

Review

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# The use of biochar for reducing carbon footprints in land-use systems: prospects and problems

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## Abstract

Biochar, a carbonaceous solid material obtained from the pyrolysis of biomass, has received considerable research attention because of its unique properties and potential to improve crop yields and soil carbon (C) sequestration while reducing environmental degradation and carbon footprints (CF). This paper summarizes the available results on several aspects of biochar research from numerous studies despite their short-term nature. The studies have shown that (1) biochar from the same source added at a given rate to different soils could have different effects, particularly on phosphorus (P) release/retention, based on the respective soil properties; (2) the elemental composition of a feedstock (the biomass source used for biochar production) is not an indication of plant-nutrient availability; (3) pyrolysis temperature has a significant influence on the properties of the biochar, but the optimal temperature depends on the desired qualities of the product such as P release, cation exchange capacity, and surface area; and (4) the risk of nutrient loss during biochar application depends on the nutrient release potential of the biochar as well as the nutrient retention properties of the soil. Some evidence from nature suggests that biochar can hold C in soils for thousands of years, but the mechanisms involved are not fully understood. In general, the available results on the effect of biochar application on field crops have been variable and site-specific so that general conclusions cannot be drawn on their applicability to a wide spectrum of situations and systems. A number of researchable priorities were identified, including CF under biochar. Similarly, although the land application of biochar to decrease CF sounds like a promising proposition, rigorous long-term studies under farm settings are required before recommending it for large-scale adoption.



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**Keywords:** Feedstock, phosphorus, soil type, carbon storage in soil fractions

## INTRODUCTION

Biochar has become an increasingly popular and prominent term in the scientific literature since the early 2000s. The International Biochar Initiative touts it as a “powerfully simple tool to combat climate change” (Available from: <https://biochar-international.org/biochar/>). Lehmann and Joseph<sup>[1]</sup> (2009) characterized biochar as “a carbon-rich organic material produced by pyrolysis of biomass from plant or animal origin.” Pyrolysis refers to combustion at low or no oxygen such that the emission of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) that occurs during the traditional charcoal making by burning the wood could be considerably reduced.

The scientific literature is replete with increasing volumes of research results, reviews, and meta-analyses on various aspects of production and field use of biochar under a variety of soil and climatic conditions<sup>[2-5]</sup>. A comprehensive review of biochar's interactions in soil environment and various mechanisms involved from plant responses, soil health and environmental standpoints was recently put forward<sup>[6]</sup>. Similarly, Schmidt *et al.* summarized 26 meta-analyses revealing the important findings of biochar research to date<sup>[7]</sup>. Critical reviews exist on various aspects of biochar research, including nutrients and soil water availability<sup>[8]</sup> and retention<sup>[9]</sup>, soil biota and biodiversity<sup>[10,11]</sup>. Nevertheless, it has yet to be used in large-scale (farm application) and long-term (over 10 years) field applications, partly due to uncertainties and lack of scientific consensus on biochar feedstock type, production, use and economic constraints<sup>[6,12,13]</sup>. Considering its relevance to climate change and carbon footprint (CF), it is important to assess the potential for the practical use of biochar in land-use systems across different soil types and climatic conditions. With that objective, this paper summarizes the observations and conclusions based on the effort to sift through and evaluate a large body of literature on biochar, although many reports are based on relatively short-term studies on a topic that deserves long-term investigations under field settings.

The Google Scholar (Available from: <https://scholar.google.com/>) database service was used to estimate the scope of the work, and multiple search functions under Google Scholar were used to sort the vast literature published to date. The keywords used for searching the database were “biochar”, “biochar and crop yield”, “biochar and nutrients”, “biochar and carbon sequestration”, and “biochar and carbon footprints”. The data range function was used to sort predominant work published in the past 20 years (2002-2022). The meta-analyses and review articles relevant to the scope of this work were given particular importance in the syntheses of the discussions in the manuscript due to their wide acceptability and scope of those analytical reviews.

## BIOCHAR AS A SOURCE OF PLANT NUTRIENTS

In the biochar literature, feedstock refers to the materials used for biochar production, unlike in animal production systems, where it refers to animal feed. The quality and properties of biochar depend on the nature of the feedstock and the method of pyrolysis employed. In commercial systems of biochar production, the pyrolysis gases flow into a thermal oxidizer, which combusts the gases and oils at high temperatures achieving clean combustion. Biochar is also produced on smaller scales in cost-effective kilns, such as in subsistence farming systems, where the quality and properties of the product will vary considerably.

The most-referenced evidence to support the beneficial effect of biochar on soil productivity and crop growth is provided by the biochar-rich dark-earth (*Terra Preta*) in the highly weathered, infertile Oxisols in Central Amazonia, Brazil. The *Terra Preta* soils are formed from the *slash and char* technique (not to be confused with the traditional *slash and burn*), also known as shifting cultivation or swidden farming, which is practiced by an estimated 200 million resource-poor farmers in several tropical regions<sup>[14-16]</sup>. Large quantities of nutrient-rich residues of kitchen waste, bones, ashes, charcoal, excreta, *etc.* over long periods are believed to have been added to the soil by the previous inhabitants of the land<sup>[17]</sup>. Despite being under continuous cultivation for centuries, these areas have maintained high productivity levels compared to the surrounding soils of the region<sup>[16]</sup>.

