



Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis

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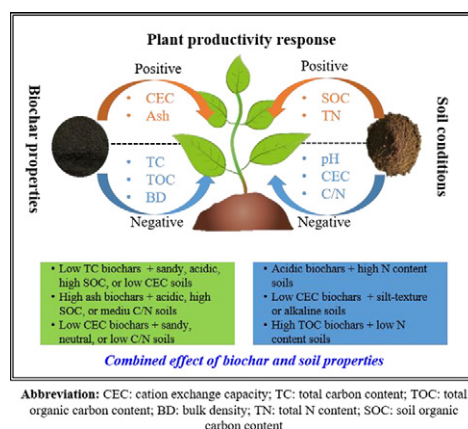
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HIGHLIGHTS

- Effect of biochar/soil properties on plant productivity response (PPR) was examined.
- Grand mean of PPR was estimated to be 16.0% regardless of biochar/soil conditions.
- PPR varied from −31.8% to 974% under different biochar/soil combinations.
- Design of functional biochar according to initial soil conditions is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Biochar application in agricultural soils can be highly beneficial to plant productivity. However, how plant productivity response (PPR) [% change of plant yield from control (without biochar application)] to biochar application is affected by biochar properties, soil conditions, and their combinations is still unclear. Therefore, a meta-analysis based on 1254 paired comparisons from 153 published studies was conducted. The grand mean of PPR was estimated to be $16.0 \pm 1.3\%$, regardless of biochar/soil conditions. Meanwhile, a large variation of PPR from −31.8% to 974% was also observed under different biochar or/and soil conditions. Specifically, biochar properties including pH, cation exchange capacity (CEC), contents of carbon and ash, bulk density, and soil conditions including texture, pH, CEC, nitrogen content, and C/N ratio significantly affected the results of PPR to biochar addition. Furthermore, the liming effect, improvement in soil physical structure, and increased nutrient use efficiency were suggested as the key mechanisms for the positive PPR in biochar-amended soils. Moreover, PPR could be significantly affected (strengthened or weakened) by the combined effect of biochar properties and soil conditions. Overall, the application of biochars with high ash content (or low carbon content) into sandy soils or acidic soils is highly recommended for increasing plant productivity. This meta-analysis will provide

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helpful information to elucidate the combined effect of biochar properties and soil conditions on plant growth, which is critical for developing engineered biochar with specific functionality to promote plant production and food security.

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1. Introduction

The increasing world population and a limited amount of arable land make a great challenge to agricultural production and global food security (Roberts, 2009). Thus, high intensity utilization of arable land and a large amount of chemical or organic fertilizer employment to seek more food supply have become the global trend in a few decades (Fan et al., 2012). However, soil degradation such as acidification (Guo et al., 2010), soil organic matter (SOM) and nutrient depletion, and pollution (Huang et al., 2017), has intensified and threatens the sustainable agricultural production. The increased soil acidification and SOM depletion may further result in deterioration of soil quality such as negative effect on soil microorganisms (Dai et al., 2017; Ding et al., 2016), and reduction of aggregate stability and water holding capacity (WHC) (Ibrahim et al., 2013). These negative effects subsequently can limit plant growth and food production. Furthermore, the intensified land use and large amount of chemical fertilizers may increase soil nutrient leaching and decline nutrient use efficiency (Guo et al., 2010). It was estimated that the recovery efficiency of nitrogen (N), phosphorous (P), and potassium (K) was approximately 33%, 20%, and 40%, respectively, in cereals worldwide, implying more than half of the applied nutrients were lost in soil-plant system or unavailable to plants (Baligar and Fageria, 2015). Therefore, how to address these issues in degraded soils using effective remediation technologies is critical to sustainable crop productivity.

Biochar, a carbon-rich material, can be produced from a wide range of biomass including crop straw, woody material, livestock manure, and other organic waste (e.g., sewage sludge, municipal biosolids) (Luo et al., 2016b; Zhao et al., 2013). Biochar can be used as a promising soil amendment to improve crop growth by modulating soil conditions (Jiang et al., 2019), because of its unique characteristics, such as large surface area (SA) and rich pore structure, abundant oxygen (O)-containing functional groups, and high cation exchange capacity (CEC) (Ding et al., 2017; Purakayastha et al., 2019; Tan et al., 2017). However, a large variation in plant productivity responses (PPR) to biochar application in soil was documented in previous studies due to the high heterogeneity of biochar properties, soil conditions, experiment designs, and/or environmental conditions (Hussain et al., 2017). For example, as summarized by Hussain et al. (2017), the PPR in biochar-amended soils ranged from −35.8% to +294%. Although a significantly increased plant productivity had been reported consistently in previous meta-analysis studies (Biederman and Harpole, 2013; Jeffery et al., 2017; Jeffery et al., 2011; Liu et al., 2013), the efficiency of plant productivity improved by biochar was highly depended on biochar properties and soil conditions. In these meta-analysis studies, biochar production conditions (feedstock and heating treatment temperature), biochar properties (pH, CEC, and C/N ratio), biochar application rate, soil conditions (texture, pH, soil organic carbon (SOC), C/N ratio, and CEC), experimental types (pot or field), tested plant types, and fertilizer utilization conditions (type and application rate) were identified as the important factors. Furthermore, the liming effect and increases in WHC and nutrient use efficiency were proposed as the most important mechanisms contributing to biochar-induced improvement in plant growth (Jeffery et al., 2017; Jeffery et al., 2011; Liu et al., 2013). However, in most of the previous meta-analyses, the effect of selected biochar properties or soil conditions on PPR were analyzed separately, and the combined or interacting effect of biochar properties and soil conditions was not well examined, thus, not understood either. Misleading biochar utilization and undesired outcomes may occur if the biochar properties and

soil conditions were considered separately. Obviously, the general trend of PPR as affected by biochar properties can vary under different soil conditions, because the responses of soil physico-chemical properties to biochar addition are not only affected by biochar properties, but also determined by the initial soil types (Al-Wabel et al., 2018). For example, Jin et al. (2016) demonstrated that the different increasing extents of tested soil indicators (i.e., pH, CEC, contents of C, N, and P) in two soil textures (silt loam and clay loam soils) were found when swine manure-biochar was applied. Moreover, Zhai et al. (2014) found that the efficiencies of soil Olsen-P and microbial biomass-P were higher in acidic Red earth soil than alkaline Fluvoaquic soil under the same maize straw biochar application. Therefore, elucidating the combined effect of biochar properties and soil conditions on plant growth is critical for choosing suitable biochar or developing engineered biochar with specific functionality for a specific soil to promote crop production. Based on this aim, only the biochar properties and soil conditions were considered in this meta-analysis to explore their combined effect on PPR, while other factors, such as biochar application rate, tested plant type, or fertilizer utilization conditions were not included in this study.

In this study, a meta-analysis based on a data set compiled from 153 studies with 1254 paired comparisons was conducted to investigate the effect of biochar properties and soil conditions, and their combined effect on PPR to biochar application. The specific objectives of this study were to: 1) investigate the general trend of PPR as affected by biochar or soil properties in biochar-amended soils, 2) examine how the PPR can be affected by biochar properties under specific soil conditions, and 3) to discuss the potential roles of biochar in plant growth improvement by modulating the soil properties and nutrient utilization. These results are expected to draw the consolidated directions for the successful application of biochar as an efficient soil amendment in crop production to increase global food security.

