system, such as permeability (Deepagoda et al., 2011; Van Verseveld and Gebert, 2020), depends highly on soil texture, degree of compaction and the effect of biochar on soil's structure-forming behaviour.

Oxidized biochar exhibited better wettability than fresh biochar and was found to retain more water in sandy soils. The enhancement in soil water retention can be explained by the increase in the oxygen functional groups on the surface of biochar and the increased porosity. It is also observed that biochar application increases the water holding capacity more in sandy soils, than loamy soils and clayey soil. These studies show that biochar improves the physical properties of coarsely textured and low fertility soils more in comparison to highly fertile or productive soils (Laghari et al., 2016).

Soil moisture availability is found to get reduced with increased biochar addition, possibly due to hydrophobicity of biochar (Glaser et al., 2002). Hydrophobicity is generally present in biochars produced at <450°C (Yi et al., 2015). It is also suggested that biochar can perform as binding agent to stabilize soil aggregates and improve water holding capacity and porosity (Jien et al., 2021). Biochar can increase the formation of 5–2 and 0.25–0.5 mm macroaggregates by 115–130 at 6% biochar application rate in clays changing the soil pore structure and increasing aggregate stability and water retention (Sun and Lu, 2014). However, large amounts of <0.25 mm aggregates formation from biochar application can clog biochar surface pores (intrapores), reduce interpores (pores between biochar and soil particles) and introduce surface sealing, reducing soil porosity and water retention. As biochar age, abiotic surface reactions alter surface chemistry, change the particle size distribution, and reduce hydrophobic properties, increase DOC leaching as it physically disintegrates with water exposure (Yi et al., 2015; Liu Y. et al., 2016). Biochar fragments over time and changes the pore structure by clogging the pores or producing aggregates to transform physical properties of the biochar-amended soil. Biochar breakage mainly occurs in wood-based and high-lignin feedstocks rather than higher cellulose feedstocks like manures, grasses, and corn-stover. Further, biochars produced at < 500°C are more prone to structural breakage, showing that porosity and particle size distribution alterations caused by biochar amendments are not stagnant, and such changes are mostly observed in sandy soils (Spokas et al., 2014).

Environmental variabilities, presence of microorganisms, biochar production method, feedstock type, and leaching capacity will determine the pore interaction between biochar and soil particles that alters soil physical properties affecting gas and water transport. Therefore, careful consideration must be made prior to field trials to optimize the effects of biochar amended soils.

Effects of Biochar Application on Soil Chemical Properties

Biochar application has shown potential benefits in ameliorating the soil's chemical properties. Soil amended with biochar has shown an increase in N concentrations, pH, and CEC that subsequently results in better crop production (Biederman and Stanley, 2013; Agegnehu et al., 2016; Adekiya et al., 2020).

Soil pH

Application of biochar can reduce soil acidity owing to its high alkalinity, high buffering capacity, and presence of the functional groups (Major et al., 2010; Liu C. et al., 2016; El-Naggar et al., 2019). It also improves supply of nutrients to plants and the release of cations, such as K, Mg, Ca, and Na from biochars leading to an increase in soil pH (Lehmann et al., 2003; Steiner et al., 2007; Lentz and Ippolito, 2012). Major et al. (2010) observed an increase in soil pH from 3.89 to 4.05 with biochar application (20 t ha^{-1}) over 4 years, indicating its long-term beneficial effects (Major et al., 2010). In another study with 20 t ha^{-1} of biochar in Sumatra, Indonesia, improvement in soil pH from 3.9 to 5.1 and decrease in soil Al^{3+} concentration from 2.67 cmolc kg^{-1} (levels toxic for plant growth) to 0.12 cmolc kg^{-1} was observed (Yamato et al., 2006). A study using wood biochar in banana crop cultivation observed improvement in soil pH and K uptake, whereas no significant impact on fruit production was seen (Steiner et al., 2009). Granatstein et al. (2009) observed that the addition of herbaceous feedstock derived biochar (39 t ha^{-1}) led to an increase in the pH of sandy soil from 7.1 to 8.1 while a minor increase was seen in the silt loamy soil (Granatstein et al., 2009). The slight increase in pH in silt loam soils was because of the high initial CEC that results in a high buffering capacity. However, a 3-year field trial reported that wood biochar did not change soil DON, DOC, NH_4^+, or NO_3^- pool but the alkalinity of biochar was completely neutralized by the end of the experimentation period (third year) (Jones et al., 2012). Thus, the contrasting outcomes indicate that there exists a significant demand for long-term field investigations for in-depth understanding of the mechanisms for longevity effects of biochar.

Salinity and Sodicity

Some soils contain high amounts of inherent salts due to irrigation with saline water or application of chemical fertilizers. Higher EC, ESP, and pH values are characteristic features of saline and sodic soils leading to aggregate breakdown via slaking, clay swelling, and dispersion mechanisms. High salt concentrations of the soil also cause osmotic stress and dehydration resulting in reduced microbial and biochemical processes (Amini et al., 2016). Salt-affected soils show poor structural stability due to the presence of lower organic matter. Therefore, applying organic conditioners (such as biochar) to the soil can mitigate the salinity stress, thus improving the plant's growth in such soils (Saifullah et al., 2018). Acidic biochar amendment (low pH) to such soils can mitigate the adverse effects of salts and fertility (Hagner et al., 2016). A field trial on soil salinity showed that saline soil amendment with biochar poultry manure compost and pyroligneous solution together led to a significant (3.6 g/kg) reduction in soil salinity and a slight increase in soil pH by 0.3 (Lashari et al., 2013). The study also detected a significant reduction in salinity with increase in leaf area index.

Divalent ions such as Ca^{2+} and Mg^{2+} are proposed for reclamation of saline-sodic soils to offset excessive exchangeable Na^+ ions, and biochar has been reported to enhance the availability of these divalent ions (Major et al., 2010; Amini et al., 2016). Mechanism of reducing salt stress is also due to the high adsorption potential of biochar. There are many laboratory studies which show the positive effects of biochar application on salinity and sodicity of the soil, however, more number of field studies are required to support this, especially in the tropical region with variable soil types.

Cation Exchange Capacity

Soil's capability to retain cations in exchangeable and plant-available form is termed as CEC, which grows proportionally to the amount of mineral negative surface charges and SOM (Glaser et al., 2002). Soil having a high CEC can hold plant nutrient cations on biochar's surface, humus, and clay, so that the nutrients are preserved and not leached and hence remain available for plant uptake (Lehmann et al., 2003; Rogovska et al., 2011). Increased buffering capacities have also been reported due to the increased CECs from biochar application in incubation conditions (Zhao et al., 2015). High buffering capacity due to high soil CEC signifies that adding basic or acidic materials has a lesser effect on pH of the soil up to a certain point (Granatstein et al., 2009). As the freshly added biochar gets exposed to water and oxygen in soil, biochar undergoes surface oxidation reactions leading to a rise in the net negative charge resulting in higher CEC. High reactivity of biochar's surface is also due to the existence of several reactive functional groups (COOH, OH, C=O, C-O, N, siloxane), some of which are dependent on pH (Cheng and Lehmann, 2009). A 2-year field experiment in degraded uplands of East Java, Indonesia (tropical) reported an increase in CEC on biochar application which was attributed to high surface negative charge resulting from oxidation of carboxylic and phenolic groups of biochar (Islami et al., 2011). Conversely (Slavich et al., 2013), in a 3-year field study in Australia (subtropical) reported no effect of green-waste biochar application (10 t ha^{-1}) on exchangeable cations and CEC of ferralsols (highly weathered acidic soil) as the total charge added on biochar surfaces was smaller in comparison to that already present on clay and soil organic matter (Slavich et al., 2013). For temperate, non-calcareous soils, significant increases in CEC upon biochar amendment have been observed (Yamato et al., 2006; Laird et al., 2010; Peng et al., 2011), whereas in calcareous soils, no effect of biochar as seen on CEC (Van Zwieten et al., 2010; Kumari et al., 2014). The effect hence depends on the surface charge type and charge density of the soil to which the biochar is added. Observations relating to CEC are still dominantly from pot studies or laboratory trials, and there is a requirement for more field studies to authenticate the results from these.

