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Biochar and fertiliser interactions in crop and pasture production

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Introduction

Biochar application to soil has changed various physical and chemical properties, such as water and nutrient retention, soil aggregation, soil pH and CEC that positively affect crop growth and yield (Jeffery *et al.* 2015; Nguyen *et al.* 2018; Chew *et al.* 2020). It has been pragmatic that biochar-induced plant growth and yields may contribute to plant nutrition and improved soil physicochemical properties (Elad *et al.* 2011). This biochar effect might be associated with microbial community structure, functional diversity and microbial activity changes, which might have complex interactions among physical, chemical and biological properties of soil, plant and biochar systems (Jaiswal *et al.* 2017). In spite of the positive impacts of biochar in agricultural systems, it is commonly expensive to apply at higher rates because of the high cost of biomass collection, operating and maintenance of pyrolysis unit (Clare *et al.* 2015). In the last decade, efforts have been made to overcome economic barriers to using biochar and fertiliser together that can capitalise on biochar effect. Biochar fertilisers are generally made of 20–80% biochar, 5–8% clay, minerals, organic and inorganic compound fertilisers containing nitrogen (N), phosphorus (P) and potassium (K). Another option is to use biochar and fertilisers as a separate component which have also shown to increase crop yields, N and P use efficiency, vegetable quality with the increase in vitamins and sugars contents, diversity of beneficial microorganisms, reduced pesticide inputs, lower greenhouse gas emissions and farm productivity (Joseph *et al.* 2013; Blackwell *et al.* 2015; Yao *et al.* 2015; Zheng *et al.* 2017). However, how biochar and fertiliser application results in productivity relative to conventional fertilisers is still poorly understood. Joseph *et al.* (2015*a*, 2015*b*) noted that when mineral-enhanced magnetic biochars were applied at low application rates, there was an increase in mycorrhizal root colonisation which led to an increase in plant nutrient uptake. Chen *et al.* (2018) reported that a rice husk and urea released N at a slower rate than urea, immobilising Cd and preventing its uptake into plants. However, the mechanism(s) behind the beneficial impact of biochar and fertiliser interactions remains unrevealed. Mechanism that has yet been explored is that how biochar–fertiliser changes the ion potential across the root membrane for uptake of nutrient cations and anions, especially nitrates (Yan *et al.* 2011; Chew *et al.* 2020). Increasing the potential difference between the root membrane and the soil termed root membrane potential can increase the free energy for the transportation of nutrients. Joseph *et al.* (2015*a*, 2015*b*) noted that the redox potential and pH of soil changed when biochar was added, and the degree of change is a function of biochar type, application rate and soil properties.

Biochar and fertiliser interactions affect soil fertility and plant productivity

Biochar research has focused on enhancing soil fertility, carbon (C) sequestration, activities of microorganisms, agricultural production, mitigating climate change, soil contamination and many other aspects (Hussain *et al.* 2017). Given the ongoing interest in biochar, this special issue included original research and review articles exploring different aspects of biochar application for improving microbial activities, soil fertility and crop and pasture production. The biochar research has progressed considerably with significant key findings on agronomic benefits, C sequestration, greenhouse gas emissions, soil acidity, soil fertility, soil health, soil salinity, etc. Still, more field-based research is required before definitive recommendations can be made to the end-users regarding the effects of biochar application across various soils, climates and land management practices.

Soil constraints that cause major problems for plant growth and crop production are chemical, physical and biological (Solaiman and Anawar 2015). Chemical constraints are acidity, salinity, sodicity and nutrient deficiencies that impact crop and pasture production. It requires a large amount of fertiliser in nutrient-deficient soil for crop production. Physically constrained soils have compacted soil layers with high bulk density and lower water movement. Soils with low organic matter have poor biological activities with reduced microbial diversity and activity. Soil amendment with biochar and proper fertiliser combinations can improve soil fertility and agronomic benefits. This Special Issue has also selected articles on how biochar and fertiliser can increase soil health and crop yields and overcome soil constraints such as acidity, salinity, drought, low fertility and remediation of contaminated soils.

Imran *et al.* (2022) wrote a review paper stating that biochar is a soil conditioner and an eco-friendly biostimulant that mainly increases crop productivity, alleviates adverse effects of abiotic stresses and improves crop yield. Biochar amendment is gaining popularity because it improves soil's physiochemical and biological properties. It enhances abiotic stress tolerance as well as the growth and yield of plants by modulating ionic homeostasis, photosynthetic apparatus, antioxidant machinery, reducing metal uptake and oxidative compensations. This review nicely summarised current reports on the impact of biochar and discussed the potential roles of biochar for crop growth and yield under stress and non-stress conditions. This review also covered possible mechanisms of how abiotic stress can be mitigated via growing plants with biochar and the limitations and prospects of biochar application in agriculture.

