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REVIEW ARTICLE

Biochar-based fertilizer effects on crop productivity: a meta-analysis

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Abstract

Aim Biochar-based fertilizers (BBF) have gained increasing interest in recent years, yet their effects on crop productivity have not been reviewed.

Methods We conducted a meta-analysis of the published literature (2011-2021) using 148 pairwise comparisons between crop productivity after additions of BBF, of conventional fertilizers (fertilized control), and a non-fertilized control.

Results On average, BBF applied at very low application rates (mean of 0.9 t ha^{-1}) increased crop productivity by 10% compared with fertilized controls and 186% compared with non-fertilized controls. This mean crop productivity increase is comparable to that reported when biochar is used as a soil conditioner (i.e., 15 t-30 t ha^{-1} to increase crop productivity by 10%). This crop yield increase suggests that biochar acts as a matrix to increase fertilizer use efficiency to a larger extent than conventional fertilizer alone. Cluster analysis revealed that BBFs have the potential to increase crop productivity by 15% when added to soils that are not responsive to conventional fertilizers. BBF produced at a highest heating temperature (HHT) of >400 °C increased crop productivity by 12% as opposed to those produced at a HHT of ≤400 °C that showed no increase. BBF with C contents >30% in the final mixture caused the largest increase in crop productivity by 17%, whereas those with C contents ≤30% had no effect.

Conclusion This study has shown that biochar can be an effective constituent of novel fertilizers with enhanced efficiency, which may contribute to lower nutrient losses and lower negative environmental impacts.

Keywords Biochar · Crop production · Enhanced-efficiency fertilizer · Nutrient use efficiency · Organo-mineral fertilizers

Introduction

Global food production is expected to increase by 50-70% between 2010 and 2050, whereas food and non-food needs (e.g., fibers, bioenergy) are expected

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to increase by 50-90% (Le Mouël and Forslund 2017). The sustainable intensification of agricultural production is thus a pressing challenge for the global community in the coming decades, along with judicious use of fertilizers. The growing demand for inorganic fertilizers, chiefly nitrogen (N) and phosphorus (P) (Tilman et al. 2002), and their overuse has grossly altered their biogeochemical cycles, which now exceed sustainable planetary boundaries (Kahiluoto et al. 2014; Campbell et al. 2017). These challenges could partly be overcome by the development of more efficient fertilizers, such as controlled-release fertilizers (Shaviv and Mikkelsen 1993) and organo-mineral fertilizers (Smith et al. 2020), along with adherence to agricultural best management practices (Roberts and Johnston 2015).

Biochar technology has emerged in the past two decades as an opportunity to recycle nutrients from waste materials and increase fertilizer use efficiency, among other benefits (Chen et al. 2019). Biochar effects on crop productivity have been quantitatively reviewed in the last decade. Examples of grand mean effect sizes reported are 10% (n = 782; mean application rate of 15.6 t ha^{-1}; Jeffery et al. 2011), 11% (n = 152; application rates generally <30 t ha^{-1}; Liu et al. 2013), 9% (n = 1125; median application rate of 30 t ha^{-1}; Jeffery et al. 2017), and 16% (n = 1254; no information on mean application rates provided; Dai et al. 2020). Ye et al. (2020) observed that biochar on its own did not increase crop productivity. However, when combined with inorganic fertilizer, biochar increased crop productivity by 15% as compared with inorganic fertilizer only. Such findings suggest that biochar plays a role on fertilizer use-efficiency that could be explored commercially.

Even though biochar enhances crop productivity, the economic feasibility of high application rates is uncertain. Bach et al. (2016) demonstrated that the vast majority of biochar application approaches will never be economical, if only productivity gains are realized, even by including financial incentives such as C credits. Thus, an alternative that has attracted growing interest in recent years is the development of biochar-based fertilizers (BBFs) (Fig. S1). The idea behind the design of BBFs is to take advantage of (i) the broad array of biochar types, which offer the opportunity to produce tailor-made biochar for specific needs, and (ii) the existence of different methods (pre- or post-pyrolysis) to load biochar with nutrients. This could make the biochar technology more cost-effective due to the enhanced efficiency and associated lower application rates (Joseph et al. 2013).

Recently, Sim et al. (2021) outlined three methods that can be utilized to produce BBF: (i) impregnation, consisting of mixing biochar with nutrient solution followed by drying; (ii) mixed granulation that consists of mixing biochar and fertilizer in powder form followed by granulation/peletization; and (iii) co-pyrolysis that involves mixing feedstock with nutrients (usually in powder form) followed by pyrolysis. Granulation or peletization using binders such as bentonite, starch, etc. facilitates field application regardless of the technique used. Sim et al. (2021) also highlight that encapsulation of nutrient loaded-biochar is a novel technique to produce BBF of slow/controlled release fertilizers with great potential to improve nutrient use efficiency. Engineered biochar designed to recover nutrients (mainly N and P) from aqueous media can also be used as BBF (Xu et al. 2018; Nardis et al. 2020).

Some studies report positive responses of BBF on crop productivity over conventional fertilizers. For instance, Peng et al. (2021) observed an average of 4% increase in maize grain yield under typical continental monsoon climate in an Alfisol in China when cultivated with NPK in combination with 1.5 t ha^{-1} of biochar compared with NPK alone. Puga et al. (2020) observed a 26% average increase in maize yield and 12% higher N use efficiency for granulated biochar with urea and additives over conventional urea under tropical conditions. Qian et al. (2014) observed rice yield increases of up to 24% using NPK-BBF over conventional NPK in a field experiment in subtropical climate. Other studies reported no effect on crop productivity increase or even negative impacts of BBF compared with conventional fertilizers. González et al. (2015) developed biochar impregnated with urea and encapsulated with polymers and observed a decrease in wheat production under greenhouse conditions compared with conventional urea. Lustosa Filho et al. (2019) found a significant maize productivity decrease for P-BBF, in granulated form, compared with triple superphosphate. In both studies, it was reported that the slow-release behavior was not synchronized with crop demand, which limited crop productivity in the short-term.