Biochar is now increasingly recommended as a nutrient source, especially in nutrient-deficient and degraded soils<sup>[18-20]</sup>. Numerous reports and meta-analyses results are available on the effect of biochar application on crop growth<sup>[21]</sup>, nutrient dynamics<sup>[22,23]</sup>, soil amelioration, microbial biomass, soil respiration<sup>[24]</sup>, and soil physical properties<sup>[25,26]</sup>. Biochar's physicochemical properties depend on feedstock type and pyrolysis conditions, especially peak pyrolysis temperature, which controls many soil physical (bulk density, water retention, aggregate stability, surface area) and chemical (pH, cation and anion exchange capacities, nutrients availability) properties when amended<sup>[27-32]</sup>. Similarly, biochar pyrolyzed from different biomass and pyrolysis conditions also affects soil biota differently<sup>[10]</sup>. In addition, biochar from the same source added at a given rate to different soils could have different effects - particularly for phosphorus (P) - based on the respective soil P saturation properties<sup>[33]</sup>. Since soil C sequestration is closely related to the application of biochar as a nutrient source, it is important to understand the amount of nutrients (e.g., P) from a given biochar source that could be safely added to the soil for plant uptake to avoid environmental P loss risks primarily in coarse-textured soils, and for P availability from a high P-retentive tropical soil. It is also important to know the nutrient content and the carbon: nitrogen ratio (C:N) of biochar, as a lower C:N ratio is reported to be critical for a promising material to serve as a nitrogen fertilizer<sup>[34]</sup>. On this aspect, efforts were also made to understand if biochars can be tailored or designed to specific purposes by using relevant properties as successful soil amendments through feedstock selection, pyrolysis conditions, and particle size choices<sup>[35]</sup>.

### **Nutrient contents of biochars from animal- and plant-based feedstocks**

Biomass can be obtained from different animal sources. Swine manure, poultry- and turkey litter, and dairy manure are some of the main livestock-derived materials that have served as feedstock for biochar production. Pyrolysis enables the elimination of pathogens and drastically reduces the waste volume while providing energy and value-added products<sup>[36-38]</sup>. However, all animal-based biochar may not have similar properties. Sharpley and Moyer<sup>[39]</sup> found that the distribution of inorganic and organic P fractions in the soil depended on manure (dairy, poultry- and swine manure) and compost type suggesting a difference in nutrient availability by different animal-based biochar sources. Thus, a blanket term "animal-based biochar" need not necessarily mean that all biochar from different animal-based sources applied at the same rate will have identical yield responses. Another difficulty is the use of the term biosolids and the biochar derived from them. Similar to manure-derived biochars, the nutrient availability from the "municipal wastewater sludge"- derived biochars also vary substantially depending on the processing method<sup>[40]</sup>.

Plant wastes such as wood chips, sawdust, leaves, bark, and branches could be good sources of biomass for pyrolysis. Cantrell *et al.* reported that the diverse range of plant residues as well as the differences in processing them may result in biochar with different physical and chemical characteristics<sup>[38]</sup>. Moreover, biomass from plant sources may contain low N, P, and potassium (K) [Table 1] and therefore may need to be supplemented with additional sources of essential nutrients. Plant-based biochar can be used in conjunction with fertilizers to help reduce nutrient leaching<sup>[41-43]</sup>. The amount and extent of different

**Table 1. Nutrient composition of biochar produced from plant- and animal-based feedstocks in a Mehlich 3 extract**

	P	K	Ca	Mg	TKN	TP	TC	C:N ratio	pH	WSP mg kg <sup>-1</sup>
	mg kg <sup>-1</sup>						%			
<b>Plant-based biochar</b>										
HWB	480	4350	670	620	1015	1900	77	755	8.8	90
Maple	103	4140	4810	670	3048	730	57	186	7.8	30
Pine	67	450	490	47	0.1	405	NA <sup>†</sup>	NA	8.4	17
<b>Animal-based biochar</b>										
PLB <sup>1</sup>	13,100	48,300	10,300	6190	18,000	29,000	30	15	9.3	307
PLB <sup>2</sup>	16,900	57,000	13,700	8280	28,300	28,100	30	11	9.1	165
Biosolids	7060	500	2330	5140	50,700	67,330	32	6	6.4	305

TP: Total phosphorus; TKN: total Kjeldahl nitrogen; TC: total carbon; WSP: pH and water-soluble P; HWB: hardwood biochar; PLB<sup>1</sup> and PLB<sup>2</sup>: poultry litter biochar from two different production batches. Mehlich 3 extractable: P (phosphorus), K (potassium), Ca (calcium), and Mg (magnesium); <sup>†</sup>NA = Not Available; Adapted from Freitas et al.<sup>[40]</sup>.

nutrients released from biochars suggest that P, K, and Mg have different types of associations with biochar<sup>[44]</sup>. For example, P can be released in relatively large amounts and remain stable over time, indicating a stable P supply over multiple seasons, whereas K might be released fast and can be depleted rapidly in soil<sup>[45]</sup>. Another study also indicated that different forms of dissolved organic carbon (DOC), N, and P existed in both freshly produced and aged biochars: greater amounts of nutrients were released from biochars made from grass compared to that from hardwoods<sup>[46]</sup>.

While various plant-based (hardwood, softwood, or grasses) biochars have been used in research to understand their ability to supply nutrients, the controversy regarding deforestation for large-scale biochar adaptation has been a concern. Several agricultural byproducts such as corncob, rice husk, bagasse, corn stover, coconut shell, banana peels, crop residues, *etc.* have been suggested and used in field trials to counter the “deforestation concern”<sup>[47-49]</sup> and tremendous amount of related work on agro-waste derived biochars so far has been carried out in China and various European countries<sup>[50,51]</sup>. Although there is research on biochars produced from individual agro-waste materials, comparable data on nutrients composition and plant availability of nutrients from agro-waste-derived biochars versus plant- and animal-based biochars are currently scarce.

## EFFECT OF BIOCHAR APPLICATION ON DIFFERENT SOIL TYPES

The impacts of biochar on crop yield under different soil types were investigated by quantitative reviews or meta-analyses. A meta-analysis using 23 studies suggested that grand mean increase of overall crop productivity or biomass increase by 10% with maximum yield benefits were from acidic to neutral pH range and in soils with coarse or median structures<sup>[52]</sup>. These results were reconfirmed with a much higher mean yield increase by 25% in the tropics under a later global scale meta-analysis with 109 independent studies and 1125 observations<sup>[53]</sup>. These quantitative reviews suggest that (1) the effects of biochar on crop yield are greater in acid tropical soils with inherent low nutrient levels compared to temperate soils with higher nutrient status; (2) biochar management in temperate regions should be more useful for non-yield benefits such as savings on lime and fertilizer costs, reduction of greenhouse gas (GHG) emissions, and other ecosystem services; (3) the main mechanisms of yield increase under biochar could be liming effect and higher water holding capacity (WHC); and (4) biochar’s overall role on stimulating yields should not be considered universal<sup>[53]</sup>.

