https://doi.org/10.17221/522/2021-PSE

Effects of biochar on soil chemical properties: A global meta-analysis of agricultural soil

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Citation: Sun Z.H., Hu Y., Shi L., Li G., Pang Z., Liu S.Q., Chen Y.M., Jia B.B. (2022): Effects of biochar on soil chemical properties: A global meta-analysis of agricultural soil. Plant Soil Environ., 68: 272–289.

Abstract: Improved soil properties are commonly reported benefits of adding biochar to agriculture soils. To investigate the range of biochar's effects on soil chemical properties (e.g., soil pH, electrical conductivity (EC), cation exchange capacity (CEC), soil organic carbon (SOC), soil total carbon (TC), and soil carbon-nitrogen ratio (C:N ratio)) in response to varied experimental conditions, a meta-analysis was conducted on previously published results. The results showed that the effect of biochar on soil chemical properties varied depending on management conditions, soil properties, biochar pyrolysis conditions, and biochar properties. The effect size (Hedges'*d*) of the biochar was greatest for SOC (0.50), the C:N ratio of soil (0.44), soil pH (0.39), TC (0.35), EC (0.21), and CEC (0.20). Among the various factors examined by aggregated boosted tree analysis, the effects of biochar on soil chemical properties were largely explained by the biochar application rate, initial soil pH, and soil sand content. In conclusion, our study suggests that improving soil chemical properties by adding biochar not only requires consideration of biochar application rates and chemical properties but also the local soil environmental factors, especially soil initial pH and sand content of the soil, should be considered.

Keywords: charcoal; organic material; agricultural condition; soil chemistry; soil fertility

Biochar is a solid product formed by high-temperature pyrolysis of organic matter, such as straw, woody material, or livestock manure, under low anoxic conditions. Biochar is widely used as an amendment to improve soil quality for plant growth (Pandey et al. 2016, Kätterer et al. 2019), resource use efficiency (Stefaniuk et al. 2017), to reduce or mitigate environmental pollution (Meng et al. 2018, Lebrun et al. 2019, Norini et al. 2019), and as an effective measure for reducing greenhouse gas emissions (Case et al. 2012, Verhoeven and Six 2014, Lin et al. 2017). Among its potential applications, agriculture is the most widely cited sector for biochar use, and biochar products have broad application prospects in ecological restoration and rehabilitation of barren lands such as degraded cultivated land, degraded grassland, and degraded orchards, as well as in new farmland (Deal et al. 2012, Jien and Wang 2013, Peake et al. 2014, Li et al. 2018).

The addition of biochar can stimulate soil carbon sequestration (Sandhu et al. 2017, Wang et al. 2017), improve soil structure (Mukherjee et al. 2014,

Supported by the Fund for Less Developed Regions of the National Natural Science Foundation of China, Grant No. 42167039, and by the Technology Innovation Center for Land Engineering and Human Settlement Environment, Shaanxi Land Engineering Construction Group Co., Ltd. and Xi'an Jiaotong University, Project No. 2021WHZ0091.

https://doi.org/10.17221/522/2021-PSE

Pranagal et al. 2017), physical and chemical properties (Herath et al. 2013, De la Rosa et al. 2014, Jeffery et al. 2015), enhance soil nutrient availability, and aggregate stability (Bayabil et al. 2015, Molnár et al. 2016). By enhancing and improving soil microbial activity, biochar also indirectly affects crop growth and development, collectively improving soil quality and fertility and ultimately improving crop yields (Cheng et al. 2017, Yao et al. 2017, Wong et al. 2019). Especially in the context of increasingly widespread biochar application, in-depth studies of biochar characteristics, application management, and evaluation of its value in large-scale agricultural production have important theoretical and practical significance for the development of sustainable agriculture (Tan et al. 2017, Yu et al. 2019). Furthermore, in the context of the diversification of biochar feedstocks, the development of production technology, and the refinement of application techniques, biochars have very heterogeneous properties differing in resources and pyrolysis conditions (Mukherjee and Zimmerman 2013). Therefore, the analysis of the impacts of individual factors no longer fully informs applications across the diverse environmental conditions of farmlands.