2. Materials and methods

2.1. Data collection

The literature, which reported the plant yields [e.g., total biomass, grain yield, aboveground biomass (shoot biomass) and/or underground biomass (root biomass)], was collected mainly from two online databases, i.e., Web of Science and Springer Link. Only one indicator of plant productivity was selected following the sequence of total biomass, grain yield, aboveground biomass (shoot biomass) and underground biomass (root biomass) if more than one indicator was reported in a given study. The time horizon of data for inclusion of literature in the databases was up to November 2017. Similar to previous studies (Jeffery et al., 2017; Liu et al., 2013), the included studies in our meta-analysis should fulfill the following criteria: 1) the study must be the original research with quantitative results of the change of plant productivity due to biochar application; 2) the reported results must comprise the means and standard deviation (SD) [or standard error (SE) in some cases, which can be changed to SD using the equation of $SD = SE \sqrt{n}$, where n is the sample size (Luo et al., 2006)]; 3) the study design had to include at least three replications. From the selected studies, only treatments for pairwise comparison between groups with biochar application and corresponding control group without BC application were extracted. Other basic data relevant to the biochar properties including pH, CEC, SA, ash content, total carbon content (TC), bulk density

(BD), total organic carbon content (TOC), total N content (TN), and C/N ratio, and soil properties including texture, pH, SOC, CEC, TN and C/N ratio, were also extracted. In the cases of the results presented only in figures, Plot Digitizer 2.6 software (<http://plotdigitizer.sourceforge.net/>) was used to extract numerical data. In the cases of lacking SD value, 10% of mean was assigned for calculating these missing SDs (Luo et al., 2006). Additionally, the pH (KCl) and pH (CaCl₂) were translated into pH (H₂O) according to the method in Nguyen et al. (2017). In total, 1254 paired comparisons from 153 studies were collected for the present meta-analysis study.

2.2. Meta-analysis

A two-stage meta-analysis was conducted. First, the overall trends of the biochar effect on plant productivity categorized by the properties of biochar or soil were explored. Second, to further investigate the combined effect of biochar properties and soil conditions on plant productivity, a sub-meta-analysis was designed, in which the mean effect size for each biochar group under different soil categories was calculated. The groups and corresponding classified standards for the selected biochar and soil property factors are listed in Tables S1 and S2. For example, the BC-pH (<7) means the biochar group with pH < 7, and the Soil-SOC (L) means the soil group with low SOC content (<10 g kg⁻¹).

The detailed information of meta-analysis had been introduced comprehensively in previous studies (Hedges et al., 1999; Jeffery et al., 2011; Liu et al., 2013; Nguyen et al., 2017). According to these studies, the effect size of PPR was calculated as a natural log value of the response ratio:

$$\ln RR = \ln \left(\frac{X_e}{X_c} \right), \quad (1)$$

where X_e and X_c are the means of biochar treatment and control, respectively. The % change of PPR can be calculated by the following equation:

$$\%change = (e^{\ln RR} - 1) \times 100. \quad (2)$$

The significant difference from the control (without biochar amendment) can be identified when the 95% confidence intervals (CIs) do not overlap the zero, and the significant difference between groups can be also identified when their 95% CIs do not overlap.

2.3. Data analysis

The MetaWin 2.1 software was employed to calculate the effect size and the 95% CIs of each categorical group, and the random effects model was selected according to the results of the heterogeneity test (Rosenberg et al., 2000). The groups with less than three pairwise comparisons were excluded from each analysis. Resampling tests were generated from 999 iterations. The funnel plot statistics and Fail-safe N technique (Rosenthal's method) were employed to test the effects of publication bias and the robustness of the meta-analysis (Rosenberg et al., 2000). The calculated Fail-safe N was used only to compare with the $5n + 1$ (n is the number of cases) when the funnel plot statistics (Kendall's Tau and Spearman Rank-Order correlation) was significant ($P < 0.05$) (Nguyen et al., 2017). The between-group variability (Q_b) among observations (n) and P value were used to test the heterogeneity between groups. The calculation of % changes in PPR was conducted in Microsoft Excel 2016. The linear regression analysis by Statistical Product and Service Solutions Software (SPSS 25.0) was performed to analyze the correlations between PPR and biochar/soil properties. The grand mean changes of soil physicochemical properties in biochar-amended soils were calculated by MetaWin 2.1 software (Rosenberg et al., 2000) to examine the effect of biochar on soil physicochemical

properties. The output of figures was analyzed using Microsoft Excel 2016 and Origin 2017.

3. Results

3.1. Statistical tests and overall plant productivity response to biochar addition

The results of the publication bias test (Tables S3–S4) showed that the publication biases existing in the literature are unlikely to influence the overall statistical significance of the results from all the primary meta-analysis cases, and the majority of sub-meta-analysis cases. Only the cases of BC-SA groups with soil-CEC (H) category, BC-BD groups with soil-TN (H) category, BC-TC groups with soil-C/N (M) category, and BC-BD, BC-TOC groups with soil-C/N (H) category were identified not passing the publication bias test. The results of heterogeneity test (Tables S5–S6) demonstrated that the significant heterogeneity was existing in most of the cases in both primary and sub-meta-analysis, because of the relevant data compiled from a wide range of literatures under variable conditions, e.g., biochar production, experiment designs (Nguyen et al., 2017). The grand mean of PPR to biochar application was estimated to be $16.0 \pm 1.26\%$, regardless of the biochar properties and soil conditions.

3.2. Effect of biochar properties or soil conditions on plant productivity response: a primary meta-analysis

3.2.1. Biochar properties

Nine biochar properties, including pH, CEC, SA, TC, ash, BD, TOC, TN, and C/N, were selected to investigate the effect of biochar on PPR, and the results are illustrated in Fig. 1. Except for the groups of BC-pH (<7), BC-ash (<10), and BC-C/N (100–200), most of the biochar groups demonstrated positive effects on plant growth, and the increased plant productivity ranged from 3.32% in the group of BC-TOC (>60) to 84.3% in the group of BC-TC (<30%). Only the BC-pH (<7) group showed a significant decrease in plant productivity (−12.3%). Notably, the total number of studies in the low BC-pH group (<7) was 53, only accounting for 4.74% of the total amount of tested biochars (1110), reflecting that most of the biochars used for improving plant productivity were alkaline. Particularly, the greater increase in plant productivity was found in the groups with lower categorized values than those of higher categorized values in the cases of BC-CEC, BC-TC, BC-BD, and BC-TOC, whereas the contrary trend was recorded in case of the BC-ash group (Fig. 1). For the BC-pH groups, the highest increase in plant productivity was recorded in case of the BC-pH (7–8) group (29.4%), which was significantly higher than that for other groups. With regard to the groups BC-SA, BC-TN, and BC-C/N, although a positive PPR was detected [except for BC-C/N (100–200)], no significant difference was found between each group. Compared to the grand mean of PPR, the extent of plant productivity improvement can be enhanced in the groups of BC-pH (7–8), BC-ash (>25), BC-TC (<30), and BC-BD (<0.3), while weakened in the groups of BC-CEC (20–30), BC-ash (10–25), BC-SA (>200), BC-BD (>0.3), and BC-TOC (>60) (Fig. 1). Overall, the biochar properties including pH, CEC, TC, ash, BD, and TOC were identified as the key factors that can significantly change PPR.