The biochar properties (mainly porosity and functional groups) depend on the feedstock and pyrolysis conditions, and together with use of additives, all these factors influence the nutrient release mechanisms of BBF. Diffusion and dissolution of nutrients are claimed as the governing mechanisms of nutrient release in BBF (Sim et al. 2021), but this is still under development. The interaction of BBF with the rhizosphere may also cause changes in redox potential and influence nutrient uptake by the root system as well as alter microbial activity (Chew et al. 2020).

Despite the need to evaluate the most suitable conditions for the use of BBF in agricultural production, studies on the effect of BBF on crop productivity have not yet been quantitatively reviewed. In this study, a meta-analysis was conducted to investigate the effect of biochar as a composite material with conventional fertilizer sources, called biochar-based fertilizer (BBF), and its effect on crop productivity and nutrient uptake when compared with (i) a fertilized control (conventional inorganic fertilizer), and (ii) a non-fertilized control.

Material and methods

Literature search

We performed a literature search focused on peer-reviewed articles in Web of Science, Scopus and Google Scholar databases before Jul 24th 2021. Publications were identified using the terms "biochar-based fertilizer" OR "biochar-compound fertilizer" OR "nutrient-enriched biochar" AND "crop yield" OR "crop productivity" OR "plant growth". Only studies that used biochar as a "fertilizer enhancer" were considered, with the following approach to produce BBF: i) mixing solid or liquid nutrients with the feedstock before the pyrolysis, ii) mixing solid or liquid nutrients with biochar; or iii) biochars that were designed for nutrient removal from aqueous media and later applied as nutrient-enriched biochar. We selected articles that included plant experiments with a fully fertilized control (fertilized control) that ideally balanced the rates of nutrients to allow a fair comparison. When a study used fertilizer rates as treatments, the pairwise comparison was done at the same nutrient rate for the BBF and the conventional fertilizer when the data allowed such comparison. We also collected data from non-fertilized controls when the study provided such information for a separate comparison. In addition to publications in English, we also considered peer-reviewed articles published in Chinese (data collected by a native Chinese speaker) due to the increasing number of Chinese publications on BBF in recent years.

Over 150 articles were evaluated and a total of 40 articles met the established criteria and were considered for the meta-analysis. A list of the selected articles and related details is provided in Table S1. Data of shoot biomass was collected as reported (either in fresh or dry weight basis) or grain yield to represent "crop productivity response", which is referred to represent either shoot biomass or crop yield or both as reported in the cited literature following Liu et al. (2013). Nitrogen (N), phosphorus (P), and potassium (K) uptake by the plant was collected when reported. When data were presented in graphical format in the original publications, data were extracted using the Web Plot Digitizer software (http://arohatgi.info/WebPlotDigitizer/). Where needed, some complementary data were provided by corresponding authors. A total of 148 pairwise comparisons were considered in the meta-analysis because some articles contributed with multiple comparisons, with data covering 11 countries, 30 feedstocks (including wood wastes, crop wastes, municipal wastes and manures), highest heating temperatures (HHT) ranging from 300 to 850 °C, and soils differing in pH, soil organic C content, texture, and level of nutrient availability.

Data grouping in sub-categories

The climatic zones were grouped based on the Köppen climate classification, and we performed analysis using both combined and separated field and pot studies for this comparison. Soil pH (in water) was grouped as (i) pH $\leq$ 6.5 representing acid soils (slightly acid; moderately acid; strongly acid; very strongly acid; extremely acid), and (ii) pH $>$ 6.5 representing neutral to alkaline soils (neutral; slightly alkaline; moderately alkaline and strongly alkaline), based on the USDA classification system, following the categories of a larger survey of biochar effects (Ye et al. 2020). The soil categories – based on the Soil Taxonomy classification system (Soil Survey Staff - NRCS/USDA 2014) – were grouped as (i) highly-weathered soils (including Oxisols and Ultisols), (ii) weakly-developed soils (including Entisols and Inceptisols), and (iii) others (including Alfisols, Mollisols, etc.).

Soil texture was grouped as (i) coarse-textured soils (sandy loam, loamy sand and sand), (ii) medium-textured soils (loam, silt loam, clay loam and silty clay loam), and (iii) fine-textured soils (clay and silty clay), based on the USDA soil classification system. The biochar C storage classes were based on the biochar classification system of Camps-Arbestain et al. (2015). The feedstock nutrient content was classified as poor or rich based on the type of feedstock, i.e., wood and plant residues feedstocks were classified as poor, while manures, sludges and other ash-rich feedstocks were classified as rich. Although large variation in feedstock composition occurred, this classification is supported by a recent biochar review work (Ippolito et al. 2020). When the C content in BBFs was not directly reported in the article, it was calculated based on the information available from the preparation of BBF. The other sub-categories were grouped based on the range of available data and practical interest regarding BBF, since there is no specific classification for these categories at present.