In recent years, the impact of biochar application on crop growth and soil properties has become a dynamic area of research focused on the obtaining of increased agricultural yields and improving degraded soils (Borchard et al. 2014, Agegnehu et al. 2016). Biochar application can improve soil properties, particularly physical properties, and increase crop production. Biochar addition to soil could alter soil microbial composition and structure and their key soil processes such as carbon mineralisation and nutrient transformation. Additionally, the wide C:N ratio of biochar may decrease soil N availability in N deficient soils, therefore reducing crop yields. Other negative aspects of biochar on soil include decreased nutrient immobilisation and accelerated resolve of native soil organic carbon (SOC) by higher soil microbial activity (Jindo et al. 2012, Dai et al. 2020). Studies have shown that biochar addition also enhances soil chemical properties, such as soil pH, cation exchange capacity (CEC), and soil total carbon (TC), ensuring nutrient retention and soil fertility (Bera et al. 2016, Giagnoni et al. 2019). Furthermore, some studies have reported inconsistent findings on the effects of biochar on soil chemical properties due to various factors, including climate, soil properties, planting systems, and biochar properties in the experimental areas (Abujabhah et al. 2016a, Ajayi and Horn 2016, Sandhu et al. 2017). This has rendered the promotion and application of biochar technology unfavourable (Verhoeven and Six 2014, Hall and Bell 2015, Vaccari et al. 2015, Zheng et al. 2017). Biochar has complex and wide-scale effects on soil chemistry, and there is still an incomplete understanding of how the biochar generated from different feedstocks and experiment conditions affect the chemical properties of different soils (Unger et al. 2011). Based on the inconsistencies in the findings from previous studies, analysing the changes in soil chemical characteristics caused by the application of biochar with different characteristics and applied under different agricultural conditions is important for identifying key drivers that have positive effects on soil chemical properties. The differences in biochar properties and application rates, soil fertility, soil texture, climatic conditions, and experimental setup and duration could limit comparison between different studies and extrapolation of results to other conditions. Despite the numerous studies on biochar-soil interaction, there is still uncertainty on how biochar modifies soil chemical properties. Hence, developing a comprehensive biochar application policy based on experimental conditions is essential.

A meta-analysis is a statistical analysis that collates and combines data from existing research on a given subject matter (Jeffery et al. 2016, Omondi et al. 2016, Gurevitch et al. 2018, Jiang et al. 2019). This method has been applied to quantitatively analyse the effects of biochar on crop yield increases (Zhang et al. 2019), soil water properties (Omondi et al. 2016, Edeh et al. 2020, Razzaghi et al. 2020), plant uptake of heavy metals (Chen et al. 2018), and soil greenhouse gas emissions (Jeffery et al. 2016, Borchard et al. 2019, Liu et al. 2019b). In these studies, biochar parameters ((a) production conditions: feedstock and pyrolysis temperature; (b) properties: pH, CEC, and C:N ratio, and (c) application rates), soil conditions (texture, pH, SOC, C:N ratio, and CEC), tested plant types, and experimental types (pot or field) were the important factors. A few meta-analysis studies have been conducted on the effects of biochar on soil chemical properties, and no study has comprehensively examined the influence of experimental conditions on soil chemical properties.

To fill this knowledge gap, we conducted a meta-analysis to compare the effects of different management conditions (experiment duration, type of crop, and biochar application rate), soil properties (soil

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texture and initial soil pH), pyrolysis conditions (feedstock and pyrolysis temperature), and biochar properties (biochar pH, carbon, nitrogen, oxygen, hydrogen, and C:N ratio of biochar) on soil chemical properties in order to provide a scientific basis for the selective application of biochar. In addition, this study aimed to determine the long-term effects of biochar on the improvement of soil environments.

