

University of Groningen

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

Vijay, Vandit; Shreedhar, Sowmya; Adlak, Komalkant; Payyanad, Sachin; Sreedharan, Vandana; Gopi, Girigan; Sophia van der Voort, Tessa; Malarvizhi, P.; Yi, Susan; Gebert, Julia

Published in:
Frontiers in Energy Research

DOI:
[10.3389/fenrg.2021.710766](https://doi.org/10.3389/fenrg.2021.710766)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2021

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Vijay, V., Shreedhar, S., Adlak, K., Payyanad, S., Sreedharan, V., Gopi, G., Sophia van der Voort, T., Malarvizhi, P., Yi, S., Gebert, J., & Aravind, P. V. (2021). Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations. *Frontiers in Energy Research*, 9, [710766]. <https://doi.org/10.3389/fenrg.2021.710766>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.



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

Vandit Vijay^{1*}, Sowmya Shreedhar¹, Komalkant Adlak², Sachin Payyanad³, Vandana Sreedharan³, Girigan Gopi⁴, Tessa Sophia van der Voort⁵, P Malarvizhi⁶, Susan Yi⁷, Julia Gebert⁷ and PV Aravind^{1,8}

¹Climate Institute, Delft University of Technology, Delft, Netherlands, ²Centre for Rural Development and Technology, Indian Institute Technology Delhi, New Delhi, India, ³Centre of Excellence in Systems, Energy & Environment, Government Engineering College Kannur, Kannur, India, ⁴MS Swaminathan Research Foundation, Wayanad, India, ⁵Campus Fryslan, University of Groningen, Leeuwarden, Netherlands, ⁶Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, India, ⁷Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands, ⁸Energy and Sustainability Research Institute Groningen, Faculty of Science and Engineering, University of Groningen, Groningen, Netherlands

OPEN ACCESS

Edited by:

Greeshma Gadlkota,
Cornell University, United States

Reviewed by:

Jyoti Phirani,
Indian Institute of Technology Delhi,
India
Luke Daemen,
Oak Ridge National Laboratory (DOE),
United States

*Correspondence:

Vandit Vijay
v.vijay@tudelft.nl
vanditvijay@gmail.com

Specialty section:

This article was submitted to
Carbon Capture, Utilization and
Storage,
a section of the journal
Frontiers in Energy Research

Received: 17 May 2021

Accepted: 16 August 2021

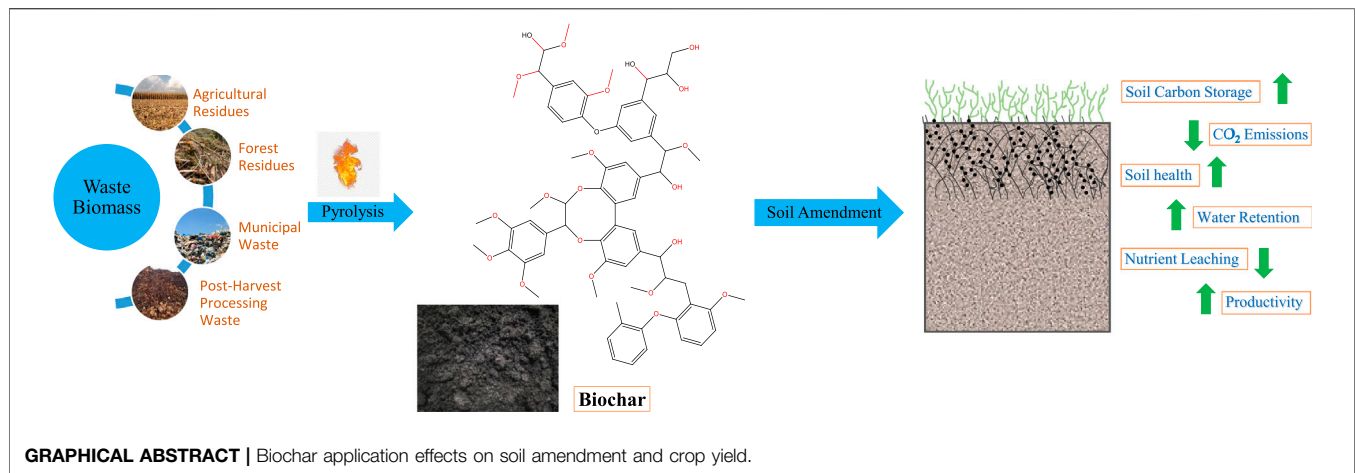
Published: 30 August 2021

Citation:

Vijay V, Shreedhar S, Adlak K, Payyanad S, Sreedharan V, Gopi G, Sophia van der Voort T, Malarvizhi P, Yi S, Gebert J and Aravind PV (2021) Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations. *Front. Energy Res.* 9:710766. doi: 10.3389/fenrg.2021.710766

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



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 (CO₂) (Glaser et al., 2002; Aeggehu 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 (CO₂, N₂O, and CH₄) reduction (Curaqueo et al., 2014; Aeggehu 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; Sanger 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., CO₂, CO, CH₄, and H₂) 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-Rodriguez 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 $>1.7 \text{ Mg m}^{-3}$ (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 $<10 \mu\text{m}$) 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 $<450^{\circ}\text{C}$ (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 $<500^{\circ}\text{C}$ 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 $2.67\text{ cmolc kg}^{-1}$ (levels toxic for plant growth) to $0.12\text{ cmolc kg}^{-1}$ 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 Sodicty

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 $>10 \text{ t ha}^{-1}$ 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 %) Water holding capacity	Increased from 7.8 to 19	+11.2	Willow wood, 10 t ha^{-1}	Red soil, Australia	Bass et al. (2016)
	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	Agegehu 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)

(Continued on following page)

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	Aquiallucic 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	Aquiallucic 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	<i>Acacia</i> tree green waste, 47 t ha ⁻¹	Kurosol, Australia	Abujabhah et al. (2016)
<i>Actinobacteria</i>	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)
<i>Acidobacteria</i>	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)
<i>Proteobacteria</i>	—	+3.0	<i>Acacia</i> 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)
<i>Alphaproteobacteria</i>	—	+1.81	<i>Zea mays</i> biochar, 30 t ha ⁻¹	Sandy loam, United Kingdom	Jenkins et al. (2017)
	—	+12	<i>Acacia</i> tree green waste, 47 t ha ⁻¹	Sandy loam, Tasmania	Abujabhah et al. (2016)
<i>Betaproteobacteria</i>	—	+11	<i>Acacia</i> tree green waste, 47 t ha ⁻¹	Sandy loam, Tasmania	Abujabhah et al. (2016)
<i>Gammaproteobacteria</i>	—	+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)
<i>Arbuscular Mycorrhizal</i> fungal abundance (in root)	—	-77	Mango wood, 116.1 t C ha ⁻¹	Alluvial sediments, Columbia	Warnock et al. (2010)
Ascomycota	—	+39	<i>Acacia</i> tree green waste, 47 t ha ⁻¹	Kurosol, Australia	Abujabhah et al. (2016)
Fungal ITS RNA 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/m²) 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 lanceolata*) (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 m³ 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. <i>Acacia mangium</i> 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 ₂ O 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 ₂ O 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 3rd year but decline in 4th 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 (2nd year), above-ground biomass (3rd 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 ₂ O 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

(Continued on following page)

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 ₂ O 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 ₂ O 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 ₂ O 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

(Continued on following page)

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 ₂ O 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 in sandy 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; Sanger 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, Ca²⁺, 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; Sanger 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 CO₂, 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 CH₄ and N₂O, whose global warming potential (GWP₁₀₀) for a 100 years time horizon is more than 28 and 265 times stronger than CO₂, respectively, have been reduced from soils with biochar application (Vijay et al., 2021). Biochar can play a greater role in short term CH₄ emission reduction to help meet the 2050 GHG targets, as methane's GWP₂₀ (for 20 years time horizon) value of 84 is much higher than its GWP₁₀₀, due to its short residence time in atmosphere (Balcombe et al., 2018). The N₂O, having a much longer residence time in the atmosphere, is a significant contributor to GHG. Around 62% of the atmospheric N₂O emissions are attributed to soils (Biernat et al., 2020). High rates of nitrogen-based fertilizer application to the fields also emit N₂O to the environment. Biochar addition to soil effectively mitigate the soil N₂O 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 N₂O 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 $<75 \mu\text{m} = 92\%$) (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 $CO_2 \text{ ha}^{-1}$ 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 $CO_2 \text{ ha}^{-1}$ 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, (Kuznyakov 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.