Meta-analysis

The natural log-transformed response ratio (ln *RR*) was used to calculate the changes between the treatments (addition of BBF) and the fertilized control (fertilized control). The response ratio (*RR)* is commonly used in meta-analysis, because it allows to quantify the proportionate change that results from a treatment versus a control group (Hedges et al. 1999). The ln *RR* was calculated as a measure of the effect size, according to the Eqs. 1 and 2:

$$\ln RR = \ln\left(\frac{X_T}{X_C}\right) \tag{1}$$

$$\ln RR = \ln\left(\frac{X_C}{X_N}\right) \tag{2}$$

where X_T is the mean value of treatment (i.e., addition of BBF); X_C is the mean value of the fertilized control that includes equivalent fertilization (Eq. 1). In a separate comparison, X_C was contrasted against another control, X_N or non-fertilized control without any fertilization or BBF to ascertain the effect of nutrients on crop productivity at a given location (Eq. 2). The meta-analysis was performed in R software version 3.6.3 (R Core Team 2020), using the "*rma.mv*" function in the "*metafor*" package (Viechtbauer 2010). We included "article" (reference) as a random effect, because different articles contributed with different numbers of pairwise comparisons, which influences the effect size (van Groenigen et al. 2019), and ln *RR* was weighted by the inverse of its variance. The mean effect size of each subcategory and the confidence intervals were calculated from the means and standard deviations. When the measures of data dispersion were provided as standard error (SE), they were converted into a standard deviation (SD) following the formula: $SD = SE\ x\sqrt{n}$, considering the number of replicates (n) reported. In those cases where it was unclear whether the dispersion data was SD or SE, we conservatively considered it to represent SE. To facilitate visualization and data interpretation, the proportional change in the mean crop productivity (ln *RR*) and the confidence interval (*CI*), was exponentially transformed using Eq. 3.

$$Change\ (\%) = \left[\exp\left(\ln RR\ or\ 95\%CI\right) - 1\right] * 100 \tag{3}$$

The overall mean effect size and the effect size in each category were considered to be significant when the 95% confidence intervals did not overlap with zero (the equivalent control group, depending on the comparison). Groups within each sub-category were considered to differ when the 95% confidence intervals did not overlap between them (Cumming and Finch 2005). For grouping, a minimum of ten pairwise comparisons (i.e., $n \geq 10$ observations), coming from at least three independent studies (i.e., $n \geq 3$ references), were considered to form a category and were presented in the meta-analysis. Otherwise, ungrouped data contributed to the calculation of the overall mean effect size.

Cluster analysis

Cluster analysis was conducted using the K-means clustering method for the general dataset that contained non-fertilized controls and specifically for different soil categories within this same dataset in order to identify mechanisms by which BBF affect crop productivity. The x-axis shows the effect size (in ln *RR*) of fertilized control vs. non-fertilized control on crop productivity, and the y-axis was calculated as the effect size (in ln *RR*) of BBF vs. fertilized control on crop productivity. To define the number of appropriate clusters for responses, Elbow plots were made using the "*fviz_nbclust*" function from "*factoextra"* package (Kassambara and Mundt 2020), and four clusters were selected for all plots. The final cluster analysis was then conducted with the selected number of clusters, and biplots of responses were generated using the "*fviz_cluster"* function from the "*factoextra*" package (Kassambara and Mundt 2020). All analyses were done using R software version 3.6.3 (R Core Team 2020).