Nutrient Offering and Retention

The monsoon season, especially in the tropical regions, leads to nutrient leaching (washing of the externally supplied nutrition) and accelerates the acidification of agricultural soil, resulting in decreased crop yield and higher fertilizer requirements. Biochar application to soils is a viable method for reducing leaching of nutrients (Luo et al., 2020). The long-term advantages of biochar addition are slower nutrient release from added organic matter, greater stabilization of organic matter, higher nutrient use efficiency, and enhanced cationic retention as a result of improved CEC (Liang et al., 2006; Lehmann, 2007; Sohi et al., 2010). Biochar derived from Brazilian pepperwood considerably decreased the total amount of phosphate, nitrate, and ammonium in the leachates by 20.6, 34, and 34.7%, respectively, relative to soil alone. Similarly, biochar from peanut hulls also decreased the leaching of ammonium and nitrate by 14 and 34%, respectively, (Yao et al., 2012). Several field investigations showed that biochar application to agricultural soil considerably decreased the leaching of N, NO_3^-, K, P, Mg, Na, and Ca from soil (Major et al., 2012; Agegnehu et al., 2015; Kammann et al., 2015; Gautam et al., 2017).

In another field study in Zambia, enhanced pH with maize-cob derived biochar application in tropical soils increased the plant available P and directly added K^+ to soil (Martinsen et al., 2014). A 2-year field trial of rice-husk biochar (10 t ha^{-1}) amendment to banana plantations in Tamil Nadu, India, investigated its potential to improve soil fertility and moisture content (Mankasingh et al., 2011). The amendment exhibited considerable enhancements in soil P, K, Na, Mg, C, and N. Authors recommended >10 t ha^{-1} biochar application rates for high mineral content tropical soils. Biochar is also reported to reduce nitrogen leaching resulting in higher levels of nitrogen in soil (El-Naggar et al., 2018; Lu et al., 2020). Nitrate retention and ammonium adsorption have been reported in several field studies after the application of biochar (Lehmann et al., 2003; Haider et al., 2017). In a biochar field trial (14 t ha^{-1}) conducted in Italy for tomatoes using wheat bran biochar the SOC, soil CEC, and the availability of P, K, Mg, and NH_4^+ were found to have significantly increased, whereas the demand for external fertilizer and water reduced (Vaccari et al., 2015).

Effects of Biochar on Soil Biological Properties

Soil harbours complex micro-organisms communities that are continuously evolving in response to the soil properties, climate, and land management practices (Thies et al., 2015). Soil microbial communities, their abundance, and activities are closely interlinked to soil respiration, organic carbon content, soil nutrient cycling, and crop productivity (Dempster et al., 2012; Song et al., 2018). Soil microbial activity is influenced by biochar addition and the effect varies with the type of soil, biochar quality, and application rate (Rousk et al., 2010; Farkas et al., 2020). A meta-analysis reported that biochar amendment considerably increased the ammonia-oxidizing archaea (AOA) abundance and denitrification gene (nirS, nirK, and nosZ) by an average of 25.3, 32.0, 14.6, and 17.0%, respectively, (Xiao et al., 2019). Biochar stimulates soil microbial activity by providing carbon substrate and growth nutrients. In addition, it serves as a suitable habitat for growth and protects them from predators (Chen et al., 2018; Lu et al., 2020). Furthermore, biochar increases the buffering capacity of soil thereby minimizing pH variations in microhabitats present inside biochar particles (Rousk et al., 2010).

TABLE 1 | Quantitative impact of biochar application on physical, chemical and biological properties of soils from field trials.

Property	Impact	% Change	Biochar feedstock, application rate	Soil type, location	References
	Positive, Negative and Neutral	**Physical properties**			
Bulk density (g cm^{-3})	Decreased from 1.29 to 1.19	−7.75	Oat hull, 20 t ha^{-1}	Silt loam Inceptisol, Chile	Curaqueo et al. (2014)
	Decreased from 1.36 to 1.30	−4.41	Wheat Straw, 40 t ha^{-1}	Aquialluvic Primisol, China	Liu et al. (2014)
	Decreased from 1.22 to 0.97	−20.49	Willow wood, 10 t ha^{-1}	Red soil, Australia	Bass et al. (2016)
	Decreased from 1.57 to 0.91	−42.04	Hard wood, 30 t ha^{-1}	Sandy Loam Alfisol, Nigeria	Adekiya et al. (2020)
Soil porosity (%)	Increased from 40.75 to 66.0	+25.25	Hardwood, 30 t ha^{-1}	Sandy Loam Alfisol, Nigeria	Adekiya et al. (2020)
	Increased from 44.9 to 47.1	+2.2	Wood, 4% w/w	Sandy clay loam, Taiwan	Jien et al. (2021)
	Increased from 51.3 to 55.1	+3.8	Oat hull, 20 t ha^{-1}	Silt loam Inceptisol, Chile	Curaqueo et al. (2014)
	—	+4.35	Mixed crop straws, 16 t ha^{-1}	Loamy entisol, China	Liu et al. (2016a)
Water content (weight %)	Increased from 7.8 to 19	+11.2	Willow wood, 10 t ha^{-1}	Red soil, Australia	Bass et al. (2016)
Water holding capacity	Increased from 26 to 31%	+5	Grain husk and paper fibre sludge, 15 t ha^{-1}	Acidic sandy soil, China	Farkas et al. (2020)
	Increased from 0.285 to 0.321 g g^{-1}	+12.63	Rice husk and cotton shell, 90 t ha^{-1}	Fluvisols, China	Liang et al. (2014)
	Increased from 38.5 to 42.0%	+3.5	Oat hull, 20 t ha^{-1}	Silt loam Inceptisol, Chile	Curaqueo et al. (2014)
Water aggregate stability (%)	Increased from 36.24 to 49.08	+12.84	Oat hull, 20 t ha^{-1}	Silt loam Inceptisol, Chile	Curaqueo et al. (2014)
			Chemical properties		
pH	Increased from 5.14 to 5.7	+10.89	Eupatorium, 40 t ha^{-1}	Silty loam Inceptisol, Nepal	Pandit et al. (2018)
	Decreased from 6.57 to 6.35	−3.35	*Acacia* green waste, 47 t ha^{-1}	Tasmania, Australia	Agegnehu et al. (2016)
	Increased from 6.21 to 6.45	+3.86	Willow wood, 10 t ha^{-1}	Red soil, Australia	Bass et al. (2016)
	Increased from 6.08 to 6.26	+2.96	Peanut shells and wheat straw 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Cation exchange capacity (cmolc kg^{-1})	Increased from 6.4 to 8.38	+30.94	Eupatorium, 40 t ha^{-1}	Silty loam soil, Nepal	Pandit et al. (2018)
	Increased from 6.56 to 11.13	+69.66	Willow wood, 10 t ha^{-1}	Red soil, Australia	Bass et al. (2016)
	Increased from 9.64 to 10.01	+3.84	Litchi branch, 30 t ha^{-1}	Red acidic soil, china	Jiang et al. (2020)
	Increased from 6.27 to 9.69	+54.55	Peanut shells and wheat straw 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Electrical Conductivity (dS m^{-1})	Increased from 0.044 to 0.128	+190.9	Willow wood, 10 t ha^{-1}	Red soil, Australia	Bass et al. (2016)
	Decreased from 0.6 to 0.57	−5	Peanut shells and wheat straw 10% (v/v)	landfill cover soil, China	Lu et al. (2020)
	Decreased from 0.08 to 0.01	−87.5	Pine wood, Pine bark and Poplar wood, 20 g/kg	Quincy sand, United States	Suliman et al. (2017)
Solid organic matter/carbon (g kg^{-1})	Increased from 15.4 to 28.32	+83.9	Rice straw, 50 t ha^{-1}	Anthraquic Gleysols, Philippines	Haefele et al. (2011)
	Increased from 0.85 to 1.17	+37.65	Wheat bran, 14 t ha^{-1}	Silty-clay, Italy	Vaccari et al. (2015)
	—	+31.8	Eupatorium, 40 t ha^{-1}	Silty loam soil, Nepal	Pandit et al. (2018)
	Increased from 8.3 to 9.9	+19.28	Wood, 4% w/w	Sandy clay loam, Taiwan	Jien et al. (2021)