MATERIAL AND METHODS

Data collection. The ISI Web of Science, Science Direct, and Google Scholar databases were searched for reports on the effects of biochar addition to agricultural soils on soil chemical properties published before May 2022. The keywords used for the literature search were biochar and soil chemical properties and/or soil pH and/or electrical conductivity (EC) and/or cation exchange capacity and/or soil organic carbon and/or soil total carbon and/or soil carbon-nitrogen ratio (C:N ratio). We only included studies that compared the changes between control (i.e., without biochar) and biochar-amended soils to form the literature database used for this meta-analysis. The information or data retrieved from the published articles included the measured soil chemical properties mentioned above, management conditions (cropping system, experiment duration, and biochar application rate), soil properties (soil texture and soil pH), pyrolysis conditions (feedstock and pyrolysis temperature) and biochar properties (biochar pH, carbon, nitrogen, oxygen, hydrogen, and C:N ratio of biochar). Ultimately, 682 comparisons with soil pH data, 326 comparisons with soil EC data, 208 comparisons with soil CEC data, 293 comparisons with SOC, 269 comparisons with total carbon, and 142 comparisons with the C:N ratio of soil were obtained from 138 previously published studies. The studies included in our dataset were from the continents of Asia, Europe, America, Africa, and Australia (Figure 1).

Data categorisation and treatment. For each of the investigated soil chemical properties, mean effect sizes were also compared when data were pooled into different categories according to management conditions, soil properties, pyrolysis conditions and biochar properties. For the meta-analysis, the duration of the experiment (the time since biochar was applied) was categorised into four levels (< 3 months, or 3–6 months, or 6–12 months, or > 12 months). Biochar application rates were grouped into low (≤ 20 t/ha), medium (21–40 t/ha), high (41–80 t/ha), and very high (> 80 t/ha) application rates (Omondi et al. 2016). Soil acidity was categorised into three different levels (acidic soil with pH ≤ 6.5, neutral soil with pH values from 6.5 to 7.5, and alkaline soil with pH > 7.5). Soil texture was classified according to the USDA Soil Classification System into fine (clay, clay loam, silty clay loam, and silty clay), medium (loam, silt loam, and silt), and coarse (sandy loam,

Figure 1. Locations of studies included in our meta-analysis

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sandy clay loam, loamy sand, and sand) texture classes (Cayuela et al. 2017). Biochar was categorised based on feedstock as crop residue biochar, wood biochar, manure biochar, and sludge biochar. Biochar pyrolysis temperatures were grouped into four categories (≤ 400 °C, 401–500 °C, 501–600 °C, and > 600 °C). Furthermore, studies were grouped according to biochar acidity at pH < 6.0, pH 6.0–8.0, and pH > 8.0; biochar carbon of < 50, 50–75, and > 75%; biochar nitrogen of < 0.5, 0.5–1, and > 1%; biochar oxygen < 10, 10–20, and > 20%; biochar hydrogen of ≤ 3 and > 3; and C:N of biochar at < 30, 30 ≤ 50, 50 ≤ 100, 100 ≤ 500 and > 500 (Cayuela et al. 2014, Gao et al. 2019). The soil pH values measured with $CaCl_2$ were converted to values measured in distilled water using a method described by Minasny et al. (2011).

Data calculations and statistical analyses. For each standard pair-wise comparison (control and biochar treatment), the standardised mean difference Hedges'*d* (Hedges and Olkin 1985, Hedges et al. 1999) was calculated between the control and biochar treatment group to determine the effect size metric. The mean effect sizes for each grouping and 95% bootstrap confidence interval (CI) were calculated using Stata 15 software (Stata, College Station, USA) with Hedges-Olkin random-effects models (Adams et al. 1997). The effect size was considered to be significant if the 95% CI did not overlap zero. While the magnitude of the mean effect *d* is difficult to interpret, Cohen's benchmark gives a rough estimation with mean effect sizes of $d > 0.8$ indicating a large effect, $0.2 < d < 0.8$ a moderate effect, and $0 < d < 0.2$ a small effect (Arft et al. 1999, Fedrowitz et al. 2014). Rosenthal's fail-safe number method was used to test the publication bias (Li et al. 2019). A Pearson correlation analysis was used to explore the relationship among the effect sizes of soil chemical properties and environmental variables using the R package "corrplot." An aggregated boosted tree (ABT) analysis was carried out using the "dismo" package in R (Hijmans et al. 2017) to quantitatively and visually evaluate the relative effect of treatment effects on soil chemical properties.