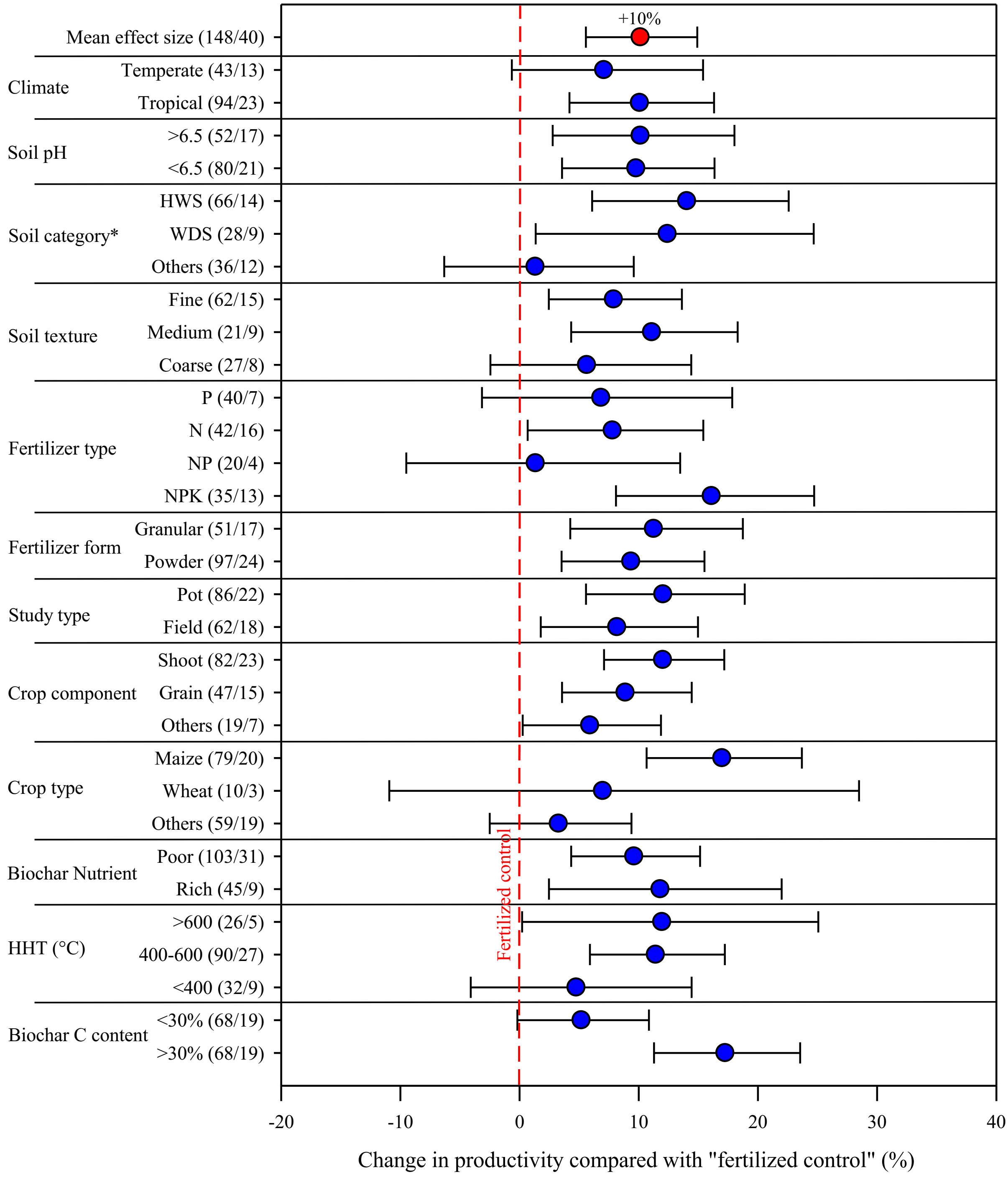
Results

Crop productivity response of BBF versus fertilized control

Biochar-based fertilizers significantly increased crop productivity by 10% (CI of 6-15%) (Fig. 1). Under tropical climate, BBF significantly increased crop productivity (mean: 10%, CI: 4-16%), while it did not increase crop productivity under temperate climate (mean: 7%, CI: −1-15%). When field studies were considered separately, BBF also caused a significant increase of crop productivity for tropical (mean: 11%, CI: 4-18%), and a lower but significant difference for temperate climates (mean: 6%, CI: 0.3-12%) (Fig. S3). Conversely, for pot studies there was no effect for temperate climates (mean: 9%, CI: −11-33%), but a significant difference was observed for tropical climates (mean: 10%, CI: 0.3-20%). Soil pH did not affect how BBF changes crop production, with soils with pH ≤ 6.5 showing nearly the same effect size (mean: 10%, CI: 4-16%) than soils with pH > 6.5 (mean: 10%, CI: 3-18%). Crop productivity in highly-weathered soils (HWS - Oxisols, Ultisols) receiving BBF was significantly greater than when applying conventional fertilizer (mean: 14%, CI: 6-23%), similarly to weakly-developed soils (WDS - Entisols, Inceptisols) (mean: 12%, CI: 1-25%), while the category of "others" did not show significant differences (mean: 1%, CI: −6-10%), yet these groups were not significantly different among them. No significant differences in crop productivity were observed in coarse-textured soils that received BBF (mean: 6%, CI: −2-14%) compared with those receiving conventional fertilizers. Conversely, a significant increase in crop productivity was observed in medium-textured (mean: 11%, CI: 4-18%) and fine-textured soils (mean: 8%, CI: 2-13%), although productivity of crops grown in the three textural classes was not significantly different, since there was an overlap in their 95% confidence intervals. The type of fertilizer used (only N, only P, NP or NPK) affected the BBF efficacy: BBF containing only P did not significant increase crop productivity (mean: 7%, CI: −3-18%), similarly to NP (mean: 1%, CI: −9-13%); however, compared with conventional fertilizers, BBF containing N (mean: 8%, CI: 1-15%) or NPK (mean: 16%, CI: 8-25%) significantly increased crop yields. Interestingly, granular BBF significantly increased crop productivity (mean: 11%, CI: 4-19%) when compared with conventional fertilizers, which was similar to the powder BBF (i.e., biochar mixed with fertilizers or enriched with nutrients in powder form) (mean: 9%, CI: 4-16%).

Both pot (mean: 12%, CI: 6-19%) and field (mean: 8%, CI: 2-15%) experiments to which BBF was applied showed a significant and similar increase in crop productivity compared with conventional fertilizers. In this study, the two categories of crop components evaluated (shoot and grain), were each associated to the type of experiment, with shoot being predominantly studied in pot experiments, and grain in field experiments. Compared with conventional fertilizer additions, both shoot (mean: 12%, CI: 7-17%) and grain productivity (mean: 9%, CI: 4-14%) similarly increase when receiving BBF. Although to a lesser extent, crop yields of other crop types (vegetables, tubers, etc.) also significantly increased (mean: 6%, CI: 0.3-12%) when BBF was compared with conventional fertilizers. Maize was the main crop studied in the selected articles and showed a significant increase in crop productivity (mean: 17%, CI: 11-24%) when treated with BBF as compared with conventional fertilizer additions, while wheat showed no significant difference (mean: 7%, CI: −11-28%), although only a minimum set of pairwise comparisons (n = 10) was available. All other crop types combined also showed no significant increase in crop productivity (mean: 3%, CI: -2-9%).