REFERENCES

Abiven, S., Hund, A., Martinsen, V., and Cornelissen, G. (2015). Biochar Amendment Increases Maize Root Surface Areas and Branching: a Shovelomics Study in Zambia. *Plant Soil* 395, 45–55. doi:10.1007/s11104-015-2533-2

Abujabbar, I. S., Bound, S. A., Doyle, R., and Bowman, J. P. (2016). Effects of Biochar and Compost Amendments on Soil Physico-Chemical Properties and the Total Community within a Temperate Agricultural Soil. *Appl. Soil Ecol.* 98, 243–253. doi:10.1016/j.apsoil.2015.10.021

Adekiya, A. O., Agbede, T. M., Olayanju, A., Ejue, W. S., Adekanye, T. A., Adenusi, T. T., et al. (2020). Effect of Biochar on Soil Properties, Soil Loss, and Cocoyam Yield on a Tropical Sandy Loam Alfisol. *Scientific World J.* 2020, 1–9. doi:10.1155/2020/93916302020

Agegehu, G., Bass, A. M., Nelson, P. N., and Bird, M. I. (2016). Benefits of Biochar, Compost and Biochar-Compost for Soil Quality, maize Yield and Greenhouse Gas Emissions in a Tropical Agricultural Soil. *Sci. Total Environ.* 543, 295–306. doi:10.1016/j.scitotenv.2015.11.054

Agegehu, G., Bass, A. M., Nelson, P. N., Muirhead, B., Wright, G., and Bird, M. I. (2015). Biochar and Biochar-Compost as Soil Amendments: Effects on Peanut Yield, Soil Properties and Greenhouse Gas Emissions in Tropical North Queensland, Australia. *Agric. Ecosyst. Environ.* 213, 72–85. doi:10.1016/j.agee.2015.07.027

Agegehu, G., Srivastava, A. K., and Bird, M. I. (2017). The Role of Biochar and Biochar-Compost in Improving Soil Quality and Crop Performance: A Review. *Appl. Soil Ecol.* 119, 156–170. doi:10.1016/j.apsoil.2017.06.008

Al-Wabel, M. I., Hussain, Q., Usman, A. R. A., Ahmad, M., Abduljabbar, A., Sallam, A. S., et al. (2019). Impact of Biochar Properties on Soil Conditions and Agricultural Sustainability: A Review. *L. Degrad. Dev.* 250, 2124–2161. doi:10.1016/j.jenvman.2019.109466

Amini, S., Ghadiri, H., Chen, C., and Marschner, P. (2016). Salt-affected Soils, Reclamation, Carbon Dynamics, and Biochar: a Review. *J. Soils Sediments* 16, 939–953. doi:10.1007/s11368-015-1293-1

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., et al. (2009). Biochar Amendment Techniques for upland rice Production in Northern Laos. *Field Crops Res.* 111, 81–84. doi:10.1016/j.fcr.2008.10.008

Atkinson, C. J., Fitzgerald, J. D., and Hipps, N. A. (2010). Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review. *Plant Soil* 337, 1–18. doi:10.1007/s11104-010-0464-5

Balcombe, P., Speirs, J. F., Brandon, N. P., and Hawkes, A. D. (2018). Methane Emissions: Choosing the Right Climate Metric and Time Horizon. *Environ. Sci. Process. Impacts* 20, 1323–1339. doi:10.1039/c8em00414e

Banwart, S. (2011). Save Our Soils. *Nature* 474, 151–152. doi:10.1038/474151a

Bass, A. M., Bird, M. I., Kay, G., and Muirhead, B. (2016). Soil Properties, Greenhouse Gas Emissions and Crop Yield under Compost, Biochar and Co-composted Biochar in Two Tropical Agronomic Systems. *Sci. Total Environ.* 550, 459–470. doi:10.1016/j.scitotenv.2016.01.143

Basu, P. (2010). *Biomass Gasification and Pyrolysis*. Elsevier. doi:10.1016/C2009-0-20099-7

Beiyuan, J., Awad, Y. M., Beckers, F., Tsang, D. C. W., Ok, Y. S., and Rinklebe, J. (2017). Mobility and Phytoavailability of as and Pb in a Contaminated Soil Using pine Sawdust Biochar under Systematic Change of Redox Conditions. *Chemosphere* 178, 110–118. doi:10.1016/j.chemosphere.2017.03.022

Bian, R., Joseph, S., Cui, L., Pan, G., Li, L., Liu, X., et al. (2014). A Three-Year experiment Confirms Continuous Immobilization of Cadmium and lead in Contaminated Paddy Field with Biochar Amendment. *J. Hazard. Mater.* 272, 121–128. doi:10.1016/j.jhazmat.2014.03.017

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.

Biederman, L. A., and Harpole, W. S. (2013). Biochar and its Effects on Plant Productivity and Nutrient Cycling: A Meta-Analysis. *GCB Bioenergy* 5, 202–214. doi:10.1111/gcbb.12037

Biernat, L., Taube, F., Loges, R., Kluf, C., and Reinsch, T. (2020). Nitrous Oxide Emissions and Methane Uptake from Organic and Conventionally Managed Arable Crop Rotations on Farms in Northwest Germany. *Sustainability* 12, 1–19. Available at: <https://ideas.repec.org/a/gam/jsusta/v12y2020i8p3240-d346748.html> (Accessed April 9, 2021). doi:10.3390/su12083240

Blanco-Canqui, H. (2017). Biochar and Soil Physical Properties. *Soil Sci. Soc. America J.* 81, 687–711. doi:10.2136/sssaj2017.01.0017

Bruand, A., and Gilkes, R. J. (2002). Subsoil Bulk Density and Organic Carbon Stock in Relation to Land Use for a Western Australian Sodosol. *Soil Res.* 40, 999–1010. doi:10.1071/SR01051

Bruun, T. B., Elberling, B., Neergaard, A., and Magid, J. (2015). Organic Carbon Dynamics in Different Soil Types after Conversion of forest to Agriculture. *Land Degrad. Develop.* 26, 272–283. doi:10.1002/ldr.2205

Busch, D., and Glaser, B. (2015). Stability of Co-composted Hydrochar and Biochar under Field Conditions in a Temperate Soil. *Soil Use Manage* 31, 251–258. doi:10.1111/sum.12180

Calys-Tagoe, E., Sadick, A., Yeboah, E., and Amoah, B. (2019). Biochar Effect on Maize Yield in Selected Farmers Fields in the Northern and Upper East Regions of Ghana. *Jeai* 30, 1–9. doi:10.9734/jeai/2019/44168

Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., and Ro, K. S. (2012). Impact of Pyrolysis Temperature and Manure Source on Physicochemical Characteristics of Biochar. *Bioresour. Tech.* 107, 419–428. doi:10.1016/j.biortech.2011.11.084

Castaldi, S., Riondino, M., Baronti, S., Esposito, F. R., Marzaioli, R., Rutigliano, F. A., et al. (2011). Impact of Biochar Application to a Mediterranean Wheat Crop on Soil Microbial Activity and Greenhouse Gas Fluxes. *Chemosphere* 85, 1464–1471. doi:10.1016/j.chemosphere.2011.08.031

Cayuela, M. L., van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., and Sánchez-Monedero, M. A. (2014). Biochar's Role in Mitigating Soil Nitrous Oxide Emissions: A Review and Meta-Analysis. *Agric. Ecosyst. Environ.* 191, 5–16. doi:10.1016/j.agee.2013.10.009

Chen, G., Fang, Y., Van Zwieten, L., Xuan, Y., Tavakkoli, E., Wang, X., et al. (2021a). Priming, Stabilization and Temperature Sensitivity of Native SOC Is Controlled by Microbial Responses and Physicochemical Properties of Biochar. *Soil Biol. Biochem.* 154, 108139. doi:10.1016/j.soilbio.2021.108139

Chen, J., Sun, X., Zheng, J., Zhang, X., Liu, X., Bian, R., et al. (2018). Biochar Amendment Changes Temperature Sensitivity of Soil Respiration and Composition of Microbial Communities 3 Years after Incorporation in an Organic Carbon-Poor Dry Cropland Soil. *Biol. Fertil. Soils* 54, 175–188. doi:10.1007/s00374-017-1253-6