The results of regression analysis demonstrated that the PPR was positively correlated with biochar properties including CEC and ash, while was negatively correlated with biochar properties including TC, BD, and TOC (Fig. 2). Other biochar properties, including pH, SA, TN, and C/N, showed non-significant correlations with PPR. These results were consistent with most of the grand trends identified by the meta-analysis above (Fig. 1), in which the higher PPRs were acquired by the biochars with higher ash content or lower TC, BD, or TOC. Notably, a significantly higher PPR to the BC-CEC group (<10 cmol kg⁻¹) than to other BC-CEC groups was found in the meta-analysis (Fig. 1), which

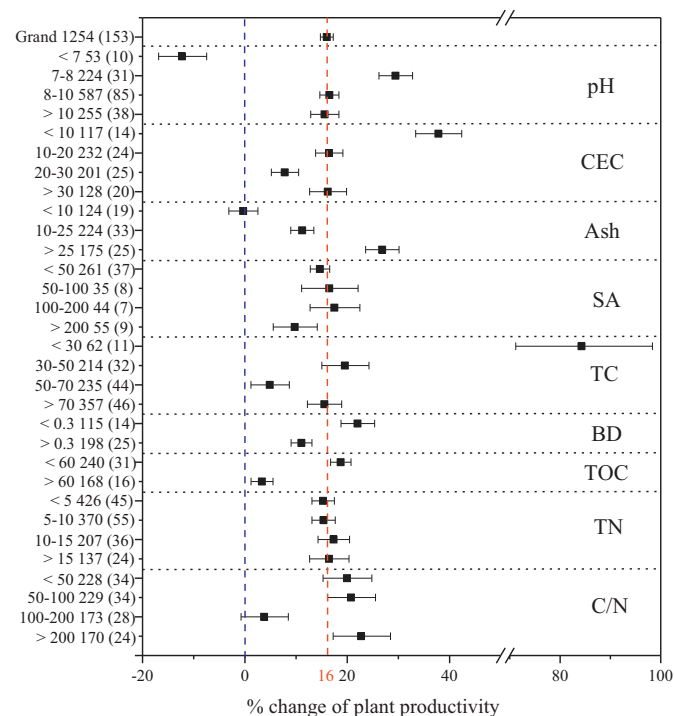


Fig. 1. Effect of biochar on plant productivity categorized by biochar property. Symbols indicate the mean % change of plant productivity relative to control with 95% confidence intervals. The y-axis shows the groups categorized by biochar properties correspondingly. The numbers after the name of group indicate the amount of pairwise comparison (without brackets) and the amount of reference those pairwise comparisons derived (with in brackets). The red dotted line indicates the grand mean % change of plant productivity responding to biochar addition, regardless of the biochar properties and soil conditions. CEC: cation exchange capacity; SA: surface area; TC: total carbon; BD: bulk density; TOC: total organic carbon content; TN: total N content.

was contradictory to the findings of the regression analysis for the same factor.

3.2.2. Soil properties

Six soil properties, including texture, pH, SOC, CEC, TN, and C/N, were selected to explore the effect of soil property on PPR in biochar-amended soils (Fig. 3). Biochar application to the majority of soil categories exhibited the consistent increases in plant productivity. Only the biochar application into the soils with a high CEC or C/N ratio produced non-significant effects on plant productivity (Fig. 3). Particularly, the plant growth would be improved much higher by the biochars applied in the soils with low pH or C/N ratio, or high TN compared to other soil groups (Fig. 3). Addition of biochar to sand-texture soils can induce a significantly higher positive PPR than silt-texture soils, but had little effects for the clay-texture soils (Fig. 3). Additionally, the level of SOC exerted a non-significant effect on the plant growth following biochar application (Fig. 3). Compared to the grand effects of biochar on plant productivity (Fig. 3), the improvement in plant productivity can be enhanced markedly by the additions of biochar to soil categories of sand-texture, acidic, CEC (L), TN (H), and C/N (L), while weakened by the additions of biochar to the soil categories of neutral, alkaline, TN (L), TN (M), and C/N (M) (Fig. 3). Consequently, the soil conditions including texture, pH, CEC, TN, and C/N ratio can be identified as the key factors that can alter the PPR significantly.

Due to the non-continuous values for soil texture, the indicator of soil sand content was used to substitute the soil texture in the regression analysis, and the result showed no statistically significant correlation between PPR (effect size) and soil sand content (Fig. 4). Nevertheless, the PPRs positively correlated with SOC and TN, and

negatively correlated with pH, CEC, and C/N (Fig. 4). These results were consistent with the overall trends identified by meta-analysis above.

3.3. Combined effect of biochar property and soil condition on plant productivity

3.3.1. Combined effect of BC-pH and soil conditions on plant productivity

Notably, the positive PPR to alkaline biochar application, which was observed in the primary meta-analysis (Fig. 1), did not occur consistently under the specific soil categories of CEC (H) and C/N (H) (Fig. S1). With regard to the acidic biochar group [BC-pH (<7)], the negative PPR observed in the primary meta-analysis turned to the positive PPR when the acidic biochars were applied into the alkaline soils (Fig. S1B). The acidic biochars demonstrated little effect on plant productivity when they were applied into the soil categories of silt-texture, acidic, SOC (M), SOC (H), CEC (L), CEC (M), TN (L), C/N (L), and C/N (H) (Fig. S1). Furthermore, the magnitude of PPR to biochar application was also increased or decreased in the specific soil categories. The negative PPR to BC-pH (<7) group (Fig. 1) could be significantly enhanced in the soil categories of CEC (L), CEC (H), TN (M), TN (H), C/N (M), and C/N (H) (Fig. S1). For the alkaline biochar groups, the positive PPR could be enhanced in the soil categories of sand-texture, acidic, CEC (L), TN (H), C/N (L), and C/N (M), and weakened in the soil categories of silt-texture, alkaline, CEC (H), and C/N (H) (Fig. S1). The maximal decrease in plant productivity reached up to -31.8% by BC-pH (<7) group within the soil-TN (M) category (Fig. S1E), and the maximal increase in plant productivity reached up to 87.1% in case of the BC-pH (7-8) group within the high TN soil category (Fig. S1E). Additionally, the significantly positive correlations between PPR and BC-pH were found in soil categories of SOC (M), CEC (M), and C/N (M), while the significantly negative correlations were recorded in the soil categories of alkaline, CEC (L), and C/N (L) (Fig. S2).

3.3.2. Combined effect of BC-CEC and soil conditions on plant productivity

Similar to the general trend of the plant productivity affected by biochar CEC, the extent of plant productivity improvement by the BC-CEC (<10) group was significantly higher than that in the other BC-CEC groups within the soil categories of sand, neutral, CEC (L), TN (L), and C/N (L) (Fig. S3). Compared to controls, the plant productivity was decreased greatly in case of the BC-CEC (<10) group within the soil categories of silt-texture, CEC (M), and TN (M), respectively (Fig. S3). Additionally, a significantly negative PPR was also found for the BC-CEC (20-30) group within the CEC (H) soil category (-22.8%, Fig. S3D), which was completely opposite to the general trend observed in the primary meta-analysis in case of the same BC-CEC group. The magnitude of increased plant productivity estimated by the primary meta-analysis could be further elevated for each BC-CEC group within the specific soil categories. The maximal increases in plant productivity reached up to 99.6%, 37.1%, 29.0%, and 34.0% in the soil categories of C/N (L), sand-texture, SOC (L), and acidic for the BC-CEC groups of <10, 10-20, 20-30, and >30, respectively (Fig. S3). Furthermore, the correlations between PPR and BC-CEC also varied across different soil conditions. Significantly positive correlations were recorded in the soil categories of acidic and alkaline, CEC (H), TN (M), and C/N (M), while significantly negative correlations were observed in the soil categories of clay-texture, neutral, CEC (L), CEC (M), TN (H) and C/N (L) (Fig. S4). Notably, there were no significant correlations between PPR and BC-CEC in all the soil-CEC categories (Fig. S4).