Among the HHT classes considered, only that of biochars produced at HHT ≤ 400 °C had no significant effect on crop productivity (when a constituent of BBF) (mean: 5%, CI: −4-14%) compared with conventional fertilizers. Conversely, crop productivity increases were observed with BBF containing biochars produced at HHT in the range of 400-600 °C



(mean: 11%, CI: 6-17%) and at HHT > 600 °C (mean: 12%, CI: 0.2-25%). The biochar nutrient content was separated into two categories (poor and rich), based on the content of nutrients derived from the feedstock and accumulated in the resulting biochar used to produce the BBF. Crop productivity increased with additions of both nutrient-poor (mean: 10%, CI: 4-15%) and nutrient-rich (mean: 12%, CI: 2-22%) biochar used to produce BBF compared with additions of conventional fertilizer. A significant

◂**Fig. 1** Change in crop productivity as a result of additions of biochar-based fertilizers (BBF) in comparison with the fertilized control (red dotted line). The comparison is for the grand mean effect size and for several categories related to the climate, soil characteristics and fertilizer characteristics. The circles represent the mean value and the bars represent the 95% confidence interval. The difference is considered significant ($p < 0.05$) from the fertilized control when the bars do not overlap with the dotted line. Sub-categories were considered to differ between them when their 95% confidence intervals did not overlap. The numbers in parenthesis represent the number of pairwise comparisons (on the left)/number of independent studies (on the right) from which the comparisons were made. * Soil categories were divided in highly-weathered soils (HWS), weakly-developed soils (WDS), and others

difference between BBF with low or high C contents (> 30% or ≤ 30%) was observed as their 95% CI did not overlap. When the C content of the BBF was ≤30%, crop productivity did not increase (mean: 5%, CI: −0.2-11%) compared with additions of conventional fertilizers. However, when the C content in the BBF was >30%, crop productivity increased significantly (mean: 17%, CI: 11-24%). The results of crop productivity response of BBF in comparison with no fertilizer application (non-fertilized control) is presented in the supplementary material (Fig. S2). Nutrient uptake was also considered in this study (Fig. S4), and showed no increase in N, P or K uptake as a result of BBF application when compared with the fertilized control, although only a limited number of studies reported on nutrient uptake.

Contrasting efficacy of fertilizer and BBF in different soils

Four different soil clusters were identified that showed differential responses to conventional fertilizers as compared to no fertilizer additions at all (non-fertilized control, x-axis) (Fig. S5; and with soil categories identified in Fig. 2). Differences in the responses of conventionally fertilized over unfertilized soils were largest for the group of highly-weathered soils. All points above the horizontal dashed line showed a positive response of BBF (y-axis) over applications of conventional fertilizers (i.e., fertilized control), while all points below the horizontal dashed line showed the opposite behavior. Cluster 1 (red) represent soils that are largely unresponsive to conventional fertilizers but more responsive to BBF. This group of response coincided mostly with the group of weakly-developed soils and that of “other soils”. Soils in cluster 2 (green) showed an intermediate response to conventional fertilizers and, in most cases, a positive effect of BBF on crop productivity over conventional fertilizer, although in a few cases there was a slight decrease in productivity. Soils in clusters 3 and 4 (blue and purple) showed a very high response to conventional fertilizer, but a trend (especially in cluster 4) of a negative response to BBF when compared with conventional fertilizers. In these two clusters (3 and 4), almost all soils are highly-weathered, and thus highly nutrient depleted, which explains the very high crop productivity response to conventional fertilizers. It should be noted that a common characteristic of the BBF included in clusters 3 and 4 is their low C contents (<30%) and granular form (Fig. S5). The negative correlation between the fertilizer effect and the biochar effect (Fig. 2c) suggests that the less responsive the soil is to conventional fertilizers the more responsive it is to BBF. Biochar was found to increase crop productivity by 15% (CI: 9-21%) in situations where inorganic fertilizer was not able to do so (calculated using the y axis intercept in Fig. 2c).

Combined effect of biochar HHT, feedstock nutrient content and C content

BBF produced at higher HHT (> 400 °C) containing either high (> 30%) (mean: 16%, CI: 9-23%) or low (≤ 30%) (mean: 11%, CI: 4-19%) C contents caused significant crop productivity increases when compared with additions of conventional fertilizers (Fig. 3a). Conversely, BBF containing biochar produced at low pyrolysis temperature (≤ 400 °C) having low C contents (≤ 30%) did not increase crop productivity compared with additions of conventional fertilizers (mean: 0.7%, CI: −6-8%).

BBF produced with nutrient-poor feedstock and containing high C contents (> 30%) caused significant crop productivity increases (mean: 16%, CI: 9-23%), as well as those BBF produced with nutrient-rich feedstock and containing high C contents (> 30%) (mean: 27%, CI: 10-48%) (Fig. 3b). Conversely, additions of those BBF with low C content (≤ 30%) resulted in no significant crop productivity increase when they were produced from either nutrient-poor (mean: 5%, CI: −2-11%) or nutrient-rich feedstock (mean: 4%, CI: −7-16%). The low number of studies precluded calculation of the effect of BBF with