Chen, P., Liu, Y., Mo, C., Jiang, Z., Yang, J., and Lin, J. (2021b). Microbial Mechanism of Biochar Addition on Nitrogen Leaching and Retention in tea Soils from Different Plantation Ages. *Sci. Total Environ.* 757, 143817. doi:10.1016/j.scitotenv.2020.143817

Cheng, C.-H., and Lehmann, J. (2009). Ageing of Black Carbon along a Temperature Gradient. *Chemosphere* 75, 1021–1027. doi:10.1016/j.chemosphere.2009.01.045

Cornelissen, G., Jubaedah, Nurida, N. L., Hale, S. E., Martinsen, V., Silvani, L., et al. (2018). Fading Positive Effect of Biochar on Crop Yield and Soil Acidity during Five Growth Seasons in an Indonesian Ultisol. *Sci. Total Environ.* 634, 561–568. doi:10.1016/j.scitotenv.2018.03.380

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G., Rutherford, D., et al. (2013). Biochar Effect on Maize Yield and Soil

- Characteristics in Five Conservation Farming Sites in Zambia. *Agronomy* 3, 256–274. doi:10.3390/agronomy3020256
- Crane-Droesch, A., Abiven, S., Jeffery, S., and Torn, M. S. (2013). Heterogeneous Global Crop Yield Response to Biochar: a Meta-Regression Analysis. *Environ. Res. Lett.* 8, 044049. doi:10.1088/1748-9326/8/4/044049
- Curaqueo, G., Meier, S., Khan, N., Cea, M., and Navia, R. (2014). Use of Biochar on Two Volcanic Soils: Effects on Soil Properties and Barley Yield. *J. Soil Sci. Plant Nutr.* 14, 911–924. doi:10.4067/S0718-95162014005000072
- Deepagoda, T. K. K. C., Moldrup, P., Schjønning, P., de Jonge, L. W., Kawamoto, K., and Komatsu, T. (2011). Density-Corrected Models for Gas Diffusivity and Air Permeability in Unsaturated Soil. *Vadose Zone J.* 10, 226–238. doi:10.2136/vzj2009.0137
- Dempster, D. N., Gleeson, D. B., Solaiman, Z. M., Jones, D. L., and Murphy, D. V. (2012). Decreased Soil Microbial Biomass and Nitrogen Mineralisation with Eucalyptus Biochar Addition to a Coarse Textured Soil. *Plant Soil* 354, 311–324. doi:10.1007/s11104-011-1067-5
- Ding, Y., Liu, Y.-X., Wu, W.-X., Shi, D.-Z., Yang, M., and Zhong, Z.-K. (2010). Evaluation of Biochar Effects on Nitrogen Retention and Leaching in Multi-Layered Soil Columns. *Water Air Soil Pollut.* 213, 47–55. doi:10.1007/s11270-010-0366-4
- Doran, J. W., and Zeiss, M. R. (2000). Soil Health and Sustainability: Managing the Biotic Component of Soil Quality. *Appl. Soil Ecol.* 15, 3–11. doi:10.1016/S0929-1393(00)00067-6
- El-Naggar, A., Lee, S. S., Awad, Y. M., Yang, X., Ryu, C., Rizwan, M., et al. (2018). Influence of Soil Properties and Feedstocks on Biochar Potential for Carbon Mineralization and Improvement of Infertile Soils. *Geoderma* 332, 100–108. doi:10.1016/j.geoderma.2018.06.017
- El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., et al. (2019). Biochar Application to Low Fertility Soils: A Review of Current Status, and Future Prospects. *Geoderma* 337, 536–554. doi:10.1016/j.geoderma.2018.09.034
- FAO (2017). Emissions Shares. Available at: <http://www.fao.org/faostat/en/#data/EM/visualize> (Accessed September 25, 2020).
- FAO (2019). *World Fertilizer Trends and Outlook to 2022*. Rome.
- Farkas, E., Feigl, V., Gruiz, K., Vaszita, E., Fekete-Kertész, I., Tolner, M., et al. (2020). Long-term Effects of Grain Husk and Paper Fibre Sludge Biochar on Acidic and Calcareous sandy Soils - A Scale-Up Field experiment Applying a Complex Monitoring Toolkit. *Sci. Total Environ.* 731, 138988. doi:10.1016/j.scitotenv.2020.138988
- Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global Consequences of Land Use. *Science* 309, 570–574. doi:10.1126/science.1111772
- Galinato, S. P., Yoder, J. K., and Granatstein, D. (2011). The Economic Value of Biochar in Crop Production and Carbon Sequestration. *Energy Policy* 39, 6344–6350. doi:10.1016/j.enpol.2011.07.035
- Gao, S., Wang, D., Dangi, S. R., Duan, Y., Pflaum, T., Gartung, J., et al. (2020). Nitrogen Dynamics Affected by Biochar and Irrigation Level in an Onion Field. *Sci. Total Environ.* 714, 136432. doi:10.1016/j.scitotenv.2019.136432
- Gaunt, J. L., and Lehmann, J. (2008). Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production. *Environ. Sci. Technol.* 42, 4152–4158. doi:10.1021/es071361i
- Gautam, D. K., Bajracharya, R. M., and Sitaula, B. K. (2017). Effects of Biochar and Farm Yard Manure on Soil Properties and Crop Growth in an Agroforestry System in the Himalaya. *Sar* 6, 74. doi:10.5539/sar.v6n4p74
- Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal - A Review. *Biol. Fertil. Soils* 35, 219–230. doi:10.1007/s00374-002-0466-4
- Godlewska, P., Ok, Y. S., and Oleszczuk, P. (2021). The Dark Side of Black Gold: Ecotoxicological Aspects of Biochar and Biochar-Amended Soils. *J. Hazard. Mater.* 403, 123833. doi:10.1016/j.jhazmat.2020.123833
- Granatstein, D., Kruger, C., Educator, Bioa., Collins, H., Garcia-Perez, M., and Yoder, J. (2009). Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment. Available at: www.pacificbiomass.org (Accessed July 7, 2020).