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TABLE 1 | (*Continued*) Quantitative impact of biochar application on physical, chemical and biological properties of soils from field trials.

Property	Impact	% Change	Biochar feedstock, application rate	Soil type, location	References
Total Nitrogen (N) (cmolc kg^{-1})	Increased from 0.18 to 0.21%	+0.03	Hardwood, 30 t ha^{-1}	Sandy Loam Alfisol, Nigeria	Adekiya et al. (2020)
	Increased from 1.41 to 1.64	+16.31	Rice straw, 50 t ha^{-1}	Anthraquic Gleysols, Philippines	Haefele et al. (2011)
	Increased from 1.04 to 1.14	+9.62	Wheat straw, 40 t ha^{-1}	Aquialluvic Primisol, China	Liu et al. (2014)
	Increased from 0.74 to 0.81	+9.46	Hard and softwood mix, 20 t ha^{-1}	Sandy loam, Belgium	Nelissen et al. (2015)
Phosphorus (P) (mg kg^{-1})	Increased from 13.3 to 14.7	+10.53	Rice husk, 41.3 t ha^{-1}	anthraquic Gleysols, Philippines	Haefele et al. (2011)
	Increased from 11.1 to 17.7	+59.46	Hardwood, 30 t ha^{-1}	Sandy Loam Alfisol, Nigeria	Adekiya et al. (2020)
	Decreased from 3.71 to 1.24	–66.58	Wood, 4% w/w	Sandy clay loam, Taiwan	Jien et al. (2021)
Available K	Increased from 0.17 to 0.21 g kg^{-1}	+23.53	Wheat straw, 40 t ha^{-1}	Aquialluvic Primisol, China	Liu et al. (2014)
	Increased from 0.1 to 0.17 cmolc kg^{-1}	+70	Hardwood, 30 t ha^{-1}	Tropical Sandy Loam Alfisol, Nigeria	Adekiya et al. (2020)
			Biological properties		
Total viable count	—	+15	*Acacia* tree green waste, 47 t ha^{-1}	Kurosol, Australia	Abujabhah et al. (2016)
Actinobacteria	Decreased from 18.71 to 8.69%	–10.02	Peanut shells and wheat straw, 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Acidobacteria	increased from 4.86 to 5.91%	+1.05	Peanut shells and wheat straw, 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Proteobacteria	—	+3.0	*Acacia* tree green waste, 47 t ha^{-1}	Kurosol, Australia	Abujabhah et al. (2016)
	Increased from 21.96 to 24.1%	+2.14	Peanut shells and wheat straw, 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Alphaproteobacteria	—	+1.81	Zea mays biochar, 30 t ha^{-1}	Sandy loam, United Kingdom	Jenkins et al. (2017)
	—	+12	*Acacia* tree green waste, 47 t ha^{-1}	Sandy loam, Tasmania	Abujabhah et al. (2016)
Betaproteobacteria	—	+11	*Acacia* tree green waste, 47 t ha^{-1}	Sandy loam, Tasmania	Abujabhah et al. (2016)
Gammaproteobacteria	—	+10			
Bacterial 16SRNA gene (*10^{6})	Increased from 600 to 1,400	+133.3	-, 15 t ha^{-1}	-, Tianjin, North China	Wang et al. (2021)
Arbuscular Mycorrhizal fungal abundance (in root)	—	–77	Mango wood, 116.1 t C ha^{-1}	Alluvial sediments, Columbia	Warnock et al. (2010)
Ascomycota	—	+39	*Acacia* tree green waste, 47 t ha^{-1}	Kurosol, Australia	Abujabhah et al. (2016)
Fungal ITSRNA gene (*10^{6})	Increased from 1 to 6	+500	-, 15 t ha^{-1}	-, Tianjin, North China	Wang et al. (2021)

Note: The impacts (increase/decrease) are presented for the control vs the highest biochar application treatment in the field trials.
'-': Information not available.

Improvement in microbial abundance after biochar addition (47 t ha^{-1}) was observed in a 3.5-years field study in Tasmania, Australia (temperate region) (Abujabhah et al., 2016). In another field study (2 years) in Australia, a rise in P-mobilizing mycorrhiza in biochar added soils was observed owing to the indirect effects of biochar on soil physico-chemical properties (Solaiman et al., 2010). An increase in the colonization rate of arbuscular mycorrhizal fungi (AMF) after application of bark charcoal of *Acacia mangium* was observed in maize in South Sumatra, Indonesia (Yamato et al., 2006). In contrast, studies have also found neutral and negative effects of biochar amendment on soil microbial activity. For a field trial on wheat crop, biochar addition (3 or 6 kg/m^2) did not show any changes on soil microbial biomass either 3 or 14 months after char addition (Castaldi et al., 2011). However, a field study of mango-wood (*Mangifera indica)* biochar application in Colombia at rates of 23.2 and 116.1 t C ha^{-1} has resulted in a decrease of AMF abundance in soils by 43 and 77%, respectively, (Warnock et al., 2010). The decrease in AMF abundance could be due to the release of ethylene or organic pyrolytic by-products, including phenolics and polyphenolics from biochar that exert a negative effect on soil microflora (Spokas et al., 2010; Warnock et al., 2010).