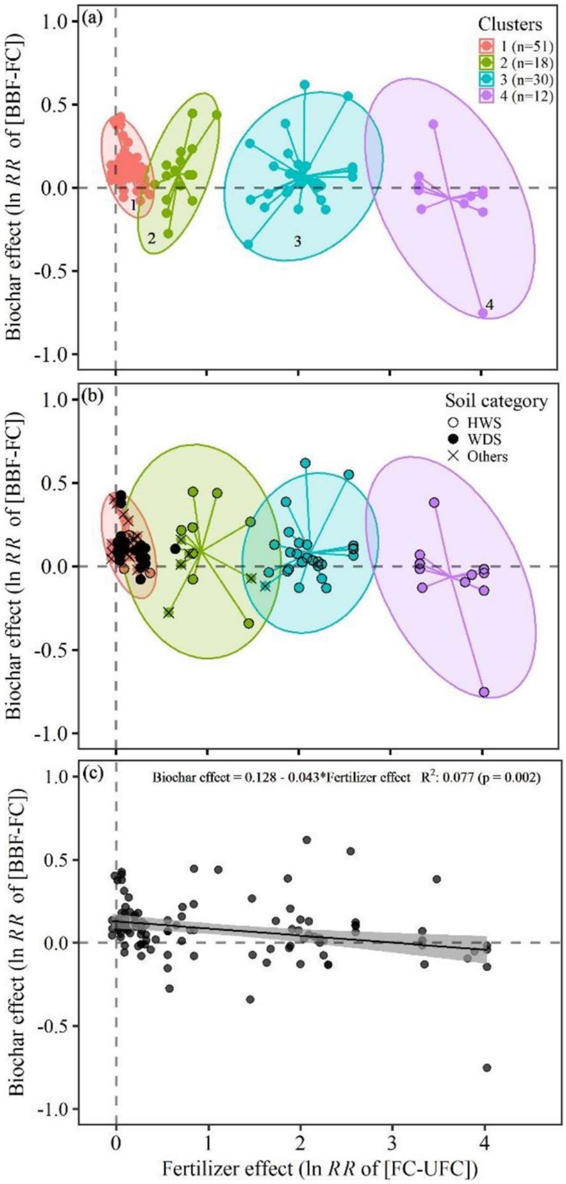


Fig. 2 (a) Cluster analysis for crop productivity response (ln *RR*); (b) detailed cluster categorized by soil categories (HWS, WDS, and "others"); and (c) correlation between the fertilized control (FC) versus non-fertilized control (UFC) ("Fertilizer effect" - x-axis) and BBF versus fertilized control (FC) ("Biochar effect" - y-axis) (grey shading indicates 95% confidence interval; n = 86)

low pyrolysis temperature and high C content biochar (Low T – High C) and nutrient rich feedstock and high C content biochar (High Nu – High C), also because such biochars are in principle not commonly available.

Discussion

Biochar as a fertilizer enhancer rather than a soil amendment

Given that biochars were added to soil as BBFs at very low application rates (max. of 2590 kg ha^{-1}; mean of 873 kg ha^{-1} and median of 635 kg ha^{-1}, only field experiments considered), they likely increased crop productivity by improving nutrient delivery to plants rather than through indirect effects such as optimizing pH or moisture availability. Biochar was used as a composite material and added at low application rates and thus, its liming contribution was minor (increase of 0.07 pH unit compared with the fertilized control, data not shown). When only field studies are considered, BBF caused a significant crop productivity increase for both acid and neutral/alkaline soils, which reinforces the role of biochar enhancing fertilizer efficacy rather than serving as a soil conditioner itself. Only in the comparison with no fertilization at all, a greater benefit of BBF on crop productivity was detected when this was applied to acid, fine textures, and highly-weathered soils in the tropics, which was also observed with conventional fertilizers. Yet this effect was probably a result of properly supplying P to low-fertility soils either as BBF or conventional fertilizers, and alleviating their well-known P deficiency (Lopes and Guilherme 2016). Moreover, geo-economic circumstances could have also contributed to these results, as soils in tropical regions have historically received lower application rates of fertilizers (Sattari et al. 2012; Schoumans et al. 2015).

In addition to the direct effects associated with the nutrient enrichment of biochar, the results from this study show that BBFs were, on average, able to further contribute to an increase in productivity beyond that of conventional fertilizers, especially when involving N fertilizers. Different mechanisms might take place depending on case-specific situations. BBF has been shown to (i) slow down the release of N and (ii) stimulate nitrification and reduce denitrification by regulating the microbial population involved with the N cycle, leading to an increase in N use efficiency by plants (Liao et al. 2020). As a soil amendment at moderate to high application rates (typically more than 1.0 t ha^{-1}), biochars can also influence soil N dynamics through its capacity to retain NH_4^+ (Wang et al. 2015) and NH_3 (Hestrin et al. 2019) and reduce

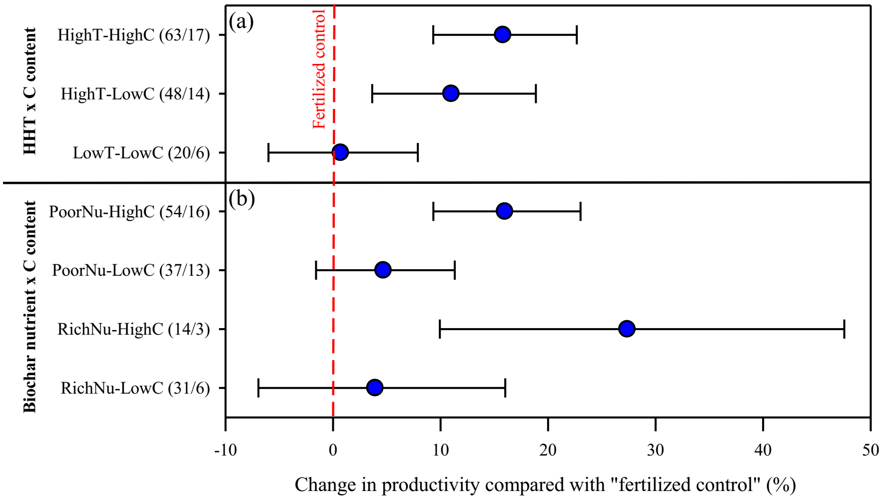


Fig. 3 Change in crop productivity as a result of additions of biochar-based fertilizers (BBF) in comparison with the fertilized control (red dotted line). The comparison is for pyrolysis temperature combined with carbon content (a) or feedstock nutrient content combined with carbon content in BBF (b). "High T" represents pyrolysis of biochar at >400 °C and "Low T" represents pyrolysis of biochar at ≤400 °C. "High C" represents BBF containing >30% C, and "Low C" represents BBF containing ≤30% C. "Poor Nu" represents biochar derived from wood and other plant derived feedstocks; "Rich Nu" represents biochar derived from manures, sludges and other ash-rich feedstocks. The circles represent the mean value and the bars represent the 95% confidence interval. The difference is considered significant ($p < 0.05$) from the fertilized control when the bars do not overlap with the dotted line. The numbers in parenthesis represent the number of pairwise comparisons (on the left)/number of independent studies (on the right) from which the comparisons were made

NH_3 volatilization (Clough et al. 2013; Fungo et al. 2019), which is particularly important for urea fertilizer. As a composite material in fertilizer, biochar might further influence N transformations as well as reduce N release rates by acting as a coating material or even by increasing water retention capacity locally around the fertilizer (Wen et al. 2017). Nitrogen interactions with C and O functional groups in biochar still deserve examination for designing more effective BBF.