- Guenet, B., Leloup, J., Raynaud, X., Bardoux, G., and Abbadie, L. (2010). Negative Priming Effect on Mineralization in a Soil Free of Vegetation for 80 Years. *Eur. J. Soil Sci.* 61, 384–391. doi:10.1111/j.1365-2389.2010.01234.x
- Guo, M., Song, W., and Tian, J. (2020). Biochar-Facilitated Soil Remediation: Mechanisms and Efficacy Variations. *Front. Environ. Sci.* 8, 521512. doi:10.3389/fenvs.2020.521512
- Haefele, S. M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A. A., Pfeiffer, E. M., et al. (2011). Effects and Fate of Biochar from rice Residues in rice-based Systems. *Field Crops Res.* 121, 430–440. doi:10.1016/j.fcr.2011.01.014
- Hagemann, N., Joseph, S., Schmidt, H.-P., Kammann, C. I., Harter, J., Borch, T., et al. (2017). Organic Coating on Biochar Explains its Nutrient Retention and Stimulation of Soil Fertility. *Nat. Commun.* 8, 1–11. doi:10.1038/s41467-017-01123-0
- Hagner, M., Kemppainen, R., Jauhiainen, L., Tiilikkala, K., and Setälä, H. (2016). The Effects of Birch (*Betula* spp.) Biochar and Pyrolysis Temperature on Soil Properties and Plant Growth. *Soil Tillage Res.* 163, 224–234. doi:10.1016/j.still.2016.06.006
- Haider, G., Steffens, D., Moser, G., Müller, C., and Kammann, C. I. (2017). Biochar Reduced Nitrate Leaching and Improved Soil Moisture Content without Yield Improvements in a Four-Year Field Study. *Agric. Ecosyst. Environ.* 237, 80–94. doi:10.1016/j.agee.2016.12.019
- Hammond, J., Shackley, S., Prendergast-Miller, M., Cook, J., Buckingham, S., and Pappa, V. A. (2013). Biochar Field Testing in the UK: Outcomes and Implications for Use. *Carbon Manag.* 4, 159–170. doi:10.4155/cmt.13.3
- Havlin, J. L. (2014). Soil Fertility and Nutrient Management.
- Hua, L., Wu, W., Liu, Y., McBride, M. B., and Chen, Y. (2009). Reduction of Nitrogen Loss and Cu and Zn Mobility during Sludge Composting with Bamboo Charcoal Amendment. *Environ. Sci. Pollut. Res.* 16, 1–9. doi:10.1007/s11356-008-0041-0
- Huang, Y., Wang, C., Lin, C., Zhang, Y., Chen, X., Tang, L., et al. (2019). Methane and Nitrous Oxide Flux after Biochar Application in Subtropical Acidic Paddy Soils under Tobacco-Rice Rotation. *Sci. Rep.* 9, 1–10. doi:10.1038/s41598-019-53044-1
- Huber-Humer, M., Gebert, J., and Hilger, H. (2008). Biotic Systems to Mitigate Landfill Methane Emissions. *Waste Manag. Res.* 26, 33–46. doi:10.1177/0734242X07087977
- Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., et al. (2017). Biochar for Crop Production: Potential Benefits and Risks. *J. Soils Sediments* 17, 685–716. doi:10.1007/s11368-016-1360-2
- Igalavithana, A. D., Lee, S.-E., Lee, Y. H., Tsang, D. C. W., Rinklebe, J., Kwon, E. E., et al. (2017). Heavy Metal Immobilization and Microbial Community Abundance by Vegetable Waste and pine Cone Biochar of Agricultural Soils. *Chemosphere* 174, 593–603. doi:10.1016/j.chemosphere.2017.01.148
- Igalavithana, A. D., Ok, Y. S., Usman, A. R. A., Al-Wabel, M. I., Oleszczuk, P., and Lee, S. S. (2015). *The Effects of Biochar Amendment on Soil Fertility*. John Wiley & Sons, 123–144. doi:10.2136/sssaspecpub63.2014.0040
- Islami, T., Guritno, B., Basuki, N., and Suryanto, A. (2011). Biochar for Sustaining Productivity of Cassava Based Cropping Systems in the Degraded Lands of East Java, Indonesia. *J. Trop. Agric.* 49, 40–46.
- Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., et al. (2017). Biochar Boosts Tropical but Not Temperate Crop Yields. *Environ. Res. Lett.* 12, 053001. doi:10.1088/1748-9326/aa67bd
- Jeffery, S., Verheijen, F. G. A., van der Velde, M., and Bastos, A. C. (2011). A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis. *Agric. Ecosyst. Environ.* 144, 175–187. doi:10.1016/j.agee.2011.08.015
- Jenkins, J. R., Viger, M., Arnold, E. C., Harris, Z. M., Ventura, M., Miglietta, F., et al. (2017). Biochar Alters the Soil Microbiome and Soil Function: Results of Next-Generation Amplicon Sequencing across Europe. *GCB Bioenergy* 9, 591–612. doi:10.1111/gcbb.12371
- Jeyasubramanian, K., Thangagiri, B., Sakthivel, A., Dhavethu Raja, J., Seenivasan, S., Vallinayagam, P., et al. (2021). A Complete Review on Biochar: Production, Property, Multifaceted Applications, Interaction Mechanism and Computational Approach. *Fuel* 292, 120243. doi:10.1016/j.fuel.2021.120243
- Jiang, S., Liu, J., Wu, J., Dai, G., Wei, D., and Shu, Y. (2020). Assessing Biochar Application to Immobilize Cd and Pb in a Contaminated Soil: a Field experiment under a Cucumber-Sweet Potato-Rape Rotation. *Environ. Geochem. Health* 42, 4233–4244. doi:10.1007/s10653-020-00564-9
- Jien, S.-H., Kuo, Y.-L., LiaoSen, C.-S., Wu, Y.-T., Wu, A. D., Tsang, D. C. W., et al. (2021). Effects of Field Scale *In Situ* Biochar Incorporation on Soil Environment