From these meta-analyses and other individual studies, biochar appears to be greatly beneficial to sandy soil by increasing the WHC<sup>[43,54]</sup> and enhancing the retention of some nutrients via electrostatic adsorption sites<sup>[41,43]</sup>. Based on the threshold P saturation ratio (PSR) for a non-calcareous soil<sup>[33]</sup>, a series of experiments were conducted at the Environmental Soil Chemistry Laboratory at the University of Florida, Gainesville, Florida, United States, to illustrate the relative influence of soil- vs. biochar properties on soil P retention. With this objective, the effect of biochar addition (representing two broadly defined sources, animal- and plant-based) to coarse- and fine-textured soils with different P retention properties on soil P availability and its environmental impact are addressed in the following sections.

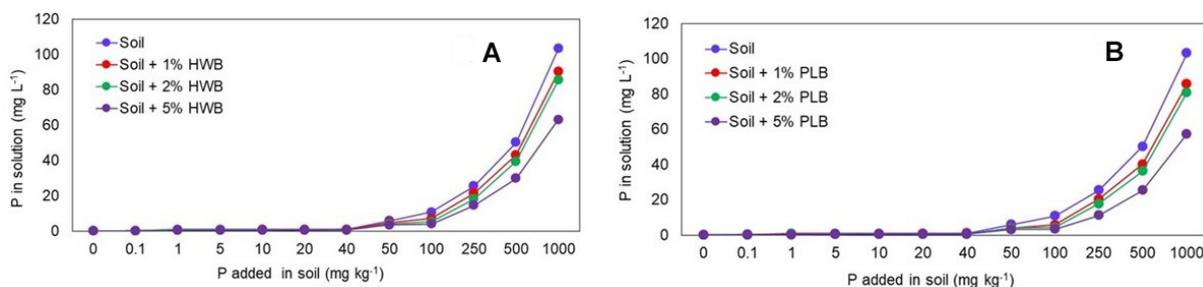
### **Sandy soils of Florida, USA**

Dari *et al.* showed that P release from a minimum P-impacted coarse-textured Candler soil (Hyperthermic, uncoated Typic Quartzipsaments) at environmentally relevant solution P concentrations are dependent on the soil's P retention capacity<sup>[55]</sup>, suggesting applications of biochar from the same feedstock (e.g., Hardwood biochar, HWB, [Figure 1A](#) or Poultry litter biochar, PLB, [Figure 1B](#)) may release P at an identical rate irrespective of the biochar source. Additionally, an increasingly higher amount of P was retained by increasing biochar amendment rate in the soil [[Figure 1](#)] above the P saturation point of the soil. The apparent benefit may not be as high as suggested by the magnitude of sorption differences, because the additional P held at very high concentrations would be released (barring strong hysteresis) when concentrations approach environmentally acceptable levels. This study showed that a more P retentive Apopka soil (loamy, siliceous, subactive hyperthermic Grossarenic Paleudults; [Figure 2](#)) may release P only when higher P concentrations are added, same as the low P retentive soil [[Figures 1A and 2A](#)]. The amount of biochar applied (1%, 2%, or 3%), irrespective of the biochar source, began to release P only when the P retention capacity of the soil was exhausted [[Figure 1 and Figure 2A and B](#)].

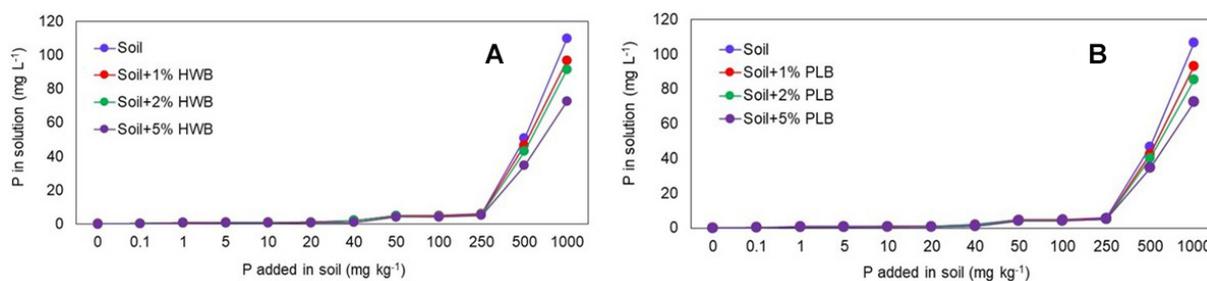
### **Clayey-loam soils of Karnataka, India**

Extending the above observation to the more P-retentive tropical soils, Chatterjee *et al.* showed that more P must be added to the soil before the soil begins to release P [[Figure 3](#)] compared to the Florida soils<sup>[56]</sup>. A rapid increase in P concentrations occurs between 50 and 100 mg kg<sup>-1</sup> for the sandy soils [[Figure 1](#)] and at ~700 mg kg<sup>-1</sup> for clayey-loam soils in the tropical soils of Karnataka. Phosphorus release patterns from these soils in [Figures 1 and 3](#) suggest minimal P release from tropical soils compared to temperate soils (with or without biochar additions), even with high P additions.