3.3.3. Combined effect of BC-ash and soil conditions on plant productivity

The plant productivity had little response in the BC-ash (<10) group according to the primary meta-analysis (Fig. 1), while this trend changed when the specific soil conditions were taken into consideration. For example, plant productivity could be significantly decreased when the biochars in the BC-ash (<10) group were incorporated into

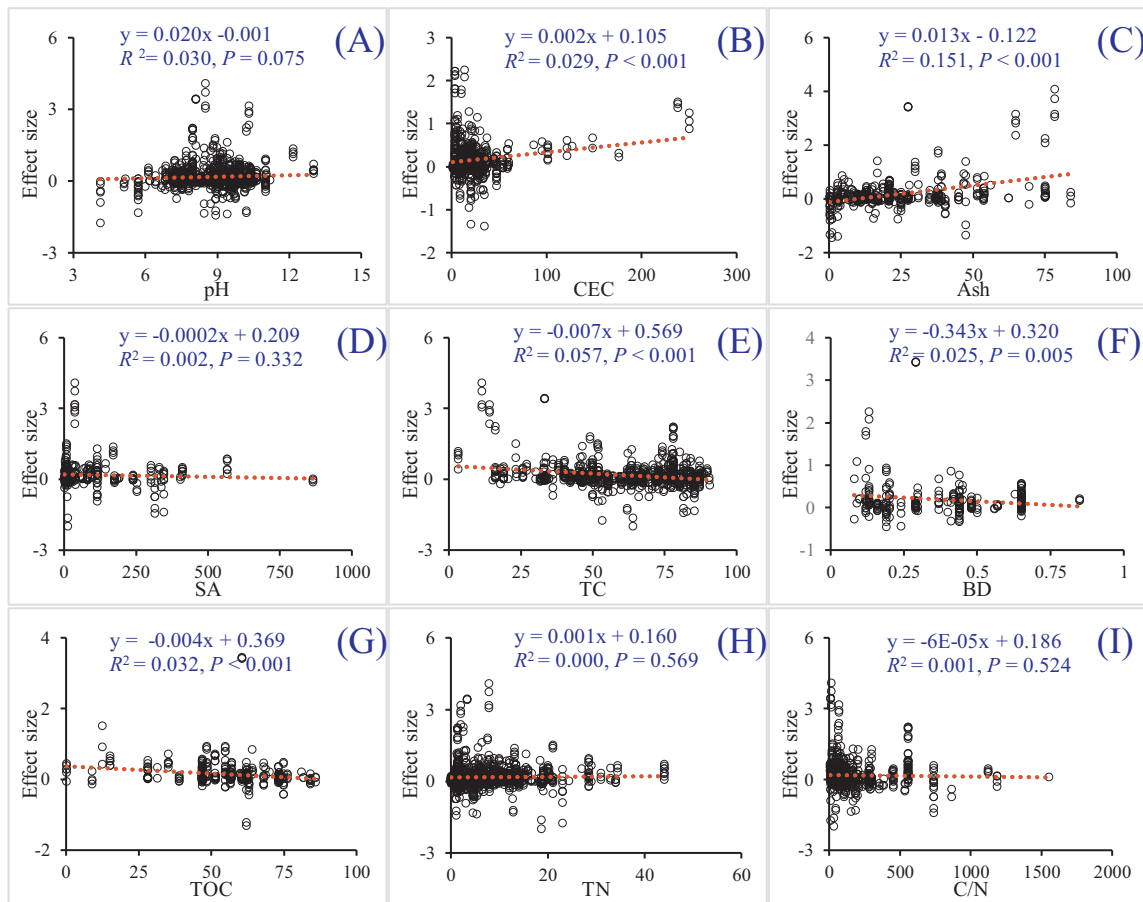


Fig. 2. Regression analysis between biochar property and plant productivity response. (A) pH; (B) CEC: cation exchange capacity; (C) ash content; (D) SA: surface area; (E) TC: total carbon content; (F) BD: bulk density; (G) TOC: total organic carbon content; (H) TN: total N content; (I) C/N ratio. The linear regression analysis was conducted using SPSS 25.0. The cases with P value < 0.05 indicate the significant relationship between biochar property and plant productivity response.

soil categories of CEC (H), TN (H), C/N (M), and C/N (H) (Fig. S5). Contrarily, the significant increases in plant productivity were also observed when the same biochars were applied to the soil categories of clay-texture, SOC (L), SOC (M), CEC (M), and TN (M) (Fig. S5). Although negative PPRs were recorded in case of the BC-ash (10–25) group combined with soil-C/N (L), and also in BC-ash (>25) group combined with soil categories of clay-texture or CEC (H), statistically significant differences from the control were not found (Fig. S5). The maximal increases in plant productivity reached up to 20.7%, 18.9%, and 134% for the BC-ash (<10), (10–25), and (>25) groups combined with the soil categories of CEC (M), acidic, and C/N (M), respectively (Fig. S5). The results of regression analysis demonstrated that the positive correlation between PPR and BC-ash was still maintained in the majority of soil categories; only a significantly negative correlation was observed under clay-texture soil condition (Fig. S6).

3.3.4. Combined effect of BC-SA and soil conditions on plant productivity

The positive PPR to the groups of BC-SA (<50), BC-SA (50–100), or BC-SA (100–200) observed in the primary meta-analysis (Fig. 1) also maintained in the majority of soil categories (Fig. S7). Only the BC-SA (<50) combined with soil-C/N (L), and BC-SA (100–200) combined with soil categories of silt-texture, neutral, alkaline, SOC (L), and TN (M) showed a slight decrease in plant productivity without any statistical significance (Fig. S7). Whereas, for the group of BC-SA (>200), the significant decreases in plant productivity only occurred in clay-texture and C/N (H) soils (Fig. S7). The maximal increases in plant productivity reached up to 113%, 28.9%, 62.6%, and 68.3% for BC-SA (<50), (50–100), (100–200), and (>200) groups combined with soil categories of C/N (M), sand-texture, C/N (M), CEC (L), and C/N (M), respectively

(Fig. S7). Similar to the result of regression analysis without considering soil conditions (Fig. 2), no significant correlation between the PPR and BC-SA was found in majority of soil categories (Fig. S8). It is noted that the PPR was identified to be negatively correlated to BC-SA under clay-texture and C/N (H) soil conditions, and positively correlated to BC-SA under CEC (L) soil condition (Fig. S8).

3.3.5. Combined effect of BC-TC and soil conditions on plant productivity

The higher improvements in plant productivity by BC-TC (<30) than other BC-TC groups were still maintained in the soil categories of sand-texture, acidic, neutral, SOC (H) and CEC (L), and the increased extent of plant productivity was also enhanced in these cases (Fig. S9). Although the decreasing trends of plant productivity were recorded in the soil categories by high BC-TC groups, no statistical significance was detected. The positive PPRs to other three BC-TC groups could be also enhanced in the specific soil cases, i.e., the maximal increases in plant productivity by BC-TC (30–50), BC-TC (50–70), and BC-TC (>70) reached up to 43.9%, 32.8% and 62.2% in soil cases of C/N (L), acidic, and C/N (L), respectively (Fig. S9). Overall, similar to the general trend of BC-TC factor in the primary meta-analysis, the biochars with low TC may promote the plant productivity greater than those with high TC. The consistent negative correlations between PPR and BC-TC were identified under majority of soil conditions, as illustrated in Fig. S10.