Several publications mainly articulated biochar and fertiliser's combined application and reported their interactions. For example, Mahmoud *et al.* (2022*a*) found the effect of biochar with recommended P dose on wheat yield and soil fertility in clayey soil during two growing seasons. The results showed an increase in soil availability and plant uptake of NPK; plant growth attributes, and wheat grain yield treated with P fertiliser alone, or when P fertiliser was combined with biochar addition. Wheat uptake of NPK increased due to the concentration of inorganic P in soil. It is noteworthy that by adding biochar to P-fertiliser with 50% P, the highest grain yield was recorded compared with 100% P and 150% P of the recommended dose. The results indicated that integrating biochar and P fertiliser can be a practical approach to improve wheat production and soil fertility.

The influence of wood biochar and mineral NPK fertilisers on wheat yield and soil properties under different management practices is reported (Ullah *et al.* 2022). Growth attributes and grain yield were obtained with the application of mixture of NPK and biochar in varying ratios. The grain and biological yields observed at 75% NPK + 5 t biochar and 50% NPK + 10 t biochar ha^{-1} were significantly higher than 20 t biochar alone. However, maximum soil organic matter, extractable P and K contents with slight increases in soil pH and EC were observed at 20 t biochar ha^{-1}. Moreover, almost all agronomic parameters were significantly better in raised beds compared to flat-bed sowing.

Shandilya and Tanti (2022) reported a conventionally produced organic biochar from stem, peel and suckers of bananas called 'kolakhar' and they evaluated the growth effect of five traditional rice varieties with contrasting characteristics for tolerance of Al toxicity and P deficiency. Biochar treatment improved biomass, photosynthetic efficiency, and antioxidant defence mechanisms in rice seedlings. The increased ascorbate peroxidase, guaiacol peroxidase, and other enzyme synthesis in seedlings growing on soil treated with kolakhar shows a potential stress-reduction strategy. Kolakhar significantly decreased Al uptake which could be exploited further for ameliorating soil acidity in a low-cost and eco-friendly way.

In order to improve the morphophysiological and yield features of sunflowers, Samreen *et al.* (2022) reported how to increase boron (B) availability in wheat straw in biochar-amended alkaline calcareous soils. In a pot experiment, diammonium phosphate (DAP) alone, B + DAP, and DAP coated with biochar and B (BC-BDAP) were used as fertilisers to grow sunflower. Wheat straw biochar was used to improve the soil quality, and the soil that included 4% of it had the highest levels of accessible B. Thus, the application of BC-BDAP fertiliser in 4% biochar-amended soil can be an efficient strategy for enhancing B availability in alkaline calcareous soils and increasing sunflower growth and yield.

Premalatha *et al.* (2022) examined the impact of biochar and water source salinity on soil characteristics and marigold (*Tagetes erecta*) crop growth. Different amounts of treated tannery effluents were used in the salinity treatments, and water hyacinth (*Eichhornia crassipes*) was used to make the biochar. Both the amount of biochar used and the salinity of the water had a big impact on soil characteristics. Soil pH increased with biochar while more salinity in the water increased electrical conductivity. Applying biochar to post-harvest soils improved the amount of accessible NPK. At increased salt concentrations, enzyme activity and plant development were reduced but enhanced by biochar use. These findings show that applying biochar at a rate of 10 t ha^{-1} considerably increases nutrient availability and enzyme activity in soils with different salinity levels by trapping soluble salts on the surface's pore space.

Under salt-stress circumstances, biochar application could reduce nutritional deficiencies and crop failure.

The impact of biochar-enriched compost on lowering salt stress after fresh application at increasing rates and in the succeeding crop was reported by Mithu *et al.* (2022). In a pot study, mungbean was grown under five distinct salt stress conditions (0, 2, 4, 8 and 12 dS m^{-1}) while biochar compost was added at four different rates (0, 1, 2 and 3%). Under three different salt stress scenarios, the field trial examined the residual impact of several organic amendments. Results showed a strong interaction between biochar and salt treatment in pot culture. Moreover, they found that the biochar compost significantly outperformed the control treatment regarding biomass production, seed yield, and K uptake. These findings imply that biochar compost can be one of the environmentally friendly ways to reduce soil salinity.

According to the study of Thi *et al.* (2022), cultivating acid sulfate soils necessitates effective treatment of their naturally low pH. They examined the development and yield of baby corn after applying lime, organic fertiliser, and biochar to reduce acidity in an acid sulfate soil (*Zea mays* L.). Lime raised soil salinity from 1.72 to 1.95 dS m^{-1}, pH (H_2O) from 3.75 to 4.12, and cob yield by 30%. They found biochar improved cob yields by 28% on both unlimed and limed soil. The best yields obtained with biochar or organic fertiliser applied singly or in combination were comparable to those obtained with liming. The use of organic fertiliser resulted in a 19% increase in overall cob production. The increases in output brought on by adding biochar or organic fertiliser were linked to better nutrient availability. The reduction in cob protein, which was associated with the increases in cob production, was most likely the result of insufficient N availability later in the season. They found that organic fertiliser and biochar applied in reasonably significant amounts can be viable treatments for cropping in acid-sulfate soils.