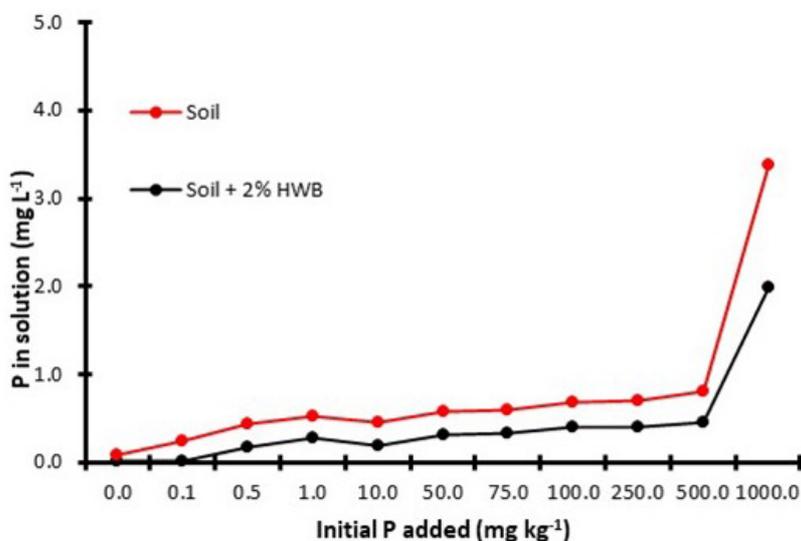
These emerging details on the phosphorus retention and release characteristics from soils with low P saturation levels are important from the environmental perspective as well as the overall CF. Sandy soils of Florida (USA) and other places with low P retention capacity, for example, tend to receive excessively high levels of P from NPK fertilizers, the application rates of which are often determined according to the N requirement of the crop or grass. This leads to the transportation and deposition of the excess water-soluble P from the non-P-retentive sandy soils, causing pollution and eutrophication of water bodies. The use of chemical fertilizers (NPK) on major crop production has been identified to leave significant CF due to chemicals mining, production, transportation, machinery and field management, and post-application GHG emissions<sup>[57-60]</sup>. The use of biochar, strictly from a fertility standpoint alone, is a desirable approach to addressing this problem, for which fundamental information on the performance of different biochars in various soil types is essential. This is a good example of how science-based management of major nutrients such as P, which has complex chemistry and enormous environmental significance, has a direct bearing on CF because reducing CF is intertwined with the larger issue of environmental integrity.



**Figure 1.** Relationship of P added to a soil and soil-biochar mixtures (1%, 2% and 5% biochar additions) to a soil with minimum P retention capacity (Candler soil from Florida, USA): (A) hardwood biochar, HWB; (B) poultry litter biochar, PLB and P remaining in solution after equilibration (Dari et al.<sup>[55]</sup>). The x-axis has been expanded to show the relationship at low (environmentally relevant) P concentrations.



**Figure 2.** Relationship of P added to a soil and soil-biochar mixtures (1%, 2% and 5% biochar additions) to a soil with greater P retention capacity (Apopka soil from Florida, USA) than the soil in Figure 1: (A) hardwood biochar, HWB; (B) poultry litter biochar, PLB and P remaining in solution after equilibration (Dari et al.<sup>[55]</sup>). The x-axis has been expanded to show the relationship at low (environmentally relevant) P concentrations.



**Figure 3.** Relationship of phosphorus (P) added to a native tropical soil in Karnataka, India, and soil-biochar mixture (2% hardwood biochar) at various P concentrations<sup>[56]</sup>. Note the differences in the y-axis scale compared to Figures 1 and 2.

### Effect of pyrolysis temperature on nutrient (P) release from biochar

The properties of biochars depend not only on the nature of feedstocks but also on the conditions under which they are produced such as pyrolysis temperature and residence time<sup>[27,61]</sup>. Biomass-to-fuel processes

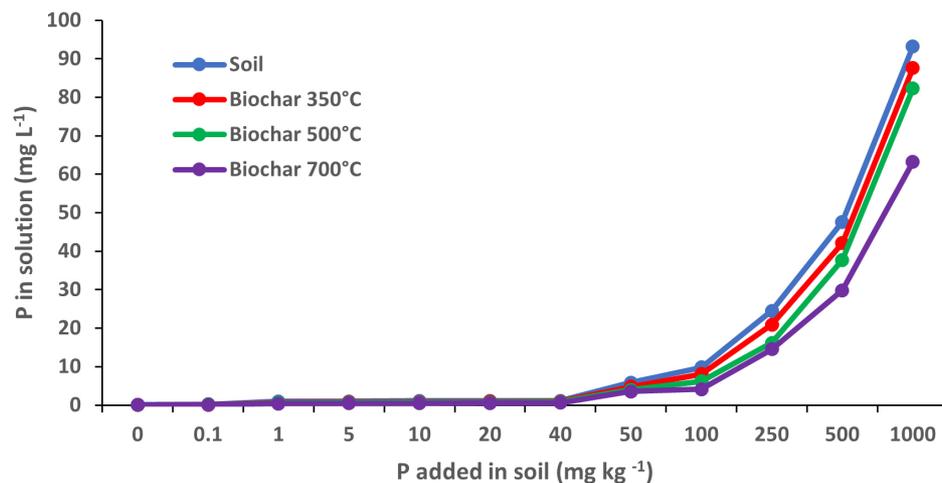
are of two categories: *slow* and *fast*<sup>[62]</sup>. Slow pyrolysis is characterized by heating the biomass at a temperature between 300–650 °C with a long residence time, ranging from a few minutes to hours, and low heating rates of 10–30 °C min<sup>-1</sup><sup>[63,64]</sup>. Fast pyrolysis refers to heating biomass at higher temperatures. Slow process is therefore a practical method for biochar preparation when producing large quantities of biochar with simultaneous production of bio-oil and syngas<sup>[65]</sup>.

Biochars produced at various temperatures and processes have contrasting nutrient contents<sup>[66]</sup>, physicochemical properties under both fresh and aged conditions<sup>[67]</sup>, and they tend to behave differently when used as soil amendments in terms of nutrients release patterns<sup>[68]</sup>. Schmidt *et al.* (2015) used Pinyon pines (*Pinus* sp.), Junipers (*Juniperus* sp.), and a combination of the two to produce biochar under controlled conditions (350 °C, 500 °C, and 700 °C) in a lab, and in transportable metal kilns used by Nevada (USA) foresters<sup>[69]</sup>. Their results indicated that although there was some variation in physical and chemical properties of biochar produced at different temperatures, the kiln-produced biochar compared favorably to the other biochar in terms of cation exchange capacity (CEC), exchangeable K, and available P while having a higher pH and lower Ca content.