3.3.6. Combined effect of BC-BD and soil conditions on plant productivity

The two BC-BD groups also showed a positive effect on plant productivity, even under different soil conditions (Fig. S11). However, the magnitude of improved plant productivity varied. The changes of PPR to the BC-BD (<0.3) and BC-BD (>0.3) groups ranged from 6.66% in clay-

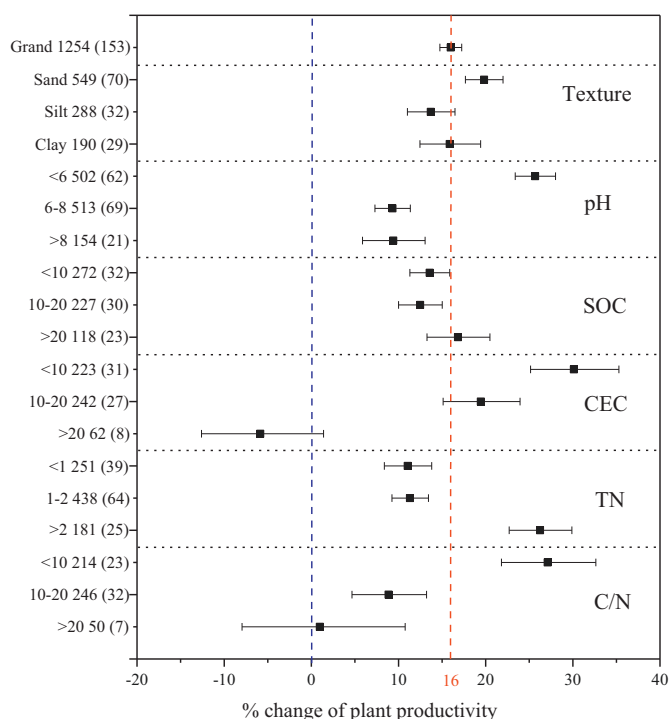


Fig. 3. Effect of biochar on plant productivity categorized by soil property. Symbols indicate the mean % change of plant productivity in relative to control with 95% confidence intervals. The y-axis shows the different groups categorized by soil properties, correspondingly. The numbers after the name of group indicate the amount of pairwise comparison (without brackets) and the amount of reference those pairwise comparisons derived (with in brackets). The red dotted line indicates the grand mean % change of plant productivity responding to biochar addition, regardless of the biochar properties and soil conditions. SOC: soil organic carbon; CEC: cation exchange capacity; TN: total N content.

texture soils to 46.1% in silt-texture soils, and from 3.08% in soil-CEC (H) to 14.8% in soil-CEC (M) (Fig. S11). Unlike the overall result of regression analysis (Fig. 2), no correlations between PPR and BC-BD were observed under all the soil conditions (Fig. S12).

3.3.7. Combined effect of BC-TOC and soil conditions on plant productivity

The greater increase in plant productivity by BC-TOC (<60) group than BC-TOC (>60) group was consistently observed across all the soil categories except for the silt-texture soil type (Fig. S13), which was similar to the general trend in primary meta-analysis. The maximal increases in plant productivity for BC-TOC (<60) and BC-TOC (>60) were 35.9% in clay textured soil, and 18.7% in silt textured soil (Fig. S13A). A significant decrease in plant productivity was also shown for BC-TOC (>60) combined with TN (L) soils (Fig. S13E). The consistent negative correlations between PPR and BC-TOC were identified under most soil conditions (Fig. S14).

3.3.8. Combined effect of BC-TN and soil conditions on plant productivity

The results of the primary meta-analysis for BC-TN demonstrated that there was no significant difference between each TN group (Fig. 1). However, this trend was changed when the soil conditions were taken into consideration. For low TN group of BC-TN (<5), the grand mean of PPR was further enhanced in soil categories of sand-texture, acidic, SOC (L), SOC (H), CEC (L), TN (L), TN (H), and C/N (L) (Fig. S15). The maximal increase in plant productivity for this group reached up to 56.3% in C/N (L) soils (Fig. S15). But a significant decrease in plant productivity by the same BC-TN group was observed in the soil category of CEC (H) (Fig. S15). For the high TN group of BC-TN (>15), the grand mean of PPR was further enhanced in soil categories of clay-texture, acidic, CEC (L) and CEC (M), and TN (H) (Fig. S15). Furthermore, a significant decrease in plant productivity for BC-TN (>15) was also recorded in C/N (M) soils (Fig. S15). For the other two medium BC-TN groups, the maximal increases in plant productivity could reach up to 35.4% in CEC (L) soils for BC-TN (5–10), and to 32.6% in acidic soils for BC-TN (10–15) (Fig. S15). Notably, biochar addition into high C/N soils [e.g., soil-C/N (H)] generally generated slight improvement in plant productivity (Fig. S15). Moreover, the results of regression analysis demonstrated that the PPR was positively correlated to BC-TN in soil categories of clay, alkaline, CEC (M), TN (M), and C/N (H), while negatively correlated to BC-TN in soil categories of sand, TN (L), and C/N (L) (Fig. S16).

3.3.9. Combined effect of BC-C/N and soil conditions on plant productivity

The positive PPR to low C/N ratio of biochar groups (<50 and 50–100) was also observed in most soil categories. The extents of

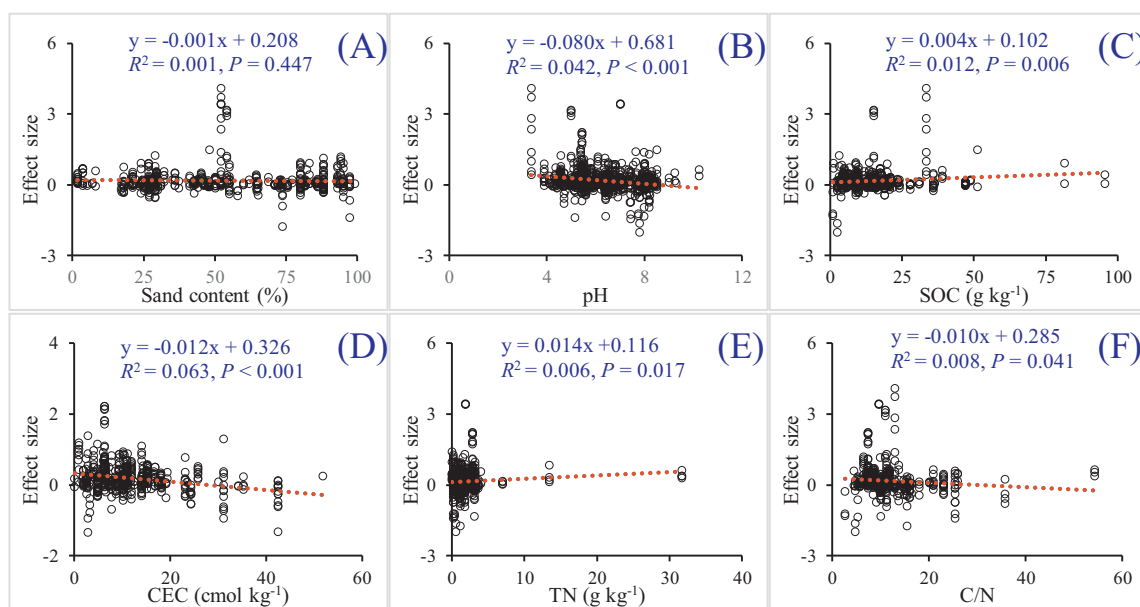


Fig. 4. Regression analysis between soil property and plant productivity response in biochar-treated soils. (A) Sand content; (B) pH; (C) SOC: soil organic carbon; (D) CEC: cation exchange capacity; (E) TN: total N content; (F) C/N ratio. The linear regression analysis was conducted using SPSS 25.0. The cases with P value < 0.05 indicate the significant relationship between soil property and plant productivity response.