- in a Tropical Highly Weathered Soil. *Environ. Pollut.* 272, 116009. doi:10.1016/j.envpol.2020.116009
- Jin, Z., Chen, C., Chen, X., Hopkins, I., Zhang, X., Han, Z., et al. (2019). The Crucial Factors of Soil Fertility and Rapeseed Yield - A Five Year Field Trial with Biochar Addition in upland Red Soil, China. *Sci. Total Environ.* 649, 1467–1480. doi:10.1016/j.scitotenv.2018.08.412
- Jobbágy, E. G., and Jackson, R. B. (2000). The Vertical Distribution of Soil Organic Carbon and its Relation to Climate and Vegetation. *Ecol. Appl.* 10, 423–436. doi:10.1890/1051-0761(2000)010[0423:tvdosoj]2.0.co;2
- Jones, D. L., Rousk, J., Edwards-Jones, G., DeLuca, T. H., and Murphy, D. V. (2012). Biochar-mediated Changes in Soil Quality and Plant Growth in a Three Year Field Trial. *Soil Biol. Biochem.* 45, 113–124. doi:10.1016/j.soilbio.2011.10.012
- Kammann, C. I., Schmidt, H.-P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C., et al. (2015). Plant Growth Improvement Mediated by Nitrate Capture in Co-composted Biochar. *Sci. Rep.* 5, 1–13. doi:10.1038/srep11080
- Kan, T., Strezov, V., and Evans, T. J. (2016). Lignocellulosic Biomass Pyrolysis: A Review of Product Properties and Effects of Pyrolysis Parameters. *Renew. Sust. Energ. Rev.* 57, 1126–1140. doi:10.1016/j.rser.2015.12.185
- Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S. S., et al. (2020). Valorization of Agricultural Waste for Biogas Based Circular Economy in India: A Research Outlook. *Bioresour. Tech.* 304, 123036. doi:10.1016/j.biortech.2020.123036
- Keller, T., Hüppi, R., and Leifeld, J. (2019). Relationship between Greenhouse Gas Emissions and Changes in Soil Gas Diffusivity in a Field experiment with Biochar and Lime. *J. Plant Nutr. Soil Sci.* 182, 667–675. doi:10.1002/jpln.201800538
- Khalifa, N., and Yousef, L. F. (2015). A Short Report on Changes of Quality Indicators for a Sandy Textured Soil after Treatment with Biochar Produced from Fronds of Date Palm. *Energ. Proced.* 74, 960–965. doi:10.1016/j.egypro.2015.07.729
- Khodadad, C. L. M., Zimmerman, A. R., Green, S. J., Uthandi, S., and Foster, J. S. (2011). Taxa-specific Changes in Soil Microbial Community Composition Induced by Pyrogenic Carbon Amendments. *Soil Biol. Biochem.* 43, 385–392. doi:10.1016/j.soilbio.2010.11.005
- Kumari, K. G. I. D., Moldrup, P., Paradelo, M., Elsgaard, L., Hauggaard-Nielsen, H., and de Jonge, L. W. (2014). Effects of Biochar on Air and Water Permeability and Colloid and Phosphorus Leaching in Soils from a Natural Calcium Carbonate Gradient. *J. Environ. Qual.* 43, 647–657. doi:10.2134/jeq2013.08.0334
- Kuz'yakov, Y., Friedel, J. K., and Stahr, K. (2000). Review of Mechanisms and Quantification of Priming Effects. *Soil Biol. Biochem.* 32, 1485–1498. doi:10.1016/S0038-0717(00)00084-5
- Laghari, M., Mirjat, M. S., Hu, Z., Fazal, S., Xiao, B., Hu, M., et al. (2015). Effects of Biochar Application Rate on sandy Desert Soil Properties and Sorghum Growth. *Catena* 135, 313–320. doi:10.1016/j.catena.2015.08.013
- Laghari, M., Naidu, R., Xiao, B., Hu, Z., Mirjat, M. S., Hu, M., et al. (2016). Recent Developments in Biochar as an Effective Tool for Agricultural Soil Management: a Review. *J. Sci. Food Agric.* 96, 4840–4849. doi:10.1002/jsfa.7753
- Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., and Karlen, D. L. (2010). Impact of Biochar Amendments on the Quality of a Typical Midwestern Agricultural Soil. *Geoderma* 158, 443–449. doi:10.1016/j.geoderma.2010.05.013
- Lal, R. (2015). Sequestering Carbon and Increasing Productivity by Conservation Agriculture. *J. Soil Water Conservation* 70, 55A–62A. doi:10.2489/jswc.70.3.55A
- Lashari, M. S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., et al. (2013). Effects of Amendment of Biochar-Manure Compost in Conjunction with Pyrolytic Soluton on Soil Quality and Wheat Yield of a Salt-Stressed Cropland from Central China Great Plain. *Field Crops Res.* 144, 113–118. doi:10.1016/j.fcr.2012.11.015
- Lee, Y., Eum, P.-R. -B., Ryu, C., Park, Y.-K., Jung, J.-H., and Hyun, S. (2013). Characteristics of Biochar Produced from Slow Pyrolysis of Geodae-Uksae 1. *Bioresour. Tech.* 130, 345–350. doi:10.1016/j.biortech.2012.12.012
- Lehmann, J. (2007). Bio-energy in the Black. *Front. Ecol. Environ.* 5, 381–387. doi:10.1890/1540-9295(2007)5[381:bitb]2.0.co;2
- Lehmann, J., Gaunt, J., and Rondon, M. (2006). Bio-char Sequestration in Terrestrial Ecosystems - A Review. *Mitig Adapt Strat Glob. Change* 11, 403–427. doi:10.1007/s11027-005-9006-5
- Lehmann, J., Kuzyakov, Y., Pan, G., and Ok, Y. S. (2015). Biochars and the Plant-Soil Interface. *Plant Soil* 395, 1–5. doi:10.1007/s11104-015-2658-3
- Lehmann, J., Pereira da Silva Jr., J., Steiner, C., Nehls, T., Zech, W., and Glaser, B. (2003). Nutrient Availability and Leaching in an Archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, Manure and Charcoal Amendments. *Plant Soil* 249, 343–357. doi:10.1023/A:1022833116184
- Lentz, R. D., and Ippolito, J. A. (2012). Biochar and Manure Affect Calcareous Soil and Corn Silage Nutrient Concentrations and Uptake. *J. Environ. Qual.* 41, 1033–1043. doi:10.2134/jeq2011.0126
- Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., et al. (2006). Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Sci. Soc. Am. J.* 70, 1719–1730. doi:10.2136/sssaj2005.0383
- Liang, F., Litong, G.-t. Lin, Q. mei., Linrong, Q.-m., and Zhao, X.-r. (2014). Crop Yield and Soil Properties in the First 3 Years after Biochar Application to a Calcareous Soil. *J. Integr. Agric.* 13, 525–532. doi:10.1016/S2095-3119(13)60708-X
- Liu, C., Wang, H., Tang, X., Guan, Z., Reid, B. J., Rajapaksha, A. U., et al. (2016a). Biochar Increased Water Holding Capacity but Accelerated Organic Carbon Leaching from a Sloping farmland Soil in China. *Environ. Sci. Pollut. Res.* 23, 995–1006. doi:10.1007/s11356-015-4885-9
- Liu, X.-J. A., Finley, B. K., Mau, R. L., Schwartz, E., Dijkstra, P., Bowker, M. A., et al. (2020). The Soil Priming Effect: Consistent across Ecosystems, Elusive Mechanisms. *Soil Biol. Biochem.* 140, 107617. doi:10.1016/j.soilbio.2019.107617
- Liu, X., Ye, Y., Liu, Y., Zhang, A., Zhang, X., Li, L., et al. (2014). Sustainable Biochar Effects for Low Carbon Crop Production: A 5-crop Season Field experiment on a Low Fertility Soil from Central China. *Agric. Syst.* 129, 22–29. doi:10.1016/j.agry.2014.05.008
- Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., et al. (2013). Biochar's Effect on Crop Productivity and the Dependence on Experimental Conditions-A Meta-Analysis of Literature Data. *Plant Soil* 373, 583–594. doi:10.1007/s11104-013-1806-x
- Liu, Y., Lu, H., Yang, S., and Wang, Y. (2016b). Impacts of Biochar Addition on rice Yield and Soil Properties in a Cold Waterlogged Paddy for Two Crop Seasons. *Field Crops Res.* 191, 161–167. doi:10.1016/j.fcr.2016.03.003
- Lu, H., Yan, M., Wong, M. H., Mo, W. Y., Wang, Y., Chen, X. W., et al. (2020). Effects of Biochar on Soil Microbial Community and Functional Genes of a Landfill Cover Three Years after Ecological Restoration. *Sci. Total Environ.* 717, 137133. doi:10.1016/j.scitotenv.2020.137133
- Luo, C., Yang, J., Chen, W., and Han, F. (2020). Effect of Biochar on Soil Properties on the Loess Plateau: Results from Field Experiments. *Geoderma* 369, 114323. doi:10.1016/j.geoderma.2020.114323
- Maestrini, B., Nannipieri, P., and Abiven, S. (2015). A Meta-Analysis on Pyrogenic Organic Matter Induced Priming Effect. *GCB Bioenergy* 7, 577–590. doi:10.1111/gcbb.12194
- Major, J., Rondon, M., Molina, D., Riha, S. J., and Lehmann, J. (2010). Maize Yield and Nutrition during 4 Years after Biochar Application to a Colombian savanna Oxisol. *Plant Soil* 333, 117–128. doi:10.1007/s11104-010-0327-0
- Major, J., Rondon, M., Molina, D., Riha, S. J., and Lehmann, J. (2012). Nutrient Leaching in a Colombian Savanna Oxisol Amended with Biochar. *J. Environ. Qual.* 41, 1076–1086. doi:10.2134/jeq2011.0128
- Majumder, S., Neogi, S., Dutta, T., Powel, M. A., and Banik, P. (2019). The Impact of Biochar on Soil Carbon Sequestration: Meta-Analytical Approach to Evaluating Environmental and Economic Advantages. *J. Environ. Manage.* 250, 109466. doi:10.1016/j.jenvman.2019.109466
- Mankasingh, U., Choi, P.-C., and Ragnarsdottir, V. (2011). Biochar Application in a Tropical, Agricultural Region: A Plot Scale Study in Tamil Nadu, India. *Appl. Geochem.* 26, S218–S221. doi:10.1016/j.apgeochem.2011.03.108
- Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Børresen, T., and Cornelissen, G. (2014). Farmer-led maize Biochar Trials: Effect on Crop Yield and Soil Nutrients under Conservation Farming. *J. Plant Nutr. Soil Sci.* 177, 681–695. doi:10.1002/jpln.201300590
- Mukherjee, A., Lal, R., and Zimmerman, A. R. (2014). Impacts of 1.5-year Field Aging on Biochar, Humic Acid, and Water Treatment Residual Amended Soil. *Soil Sci.* 179, 333–339. doi:10.1097/SS.0000000000000076