Garbuz *et al.* (2022) reported that soil enzyme activity is a major regulator of C and nutrient cycling in grazed pastures. Under permanent pastures, they looked at the impact of adding biochar on the activity of seven enzymes involved in the C, N and P cycles. They did a 1-year field-based mesocosm experiment using four pastures with various animal and nutrient management approaches, including dairy cow grazing on the Andosol with or without effluent and sheep grazing on the Cambisol with either nil or high P fertiliser input. Three soil amendments were used: (1) lime added at the liming equivalent of biochar (positive control); (2) willow biochar added at 1% w/w; and (3) no amendments (negative control). The Andosol possessed higher dehydrogenase, urease, alkaline and acid phosphatase, and nitrate-reductase activities when compared to the Cambisol, which was consistent with its higher pH and fertility. All enzymes in both soils were made more active by adding biochar, except for acid phosphatase and peroxidase, while peroxidase and nitrate-reductase were made more active by adding lime. After adding biochar, there was a correlation between elevated enzyme activity and soil biological activity. Due to increased root biomass following the addition of biochar, cellulase activity was raised by 40–45%. The impact of biochar and lime addition on soil pH can be used to explain the change in acid and alkaline phosphatase activity. Their findings shed light on how to realise biochar's potential advantages in delivering ecosystem services for pastures that are used for grazing.

Biochar and fertiliser interactions affect soil contamination and phytoremediation

According to Ahmad *et al.* (2022), commercially available hardwood biochar applied at a rate of 10 g kg^{-1} soil for the immobilisation of heavy metals varied with particle sizes (3, 3–6, and 6–9 mm). The contamination of Cd, Pb, and Ni was significantly reduced by biochar particles with diameters of 3, 3–6, and 6–9 mm by 35%, 10%, 9%, 61%, 60%, and 35%, respectively. By applying biochar particles with diameters of 3, 3–6, and 6–9 mm, soil porosity was enhanced by 10.3%, 4.2%, and 3%; saturation percentage was increased by 100%, 42%, and 27%; and pH was increased by 0.53%, 2.6%, and 4%, and organic matter by 33.6%, 19.7% and 16.8%. Electrical conductivity decreased by 19%, 20%, and 24%, whereas soil bulk density dropped by 12%, 5%, and 2.3%. Under the application of biochar, the contamination factor for Cd was >1 (moderate contamination), whereas the contamination factors for Pb and Ni were 1 (low contamination). The smallest biochar particles (3 mm) had the most significant impact on soil physicochemical parameters and the stabilisation of heavy metals. Therefore, for optimal heavy metal immobilisation and to improve the soil's physicochemical qualities, heavy metal-polluted soils should be treated with fine biochar.

Mahmoud *et al.* (2022*b*) used spectroscopy analysis of grown canola plants to assess the impact of rice straw biochar (RB), rice straw compost (RC) and their mixtures on the immobilisation of pesticides (atrazine, glyphosate and chlorpyrifos) in contaminated soil. GC or HPLC analysis were done to determine whether pesticide residues have been immobilised, as well as the chemical makeup of RB and RC, and their addition at varied concentrations to contaminated soil. The findings demonstrated an increase in the exchangeable Ca^{2+} levels, organic matter (OM), cation exchange capacity (CEC), uptake of N, P and K, and dry weight of canola plants following RB or RC alone or their combinations. In soil modified by RC and RB, pesticide concentrations decreased with rising OM, CEC and exchangeable Ca^{2+}. Compared to control, adding RB at levels of 0.5% and 1.0% reduced chloropyrifos by 43.2% and 63.1%, glyphosate by 32.8% and 77.3%, and atrazine by 21.9% and 72.2%. Their findings suggested that pore filling, hydrophobic effect, H-bonding, degradation, and enhancement of soil characteristics were the main mechanisms of pesticide immobilisation in the alkaline soils modified with RC and RB. Their findings concluded that modified rice straw might be added as soil amendments for contaminants remediation.

Mehmood *et al.* (2022) examined the effects of three soil amendments, biochar, slag, and ferrous manganese ore (FMO) applied at 3% and 6%, on the bioavailability of heavy metals in contaminated soil, their bioaccumulation, and activities of antioxidant enzymes in water spinach (*Ipomoea aquatica*) plants. The most increased plant fresh biomass was 6% biochar, with 32.3% increase in roots and 47.98% in shoots compared to control soil. Each alteration decreased lead and cadmium's bioavailability. Their findings showed that the biochar, slag and FMO had a substantial impact on the physical, chemical and biological aspects of soil as well as metal bioavailability and fertility status, potentially protecting soil health and promoting the growth of plants.

Zhou *et al.* (2022) reported that chestnut shell biochar promoted Pakchoi plant shoot weight, root weight, shoot length and root length. Applying biochar also effectively increased soil pH and reduced the bioavailability and migration of heavy metals. Besides, membrane integrity and chlorophyll content were enhanced because of the alleviation of oxidative stress. Noticeably, biochar application reduced the Cd concentration in roots by 40–60%, and enhanced accumulation of Pb by 75–191%. This study has shown the remediation potential of chestnut and provided a clue for sustainable management of chestnut shell waste for further development of the chestnut industry.

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