RESULTS

The overall effect of biochar on soil chemical properties. Averaged across the entire dataset, the addition of biochar significantly increased all soil chemical properties (e.g., soil pH, EC, CEC, SOC, TC, and C:N ratio of soil) that were considered in our analysis (Figure 2). When separating the dataset into different categories, we observed that biochar significantly increased soil pH, SOC, and C:N ratio in all of the investigated variable groups, except for the soil pH and SOC in the oxygen content of the biochar variable (Figure 3, Table 1). Moreover, type of crop, sand, silt, clay content, initial soil pH, feedstock materials, pyrolysis temperature, carbon, nitrogen, the hydrogen content of biochar, and the C:N ratio of biochar had positive effects on soil EC in the biochar addition treatments (Figure 3, Table 1). The experimental duration and carbon of biochar had a positive effect on soil CEC in the biochar addition treatments (Figure 3, Table 1).

Impacts of management conditions on the effects of biochar addition. Soil pH, SOC, and CEC showed the strongest responses to biochar application in experiments lasting 3–6 months. Meanwhile, experiments lasting < 3 months, 6–12 months and > 12 months produced the most significant effect on soil TC, EC, and C:N ratio, respectively (Figure 4). Soil pH, SOC, and the C:N ratio showed consistent positive responses to horticulture, maize, and rice, while soil EC, CEC, and TC had the highest responses to maize, perennials, and rice, respectively (Figure 4). On average, biochar effects on soil pH, SOC, TC, and C:N ratio were significant when its application

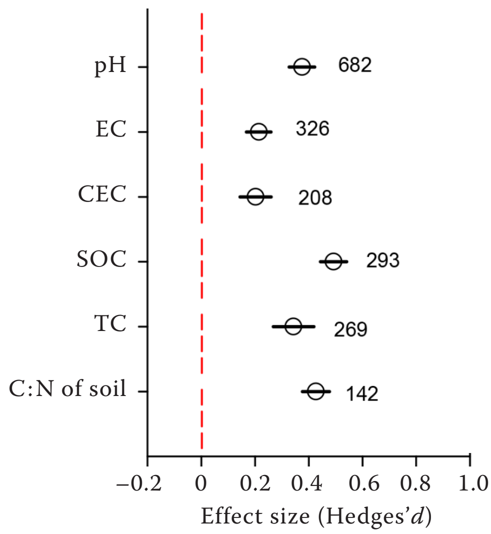

Figure 2. Total effect of biochar on soil pH, electrical conductivity (EC), cation exchange capacity (CEC), soil organic carbon (SOC), soil total carbon (TC) and soil carbon nitrogen ratio (C:N ratio). The effect size was considered statistically significant if the 95% bootstrap confidence interval (CI) did not include zero. The numbers next to the bars are sample sizes for each variable