- Mulligan, C. N., Yong, R. N., and Gibbs, B. F. (2001). Remediation Technologies for Metal-Contaminated Soils and Groundwater: An Evaluation. *Eng. Geology*. 60, 193–207. doi:10.1016/S0013-7952(00)00101-0
- Nair, V. D., Nair, P. K. R., Dari, B., Freitas, A. M., Chatterjee, N., and Pinheiro, F. M. (2017). Biochar in the Agroecosystem–Climate-Change-Sustainability Nexus. *Front. Plant Sci.* 8, 2051. doi:10.3389/fpls.2017.02051
- Nelissen, V., Ruysschaert, G., Manka'Abusi, D., D'Hose, T., De Beuf, K., Al-Barri, B., et al. (2015). Impact of a Woody Biochar on Properties of a sandy Loam Soil and spring Barley during a Two-Year Field experiment. *Eur. J. Agron.* 62, 65–78. doi:10.1016/j.eja.2014.09.006
- Nie, C., Yang, X., Niazi, N. K., Xu, X., Wen, Y., Rinklebe, J., et al. (2018). Impact of Sugarcane Bagasse-Derived Biochar on Heavy Metal Availability and Microbial Activity: A Field Study. *Chemosphere* 200, 274–282. doi:10.1016/j.chemosphere.2018.02.134
- Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., and Pan, G. (2016). Quantification of Biochar Effects on Soil Hydrological Properties Using Meta-Analysis of Literature Data. *Geoderma* 274, 28–34. doi:10.1016/j.geoderma.2016.03.029
- Pachauri, R. K., and Meyer, L. (2015). *Climate Change 2014 Synthesis Report*. Geneva, Switzerland: Gian-Kasper Plattner. Available at: <http://www.ipcc.ch> (Accessed April 8, 2021).
- Pandit, N. R., Mulder, J., Hale, S. E., Zimmerman, A. R., Pandit, B. H., and Cornelissen, G. (2018). Multi-year Double Cropping Biochar Field Trials in Nepal: Finding the Optimal Biochar Dose through Agronomic Trials and Cost-Benefit Analysis. *Sci. Total Environ.* 637, 1333–1341. doi:10.1016/j.scitotenv.2018.05.107
- Peake, L. R., Reid, B. J., and Tang, X. (2014). Quantifying the Influence of Biochar on the Physical and Hydrological Properties of Dissimilar Soils. *Geoderma* 235–236, 182–190. doi:10.1016/j.geoderma.2014.07.002
- Peng, X., Ye, L. L., Wang, C. H., Zhou, H., and Sun, B. (2011). Temperature- and Duration-dependent rice Straw-Derived Biochar: Characteristics and its Effects on Soil Properties of an Ultisol in Southern China. *Soil Tillage Res.* 112, 159–166. doi:10.1016/j.still.2011.01.002
- Purakayastha, T. J., Bera, T., Bhaduri, D., Sarkar, B., Mandal, S., Wade, P., et al. (2019). A Review on Biochar Modulated Soil Condition Improvements and Nutrient Dynamics Concerning Crop Yields: Pathways to Climate Change Mitigation and Global Food Security. *Chemosphere* 227, 345–365. doi:10.1016/j.chemosphere.2019.03.170
- Raboin, L.-M., Razafimahafaly, A. H. D., Rabenjarisoa, M. B., Rabary, B., Dusserre, J., and Becquer, T. (2016). Improving the Fertility of Tropical Acid Soils: Liming versus Biochar Application? A Long Term Comparison in the highlands of Madagascar. *Field Crops Res.* 199, 99–108. doi:10.1016/j.fcr.2016.09.005
- Ramazan, M., Khan, G. D., Hanif, M., and Ali, S. (2012). Impact of Soil Compaction on Root Length and Yield of Corn (*Zea mays*) under Irrigated Condition. *Middle East. J. Sci. Res.* 11, 382–385.
- Ramrez-Rodriguez, V., Lpez-Bucio, J., and Herrera-Estrella, L. (2007). *Adaptive Responses in Plants to Nonoptimal Soil pH*. In Plant Abiotic Stress. Oxford, UK: Blackwell Publishing Ltd), 145–170. doi:10.1002/9780470988503.ch6
- Randolph, P., Bansode, R. R., Hassan, O. A., Rehrah, D., Ravella, R., Reddy, M. R., et al. (2017). Effect of Biochars Produced from Solid Organic Municipal Waste on Soil Quality Parameters. *J. Environ. Manage.* 192, 271–280. doi:10.1016/j.jenvman.2017.01.061
- Reddy, K. R., Yargicoglu, E. N., Yue, D., and Yaghoubi, P. (2014). Enhanced Microbial Methane Oxidation in Landfill Cover Soil Amended with Biochar. *J. Geotech. Geoenviron. Eng.* 140, 04014047. doi:10.1061/(asce)gt.1943-5606.0001148
- Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T., and Meek, D. (2011). Impact of Biochar on Manure Carbon Stabilization and Greenhouse Gas Emissions. *Soil Sci. Soc. America J.* 75, 871–879. doi:10.2136/sssaj2010.0270
- Rondon, M. A., Lehmann, J., Ramirez, J., and Hurtado, M. (2007). Biological Nitrogen Fixation by Common Beans (*Phaseolus vulgaris* L.) Increases with Bio-Char Additions. *Biol. Fertil. Soils* 43, 699–708. doi:10.1007/s00374-006-0152-z
- Rousk, J., Bååth, E., Brookes, P. C., Lauber, C. L., Lozupone, C., Caporaso, J. G., et al. (2010). Soil Bacterial and Fungal Communities across a pH Gradient in an Arable Soil. *ISME J.* 4, 1340–1351. doi:10.1038/ismej.2010.58
- Sahota, S., Vijay, V. K., Subbarao, P. M. V., Chandra, R., Ghosh, P., Shah, G., et al. (2018). Characterization of Leaf Waste Based Biochar for Cost Effective Hydrogen Sulphide Removal from Biogas. *Bioresour. Tech.* 250, 635–641. doi:10.1016/j.biortech.2017.11.093
- Saifullah, Dahlawi, S., Naeem, A., Rengel, Z., and Naidu, R. (2018). Biochar Application for the Remediation of Salt-Affected Soils: Challenges and Opportunities. *Sci. Total Environ.* 625, 320–335. doi:10.1016/j.scitotenv.2017.12.257
- Sänger, A., Reibe, K., Mumme, J., Kaupenjohann, M., Ellmer, F., Roß, C.-L., et al. (2017). Biochar Application to sandy Soil: Effects of Different Biochars and N Fertilization on Crop Yields in a 3-year Field experiment. *Arch. Agron. Soil Sci.* 63, 213–229. doi:10.1080/03650340.2016.1223289
- Scheutz, C., Kjeldsen, P., Bogner, J. E., De Visscher, A., Gebert, J., Hilger, H. A., et al. (2009). Microbial Methane Oxidation Processes and Technologies for Mitigation of Landfill Gas Emissions. *Waste Manag. Res.* 27, 409–455. doi:10.1177/0734242X09339325
- Schmidt, H., Pandit, B., Martinsen, V., Cornelissen, G., Conte, P., and Kammann, C. (2015). Fourfold Increase in Pumpkin Yield in Response to Low-Dosage Root Zone Application of Urine-Enhanced Biochar to a Fertile Tropical Soil. *Agriculture* 5, 723–741. doi:10.3390/agriculture5030723
- Schmidt, M. W. I., and Noack, A. G. (2000). Black Carbon in Soils and Sediments: Analysis, Distribution, Implications, and Current Challenges. *Glob. Biogeochem. Cycles* 14, 777–793. doi:10.1029/1999GB001208
- Shackley, S., Sohi, S., Ibarrola, R., Hammond, J., Mašek, O., Brownsort, P., et al. (2012). Biochar Biochar, Tool for Climate Change Mitigation and Soil Management. In *Encyclopedia of Sustainability Science and Technology*. New York: Springer, 845–893. doi:10.1007/978-1-4419-0851-3_386
- Shareef, T. M. E., and Zhao, B. (2017). Review Paper: The Fundamentals of Biochar as a Soil Amendment Tool and Management in Agriculture Scope: An Overview for Farmers and Gardeners. *Jacen* 06, 38–61. doi:10.4236/jacen.2017.61003
- Singh, B. P., and Cowie, A. L. (2014). Long-term Influence of Biochar on Native Organic Carbon Mineralisation in a Low-Carbon Clayey Soil. *Sci. Rep.* 4, 1–9. doi:10.1038/srep03687
- Slavich, P. G., Sinclair, K., Morris, S. G., Kimber, S. W. L., Downie, A., and Van Zwieten, L. (2013). Contrasting Effects of Manure and green Waste Biochars on the Properties of an Acidic Ferralsol and Productivity of a Subtropical Pasture. *Plant Soil* 366, 213–227. doi:10.1007/s11104-012-1412-3
- Sohi, S. P., Krull, E., Lopez-Capel, E., and Bol, R. (2010). A Review of Biochar and its Use and Function in Soil. In *Advances in Agronomy*. Academic Press, 47–82. doi:10.1016/S0065-2113(10)05002-9
- Solaiman, Z. M., Blackwell, P., Abbott, L. K., and Storer, P. (2010). Direct and Residual Effect of Biochar Application on Mycorrhizal Root Colonisation, Growth and Nutrition of Wheat. *Soil Res.* 48, 546–554. doi:10.1071/SR10002
- Song, D., Tang, J., Xi, X., Zhang, S., Liang, G., Zhou, W., et al. (2018). Responses of Soil Nutrients and Microbial Activities to Additions of maize Straw Biochar and Chemical Fertilization in a Calcareous Soil. *Eur. J. Soil Biol.* 84, 1–10. doi:10.1016/j.ejsobi.2017.11.003
- Song, L., Hou, L., Zhang, Y., Li, Z., Wang, W., and Sun, Q. (2020). Regular Biochar and Bacteria-Inoculated Biochar Alter the Composition of the Microbial Community in the Soil of a Chinese Fir Plantation. *Forests* 11, 951. doi:10.3390/f11090951
- Song, W., and Guo, M. (2012). Quality Variations of Poultry Litter Biochar Generated at Different Pyrolysis Temperatures. *J. Anal. Appl. Pyrolysis* 94, 138–145. doi:10.1016/j.jaap.2011.11.018
- Song, Y., Li, Y., Cai, Y., Fu, S., Luo, Y., Wang, H., et al. (2019). Biochar Decreases Soil N₂O Emissions in Moso Bamboo Plantations through Decreasing Labile N Concentrations, N-Cycling Enzyme Activities and Nitrification/denitrification Rates. *Geoderma* 348, 135–145. doi:10.1016/j.geoderma.2019.04.025
- Spokas, K. A., Baker, J. M., and Reicosky, D. C. (2010). Ethylene: Potential Key for Biochar Amendment Impacts. *Plant Soil* 333, 443–452. doi:10.1007/s11104-010-0359-5
- Spokas, K. A., Novak, J. M., Masiello, C. A., Johnson, M. G., Colosky, E. C., Ippolito, J. A., et al. (2014). Physical Disintegration of Biochar: An Overlooked Process. *Environ. Sci. Technol. Lett.* 1, 326–332. doi:10.1021/ez500199t
- Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., de Macêdo, J. L. V., Blum, W. E. H., et al. (2007). Long Term Effects of Manure, Charcoal and mineral Fertilization on Crop Production and Fertility on a Highly Weathered Central Amazonian upland Soil. *Plant Soil* 291, 275–290. doi:10.1007/s11104-007-9193-9
- Steiner, C., Teixeira, W., and Zech, W. (2009). The Effect of Charcoal in Banana (*Musa* Sp.) Planting Holes - an On-Farm Study in central Amazonia, Brazil. In