Mukherjee and Zimmerman<sup>[46]</sup> also reported that greater amounts of nutrients were released from biochars made at lower temperatures compared to those at higher temperatures: biochar produced at low temperatures (250 °C) released more nutrients than HWB (pine and oak) produced at higher (400 °C and 650 °C) temperatures. Nair *et al.* found that phosphorus additions on soil and soil-biochar mixtures with biochar produced at 350 °C, 500 °C, and 700 °C to the *Candler* soil from Florida released P from the soil at the same level of P addition irrespective of the temperature at which the biochar was produced [Figure 4]<sup>[70]</sup>. Thus, at environmentally relevant P concentrations, P release from soil-biochar mixtures does not seem to depend on the temperature, feedstock type, or production methodology (kiln *vs.* lab) of the biochar. However, once the inflection point is reached, the biochar prepared at the higher temperature releases less P [Figure 4]. Tomczyk *et al.* indicated that high pyrolysis temperature would promote the production of biochar with a strongly developed specific surface area, high porosity, pH, and ash- and C contents, but with low values of CEC and volatile matter<sup>[28]</sup>. The high surface area of the biochar is likely responsible for P retention after the inflection point [Figure 4].

## BIOCHAR AND SOIL CARBON SEQUESTRATION

Any biomass added to the soil is subjected to decomposition and most of the C in the added material is released into the atmosphere. However, the conversion of feedstocks into biochar could reduce CO<sub>2</sub> and methane emissions that occur during the natural decomposition or burning of the material. Carbon is the major constituent of biomass (over 70%) and about 60% of this biochar C is highly and aromatically stable<sup>[71]</sup>. A relatively larger part of biochar is predominantly made of refractory C while a smaller fraction is made of labile C, and this relative composition helps sequester C in soil<sup>[1,27]</sup>. The stability of biochar C in soil ranges depending on the feedstocks and pyrolysis temperatures. Biochar C degradation rate, half-life, and mean residence time (MRT) were estimated in laboratory and field studies that suggest variability in the biochar C stability in the environment<sup>[72–74]</sup>. A meta-analysis of biochar decomposition in soil and estimation of its MRT using 128 observations of biochar-derived CO<sub>2</sub> showed that only 3% of the biochar was bioavailable, and the remainder contributed to long-term C storage in the soil<sup>[75]</sup>. Brassard *et al.* reported, based on an evaluation of 76 biochars from 40 studies, that biochars with lower N content (C/N ratio > 30) were more suitable for mitigation of N<sub>2</sub>O emissions from soil, and those produced at higher pyrolysis temperature could have high C sequestration potential<sup>[76]</sup>. Hardwood-derived biochars with a higher C:N ratio [Table 1] will, therefore, be appropriate for N<sub>2</sub>O mitigation.



**Figure 4.** Phosphorus release from Candler soil, Florida, USA and temperature specific biochar (from *Juniperus osteosperma*) (350 °C, 500 °C, 700 °C) added to the soil (Nair et al.<sup>[70]</sup>).

### Carbon storage in soil fractions

There is some evidence that biochar application is effective in soil aggregation, thereby improving both native soil organic C and biochar stabilization, e.g., C storage in soil fractions in an intensive cropping system in North China<sup>[77]</sup>. Soil aggregate fractions are categorized into macroaggregates (250-2000  $\mu\text{m}$ ), microaggregates (53-250  $\mu\text{m}$ ), and the silt+clay fraction (< 53  $\mu\text{m}$ ). Nair et al. reported the results of several studies on the depth-wise distribution of soil aggregate fractions in soils and their soil organic carbon (SOC) content up to 1-meter depth in different land-use systems and soil orders in different parts of the world<sup>[16]</sup>. The authors noted the considerable differences in the percentage weight of soil fractions and SOC in the fractions within 1-meter depth of soils in land-use systems in USA, Spain, Mali, and Brazil. The SOC concentration generally increased with fraction size except for Spodosols, Inceptisols and Alfisols in these studies, with the C reported to be most stable in the smallest fraction (data not shown). However, in a range of tropical and temperate soils, the distribution by weight and SOC content in the various soil fractions is highly variable. These differences in soil aggregate-fraction distribution, and the resulting C sequestration potential, add to the problem of understanding C sequestration and saturation limits over a range of soils. Reviewing the studies on the topic, Blanco-Canqui<sup>[26]</sup> suggested that the mechanisms by which biochar alters soil physical properties, such as aggregation, are not well understood primarily because the studies were of short-term nature and laboratory-based while simultaneously suggesting that sandy soils responded more to biochar than clayey soils. However, an earlier comprehensive review on biochar impacts on soil physical properties and GHG emissions suggested that soil aggregation under biochar amendment may require a substrate and put forward a 2-phase complexation hypothesis to shed light on soil/biochar interactions<sup>[25]</sup>. Many studies exist on biochar impacts on soil C pools<sup>[78,79]</sup>, and a recent global meta-analysis including 586 paired comparisons from 169 studies across the globe found that while the rate of biochar application, soil texture, soil C content, climate zone, experiment type and duration have significant influences on total soil C storage, feedstock, pyrolysis temperature, biochar C content and soil pH had no effects on total C<sup>[80]</sup>. This meta-analysis found that the increase in total C in fine-textured soils was significantly ( $P < 0.05$ ) greater (81.3%) than in coarse-textured soils (53.4%)<sup>[80]</sup>, suggesting that fine-textured soils can store higher C than coarse-textured soils under biochar amendment.