Further, owing to different mechanisms of action, biochar may elicit variable metabolic responses in microbial populations resulting in specific taxonomic shifts in the composition of microbial community (Khodadad et al., 2011). A field study conducted at three European locations (West Sussex, UK; Prato Sesia, Italy; Lusignan, France) using Zea mays-derived biochar (30 t ha^{-1}) showed significant changes in the composition of the microbial community (Jenkins et al., 2017). After a year of biochar application, the UK site showed an increase in *Gemmatimonadetes*, and *Acidobacteria*, the Italian site showed an increase in *Gemmatimonadetes*, and *Proteobacteria* whereas the French site reported no significant impact on the abundance of individual bacterial taxa. Further, fungal diversity was influenced by biochar treatment in Italy and France but was unaffected in the UK samples. An increase in abundance of *Proteobacteria*, *Bacteroidetes*, and *Actinobacteria* and a decrease in that of *Acidobacteria*, *Chloroflexi*, and *Gemmatimonadetes* on biochar treatment was earlier reported in a laboratory study in China using Zea mays biochar (Xu et al., 2016). Another field study in Foshan, Southern China (subtropical) using sugarcane bagasse biochar showed an increased bacterial and actinomycetes population and decreased fungal population (Nie et al., 2018). On the contrary, a significant increase in the fungal community diversity and decrease in the bacterial community diversity was reported on biochar amendment in the soil of a Chinese fir plantation (*Cunninghamia lanceolate*) (Song et al., 2020). **Table 1** presents the effects of biochar application on physical, chemical and biological properties of soils.

Effects of Biochar on Contaminant Removal

Growing anthropogenic activities such as urbanization and industrialization have resulted in increased concentration of heavy metal and other toxic materials in the soil and water. This directly impacts soil health by increasing stresses and soil-plant-food transfer, ultimately increasing contaminant uptake in the human body (Mulligan et al., 2001). Cd, Cu, Zn, Pb etc., are commonly found heavy metals in the soil. Cd and Pb presence in rice grains raised health concerns as rice is cultivated in large areas of Asia. Biochar addition can lead to immobilization of heavy metals in soils, thereby decreasing its accumulation in plants (Hua et al., 2009; Beiyuan et al., 2017; Igalavithana et al., 2017). In a 3-year long-term field study, cadmium and lead uptake by rice plants have been reduced by 67 and 69%, respectively, due to large reduction in accumulation by the plant roots (Bian et al., 2014). Application of litchi branch biochar reduced the available cadmium, and lead content in a mining contaminated agriculture soil (South China) under cucumber-sweet potato-grape rotation leading to the reduced uptake of these metals by the three crops (Jiang et al., 2020).

Compost and biochar composites can also be utilized for remediating contaminated soil, apart from their application for improving soil fertility (Wu et al., 2017; Wang et al., 2021). Integrating biochar with nanotechnology can provide hybrid nanomaterial-biochar composites which are environmentally benign and have a significant potential to improve fertility of the soil and remediate wide-ranging contaminants (Zhang et al., 2012; Zou et al., 2016). However, there exists limited literature on field trials compared to laboratory studies.

Effects of Biochar on Plant Growth and Crop Yield

Several field studies have investigated biochar application effects on plant growth and crop yield (Andrew et al., 2013; Biederman and Stanley, 2013; Liu et al., 2014; Jeffery et al., 2017; Cornelissen et al., 2018). Its application has improved crop productivity more prominently in nutrient-deficient and degraded soils (Zhang et al., 2012; Laghari et al., 2015) compared to healthy and fertile soils (Van Zwieten et al., 2010; Hussain et al., 2017). A four-season field trial in Philippines and Thailand (tropical climate) using rice-husk biochar on dry, poor, non-acidic soil, improved yields ranging from 16–35% due to the enhanced water retention and increased availability of K and P (Haefele et al., 2011). Another field study in Ghana found significant increase in the maize yield along with improved soil pH, SOC and the available N, P and K on application of Sorghum and rice-husk biochar (2 t ha^{-1}) (Calys-Tagoe et al., 2019). Similarly, upto 30% increase in crop yield was observed on durum wheat in the Mediterranean region with application of coppiced woodlands biochar at 30 and 60 t ha^{-1} (Vaccari et al., 2011). A field trial in South Sumatra (Indonesia), reported the improvement in soil chemical properties, development of a suitable environment for root growth, and mycorrhizal fungal colonization leading to an increase in maize and peanut yield upon addition of charred bark (37 t ha^{-1}) of *Acacia mangium* (Yamato et al., 2006). Significant increase in maize and common bean (in rotation) yield was observed on application of eucalyptus-based biochar at 10 to 50 t ha^{-1} in acidic soils in Madagascar (humid tropical climate) owing to increased soil pH and lower exchangeable aluminium (Raboin et al., 2016). A field study on pumpkin cultivation in Nepal (subtropical climate) showed that addition of cow urine-biochar combination (0.75 t ha^{-1} biochar and 6.3 m^3 ha^{-1} cow urine) led to a yield increase of >300 and 85% in comparison to only urine and only biochar treatment, respectively (Schmidt et al., 2015). The increase was due to the development of an organic coating on inner pore biochar surface through urine impregnation, which increased biochar's capability to capture and exchange plant nutrients. Thus, these studies suggest that biochar amendment is an effective approach for increasing the crop yield that is not only associated with the improvement of soil structure and carbon content but also with the improvement in nutrient availability, nutrient use efficiency and impact on soil microbial community.

TABLE 2 | Summarised impact of biochar as observed in some field trials.

References	1. Biochar feedstock 2. Application rate 3. Target crop	Soil type	Climate/Location	Time span of study	Impact
Yamato et al. (2006)	1. *Acacia* mangium 2. 10 L m^{-2} 3. Maize, Cowpea and Peanut	Acidic	Tropical Sumatra, Indonesia	twice in 2 years (2003 and 2004)	**Positive:** crop yield, root amount and colonization rate of AMF, total N and available P_2O_5 contents, pH, CEC, amounts of exchangeable cations and reduction in exchangeable Al^{3+} content
Asai et al. (2009)	1. Teak and Rosewood 2. 4,8,16 t ha^{-1} 3. Rice	—	Tropical Laos	6 months	**Positive:** soil physical properties, saturated hydraulic conductivity, P availability and nutrient uptake efficiency. **Negative:** leaf SPAD values, plant N uptake, biochar without N fertilizer decreased grain yield
Zhang et al. (2010)	1. Wheat straw 2. 10 and 40 t ha^{-1} 3. Rice	Stagnic Anthrosol	Subtropical Jiangsu, China	—	**Positive:** crop yield, total N_2O emissions sharply decreased, increase in pH, SOC and total N, decreased bulk density. **Negative:** increase in total soil CH_4-C emissions
Major et al. (2010)	1. Wood 2. 8,20 t ha^{-1} 3. Maize-Soybean (rotation)	Oxisol, Colombian savanna Acidic	Tropical Columbia	4 years (2003–2006)	**Positive:** increased crop yield in 2nd and 3 rd year but decline in 4 th year, pH, available Ca and Mg. **Neutral:** Total C and N contents, CEC
Jones et al. (2012)	1. Wood-based 2. 0, 25, and 50 t ha^{-1} 3. Maize (1st year) and Grass (2nd and 3rd year)	Eutric Cambisol, sandy clay loam texture	Temperate Wales, England	3 years	**Positive:** soil pH (year 2), grass foliar uptake rate of N (2 nd year), above-ground biomass (3 rd year), basal soil respiration and microbial growth rates. **Neutral:** maize growth, leaf chlorophyll content, total N, exchangeable Na and Ca, electrical conductivity, C (DOC), moisture content, bulk density, NO_3^- or NH_4^+ pool sizes, N mineralization and denitrification. **Fading:** after 3 years, alkalinity associated with biochar fully neutralized and biochar lost most of its cations (Na, K, Ca)
Lentz and Ippolito (2012)	1. Hardwood 2. 22.4 t ha^{-1} 3. NA	Portneuf silt loam calcareous	Idaho United States	2 years	**Positive:** 1.5 times increase in available soil Mn and a 1.4 times increase in TOC. **Neutral:** pH or availability of P and cations, total N, extractable soil nutrients other than Mn
Liu et al. (2014)	1. Wheat straw 2. 0, 20, 40 t ha^{-1} 3. Wheat and Maize (rotation)	Calcic Aquialluvic Primisol, calcareous	Semi-humid Temperate, Henan, China	5 crop seasons	**Positive:** decreased N_2O emission, SOC, available potassium (K), total nitrogen and decreased bulk density. **Neutral:** crop yield, total CO_2 efflux, soil pH and available P
Liang et al., (2014)	1. Rice husk and cotton seed shell 2. 30, 60, and 90 t ha^{-1} 3. Wheat (winter), Maize (summer) (in rotation)	Fluvisols, calcareous sandy loam soil	Continental Beijing, China	3 years	**Positive:** slight increase in soil pH, increase in grain yield by 7–10%. Exchangeable K increased. **Neutral:** soil P and CEC. **Negative:** N decreased. Overall, no major effect on crop yield or nutrient availability. Authors proposed biochar addition mainly for C sequestration in calcareous soils
Curaqueo et al. (2014)	1. Oat hull 2. 0, 5, 10, and 20 t ha^{-1} 3. Barley	Inceptisol, Silt loam	Chile	195 days	**Positive:** pH, electrical conductivity, total exchangeable bases, and barley yield. **Neutral:** WHC
Busch and Glaser (2015)	1. Conifer wood bark 2. 24.2 t ha^{-1} 3. NA	Regosol, arid soil	Temperate, Halle, Germany	2 years	**Positive:** overall increase in soil N and TOC. **Neutral:** No change in pH Fading effect of biochar seen with time
Abiven et al. (2015)	1. Maize cobs 2. 4t ha^{-1} 3. Maize	Oxisol, Acidic sandy	Tropical, Zambia	6 months	**Positive:** crop yield, root biomass twice as high as control, more developed root system, increased immobile nutrient uptake