increased plant productivity by these two biochar groups were enhanced in soil categories of clay-texture, acidic, SOC (H), and CEC (M) (Fig. S17). For the high C/N of BC group (>200), the greater improvements in plant productivity occurred in soil categories of sand-

texture, CEC (L), TN (H), and C/N (L). For BC-C/N (100–200) group, the significant decreases in plant productivity were found in the soil categories of neutral and CEC (H) (Fig. S17). As the regression analysis illustrated that the significantly positive correlation between PPR and

Table 1

Summary of the meta-analysis results of the present and four previous studies to show the differences.

Items		Jeffery et al. (2011)	Biederman and Harpole (2013)	Liu et al. (2013)	Jeffery et al. (2017)	Present study
Data description	Data size	177 paired comparison from 16 studies	371 paired comparison from 114 studies	880 paired comparison from 103 studies	1125 paired comparison from 109 studies	1254 paired comparison from 153 studies
	Time range	Up to 1st March 2010	Up to 25 June 2012	Up to April 2013	Up to December 2014	Up to November 2017
Overall change/%		10	NM ^b	11.0 ± 1.4	13	16.0 ± 1.26
Biochar properties	pH	NM	Alkaline BCs showed more pronounced positive effect on CP than acidic BCs	Significant increase of CP for alkaline BC groups (>7); significant decrease of CP for non-alkaline BC group (<7)	Significant increases of CP for alkaline and neutral BC groups; no significant changes of CP for acidic BC groups	Significant increase of CP for neutral and alkaline groups; significant decrease of CP for acidic group
	CEC ^a	NM	NM	NM	Significantly higher increase of CP for high CEC BC group (>200 cmol kg ⁻¹) than those low CEC BC groups (<100 cmol·kg ⁻¹)	Significant greater increase of CP for low CEC group (<10 cmol kg ⁻¹) than other groups
	Ash	NM	NM	NM	Significant higher increase of CP for low ash group (<10%) than other groups; no significant changes for medium AC group (<10–25%).	Significant greater increase of CP for high ash group (>25%) than other groups; no significant changes for low ash group (<10%)
	SA	NM	NM	NM	NM	No significant differences between different SA groups
	TC	NM	NM	NM	No significant differences between different TC groups	Higher increase of CP for low CC groups (<50%) than high TC groups (>50%)
	BD	NM	NM	NM	NM	Significant higher increase of CP for low BD group (<0.3) than the high BD group (>0.3)
	TOC	NM	NM	NM	NM	Significant higher increase of CP for low TOC group (<60%) than the high TOC group (>60%)
	TN	NM	NM	NM	NM	No significant differences between different TN groups
	C/N	NM	No significant differences between different C/N groups	NM	Significant increase of CP for low C/N groups (<40); significant decrease of CP for high C/N groups (>150)	No significant increase of CP for medium C/N group (100–200)
	Texture	Much higher increase of CP sand soils; no statistically significant change in fine-texture.	NM	Great higher CP increase for sand group than other groups	Significant increases of CP in both medium and fine texture groups; no statistically significant change in coarse-texture group.	Higher increase of CP in sand soils, but no significant difference between different groups
Soil properties	pH	Significant increase in both acidic and neutral soils; no significant change in very acidic soils	Acidic groups showed a greater positive response than alkaline groups	Significant higher increases of CP for acidic groups (<6.5) than neutral and alkaline groups (>6.5); no statistically significant change in neutral group (6.5–7.5)	Higher increase of CP for acidic groups than neutral and alkaline groups	Significant higher increase of CP for acidic group (<6) than neutral and alkaline groups.
	SOC	NM	NM	Significant higher increase of CP for high SOC group (>20) than other SOC groups	Significant increases of CP for high SOC groups (>1%); no significant changes for low SOC group (<1%)	No significant difference between different SOC groups
	CEC	NM	NM	NM	NM	Significant higher increase of CP for low CEC group (<10) than other groups; no significant change of CP for high CEC group (>20)
	TN	NM	NM	NM	NM	Significant higher increase of CP for high TN group (>2) than other groups
	C/N	NM	NM	Significant higher increases of CP for low C/N group (<9) than high C/N groups	Significant increases of CP for low C/N group (<12.5); no statistically significant change for high C/N group (>12.5).	Significant higher increase of CP for low C/N group (<10) than other groups; no significant change of CP for high C/N group (>20)

^a CEC: cation exchange capacity; SA: surface area; TC: total carbon content; TOC: total organic carbon content; BD: bulk density; TN: total N content; and CP: crop productivity.

^b NM: not mentioned.

BC-C/N was detected in the soil categories of sand-texture, CEC (L), TN (H), and C/N (L), the negative correlation was identified in the soil categories of clay-texture, CEC (M), TN (L), C/N (M), and C/N (H) (Fig. S18).

4. Discussions

4.1. Comparison between current and previous studies

Regardless of biochar properties and soil conditions, the grand mean of PPR induced by biochar ($16.3 \pm 1.26\%$) estimated in this study is slightly higher than those estimated in previous studies (10–13%) (Table 1). This variation may be attributed to the bigger sample size (1254 paired comparisons from 153 studies) than other previous studies (Table 1), which could cause differences in the data source, and further influence the results of the meta-analysis.

The inconsistent results of PPR to biochar application were also observed between our study and previous studies related to the different biochar properties, such as BC-CEC and BC-ash (Table 1), which could be attributed to the different classified standards of these properties. For example, the classified standards of BC-CEC in Jeffery et al. (2017) were 1–50, 51–100, 101–200 and >200 cmol kg^{−1}, whereas the <10, 10–20, 20–30 and >30 cmol kg^{−1} in the present study. Furthermore, a large portion of collected observations in Jeffery et al. (2017)'s study were located into 1–50 group (74.8%), and the observations in >200 group only accounted for 8.21% of the total observations, which may induce the publication bias to their results (Jeffery et al., 2017). The distribution of the collected data among different BC-CEC groups was more homogeneous in the present study than those reported by Jeffery et al. (2017). Therefore, a uniform classified standard, such as the grading standard proposed by IBI (International Biochar Initiative), is needed to improve the comparability between different studies. Furthermore, the biochar properties including SA, BD, TOC, and TN, and soil properties including CEC and TN, and the combined effect of biochar/soil conditions on PPR were investigated for the first time in our meta-analysis. These could be more beneficial to understanding the PPR to biochar addition under different biochar/soil conditions.