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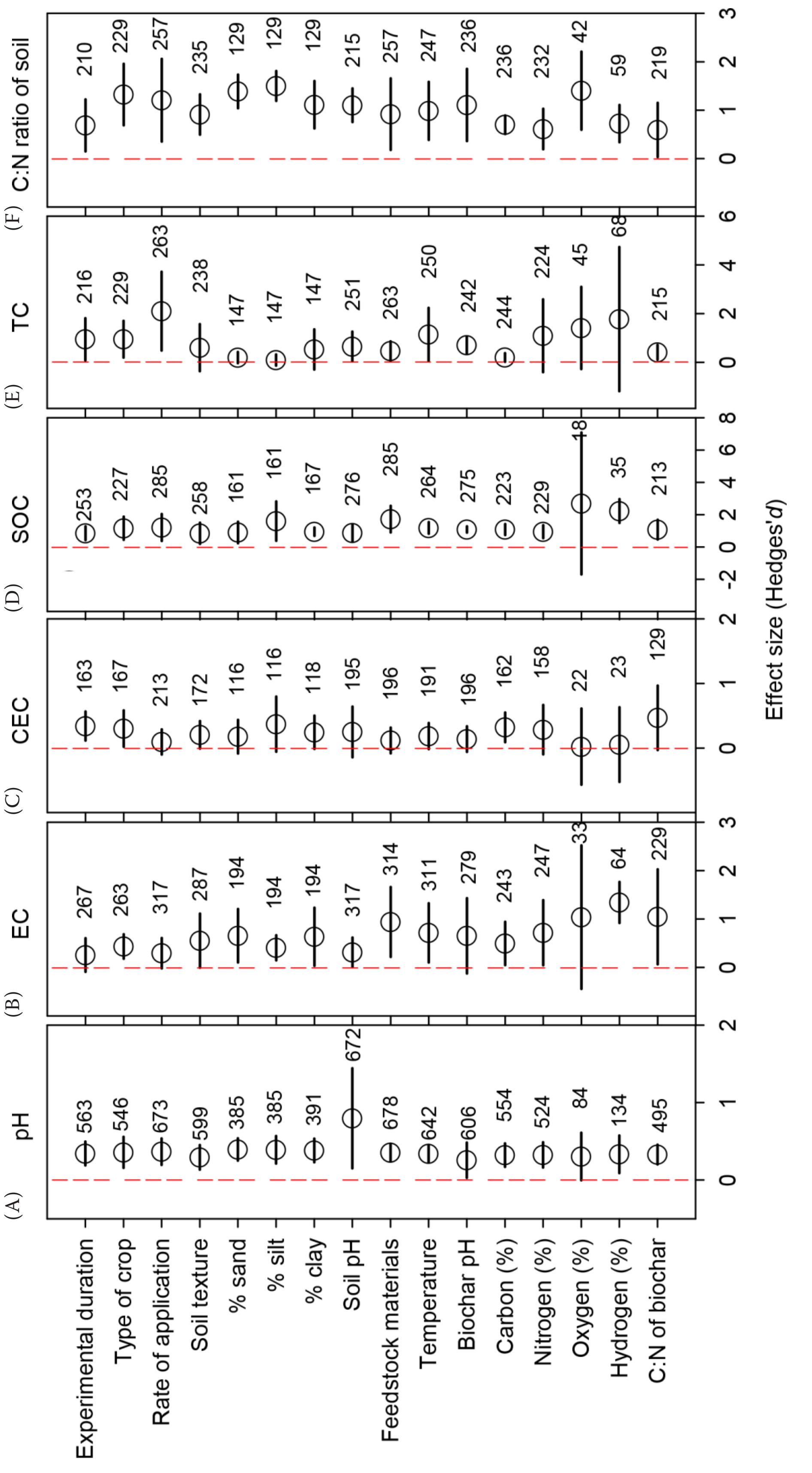

Figure 3. Total effect of biochar on soil chemical properties (A) soil pH; (B) electrical conductivity (EC); (C) cation exchange capacity (CEC); (D) soil organic carbon (SOC); (E) soil total carbon (TC), and (F) soil carbon nitrogen ratio (C:N ratio) of soil to biochar addition in agriculture soil under different conditions. The effect size was considered statistically significant if the 95% bootstrap confidence interval (CI) did not include zero. The numbers next to the bars are sample sizes for each variable

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Table 1. Summary of the effect size Hedges'*d* of soil chemical properties under different conditions