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TABLE 2 | (*Continued*) Summarised impact of biochar as observed in some field trials.

References	1. Biochar feedstock 2. Application rate 3. Target crop	Soil type	Climate/Location	Time span of study	Impact
Vaccari et al. (2015)	1. Wheat bran 2. 14 t ha^{-1} 3. Tomato	Alkaline and silty-clay	Temperate Italy	3 months	**Positive:** soil pH, CEC, SOC, K and Na, P, root weight and length. **Neutral:** crop yield, Mg^{2+}, and Ca^{2+}
Nelissen et al. (2015)	1. Woody biochar 2. 20 t ha^{-1} 3. Spring Barley	Sandy loam soil	Temperate, Merelbeke (Belgium)	2 years	**Positive:** SOC, short-term increase in plant-available soil K. **Neutral:** crop yield and nutrient uptake, soil water content, NH_4^+, NO_3^- concentrations, measured soil physical, chemical and biological properties
Agegnehu et al. (2016)	1. Waste willow wood 2. 25 t ha^{-1} 3. Maize	Red Ferrosol, acidic	Tropical, Queensland, Australia	145 days	**Positive:** maize yield, SOC, SWC, CEC, soil nutrient status, available P, total N, exchangeable Ca, **Neutral:** exchangeable Mg, K and Na
Liu et al. (2016a)	1. Mixed crop straws 2. 16 t ha^{-1} 3. NA	Loamy soil	Sichuan China	—	**Positive:** increase in soil water holding capacity, increase in total porosity, slight decrease in bulk density, and increase in SOM by 2.6–4.5 g kg^{-1}
Sänger et al. (2017)	1. Maize silage 2. 7.7 t ha^{-1} 3. Wheat, Rye and Maize	Cambisol, Sandy loam	Temperate, Germany	3 years	**Positive:** soil nutrient **Neutral:** yield and interaction with N fertilizer supply
Gautam et al. (2017)	1. Grass 2. 5 t ha^{-1} 3. Coffee	Clay soil acidic	Subtropical, Nepal	—	**Positive:** SOC, pH, crop growth (height), K **Neutral:** crop yield, TN, CEC (slightly higher but not statistically significant differences)
Cornelissen et al. (2018)	1. Rice husk, cocoa shell 2. 5,15 t ha^{-1} 3. Maize	Ultisol sandy loam acidic	Tropical, Sumatra Indonesia	5 growth seasons, 2012–2014	**Positive:** Maize yield. **Fading:** biochar must be applied every third season to offset its declining effects
Pandit et al. (2018)	1. Eupatorium adenophorum 2. 5, 10, 15, 40 t ha^{-1} 3. Maize and mustard	Inceptisol silty loam acidic	Subtropical, Nepal	Multi-seasonal	**Positive:** crop yield, cost benefit C sequestration, plant available K+, P, pH, total organic C% and CEC.
Jin et al. (2019)	1. Wheat straw 2. 2.5, 5, 10, 20, 30, and 40 t ha^{-1} 3. Rapeseed and sweet potato (rotation)	Ultisol, upland red soil acidic	Subtropical Jianxi, China	5 years	**Positive:** crop yield, soil pH, available P, SOC, hydraulic conductivity, water retention, Soil N, NH_4^+-N and NO_3^-N content, enhanced soil microorganisms and enzymatic activities. **Fading:** biochar application effects on soil nutrients and crop yield faded with time
Song et al. (2019)	1. Bamboo leaf 2. 5, 10 t ha^{-1} 3. Moso bamboo	Ferralsol sandy silt	Subtropical, Zhejiang China	2 years	**Positive:** decreased N_2O emission, soil moisture content, water soluble organic C, **Negative:** N availability and enzyme activities
Yang et al. (2019)	1. Rice Straw 2. 20 and 40 t ha^{-1} 3. Rice	Hydragric Anthrosol	Subtropical, Jiangsu China	2 seasons	**Positive:** CH_4 and N_2O emissions, Rice yield, enhanced soil DOC, total N, NH^{4+}-N and reduced NO^{3-}-N concentrations
Huang et al. (2019)	1. Tobacco straw 2. 10, 40, and 80 t ha^{-1} 3. Tobacco and Rice	Anthrosol, acidic	Subtropical, China	2 seasons	**Positive:** Potassium and SOM content, bulk density decreased, $CH_4$and N_2O emissions decreased
Adekiya et al. (2020)	1. Hardwood 2. 0, 10, 20, and 30 t ha^{-1} 3. Cocoyam	Alfisol sandy loam	Nigeria	2 years	**Positive:** Cocoyam yield, soil bulk density, porosity, mean weight diameter (MWD) of soil aggregates, soil organic matter, pH, N, P, K, and CEC
Jiang et al. (2020)	1. Litchi branch 2. 10, 20, and 30 t ha^{-1} 3. Cucumber-sweet potato-rape (rotation)	Red soil acidic	Guangdong Subtropical, China	1 year	**Positive:** pH, CEC, SOM, Cd, and Pb uptake decrease, crop yield, chlorophyll content of plants

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TABLE 2 | (*Continued*) Summarised impact of biochar as observed in some field trials.