### FIELD APPLICATION OF BIOCHAR

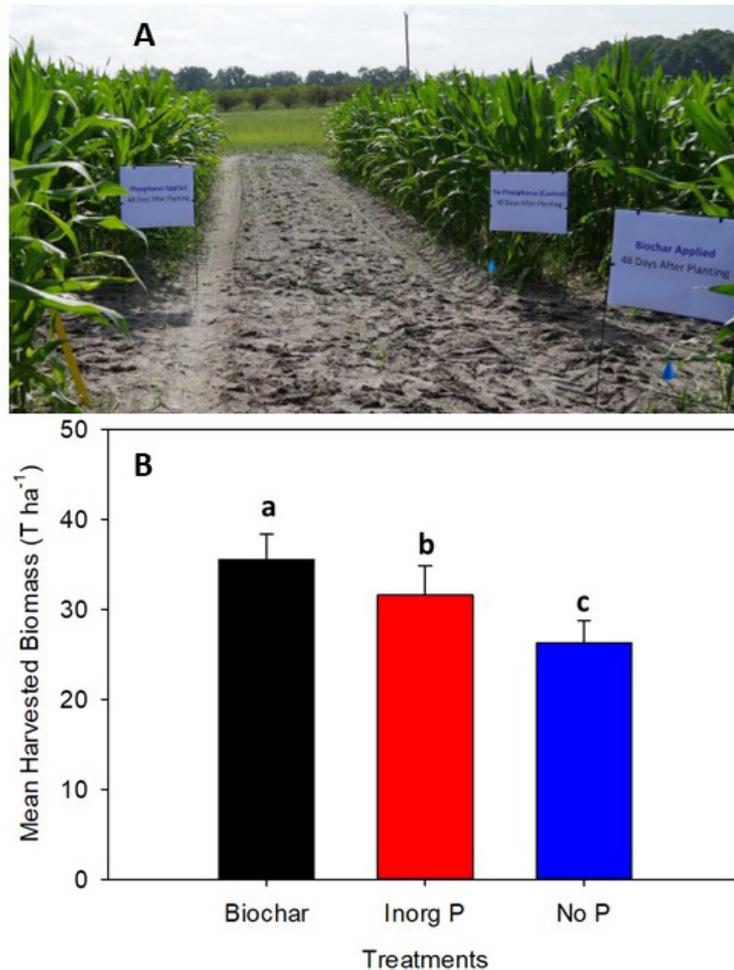
Reports on the effects of biochar application to field crops on crop growth and yield as in conventional agronomic experiments have been increasing in the past decade. Several meta-analyses compiling data

quantitatively reported the mean effects of biochar on crop yields. It is shown that biochar can increase crop yield by 10% ( $n = 782$ , application rate  $15.6 \text{ Mg ha}^{-1}$ )<sup>[52]</sup>, 11% ( $n = 152$ , application rate  $< 30 \text{ Mg ha}^{-1}$ )<sup>[81]</sup>, 9% ( $n = 1125$ , application rate  $30 \text{ Mg ha}^{-1}$ )<sup>[53]</sup> and 16% ( $n = 1254$ )<sup>[82]</sup>. A 2-year non-irrigated field study on a degraded Crosby silt loam soil in Ohio did not find any significant difference in soybean and corn biomass under an oak-derived biochar pyrolyzed at  $650 \text{ }^\circ\text{C}$  and under  $7.5 \text{ Mg ha}^{-1}$  application rate<sup>[83]</sup>. In a two-year field study on the effects of poultry litter biochar (PLB) on a rotational (rye, *Secale cereal* L./silage corn, *Zea mays* L./sorghum, [*Sorghum bicolor* (L.) Moench]) cropping cycle in Florida, USA, Freitas *et al.* [Figure 5] reported significantly higher biomass during the 2-year combined cycle from the biochar-applied compared with the fertilized and control (without any P fertility source) plots on an Entisol, but no difference in harvested biomass was observed on the Spodosol (Data not shown)<sup>[84]</sup>. Poultry litter biochar contains the phosphate mineral whitlockite,  $\beta\text{-Ca}_3(\text{PO}_4)_2$ <sup>[44,55]</sup>, and has the potential to be a slow P-release fertilizer due to the steady dissolution of the material. Corn yield responses were similar to the control, inorganic P, and biochar P at the Spodosols site, while the corn yield was in the order: control  $<$  inorganic P  $\leq$  biochar P at the Entisols site<sup>[84]</sup>. All treatments were identical at the two locations, suggesting that harvested biomass and corn yield responses may depend on soil properties and other local conditions.

Bai *et al.* reported from a meta-analysis involving 57 studies and 627 paired data that biochar alone could be as effective as inorganic fertilizers to increase crop growth by up to 25% compared to control, whereas biochar with inorganic fertilizer mix increased the crop yield by an additional 10% indicating that co-application of biochar and synthetic fertilizer or amendment could enhance crop yield significantly<sup>[85]</sup>. Such conflicting information available in literature further points out the importance of site-specific evaluation of biochar additions and that there is no “one size fits all” suggestion for biochar application across all biochar and soil types. A summary of major research results reported on the effect of biochar application on plant nutrition and soil nutrient dynamics in different parts of the world shows the site-specificity nature of biochar application<sup>[20]</sup>.

Biochar-based fertilizers (BBF) have also been tested to gain insights into the effectiveness of BBF on yield. Melo *et al.* conducted a meta-analysis using 148 pair-wise comparisons over a 10-year (2011-2021) period to understand if BBF can effectively replace traditional fertilizer as the nutrient source for crop productivity<sup>[86]</sup>. The BBF alone, with a low application rate ( $0.9 \text{ Mg ha}^{-1}$ ), was shown to increase crop yield by 10% compared to inorganic fertilizers and by 186% compared to control without any fertilizer. Pyrolysis temperature greater than  $400 \text{ }^\circ\text{C}$  and C content of more than 30% increased yield by 12% and 17%, respectively, with no increase in yield found for the biochars produced at  $< 400 \text{ }^\circ\text{C}$  and biochar with  $< 30\%$  C content - further suggest that biochars may be grouped based on their properties and application rates in relation to the effect on to increase crop yield<sup>[86]</sup>.