- Amazonian Dark Earths: Wim Sombroek's Vision. Springer Netherlands, 423–432. doi:10.1007/978-1-4020-9031-8_24
- Suddick, E. C., and Six, J. (2013). An Estimation of Annual Nitrous Oxide Emissions and Soil Quality Following the Amendment of High Temperature walnut Shell Biochar and Compost to a Small Scale Vegetable Crop Rotation. *Sci. Total Environ.* 465, 298–307. doi:10.1016/j.scitotenv.2013.01.094
- Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A.-M., Dallmeyer, I., and Garcia-Pérez, M. (2017). The Role of Biochar Porosity and Surface Functionality in Augmenting Hydrologic Properties of a sandy Soil. *Sci. Total Environ.* 574, 139–147. doi:10.1016/j.scitotenv.2016.09.025
- Sun, F., and Lu, S. (2014). Biochars Improve Aggregate Stability, Water Retention, and Pore-Space Properties of Clayey Soil. *Z. Pflanzenernähr. Bodenk.* 177, 26–33. doi:10.1002/jpln.201200639
- Taghizadeh-Toosi, A., Clough, T. J., Sherlock, R. R., and Condron, L. M. (2012). Biochar Adsorbed Ammonia Is Bioavailable. *Plant Soil* 350, 57–69. doi:10.1007/s11104-011-0870-3
- Thies, J. E., Rillig, M. C., and Graber, E. R. (2015). Biochar Effects on the Abundance, Activity and Diversity of the Soil Biota Landscape-Scale Biodiversity and the Balancing of Provisioning, Regulating and Supporting Ecosystem Services (BASIL) View Project Vegetational Dynamics in a Terminated Long-Term Ex. In *Biochar For Environmental Management: Science, Technology and Implementation*. Available at: <https://www.researchgate.net/publication/283435189> (Accessed July 7, 2020). 327–389.
- Thomas, S. C., and Gale, N. (2015). Biochar and forest Restoration: a Review and Meta-Analysis of Tree Growth Responses. *New Forests* 46, 931–946. doi:10.1007/s11056-015-9491-7
- Tilman, D., Balzer, C., Hill, J., and Befort, B. L. (2011). Global Food Demand and the Sustainable Intensification of Agriculture. *Proc. Natl. Acad. Sci.* 108, 20260–20264. doi:10.1073/pnas.1116437108
- USEPA (2020). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018. Available at: <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks> (Accessed May 14, 2021).
- Vaccari, F. P., Baronti, S., Lugato, E., Genesio, L., Castaldi, S., Fornasier, F., et al. (2011). Biochar as a Strategy to Sequester Carbon and Increase Yield in Durum Wheat. *Eur. J. Agron.* 34, 231–238. doi:10.1016/j.eja.2011.01.006
- Vaccari, F. P., Maienza, A., Miglietta, F., Baronti, S., Di Lonardo, S., Giagnoni, L., et al. (2015). Biochar Stimulates Plant Growth but Not Fruit Yield of Processing Tomato in a fertile Soil. *Agric. Ecosyst. Environ.* 207, 163–170. doi:10.1016/j.agee.2015.04.015
- Van Der Voort, T. S., Hagedorn, F., McIntyre, C., Zell, C., Walthert, L., Schleppei, P., et al. (2016). Variability in 14C Contents of Soil Organic Matter at the Plot and Regional Scale across Climatic and Geologic Gradients. *Biogeosciences* 13, 3427–3439. doi:10.5194/bg-13-3427-2016
- Van Verseveld, C. J. W., and Gebert, J. (2020). Effect of Compaction and Soil Moisture on the Effective Permeability of Sands for Use in Methane Oxidation Systems. *Waste Manag.* 107, 44–53. doi:10.1016/j.wasman.2020.03.038
- Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., et al. (2010). Effects of Biochar from Slow Pyrolysis of Papermill Waste on Agronomic Performance and Soil Fertility. *Plant Soil* 327, 235–246. doi:10.1007/s11104-009-0050-x
- Ventura, M., Alberti, G., Panzacchi, P., Vedove, G. D., Miglietta, F., and Tonon, G. (2019). Biochar Mineralization and Priming Effect in a poplar Short Rotation Coppice from a 3-year Field experiment. *Biol. Fertil. Soils* 55, 67–78. doi:10.1007/s00374-018-1329-y
- Ventura, M., Alberti, G., Viger, M., Jenkins, J. R., Girardin, C., Baronti, S., et al. (2015). Biochar Mineralization and Priming Effect on SOM Decomposition in Two European Short Rotation Coppices. *GCB Bioenergy* 7, 1150–1160. doi:10.1111/gcbb.12219
- Vijay, V. K., Kapoor, R., Trivedi, A., and Vijay, V. (2015). Biogas as Clean Fuel for Cooking and Transportation Needs in India. In *Advances in Bioprocess Technology*. Springer International Publishing, 257–275. doi:10.1007/978-3-319-17915-5_14
- Vijay, V., Subbarao, P. M. V., and Chandra, R. (2021). An Evaluation on Energy Self-Sufficiency Model of a Rural Cluster through Utilization of Biomass Residue Resources: A Case Study in India. *Energ. Clim. Change* 2, 100036. doi:10.1016/j.egycc.2021.100036
- Voltr, V. (2012). Concept of Soil Fertility and Soil Productivity: Evaluation of Agricultural Sites in the Czech Republic. *Arch. Agron. Soil Sci.* 58, S243–S251. doi:10.1080/03650340.2012.700511
- Wang, F., Wang, X., and Song, N. (2021). Biochar and Vermicompost Improve the Soil Properties and the Yield and Quality of Cucumber (*Cucumis Sativus* L.) Grown in Plastic Shed Soil Continuously Cropped for Different Years. *Agric. Ecosyst. Environ.* 315, 107425. doi:10.1016/J.AGEE.2021.107425
- Wang, J., Xiong, Z., and Kuzyakov, Y. (2016). Biochar Stability in Soil: Meta-analysis of Decomposition and Priming Effects. *GCB Bioenergy* 8, 512–523. doi:10.1111/gcbb.12266
- Wang, L., Li, L., Cheng, K., Ji, C., Yue, Q., Bian, R., et al. (2018). An Assessment of Energy, Energy, and Cost-Benefits of Grain Production over 6 Years Following a Biochar Amendment in a rice Paddy from China. *Environ. Sci. Pollut. Res.* 25, 9683–9696. doi:10.1007/s11356-018-1245-6
- Wang, Y., Villamil, M. B., Davidson, P. C., and Akdeniz, N. (2019). A Quantitative Understanding of the Role of Co-composted Biochar in Plant Growth Using Meta-Analysis. *Sci. Total Environ.* 685, 741–752. doi:10.1016/j.scitotenv.2019.06.244
- Warnock, D. D., Mummey, D. L., McBride, B., Major, J., Lehmann, J., and Rillig, M. C. (2010). Influences of Non-herbaceous Biochar on Arbuscular Mycorrhizal Fungal Abundances in Roots and Soils: Results from Growth-Chamber and Field Experiments. *Appl. Soil Ecol.* 46, 450–456. doi:10.1016/j.apsoil.2010.09.002
- Wei, W., Yang, H., Fan, M., Chen, H., Guo, D., Cao, J., et al. (2020). Biochar Effects on Crop Yields and Nitrogen Loss Depending on Fertilization. *Sci. Total Environ.* 702, 1–9. doi:10.1016/j.scitotenv.2019.135991
- Weldon, S., Rasse, D. P., Budai, A., Tomic, O., and Dörsch, P. (2019). The Effect of a Biochar Temperature Series on Denitrification: Which Biochar Properties Matter? *Soil Biol. Biochem.* 135, 173–183. doi:10.1016/j.soilbio.2019.04.018
- West, T. O., and McBride, A. C. (2005). The Contribution of Agricultural Lime to Carbon Dioxide Emissions in the United States: Dissolution, Transport, and Net Emissions. *Agric. Ecosyst. Environ.* 108, 145–154. doi:10.1016/j.agee.2005.01.002
- Wong, J. T. F., Chen, Z., Ng, C. W. W., and Wong, M. H. (2016). Gas Permeability of Biochar-Amended clay: Potential Alternative Landfill Final Cover Material. *Environ. Sci. Pollut. Res.* 23, 7126–7131. doi:10.1007/s11356-015-4871-2
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., and Joseph, S. (2010). Sustainable Biochar to Mitigate Global Climate Change. *Nat. Commun.* 1. doi:10.1038/ncomms1053
- Woolf, D., and Lehmann, J. (2012). Modelling the Long-Term Response to Positive and Negative Priming of Soil Organic Carbon by Black Carbon. *Biogeochemistry* 111, 83–95. doi:10.1007/s10533-012-9764-6
- Wu, H., Lai, C., Zeng, G., Liang, J., Chen, J., Xu, J., et al. (2017). The Interactions of Composting and Biochar and Their Implications for Soil Amendment and Pollution Remediation: a Review. *Crit. Rev. Biotechnol.* 37, 754–764. doi:10.1080/07388551.2016.1232696
- Xiang, Y., Deng, Q., Duan, H., and Guo, Y. (2017). Effects of Biochar Application on Root Traits: a Meta-Analysis. *GCB Bioenergy* 9, 1563–1572. doi:10.1111/gcbb.12449
- Xiao, X., Chen, B., Chen, Z., Zhu, L., and Schnoor, J. L. (2018). Insight into Multiple and Multilevel Structures of Biochars and Their Potential Environmental Applications: A Critical Review. *Environ. Sci. Technol.* 52, 5027–5047. doi:10.1021/acs.est.7b06487
- Xiao, Z., Rasmann, S., Yue, L., Lian, F., Zou, H., and Wang, Z. (2019). The Effect of Biochar Amendment on N-Cycling Genes in Soils: A Meta-Analysis. *Sci. Total Environ.* 696, 133984. doi:10.1016/j.scitotenv.2019.133984
- Xu, N., Tan, G., Wang, H., and Gai, X. (2016). Effect of Biochar Additions to Soil on Nitrogen Leaching, Microbial Biomass and Bacterial Community Structure. *Eur. J. Soil Biol.* 74, 1–8. doi:10.1016/j.ejsobi.2016.02.004
- Yamato, M., Okimori, Y., Wibowo, I. F., Anshori, S., and Ogawa, M. (2006). Effects of the Application of Charred Bark of *Acacia Mangium* on the Yield of maize, Cowpea and Peanut, and Soil Chemical Properties in South Sumatra, Indonesia. *Soil Sci. Plant Nutr.* 52, 489–495. doi:10.1111/j.1747-0765.2006.00065.x
- Yang, S., Xiao, Y. N., Sun, X., Ding, J., Jiang, Z., and Xu, J. (2019). Biochar Improved rice Yield and Mitigated CH₄ and N₂O Emissions from Paddy Field under Controlled Irrigation in the Taihu Lake Region of China. *Atmos. Environ.* 200, 69–77. doi:10.1016/j.atmosenv.2018.12.003