4.2. Role of biochar in soil structural property improvements

Generally, the biochar properties of low BD, high SA, and developed pore structure may potentially improve the structural properties of amended soils, such as BD, SA, porosity, pore size

distribution, and aggregate stability (Al-Wabel et al., 2018; Burrell et al., 2016; Mukherjee et al., 2014; Obia et al., 2016; Zheng et al., 2018b). The structural improvement, therefore, could further increase the soil WHC, improve nutrient cycle, and microbial community (Tan et al., 2017), which are beneficial to plant growth (Lone et al., 2015; Tan et al., 2017). Liang et al. (2006) found that the SA of black carbon-rich Anthrosols was up to 4.8 times higher than that of the adjacent black carbon-poor soil, which probably elevated the charge density of Anthrosols by surface oxidation of black carbon, and further resulted in higher soil CEC compared to the black carbon-poor soil. Additionally, the decrease in soil BD (−7.47%) and increase in soil porosity (+6.27%) could contribute to the positive increase in soil WHC (+9.82%) (Table 2). The benefits of biochar application to plant productivity through the positive improvement in soil structural properties can be supported directly by the negative relationship between PPR and BC-BD observed in this present study (Fig. 2). Furthermore, soil WHC and water use efficiency have been reported to be increased more effectively by biochar addition in the low-silt/sand soils than in cases of the clay soils (Al-Wabel et al., 2018). As a result, more effective improvement in plant productivity for biochar addition to sand-texture soils than other texture soils was observed consistently in previous and present studies (Jeffery et al., 2011; Liu et al., 2013) (Fig. 3). This indicates that using biochar in sandy/dryland soils may be the preferred strategy for enhancing plant productivity through improving the WHC of soils. A multi-year and multi-location observation conducted by Laird et al. (2017) also confirmed that the anticipated increase in annual average crop yield was found when the biochar was applied in a poor sand-texture soil located in a region in Washington, USA.

Unexpectedly, the BC-SA demonstrated the non-significant effect on PPR (Figs. 1 and 2), indicating that the magnitude of biochar SA may not be related to plant growth improvement closely. Generally, the large SA of biochar may potentially supply more sorption sites for SOM and other nutrients (Zheng et al., 2018b). However, the sorption effectiveness of biochar in soils is not only determined by its SA, but also regulated by the components on biochar surface (i.e., O-containing functional groups and its species, minerals) or the minerals in soils (Zheng et al., 2018b). Therefore, considering the utilization of biochar in agricultural soils, the quantity and species of components on biochar surface should receive more attentions, rather than the magnitude of biochar SA alone, which needs to be further investigated.

Table 2
Grand responses of soil physicochemical properties to biochar addition.

Soil properties	Data size ^a	Grand mean: % change ^b	95% CI ^d
pH	305 pairs of data from 59 studies	8.78 ^{ac}	7.64
SOC ^e	180 pairs of data from 30 studies	47.6 [*]	42.7
Porosity	21 pairs of data from 4 studies	6.27 [*]	4.49
WHC	122 pairs of data from 23 studies	9.82 [*]	6.10
BD	138 pairs of data from 25 studies	−7.47 [*]	−8.64
CEC	85 pairs of data from 14 studies	19.4 [*]	16.4
EC	110 pairs of data from 19 studies	1.92	−5.19
TN	170 pairs of data from 33 studies	22.2 [*]	18.6
Available N	50 pairs of data from 7 studies	3.90	−0.29
Ammonium N	104 pairs of data from 18 studies	−6.91	−13.38
Nitrate N	103 pairs of data from 18 studies	2.51	−5.96
Available P	119 pairs of data from 25 studies	32.4 [*]	25.6
Available K	57 pairs of data from 14 studies	48.3 [*]	36.2
N uptake	103 pairs of data from 14 studies	3.15	−1.45
P uptake	62 pairs of data from 10 studies	5.46	−3.16
K uptake	62 pairs of data from 10 studies	11.6 [*]	4.73

^a The data used in this meta-analysis compiled from the published references, which were listed in Table S7 in Supplementary data.
^b The values of % change were calculated by the values of effect size using the software of MetaWin2.1 (detail processes can be seen in Section 3.2).
^c The values of % change labeled with asterisk mean that they were significantly affected by biochar addition (the corresponding values of 95% CI don't overlap the zero).
^d 95% CI: 95% confidence interval, which can be concluded that the soil properties were significantly affected by biochar addition if the values of 95% CI did not overlap the zero.
^e SOC: soil organic carbon; SOM: soil organic matter; WHC: water holding capacity; BD: bulk density; CEC: cation exchange capacity; EC: electronic conductivity; TN: total N content.

4.3. Role of biochar in soil chemical property improvements

Soil pH is one of the most important factors to influence plant growth directly via affecting the microbial community and nutrients cycle (Dai et al., 2017). The liming effect of biochar, which is determined by its alkaline property, is regarded as one of the most important mechanisms for elevating plant productivity, especially for acidic soils (Jeffery et al., 2011; Liu et al., 2013). On average, the soil pH can be significantly increased by 8.78% in the biochar-amended soils (Table 2). Moreover, the increased extent of soil pH was found to be positively correlated to the increased amount of plant productivity (Jeffery et al., 2011). This mechanism was also confirmed by the negative correlation between PPR and soil pH in the present meta-analysis (Fig. 4B). Furthermore, the positive PPR to biochar application in alkaline soils was also recorded (Fig. 3), even for those high alkaline biochars [e.g., the BC-pH (>10) group] (Fig. S1B). This indicated that the changes in alkaline soil properties including SOM content, electronic conductivity, C/N and CEC induced by biochar (Liu et al., 2019; Luo et al., 2017; Zheng et al., 2018a) may be the main contributors to the positive PPR, rather than the change in soil pH. However, a negative correlation between PPR and BC-pH was also observed for biochar applied in the alkaline soils (Fig. S2), implying that the decrease in soil alkalinity could also contribute to the plant productivity improvement in alkaline soils. This is also why acidic biochar prepared via pyrolyzing switchgrass at low temperature (350 °C) (Ippolito et al., 2016) or adding HCl to the prepared biochars has been proposed to be used in the alkaline soil remediation (Sadeh-Zadeh et al., 2018). Therefore, the changes in soil pH regulated by biochar and its effect on plant growth in the alkaline soils still need to be examined.

SOC is another key soil factor affecting plant growth as it is the main source of energy and key trigger for nutrient availability (Diacono and Montemurro, 2010). Maintaining and increasing the SOC content in agricultural soils, therefore, result in positive impacts on plant production (Diacono and Montemurro, 2010). In the present study, the SOC content significantly increased by 47.6% on average in biochar-amended soils (Table 2) due to biochar's high recalcitrant C content, which was also reported extensively in previous studies (Dong et al., 2016; Du et al., 2016; Luo et al., 2016b). However, compared to the TOC input by biochar, the components of OC embodied in biochar, especially for the active OC fractions such as dissolved organic carbon, are more important to improving plant productivity. For example, the greater increase in plant productivity was found for the biochars with low C content (84.3% for TC < 30%) than those with high C content (15.5% for TC > 70%) (Figs. 1 and 2). Generally, the biochars produced at low temperature (<500 °C) or/and from non-lignin-derived materials (i.e., crop straw and manures) exhibited lower TC content than those produced at high temperature (>500 °C) or/and from lignin-derived materials (i.e., woody material) (Zhao et al., 2013). Correspondingly, the content of labile C, ash, and nutrients (i.e., N, P, K, Ca, and Mg) may be also higher in the former biochars than the latter ones (Bird et al., 2011), which may potentially enhance the nutrients supply and soil microbial activity (Chen et al., 2016). Similarly, Jeffery et al. (2017) demonstrated that the greater increase in plant productivity was achieved by the addition of biochars produced from the 'nutrient' feedstock (i.e., manures and biosolids) than those produced from 'structure' feedstock (i.e., wood and straw) in the nutrient-deficient tropical soils. Additionally, the presence of environmentally persistent free radicals (EPFRs) in biochar could potentially decrease plant growth (Odinga et al., 2020). For example, the seed germination and root and shoot growth were significantly inhibited by biochar due to the introduction of EPFRs, which damaged the plasma membrane (Liao et al., 2014). However, the relationship between biochar EPFR content and PPR was not explored in the present meta-analysis due to the insufficient published data. Therefore, characterizing the components of OC embodied in biochar and their relationships to plant growth is more important than the total amount of carbon input.