Summarizing the available data on the role of biochar in agroforestry systems, Nair *et al.* reported that although data on several field-based work were available, long-term field observations were lacking<sup>[16]</sup>. The limited number of field studies reported have been under relatively short durations ( $< 3$  years), and all soil-process investigations have been confined to the top 30 cm (or lesser) soil depths. Further, as pointed out earlier, the reported results are highly variable depending on the soil types, feedstocks, and pyrolysis methods used for biochar preparation. Although the numerous meta-analyses are excellent at predicting an “overall trend” of various aspects of properties of the amended soils or crop yields, they do not generally address specific recommendations, such as the kind of biochar that is good for specific soils under various agronomic or environmental conditions. Thus, a widely applicable set of recommendations on the use of biochar has not yet become available even for annual crops, let alone the perennial systems such as tree crops and agroforestry. Nevertheless, there are some opportunities for biochar application in specialized



**Figure 5.** (A) Field plot study at the University of Florida's Plant Science Research and Extension Unit, Citra, Florida with silage corn (*Zea mays*). Treatments were: Poultry litter biochar (760 kg biochar ha<sup>-1</sup>, same total P rate as inorganic fertilizer), inorganic P (20 kg P ha<sup>-1</sup>) per cropping cycle and control plots with no P additions. (B) Mean biomass (t ha<sup>-1</sup>) harvested in a two-year-long cropping cycle (rye, silage corn, sorghum) followed by the same letter are not statistically different at the 5% level<sup>[16,84]</sup>. Photo credit: Barbara Larson.

situations. For example, biochar application to tree nurseries and spot application in the planting pits of trees (e.g., for the establishment of nitrogen-fixing trees in acid soils) are worth investigating<sup>[20]</sup>. The high WHC of biochar is an attribute that could be exploited successfully for tree planting in arid and semiarid lands. Further, the co-application of biochar with limited quantities of inorganic fertilizers in high-value and commercial agricultural systems such as shaded perennial systems could reduce the overall production cost and the CF of fertilizer use. As discussed in the earlier section, several byproducts from agricultural lands can be used as excellent biochar feedstocks. These include wastes from non-destructively harvested tree crops such as palms, coffee, cacao, and a variety of other species. Materials such as coconut husk and shells, the outer covering of cacao pods, stalks and straw of cereals, and a variety of other locally available materials are excellent feedstocks of biochar. Biochar production from these “wastes” will also minimize costs associated with the off-site disposal of such materials. Biochar application in agriculture and other land-use systems, including reclaimed lands, is an area that deserves further research and development attention.

## BIOCHAR APPLICATION FOR REDUCING CARBON FOOTPRINTS

Based on the above discussion, we suggest some options for the land application of biochar. Of interest is the availability of P during biochar applications. Biochar can interact with biotic and abiotic components of the soil and modify soil P biochemical processes by altering chemical forms of P, soil P sorption and desorption capacities, microbial biomass, enzymatic activities, mycorrhizal associations, and microbial production of metal-chelating organic acids. Further, feedstock types and pyrolysis conditions are critical for the fate of P in soil and water<sup>[87]</sup>. Soil type is of primary importance in understanding P release from soil; P retention and release at environmentally relevant threshold concentrations are properties of the soil and the nature of biochar additions becomes important only after the sites are saturated with P. This would include adding modified biochars<sup>[88]</sup> or biochar/compost additions<sup>[89,90]</sup> to the soil as an amendment. Composting with biochar additions has gained interest in recent years to reduce GHGs and odorous emissions, as well as the availability of heavy metals<sup>[90]</sup>. Oldfield *et al.* reported that blending biochar and compost is favorable from both soil C sequestration and nutrient recovery perspectives<sup>[91]</sup>. This is important because biochar has long been touted as a tool for soil C sequestration in addition to its beneficial effects on soil health and fertility<sup>[92-94]</sup>.

One of the major problems in tropical soil management is the lack of soil P availability due to their high P retentive capacity [Figure 2]. The addition of biochar to the soil might help retain moisture and nutrients, acting as a buffer between added P and the P retentive soil allowing the P to be available to plants while at the same time increasing soil C sequestration. Phosphorus-rich biochar (such as from animal-derived ones) would be advantageous for P-deficient soils with higher silt+clay fraction for better P supply but probably less preferable for soil C sequestration [Table 1]. While it is possible to add higher rates of P-rich biochar to improve soil C sequestration, such applications may have adverse environmental impacts such as eutrophication or GHG emissions. For example, excessive addition of animal-based biochar may result in its loss via surface runoff resulting in eutrophication of receiving waters. Therefore, site-specific conditions will determine the amount and type of biochar to be added.

Overall, the research results on the effects of field application of biochar are specific to the sites and study conditions such that general conclusions cannot be drawn on their applicability to a wide spectrum of situations and systems<sup>[20]</sup>. The biochar application rates are highly variable and sometimes excessive (> 10 Mg ha<sup>-1</sup>). On the other hand, the addition of small quantities of biochar with a low C:N ratio may not be beneficial for C sequestration, as discussed earlier. Thus, a proper understanding of the compositional variations in biochars from different feedstocks is critically important for their judicious use as a fertilizer source and for soil C sequestration.

### Carbon footprint under biochar amendments in agricultural systems

Estimation of CF under biochar amendment in various farming systems is scarce due to complexity and lack of availability of relevant data. However, few studies estimated CF using various methods using the Life Cycle Analysis (LCA) approach [Table 2]. Most of these studies were conducted in China and CF was estimated considering C sources (such as pyrolysis energy cost, fertilizer and pesticide input, farm work, and soil GHG emissions, *etc.*) and sinks (such as soil C increment by biochar addition, biomass addition and pyrolytic gas offsets, *etc.*). The results indicate that in almost all cases, biochar amendment significantly decreased CF in terms of equivalent CO<sub>2</sub> reduction per hectare farming field per unit of time. For example, a 3-year field study focused on rice production compared CF under control, corn straw (6 Mg<sup>-1</sup> ha<sup>-1</sup> year) and corn straw-derived biochar (2.4 Mg<sup>-1</sup> ha<sup>-1</sup> year); while their average estimation of control was 0.24 kg CO<sub>2</sub>-C<sub>e</sub> kg<sup>-1</sup> grain, the same for the system under biochar varied from 0.04-0.44 CO<sub>2</sub>-C<sub>e</sub> kg<sup>-1</sup> grain suggesting biochar has the potential to significantly reduce the CF of rice production depending on the energy-efficient