- Yao, Y., Gao, B., Zhang, M., Inyang, M., and Zimmerman, A. R. (2012). Effect of Biochar Amendment on Sorption and Leaching of Nitrate, Ammonium, and Phosphate in a sandy Soil. *Chemosphere* 89, 1467–1471. doi:10.1016/j.chemosphere.2012.06.002
- Yargicoglu, E. N., and Reddy, K. R. (2018). Biochar-Amended Soil Cover for Microbial Methane Oxidation: Effect of Biochar Amendment Ratio and Cover Profile. *J. Geotech. Geoenviron. Eng.* 144, 04017123. doi:10.1061/(asce)gt.1943-5606.0001845
- Yi, S., Chang, N. Y., and Imhoff, P. T. (2020). Predicting Water Retention of Biochar-Amended Soil from Independent Measurements of Biochar and Soil Properties. *Adv. Water Resour.* 142, 103638. doi:10.1016/j.advwatres.2020.103638
- Yi, S., Witt, B., Chiu, P., Guo, M., and Imhoff, P. (2015). The Origin and Reversible Nature of Poultry Litter Biochar Hydrophobicity. *J. Environ. Qual.* 44, 963–971. doi:10.2134/jeq2014.09.0385
- Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., et al. (2019). Biochar Amendment Improves Crop Production in Problem Soils: A Review. *J. Environ. Manage.* 232, 8–21. doi:10.1016/j.jenvman.2018.10.117
- Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., et al. (2012). Effects of Biochar Amendment on Soil Quality, Crop Yield and Greenhouse Gas Emission in a Chinese rice Paddy: A Field Study of 2 Consecutive rice Growing Cycles. *Field Crops Res.* 127, 153–160. doi:10.1016/j.fcr.2011.11.020
- Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., et al. (2010). Effect of Biochar Amendment on Yield and Methane and Nitrous Oxide Emissions from a rice Paddy from Tai Lake plain, China. *Agric. Ecosyst. Environ.* 139, 469–475. doi:10.1016/j.agee.2010.09.003
- Zhang, D., Pan, G., Wu, G., Kibue, G. W., Li, L., Zhang, X., et al. (2016). Biochar Helps Enhance maize Productivity and Reduce Greenhouse Gas Emissions under Balanced Fertilization in a Rainfed Low Fertility Inceptisol. *Chemosphere* 142, 106–113. doi:10.1016/j.chemosphere.2015.04.088
- Zhang, J., and You, C. (2013). Water Holding Capacity and Absorption Properties of wood Chars. *Energy Fuels* 27, 2643–2648. doi:10.1021/ef4000769
- Zhang, Y., Ding, J., Wang, H., Su, L., and Zhao, C. (2020). Biochar Addition Alleviate the Negative Effects of Drought and Salinity Stress on Soybean Productivity and Water Use Efficiency. *BMC Plant Biol.* 20, 288. doi:10.1186/s12870-020-02493-2
- Zhao, R., Coles, N., Kong, Z., and Wu, J. (2015). Effects of Aged and Fresh Biochars on Soil Acidity under Different Incubation Conditions. *Soil Tillage Res.* 146, 133–138. doi:10.1016/j.still.2014.10.014
- Zimmerman, A. R., Gao, B., and Ahn, M.-Y. (2011). Positive and Negative Carbon Mineralization Priming Effects Among a Variety of Biochar-Amended Soils. *Soil Biol. Biochem.* 43, 1169–1179. doi:10.1016/j.soilbio.2011.02.005
- Zimmerman, A. R., and Gao, B. (2011). “The Stability of Biochar in the Environment,” in *Biochar and Soil Biota*. Editors N. Ladygina and F. Rineau (Boca Raton: CRC Press), 1–40.
- Zou, Y., Wang, X., Khan, A., Wang, P., Liu, Y., Alsaedi, A., et al. (2016). Environmental Remediation and Application of Nanoscale Zero-Valent Iron and its Composites for the Removal of Heavy Metal Ions: A Review. *Environ. Sci. Technol.* 50, 7290–7304. doi:10.1021/acs.est.6b01897

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2021 Vijay, Shreedhar, Adlak, Payyanad, Sreedharan, Gopi, Sophia van der Voort, Malarvizhi, Yi, Gebert and Aravind. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.