References	1. Biochar feedstock 2. Application rate 3. Target crop	Soil type	Climate/Location	Time span of study	Impact
Lu et al. (2020)	1. Peanut shells and wheat straw 2. 5 and 10% (v/v) 3. NA	landfill cover soil	Subtropical, Shenzhen, China	3 years	**Positive:** CEC, SOM, water content, total N, total P, total C, richness of bacterial, and archaeal species, increase in genes involved in P cycling **Neutral:** electrical conductivity, DOC, soil pH, H content, available N content **Negative:** abundance of genes related to C and N cycling
Farkas et al. (2020)	1. Grain husk and paper fibre sludge 2. 3, 15, and 30 t ha^{-1} 3. NA	Lamellic Arenosol (acidic) and Mollic Umbrisol, calcareous	Temperate, Hungary	2.5 years	**Positive:** CEC Positive effects w.r.t. OM, pH, WHC, nutrient (P, K) content, increased microbial activity and diversity seen in acidic sandy soil. Neutral effects on calcareous soil
Gao et al. (2020)	1. Softwood 2. 29 and 58 t ha^{-1} 3. Onion	Hanford, sandy loam	Temperate, United States	3 years	**Positive:** SOC, pore water pH, and electrical conductivity. **Neutral:** crop yield, N loss, N_2O emissions

Some field studies have reported an increase in crop yield from the second year rather than after immediate application of biochar (season 1). A 4-year field trial with wood-based biochar (8 and 20 t ha^{-1}) on yield of maize and soybean (in rotation) in Columbian tropical region showed no increase in the maize yield during the first year (Major et al., 2010). However, second, third and fourth year reported an increase of 20, 30, and 140%, respectively, indicating a long-term effect of biochar on the crop yield. Similar result was observed on maize and mustard (in rotation) in acidic silty loam in Rasuwa, Nepal where no considerable effect was seen on crops yield in the first year (Pandit et al., 2018). However, 50, 47, and 93% increase in maize and 96, 128, and 134% increase in mustard yield at 15, 25, and 40 t ha^{-1}biochar application rate was observed during the second year. Yields of both maize and mustard correlated strongly with plant available P, K^+, total organic carbon %, pH and CEC, and improved with increasing biochar application rate. Results from these studies show that biochar needs a certain degree of aging in soil before starting to exert a positive impact on the crop yield. Similarly, Haider et al. (2017) also found aged biochar to be more effective in comparison with fresh biochar for nutrient capture and enhanced crop yield over time (Haider et al., 2017). It may be due to the slow development of an organic coating on biochar's surface after aging in compost media which enhances nutrient retention (Hagemann et al., 2017). These observations substantiate the requirement of long-term field trials of biochar application to accurately analyze its effects on crop yield and soil quality.

Some field studies have also reported a decline in crop yield and other negative effects of biochar application with time. Jin et al. (2019) investigated the effect of wheat straw biochar application (0–40 t ha^{-1}) on the yield of rapeseed in upland red soil of China over a 5-year field trial. Increase in rapeseed yield was observed during the first year when biochar application rate was more than 10 t ha^{-1} following which the effect of biochar started to fade as its influence on soil pH, bulk density, available P, soil organic carbon, and available water content reportedly decreased (Jin et al., 2019). Similarly (Cornelissen et al., 2018), in a field trial in highly acidic ultisol (pH 3.6) in Indonesia, observed that after an initial increase in maize yield and soil pH, the effects of biochar started to fade after the third season recommending reapplication of biochar after 3–5 seasons. Fading was due to the continued nutrient leaching and depletion of alkalinity associated with biochar (Cornelissen et al., 2018). Another study showed that 3 years after biochar application to a maize and grass field trial insandy clay loam of Wales (temperate), the alkalinity associated with biochar was neutralized and biochar lost most of its cations (Na, K, Ca) (Jones et al., 2012). Similarly (Steiner et al., 2007), investigated the effects of biochar over four planting seasons in Brazilian Amazon oxisol (pH = 4.5), and reported a cumulative increase in yield of approximately 75% for rice and sorghum that faded with time in subsequent seasons (Steiner et al., 2007). A summarized impact of biochar as observed in some field trials is presented in **Table 2**. These studies indicate the fading effectiveness of biochar after multiple growth seasons and highlight the need to investigate multiple biochar amendments.

Meta-analysis presents a better understanding of the influence of biochar on different soil types across the globe. Several meta-analysis studies have explored the effect of biochar application on plant growth and crop yield. A meta-analysis (111 publications) revealed that biochar application did not have a considerable effect on crop yield in the temperate regions, whereas an average of 25% increase in crop yield was observed in the tropical regions (Jeffery et al., 2017). Similarly, another meta-analysis derived from 17 studies on the response of tree growth following biochar application revealed a 38% higher plant growth in tropical regions in comparison to 10% plant growth in temperate regions (Thomas and Gale, 2015). The liming effect, increased water holding capacity, and enhanced nutrient availability following biochar addition were adjudged as the reasons for the yield increase in tropical conditions. On the contrary, lower effects of biochar amendment in temperate regions can be attributed to high fertility, high CEC, high water retention capacity, and rich nutrient availability of the temperate soil that results in the yield already nearing its maximum potential.

The average overall increase in crop yield due to biochar amendment was found to be 13% (Liu et al., 2013), closer to the increase of 11% reported previously by another meta-analysis covering over 100 published experiments (Jeffery et al., 2011). The meta-analysis (103 publications) also revealed that biochar application to soils had a higher effect on crop yield in the pot experiments than in the field trials, in acidic soils ($pH < 5$) than in neutral soils, and in sandy soils than in loam and silt soils (Liu et al., 2013). Similarly, a meta-analysis (114 publications) reported a significant positive effect (~20% increase) of biochar addition on crop yield and concluded that pH and soil quality increase (largely N, P, K) were major reasons for the same effects (Biederman and Stanley, 2013). These outcomes were confirmed by another meta-analysis (84 publications) which suggested that soil CEC and organic carbon were strong predictors of crop yield response (Andrew et al., 2013). Overall, the meta-analysis studies broadly indicate biochar to be a suitable tool for improving crop yield in acidic and nutrient-poor soils.

Contrary to the positive effects of biochar application, studies have also reported negative effects of application of biochar on the crop yield, plant growth, and nutrient availability (Jeffery et al., 2017; Sänger et al., 2017; Zhang et al., 2020). In some studies, the application of freshly prepared biochar has been reported to hinder crop yield due to the immobilization of nutrients (Ding et al., 2010; Taghizadeh-Toosi et al., 2012; Kammann et al., 2015). (Bass et al., 2016) studied the influence of biochar on papaya and banana yield and soil properties in Queensland, Australia (tropical climate). A positive effect on soil properties was observed with increase in CEC, Ca^{2+}, K^+, SOC content, and water retention, whereas no effect on papaya yield and a negative effect on banana yield (−18%) was seen (Bass et al., 2016). In a field study in China (subtropical climate) uptake of N, P, and K by plants was reduced in rice and wheat crops after 6 years of experimentation (Wang et al., 2018). Few studies have shown no or negative effects of biochar application on crop yields in temperate zones (Schmidt et al., 2015; Sänger et al., 2017; Wei et al., 2020). A 3-year study consisting of seven field trials at five different sites in the UK (temperate zone) showed no increase in crop yield on biochar addition with three statistically positive, one negative and other with no response (Hammond et al., 2013). It is seen that the negative effects of biochar application on crop yields have largely been witnessed in temperate regions as biochar significantly raised the soil pH causing over-liming effect resulting in immobilization of major micronutrients such as Mg, Fe, B, and P.