Especial BBF formulations to solve specific soil problems

A number of different BBF preparation methods were used in the articles included in this meta-analysis (Table S1), involving physical mixture, impregnation, co-pyrolysis, coating/encapsulation, mixed granulation, and nutrient-loaded adsorbent. Each preparation method is aimed at enhancing the nutrient use efficiency from fertilizers by different mechanisms including co-precipitation, surface complexation, electrostatic interaction, chemisorption and even physical adsorption (Sim et al. 2021), which associated with coating can significantly reduce nutrient losses compared with conventional fertilizers (Ye et al. 2019), and sustains nutrient release longer causing higher residual fertilization effects (Lustosa Filho et al. 2019).

Recent studies have pointed out that encapsulated BBF might have superior characteristics for sustained release of nutrients as compared with conventional fertilizers or other types of slow/controlled release fertilizers (Sim et al. 2021), especially for controlled release of N fertilizers and reduce N losses under variable soil-plant-environment systems. However, we did not observe differences for BBF applied as both powder or granular form, which is an advantage for formulating BBF in a simpler and cheaper way. Even so, especially for N, there might be benefits for controlled N release with BBF under soil-plant systems that show high N losses (e.g. sandy soils). Under conditions of large losses by leaching or gas emission, other additives (e.g. clay, adhesives, polymers, etc.) are often used and are known to better control the N release rate (Liu et al. 2019) that can reduce such N losses and increase N use efficiency (Dong et al. 2019). Khajavi-shojaei and Moezzi (2020) observed that $MgCl_2$-modified biochar-based slow-release fertilizer increased N use efficiency by 24% and shoot dry weight of maize by 24% when compared with ammonium nitrate in a pot experiment. Zhang et al. (2021) observed that a powder-coated biochar-enriched N fertilizer increased yield by 28-39% under field conditions for tobacco cultivation and attributed this to a sustained release of N (measured by the ^{15}N isotopic technique).

For P, we did not observe any specific effect of BBF on crop productivity increase either in highly-weathered soils or weakly-developed soils. BBF has been shown to reduce the release rate and slower the diffusion of P compared with highly water-soluble fertilizer (Lustosa Filho et al. 2019), which might lead to a reduction in either P fixation in highly-weathered soils or leaching in weakly-developed soils. But such reduction in P release rates, especially caused by co-pyrolysis of inorganic P additions and feedstock at high HHT and/or granulation, might not sufficiently supply P causing lower P uptake and consequently lower crop productivity. A BBF produced by a sequential treatment with KOH and H_3PO_4 was shown to increase crop productivity and plant P uptake compared with triple superphosphate fertilizer, although such effect was only observed in the clayey soil and not for sandy or loam soils. This effect was attributed to pH buffering of BBF in the fertilizer zone that kept soil solution pH between 7 and 8 in the clayey soil for the whole plant growth period, while triple superphosphate decreased soil solution pH to around 3.0 and kept it lower than BBF for at least 40 days (Borges et al. 2020). Further studies are needed to unravel the mechanisms of P delivery from BBF that enhance P use efficiency under different soil-plant systems. BBF enriched with NPK showed significant crop productivity increases as opposed to those enriched with NP. The absence of effects of NP-based BBF on crop productivity was likely influenced by the low number of studies (n = 4) when compared to the NPK-based BBF studies (n = 13). More studies under different soil-plant conditions must be carried out to draw solid conclusions on different combinations of nutrient-enriched BBF.

These observations also illustrate the opportunity for biochar as part of BBF to increase nutrient use efficiency. Given that our meta-analysis was not able to identify sufficient studies in the scientific literature (16 out of 40 studies on BBF) that reported nutrient uptake, this illustrates the need for future research that explicitly includes data on plant nutrient uptake as well as changes in soil properties, such as nutrient availability, soil pH, and soil organic carbon content with BBF in comparison with conventional fertilizers.

Soils less responsive to conventional fertilizers are more responsive to BBF

BBFs were more effective in eliminating those crop productivity constraints that conventional fertilizers could not sufficiently address, as shown by the 15% (CI: 9-21%) crop productivity increase in soils non-responsive to fertilizer application while productivity did not differ in soils where crops responded to conventional fertilizers. Several reasons may explain this effect as will be discussed later, but at this point of our knowledge and with the limited dataset to date, it is still difficult to draw solid conclusions as productivity responses were, to a great extent, influenced by site-specific conditions. In our study, the soils less responsive to conventional fertilizers were found in categories of weakly-developed soils and “other” soils as opposed to highly-weathered soils (i.e., nutrient-poor with low cation exchange capacity) that were highly responsive to conventional fertilizers.

Common characteristics of soils responsive to conventional fertilizers that at the same time showed negative responses to BBFs include acidity (pH <6.5) and fine soil texture (clay or clay-loam). Common characteristics of BBFs that caused crop productivity declines had low C contents (<30%) and low HHT (<400 °C). This points that C content and form (as influenced by HHT) are key to design efficient BBF.