Soil CEC plays an important role in soil quality, such as retention of cationic nutrients (e.g., K, Mg, Ca, and others), and thus may be beneficial to plant uptake (Purakayastha et al., 2019). The release of exchangeable cations (i.e., Ca, Mg, K, and Na) introduced by biochars could increase the concentration of exchangeable cations in soil (Moon et al., 2017). The biochar-induced improvement in soil CEC (19.4%, Table 2) may subsequently promote plant productivity, which can be supported by the positive correlation between PPR and BC-CEC, and a negative correlation between PPR and soil CEC, respectively (Figs. 2B and 4D). The initial soil properties (e.g., pH, humic materials content, and CEC) have been suggested to mediate the improvement in soil CEC by biochars (Mukherjee et al., 2011). Therefore, the inconsistent relationships of PPR and biochar CEC were also observed among the biochar application within different soil conditions (Figs. S3 and S4). Therefore, apart from biochar itself, the effect of biochar on soil CEC under different soil conditions, as mentioned above, should be further examined.

4.4. Roles of biochar in soil nutrient cycle

Increasing soil N retention and its use efficiency after biochar application have been frequently reported in relating to plant productivity improvement, because of the additional N supply or/and improvement in N cycle contributed by biochar (Ding et al., 2016; Luo et al., 2016a; H. Wang et al., 2017; Z. Wang et al., 2017; Zheng et al., 2013b). However, the relative contributions of these two roles of biochar as N supplier or N improver are still unclear. In the present study, our meta-analysis results indicated that the role of biochar in soil may be more inclined to N improver by regulating the N cycle than as a N supplier. This can be supported by the insignificant effect of BC-TN on the PPR (Fig. 1) and the insignificant correlation between PPR and BC-TN (Fig. 2H), while the positive correlation between PPR and soil-TN (Fig. 4F). Moreover, biochar addition also showed little impact on the soil content of available N (NH_4^+ - and NO_3^- -N) (Table 2). This may be ascribed to the less available N provided by biochar (Zheng et al., 2013b) or the provided N was immobilized in the soil due to biochar-induced high C/N ratio (Z. Wang et al., 2017). Biochar could potentially implicate the soil N cycle through several mechanisms including: 1) decrease or increase the soil inorganic N content via N adsorption or desorption by biochar (Nguyen et al., 2017; Zheng et al., 2013a; Zheng et al., 2013b), 2) impact the microbial processes of N mineralization or immobilization via the changes in the content of soil mineralizable substrates (i.e., labile organic compounds) (Nguyen et al., 2017; Zheng et al., 2013a), and 3) alter the balance between the processes of nitrification and denitrification through the alterations of soil properties (i.e., pH and aeration) (Nguyen et al., 2017; Wang et al., 2015; Wang et al., 2013). However, the extent and dominant mechanisms of N cycling as affected by biochar are highly determined by its surface properties (i.e., SA, acidic functional groups, and CEC), and the species and amount of NH_4^+ -N and NO_3^- -N in soils (Ding et al., 2016; Nguyen et al., 2017). For example, a previous study showed that the adsorption capacity of biochar to NH_4^+ -N (372–2102 mg g^{-1}) is generally higher than NO_3^- -N (171–533 mg g^{-1}) due to the negative surface charge of biochar (Zheng et al., 2013b). The C/N ratios of biochar or soil have been regarded as the indicators to predict whether the N is immobilized (higher than 20) or mineralized (lower than 20) by microbes in biochar-amended soils (Chan and Xu, 2009; Nguyen et al., 2017; Novak et al., 2010). Therefore, the application of biochar into the soils with high C/N (or low TN content) may decrease N availability and limit plant growth, as the negative correlation between PPR and soil C/N ($R^2 = 0.008$, $P = 0.041$) showed in Fig. 4F. Furthermore, Jeffery et al. (2017) found that biochars with the lowest C/N (<20) may significantly increase plant productivity, while the biochars with the highest C/N (>200) may significantly decrease the plant productivity. However, this trend was not found in our study (Figs. 1 and 2I), and even the greater improvement in plant productivity could be acquired by BC-C/N (>200) group than other low BC-C/N groups under the specific soil conditions

[i.e., sand-texture, CEC (L), TN (H), and C/N (L)] (Figs. S17 and S18). Therefore, compared to BC-C/N, the soil-C/N could affect the PPR in biochar-amended soils more greatly. In addition, PPR to biochar application could be greatly affected by the condition of N fertilizer co-applications or other additives (e.g., wood vinegar) (Aller et al., 2018; Zhang et al., 2020), although it was not explored in this study. Aller et al. (2018) reported that the positive PPRs to biochar applications were observed only when the co-applied N fertilizer was at a high application rate (200 kg ha^{-1}). Further studies are needed to investigate the plant growth response to the interactions between biochar and fertilizer.

Biochars, particularly produced from animal manure and sewage sludge, were regarded as the important P and K sources for plant growth in low-P or -K soils (Hansen et al., 2017; Zheng et al., 2013b). On average, the contents of soil available P and K could be significantly increased by 32.4% and 48.3%, respectively (Table 2). Additionally, Zheng et al. (2018a) demonstrated that P-solubilizing bacteria (*Pseudomonas* and *Bacillus*) were more abundant in biochar-amended soil, thus, the fixed P forms in soil minerals, SOM, or biochars could be solubilized or transformed into available P. Zheng et al. (2013b) also recommended that the high-temperature giant reed biochar (i.e., 600°C) could be a suitable amendment for K-deficient soils. Therefore, using P and K-rich biochars may not only play the roles of nutrient suppliers, but also the improvers. However, the direct effects of biochar P and K contents on plant productivity were not included in this meta-analysis, because of the limited relevant data available in the published literature.

5. Conclusions and recommendations

The meta-analysis in the present study showed that the grand effect of biochar on plant productivity was estimated to be $16.0 \pm 1.26\%$, regardless of biochar properties and soil conditions. However, the efficiency of biochar in improving plant growth could be greatly affected by the combined effect of biochar properties and soil conditions; thus, PPR displays substantial variation (-31.8% to 974%). Furthermore, the underlying mechanisms contributed to the positive PPR also changed for the same biochar under different soil conditions. The findings in the present study positively contributed to the understanding of the underlying mechanisms of biochar in enhancing plant production, and promoting the effective application of biochar in plant production. In summary, we highlighted that, to increase the effective biochar utilization in agricultural soils, the properties of biochar should be selected carefully before their application to soils according to the conditions of targeted soils and specific problems to solve.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.136635>.

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