Thus, it can be concluded from several field studies that improved crop yield due to biochar addition is prominently witnessed in less fertile, acidic, weathered soils in the tropics than in the temperate regions (Jones et al., 2012; El-Naggar et al., 2019), and the effect is due to its ability to neutralize the soil pH (liming effect) and improvement in physico-chemical and biological properties of soils (Jeffery et al., 2011; Cornelissen et al., 2013; Martinsen et al., 2014; Pandit et al., 2018). The implications of this observation are crucial, as around 30% of the world's soils are acidic in nature, including >50% of potential arable land (Galinato et al., 2011). Moreover, the variabilities observed in crop yield and plant growth amongst different investigations can be attributed to different soil properties (texture, pH),feedstocks for biochar and the production methodologies, application rates, targeted crops, and local climatic conditions (Jeffery et al., 2011; Mukherjee et al., 2014). The inconsistent impacts of biochar application on crop yield necessitate improved understanding of the underlying mechanisms of biochar towards promoting crop productivity. This can be done by employing biochar derived from a wide range of feedstocks in different soil types for long-term field trials.

Carbon Sequestration, and GHG Emission Reduction With Biochar Application

Climate change mitigation through carbon sequestration is another significant biochar application apart from improved crop yield (Lehmann, 2007; Sohi et al., 2010; Majumder et al., 2019). Carbon sequestration is the long-term capturing and storing of atmospheric CO_2, to mitigate global warming. The major pools of carbon are atmospheric, terrestrial, ocean, and geological (Woolf et al., 2010). The carbon in these pools has a variable lifetime, with interconnected/interlinked flows. Carbon in the active carbon pool moves quickly between different pools, and to reduce atmospheric carbon, it is required to move to a passive pool having inert or stable carbon (Lehmann, 2007). With time, biochar is being considered as a serious option for realizing the global climate change targets since it offers a facile flow of carbon from the active pool to the passive pool. Applied biochar is present in soil in a highly stabilized form that can store carbon over hundreds to thousands of years, converting it into a major carbon sink (Schmidt and Noack, 2000). Carbon sequestration in biochar enhances carbon's storage time in comparison with other terrestrial sequestration approaches like afforestation or reforestation (Wang et al., 2016). Biochar amendment can thus play a significant role in carbon removal from the atmosphere and simultaneous reduction of GHG emissions.

Emissions of radiatively active gases such as CH_4 and N_2O, whose global warming potential (GWP_{100}) for a 100 years time horizon is more than 28 and 265 times stronger than CO_2, respectively, have been reduced from soils with biochar application (Vijay et al., 2021). Biochar can play a greater role in short term CH_4 emission reduction to help meet the 2050 GHG targets, as methane's GWP_{20} (for 20 years time horizon) value of 84 is much higher than its GWP_{100}, due to its short residence time in atmosphere (Balcombe et al., 2018). The N_2O, having a much longer residence time in the atmosphere, is a significant contributor to GHG. Around 62% of the atmospheric N_2O emissions are attributed to soils (Biernat et al., 2020). High rates of nitrogen-based fertilizer application to the fields also emit N_2O to the environment. Biochar addition to soil effectively mitigate the soil N_2O emissions and the mitigation can be attributed to the inhibition of either stage of nitrification and/or denitrification as reported in both field and lab studies (Rondon et al., 2007; Cayuela et al., 2014; Weldon et al., 2019). Improved soil aeration from biochar application decreases denitrification due to inhibition of activity of anaerobic microorganisms involved in denitrification. Biochar application leads to microbial immobilization of available N in soil, reducing the N_2O source capacity of soil. Improved pH from application of biochar drives the formation of N_2 from N_2O. Furthermore, the enhanced fertility of soil with biochar application will also assist farmers to adapt to the changing climate, thus reducing the intensity of climate change (Zhang et al., 2016).

Application of 5 t ha^{-1} biochar in bamboo plantations in China has shown reduction in soil N_2O efflux by 28.8% in the first year and 19.7% in the second year (Song et al., 2019). Increasing application rate of biochar to 15 t ha^{-1} led to 31.3 and 30.1% reduction in N_2O flux over the first and second year, respectively, with respect to the control. Biochar application reduced soil N_2O emissions by decreasing the concentrations of soil labile N forms and hindering the activities of N-cycling enzymes (Song et al., 2019). A field study on maize crop in Switzerland reported that the enhanced soil gas diffusivity in biochar added soil (and thus improved soil aeration), may lead to reduced N_2O emission (Keller et al., 2019). However, Suddick and Six (2013) found no considerable change in N_2O flux with the application of biochar and compost. The study recommended that certain biochar types may be less suitable for N_2O mitigation in some agricultural soils, at least on shorter temporal scales, or that a minimum biochar quantity is needed for effective reduction (Suddick and Six, 2013). Findings are corroborated with another study wherein it was observed that N_2O emissions do not always get reduced, and sometimes biochar application shows neutral or negative effects (Gao et al., 2020).

Improved aeration, especially of fine-grained soils, also enhances the sink capacity for CH_4 by increasing the abundance of methanotrophic *proteobacteria*, enhancing CH_4 oxidation and thereby reducing CH_4 emissions (Al-Wabel et al., 2019). Biochar application was found to reduce the total CH_4 and N_2O emissions from paddy fields under controlled irrigation in two rice seasons (Yang et al., 2019). Controlled irrigation considerably reduced CH_4 emissions while increasing N_2O emissions in comparison with flood irrigation management. Biochar application (20 t ha^{-1}) in this study did not have any effect on SOC or soil pH, whereas it increased the soil DOC, Total N, NH_4^+-N significantly and reduced NO_3^--N concentrations compared to non-amended soil (Yang et al., 2019). Another study reported that the biochar addition reduced the abundance of methanogenic archaea resulting in lower CH_4 emission (Huang et al., 2019). Beyond its application in the agricultural context, biochar has also gained interest in the waste management industry as a media to enhance control of landfill gas emissions. Landfills are one of the largest contributors of global anthropogenic CH_4 emissions at approximately 17.4% of the total CH_4 emissions in 2018 in the United States alone (USEPA, 2020). One of the options for long-term reduction of CH_4 fluxes is the microbial oxidation of CH_4 in biofilters, biowindows, or biocovers (Huber-Humer et al., 2008; Scheutz et al., 2009). The performance of these engineered methane oxidation systems can be enhanced if the soils in use are amended with biochar. Reddy et al. (2014) showed that both, abundance of methanotrophs and the CH_4 oxidation capacity, were increased by adding 20% biochar from wood chips to a fine-grained soil (fraction <75 μm = 92%) (Reddy et al., 2014). In a more coarsely grained, sand-dominated soil, enhanced CH_4 oxidation following 10% biochar amendment as attributed to the positive effect of biochar on the soil's water retention capacity (Yargicoglu and Reddy, 2018).

The amelioration of crop productivity in tropical conditions after biochar application results in higher photosynthesis rates and higher CO_2 reduction in the atmosphere if part of the C fixed by photosynthesis is sequestered in the soil in the long term. Biochar is reported to be 10 to 100 times more stable than most of the other soil organic matter due to its condensed aromatic content (Jeffery et al., 2011). A meta-analysis (128 studies) on the stability of biochar in soils estimated the mean residence time of biochar labile and recalcitrant fraction, pool size = 3% and pool size = 97% as 108 days and 556 years, respectively, indicating that the major part of biochar (97%) contributes to long-term carbon sequestration in soil (Wang et al., 2016). A model prediction estimated that biochar production and implementation to soil can potentially offset a maximum of 1.8 Pg $CO_{2eq.}$ emissions (12% of anthropogenic $CO_{2eq.}$ emissions) every year, and over the century, the total net offset of emissions from biochar would be 130 Pg CO_2eq. (Woolf et al., 2010).