Besides the use of other additives to improve the sustained release of nutrients from BBF, with special attention to N fertilizers (Sim et al. 2021), a focus has been placed on modifying biochar prior or after pyrolysis for further preparation of BBF aiming to solve specific soil problems, such as increase of soil CEC or reduce heavy metals availability that conventional fertilizers cannot solve (Chen et al. 2021). For instance, these researchers found in a field experiment that BBF increased maize productivity in a soil slightly contaminated with cadmium by increasing soil CEC reducing its availability and transfer to maize, while conventional fertilizers did not show any effect on cadmium availability or on soil characteristics. Therefore, one cannot solely consider the biochar effect on N use efficiency through the use of BBF but also its combination with other additives plays a role in creating an enhanced-efficiency fertilizer. Even so, in our database, of those BBF that contain high C contents (> 30%), only Puga et al. (2020) used bentonite and gelatinized maize flour for BBF granulation, and Khajavi-shojaei and Moezzi (2020) prepared a $MgCl_2$-modified biochar and soaked it with ammonium nitrate followed by mixture and coating with polyvinyl alcohol and corn starch. These are encouraging results towards assessing the feasibility of using biochar in small amounts of <1 t ha^{-1} as a fertilizer enhancer, since most cost-benefit analyses performed so far did only examine application rates of several tons per hectare (Bach et al. 2016; Latawiec et al. 2019). For relatively high fertility soils, BBF can be tailor made to solve specific problems that conventional fertilizers cannot, thus they might increase crop productivity in soils non-responsive to conventional fertilizers.

Localized biochar effects to promote BBF efficacy

Many different feedstocks have historically been used to produce biochar, with compositions that vary from low (e.g., wood biomass) to high (e.g., manures and sludges) ash content, where plant nutrients (except N) concentrate. Most biochars are enriched in nutrients compared with the original feedstock (Figueredo et al. 2017) and these tend to be released to the soil as the ash in biochar solubilizes (El-Naggar et al. 2019). In this meta-analysis, we separated biochars into those that are poor or rich in nutrients according to the feedstock source as reported in the selected references. Despite the mean effect size being slightly higher for nutrient-rich than for nutrient-poor biochars, the two classes were not significantly different from each other. Thus, the contribution of nutrients (mainly P and K) from feedstock used in producing BBF does not seem to guarantee higher crop productivity response, which could be related to their relatively low amounts when compared with conventional fertilizer sources, and the fact that their contribution was probably masked by the loading of external nutrients during the production of the BBF.

The results obtained indicated that BBFs are effective at increasing crop productivity regardless of soil pH and without having an apparent impact on it. Yet, BBFs enriched with alkaline materials (e.g., KOH) might contribute to improve P use efficiency in clayey and P-fixing soils through localized pH-buffering reactions that enhances P availability to plants where the P resides (Borges et al. 2020).

Therefore, it is possible that biochar properties related to its C forms and content are probably more important than its nutrient contents or its ability to improve bulk soil pH, and those C properties may enhance nutrient use efficiency in BBF. This is consistent with the much higher effect size on crop productivity of those BBFs with biochars that have more than 30% C than those with less than 30% C, when compared with conventional fertilizers. Biochars with high C contents, even when produced at low HHT, have been shown to increase specific root surface area, root branching and fine roots under field conditions in sandy soils resulting in higher crop productivity (Abiven et al. 2015). Moreover, the fact that higher and significant crop productivity for biochars produced at higher HHT (> 400 °C) is consistent with the more important role of HHT for increasing root length than biochar source or biochar pH (Xiang et al. 2017).

An aspect that deserves further research attention is the increase in direct electron transfer from C matrices (e.g. biochar) with increased HHT (Sun et al. 2018). This can affect several biogeochemical reactions involving redox reactions and potentially facilitate the energetics of nutrient uptake by plants (Chew et al. 2020). BBFs produced from C-rich feedstocks at high HHT appear to be more effective at storing and donating electrons in the rhizosphere, which stimulate mycorrhizal colonization of the nutrient-loaded biochars and increase root membrane potential that can result in higher nutrient uptake and higher plant biomass (Chew et al. 2020). This electron transfer capacity of biochar has been demonstrated under reduced conditions and changed the abundance of bacteria involved in the N cycle that might enhance the risk of N fertilizer loss (Zhou et al. 2016).

Conclusions and recommendations

Biochar-based fertilizers have the potential to improve nutrient use efficiency and increase crop productivity by applying biochar at minor quantities. We found that BBF caused the highest increases in crop productivity in soils of initially high fertility and of low response to conventional fertilizers. Thus, the BBF preparation method should be carefully chosen to solve site-specific limitations and be designed to create enhanced efficiency fertilizers with both economic and environmental benefits. This should increasingly attract the interest of the fertilizer industries and motivate the development of a circular economy with the recycling of locally-available organic wastes. The positive effects of biochars having both high C and made at high HHT as a composite material for BBF production deserves further research attention. Specifically, there is a need to assess whether BBF causes changes in the electron transfer properties in the rhizosphere, which might be responsible for improving nutrient-use efficiency and the observed crop productivity increases. Also, studies including cost-benefit analyses of BBF under field conditions are needed to examine under what conditions BBF can contribute to sustainability in food and fiber production in the near future. Another question that remains open is whether over time the use of BBF will improve nutrient use efficiency that allow reductions in nutrient applications, especially in combination with other practices designed to promote sustainability (e.g., cover crops, crop rotation, etc.) that might help to improve soil health.

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Declarations

Conflicts of interest/Competing interests The authors declare there is no conflict of interest.

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