**Table 2. Estimation of carbon footprint (CF) under various biochar systems**

Production system	Country	Study duration (years)	Soil type	Biochar type	Application rate (Mg/ha)	C footprint	Reference
Rice	China	3	Inceptisols	Corn-straw biochar, 400 °C	2.4	Control: 0.24 kg CO <sub>2</sub> -C/kg yield, Biochar: 0.04-0.44 kg CO <sub>2</sub> -C/kg yield	Liu et al. <sup>[95]</sup>
Rice	Vietnam	8	nr	Rice-straw biochar	18	Control: 1.49, 4.5 kg CO <sub>2</sub> -C/ha/spring, summer, Biochar: 1.11, 3.85 kg CO <sub>2</sub> -C/ha/spring, summer	Mohammadi et al. <sup>[98]</sup>
Rice	Mainland China	Variable and compiled data from six studies	Variable and compiled data from six studies	Wheat-straw biochar, 350-500 °C	20	Control: 14.36-16.79 kg CO <sub>2</sub> -C/ha/year, Biochar: -11.96-18.04 kg CO <sub>2</sub> -C/ha/year	Xu et al. <sup>[50]</sup>
Maize	Mainland China	Variable and compiled data from six studies	Variable and compiled data from six studies	Wheat-straw biochar, 350-500 °C	20	Control: 4.29-5.46 kg CO <sub>2</sub> -C/ha/year, Biochar: -28.98-10.66 kg CO <sub>2</sub> -C/ha/year	Xu et al. <sup>[50]</sup>
Maize	China	3	nr	Maize-straw biochar, 450-500 °C	4.5	*Control: 11000 kg CO <sub>2</sub> -C/ha, *Biochar: 10500 kg CO <sub>2</sub> -C/ha/year	Liu et al. <sup>[99]</sup>
Maize	China	3	nr	Maize-straw biochar, 450-500 °C	9	*Control: 11000 kg CO <sub>2</sub> -C/ha, *Biochar: 10000 kg CO <sub>2</sub> -C/ha/year	Liu et al. <sup>[99]</sup>
Soybean	USA	1	Alfisols	Oak biochar, 650 °C	7.5	Control: 3600 kg CO <sub>2</sub> -C/ha/season, Biochar: -4200 kg CO <sub>2</sub> -C/ha/season	Mukherjee et al. <sup>[83]</sup>
Wheat, rye, barley, oat, fava bean, spring rapeseed and potato	Finland	na	Marginal lands	Willow biochar	25	-1875 kg CO <sub>2</sub> -C/Mg/100 years	Leppäkoski et al. <sup>[97]</sup>

nr: Not reported; na: not applicable; \*data estimated from the figures.

pyrolysis techniques<sup>[95]</sup>. Similarly, CF computation was employed to assess the mitigating potential of biochar amendment by estimating all the direct and indirect GHG emissions in the full LCA of crop production, including production and field application of biochar from six studies and seven sites in Mainland China<sup>[50]</sup>. Biochar amendment reduced the CFs by 20.37-41.29 Mg CO<sub>2</sub>e ha<sup>-1</sup> and 28.58-39.49 Mg CO<sub>2</sub>e ha<sup>-1</sup> for paddy rice and maize production, respectively, compared to control treatments without any biochar application<sup>[50]</sup>. A net C gain was reported under oak biochar pyrolyzed at 650 °C compared to control for soybean production in Ohio, considering GHG emissions, biochar addition and biomass input as the only variables<sup>[83]</sup> [Table 2]. A 3-year study under cardoon (*Cynara cardunculus* L.) energy crop grown in a Mediterranean area (Sardinia, Italy) experimented with five combinations of nitrogen fertilization patterns including biochar and cover crops and CF was estimated under each scenario<sup>[96]</sup>. Although their results suggest that the rates of C sequestration ranged from 72.7 (high input) to 26.2 (low input) Mg CO<sub>2</sub>e Mg<sup>-1</sup> of biomass, however, the GHG emissions exceeded GHG removal and the combined use of biochar and cover crop had no positive effects on C sequestration or GHG emission reduction, unlike these treatments individually, implying no single best option was identified among the treatments<sup>[96]</sup>. Note that the estimation of LCA of any biochar production is important to understand if that specific biochar is suitable for specific crop production, yet, the data on any biochar's CF is rare. The only CF estimation of -1875 kg CO<sub>2</sub>-C<sup>-1</sup> Mg<sup>-1</sup> 100 years was reported on willow biochar for a range of crops (wheat, rye, barley, oat, fava bean, spring rapeseed and potato) under marginal lands in Finland, indicating that willow biochar produced from marginal lands can be used for compensating agricultural GHG emissions<sup>[97]</sup>. The data on CF under biochar produced from agricultural feedstocks under different crops and soil types are scanty and

can be a researchable priority.

## CONCLUSIONS

Land application of biochar to decrease CF sounds like a promising proposition, but several challenges and obstacles remain to be overcome before the promise could realistically be fulfilled. Briefly, biochar from the same source added at a given rate to different soils could have different effects - particularly for P - based on the respective soil properties. The elemental composition of a feedstock is not an indication of plant-nutrient availability, and the risk of nutrient loss during biochar application depends on the nutrient release potential of the biochar as well as the nutrient retention properties of the soil. While there is some evidence that biochar application is effective in soil aggregation, the highly variable distribution by weight and SOC content in various soil fractions across a range of temperate and tropical soils adds to the problem of understanding C sequestration and saturation limits in soils. Until these uncertainties are resolved based on more rigorous research and elaborate long-term field trials, we can only project the benefit of biochar application under different site-specific scenarios including soil type, feedstock availability at a given location, and climatic conditions, without making confident recommendations for largescale adoption. Very little data are available on the estimation of CF under biochar amendment and this aspect is a high researchable priority. Research and development efforts in biochar have so far been uncoordinated and based on the personal enthusiasm of the scientists involved but largely unsupported by mainstream research entities and policy directives; therefore, the promises and opportunities offered by the available information remain largely underutilized.

## DECLARATIONS

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### Authors' contributions

Contribution to the conception and the development of the first draft: Nair VD

Contribution to literature review and estimation of CF under various biochar systems: Mukherjee A

### Availability of data and materials

Not applicable.

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### Conflicts of interest

Both authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

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