Production of biochar from crop waste and its amendment is reported to avoid 4,348–4,878 kg CO_2 ha^{-1} emissions in a year based on modelling predictions (Gaunt and Lehmann, 2008). As biochar contains 60–80% (approx.) of carbon, for every tonne of biochar added to soil 0.6–0.8 tonnes of carbon can be sequestered which is equivalent to the 2.2–2.93 MT of CO_2 (Galinato et al., 2011). Limestone is commonly used to reduce the soil pH for agricultural applications, however, per tonne of limestone usage leads to 0.059 MT C or 0.22 MT CO_2 emission in the atmosphere. These emissions can be avoided by using biochar in place of lime. It is estimated that if 6.48 MT lime usage per hectare of land is replaced by 76.53 MT biochar, it can offset 225.6 MT CO_2 ha^{-1} through avoided emissions and biochar carbon sequestration (West and McBride, 2005).

Priming Effect

Biochar addition to soil has exhibited priming effects in several studies. Priming refers to an alteration in native SOC decomposition owing to the addition of a new organic substrate such as biochar. Based on the increase or decrease in the rate of SOC mineralization on biochar addition, priming effects can be positive or negative, respectively, (Kuzyakov et al., 2000; Guenet et al., 2010; Maestrini et al., 2015). It is to be noted that C sequestration will be partially compromised during positive priming, whereas C sequestration potential will be higher than expected during negative priming (Woolf and Lehmann, 2012).

Previous studies suggest that biochar priming gets influenced from many factors including experimental duration, biochar properties (type of feedstock and pyrolysis temperature), soil properties (carbon content, pH) and incubation conditions including soil temperature and moisture (Singh and Cowie, 2014; Wang et al., 2016; Chen G. et al., 2021). A meta-analysis of 18 studies reported that biochar addition results in positive priming for a short-term followed by negative priming for a long-term (Maestrini et al., 2015). It was indicated that a positive priming effect was induced due to the availability of labile fraction in biochar that triggered the activity of soil microorganisms in the short term. Positive priming may happen as a direct effect of enhanced production of extracellular enzymes due to the added substrate or indirect mechanisms, such as the improvement in soils aeration, structure, or moisture. The negative priming effects were elucidated by various mutual non-exclusive mechanisms, including the deactivation of microbial enzymes, decreased microbial accessibility of interior SOC by promoting soil aggregation, and the physical protection of organic matter by sorption on biochar surfaces, after the ceasing of positive priming (Guenet et al., 2010; Zimmerman et al., 2011; Liu et al., 2020).

A 3-year field study conducted in coppice plantations in Northern Italy established the role of plant roots in positive priming due to enhanced biochar decomposition (Ventura et al., 2019). However, biochar was found to decrease the decomposition of SOM by 16%, in the absence of roots, indicating a negative priming effect. Another field-study conducted in Europe, showed that the decomposition rate of biochar in field was greater than expected from lab incubations and highlighted that biochar stability cannot be accurately estimated in lab incubations (Ventura et al., 2015). An incubation study of grass and wood biochars in sandy soils witnessed both negative and positive priming (Zimmerman et al., 2011). Positive priming was witnessed in low-temperature biochars in the initial 3 months of the experimentation due to the mineralization of more labile components of biochar over the short term. However, in the longer term (250–500 days), mineralization of both SOC and biochar was found to be repressed, due to sorption of native SOM to surface and pores of biochar and physical protection.

It is observed that there still exists a large gap in the understanding of the effects of biochar application on soil C accumulation following various C input patterns. Further, many uncertainties are noticed in different studies for the factors affecting the amplitude and the direction of priming due to biochar addition (Maestrini et al., 2015). It has also been observed that most of the existing studies are short-term incubation, and it is challenging to extrapolate short-term laboratory incubations to long-term effects in the natural environment. Therefore, long-term field trials are essential to facilitate direct evidence for biochar-induced priming effect on SOC mineralisation.

CONCLUSION

The following conclusions are drawn based on the analysis of biochar field trials.

- Needs and effects of biochar application

Studies on biochar application to soil indicate that it can be a sustainable solution for handling soil fertility and associated environmental issues. The available literature indicates that application of biochar can exhibit positive effects on soil health and crop yield due to several factors including increased nutrient availability, water retention capacity, soil microbial biomass, soil pH, and CEC. It can also have neutral/negative effects due to immobilization of nutrients, over-liming effects or in soils which are already nutrient rich, fertile and have neutral pH. The crops considered for the field trials, feedstock materials, and pyrolysis parameters vary with different studies. In addition, biochar application rates, soil systems, and agro-climatic conditions are very diverse, thereby, making it difficult to have a generalized consensus on results which is hindering the present understanding of potential of biochar to increase crop productivity and alleviate climate change.

- Higher benefits of biochar in tropical regions

General trends clearly indicate that biochar application provides more benefits in terms of soil properties and crop yield in tropical regions than in other regions due to relatively poor soil quality characteristics in the tropics. Application of biochar made from different feedstocks cannot always provide the same effect for the same soil property in less fertile soils. Therefore, the application of apt biochar to the suitable soil should be considered when enhancement in a particular soil function is sought. Thus, it is important to map climatic conditions, soil types, soil pH, soil nutrients, and biochar properties to specific crops and their yield with changes in these parameters.

- Properties of original soil

The impact of biochar amendment on soil chemical, physical and therefore biological quality, together determining soil health and agricultural productivity, depend very much on the property inventory of the original soils. Opposed effects on soil physical properties such as compactibility, water retention, and air transport properties, for example, are reported for biochar amendment to coarse-grained and fine-grained soil due to the fundamental differences in structure forming potential (leading to macroporosity), pore-size distribution and connectivity and tortuosity of the pores. The extent of beneficial effects of biochar on soil chemical properties is, for example, is dictated by properties such as the soil's original buffering capacity, surface charge type and density, amount, type and stability of soil organic matter. Effects hence are always soil and site-specific.

- Lack of long-term biochar field trials

Overall, it can be concluded that number of biochar field trials are severely lacking in comparison to small scale studies (i.e., pot studies, laboratory incubations or greenhouse studies). Different effects of biochar application obtained in small scale studies need to be validated with field studies. Further, many of the available field trials have a time span of 3 months to 1 year, however long-term field trials are lacking to decisively establish the extent of biochar application effects.

- Fading effects of biochar with time

Some studies have revealed that the effects of biochar application on soil properties and crop yield faded with time, necessitating repeated application after regular intervals which needs to be investigated with longer term studies. Some studies have shown a time-lag in the appearance of positive effects of biochar, indicating that aged biochar is more effective than fresh biochar.

Hence, there is an overall need for well-designed, replicated and longer-term (i.e., >12 months/> 5 years) field trials on diverse representative soils to enable robust recommendations to the researchers and users (farmers) on the favourable feedstocks, optimal biochar production conditions, their application rates, and suitable soil type.

AUTHOR CONTRIBUTIONS

VV, SS, and KA: Conceptualization, Writing–Original Draft, Review and Editing. SP: Writing–Original Draft. VS, GG, PM, SY, JG, and TS: Review and Editing. PA: Conceptualization, Supervision, Review and Editing. All authors contributed to the article and approved the submitted version.

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