Variable	pH	EC	CEC	SOC	TC	C:N ratio
Experimental duration	**0.38** (0.19–0.56)	0.13 (–0.04–0.30)	**0.31** (0.08–0.53)	**0.46** (0.29–0.64)	**0.42** (0.23–0.62)	**0.44** (0.19–0.69)
Type of crop	**0.35** (0.16–0.53)	**0.27** (0.10–0.44)	**0.26** (0.03–0.49)	**0.50** (0.31–0.69)	**0.26** (0.07–0.46)	**0.53** (0.31–0.74)
Rate of application	**0.41** (0.22–0.61)	0.15 (–0.01–0.30)	0.08 (–0.1–0.27)	**0.49** (0.28–0.69)	0.51 (–0.0–1.07)	**0.36** (0.19–0.54)
Soil texture	**0.31** (0.15–0.47)	**0.19** (0.02–0.35)	0.19 (–0.0–0.40)	**0.47** (0.30–0.65)	0.37 (–0.1–0.90)	**0.37** (0.07–0.68)
Sand (%)	**0.41** (0.27–0.55)	**0.27** (0.07–0.47)	0.17 (–0.0–0.43)	**0.48** (0.26–0.71)	0.17 (–0.0–0.40)	**0.45** (0.21–0.70)
Silt (%)	**0.41** (0.23–0.58)	**0.30** (0.10–0.50)	0.29 (–0.0–0.59)	**0.56** (0.25–0.87)	0.09 (–0.1–0.32)	**0.45** (0.20–0.70)
Clay (%)	**0.39** (0.23–0.55)	**0.25** (0.05–0.45)	0.23 (–0.0–0.49)	**0.49** (0.27–0.70)	0.23 (–0.0–0.50)	**0.36** (0.11–0.60)
Initial soil pH	**0.60** (0.11–1.08)	**0.17** (0.02–0.33)	0.12 (–0.0–0.32)	**0.46** (0.30–0.63)	**0.46** (0.10–0.82)	**0.47** (0.28–0.66)
Feedstock materials	**0.36** (0.23–0.50)	**0.14** (–0.02–0.30)	0.10 (–0.1–0.30)	**0.48** (0.31–0.64)	**0.39** (0.06–0.71)	**0.33** (0.16–0.50)
Temperature	**0.37** (0.25–0.48)	**0.25** (0.09–0.41)	0.17 (–0.0–0.37)	**0.50** (0.33–0.68)	**0.31** (0.08–0.54)	**0.44** (0.22–0.66)
Biochar pH	**0.27** (0.01–0.52)	0.16 (–0.01–0.32)	0.12 (–0.0–0.32)	**0.50** (0.33–0.67)	**0.53** (0.26–0.80)	**0.60** (0.27–0.94)
Carbon (%)	**0.35** (0.18–0.52)	**0.25** (0.08–0.43)	**0.28** (0.06–0.51)	**0.52** (0.33–0.71)	**0.19** (0.01–0.37)	**0.45** (0.26–0.64)
Nitrogen (%)	**0.37** (0.17–0.57)	**0.30** (0.04–0.55)	0.27 (–0.0–0.61)	**0.49** (0.30–0.67)	0.37 (–0.1–0.85)	**0.42** (0.20–0.64)
Oxygen (%)	0.31 (–0.01–0.62)	0.37 (–0.12–0.86)	0.07 (–0.5–0.69)	0.86 (0.00–1.72)	**0.64** (0.22–1.07)	**0.45** (0.02–0.89)
Hydrogen (%)	**0.36** (0.12–0.60)	**0.35** (0.00–0.70)	0.05 (–0.5–0.63)	**0.64** (0.14–1.14)	0.90 (–0.3–2.14)	**0.44** (0.07–0.80)
C:N of biochar	**0.36** (0.23–0.49)	**0.44** (0.030–0.85)	0.45 (–0.0–0.91)	**0.51** (0.31–0.71)	**0.32** (0.12–0.51)	**0.38** (0.03–0.73)
Overall	**0.39** (0.33–0.42)	**0.21** (0.17–0.26)	**0.20** (0.14–0.26)	**0.50** (0.44–0.54)	**0.35** (0.27–0.42)	**0.44** (0.38–0.48)

Bold numbers represented significant changes when the 95% confidence interval of the effect size did not overlap with zero. pH – soil pH; EC – electrical conductivity; CEC – cation exchange capacity; SOC – soil organic carbon; TC – soil total carbon; C:N ratio – soil carbon nitrogen ratio

rate was higher than 40 t/ha, while its effects on soil EC were higher when the rate was between 21 and 40 t/ha. However, the effects on soil CEC were not significant at any of the application rates (Figure 4).

Impacts of soil properties on the effects of biochar addition. In general, treatment effects on soil pH, EC, SOC, TC, and the C:N ratio increased with soil texture and initial soil pH. The effect size of SOC, TC, and the C:N ratio was generally greater in medium texture soil than in soil with other textures, while soil pH and CEC had the highest responses to coarse texture. In contrast soil, EC had the highest response to fine texture soils (Figure 5). On average, soil pH, CEC, SOC, TC, and the C:N ratio showed consistently positive responses to biochar amendment at a lower initial soil pH (acidic), whereas soil EC showed a positive response when the initial soil pH was alkaline (Figure 5).

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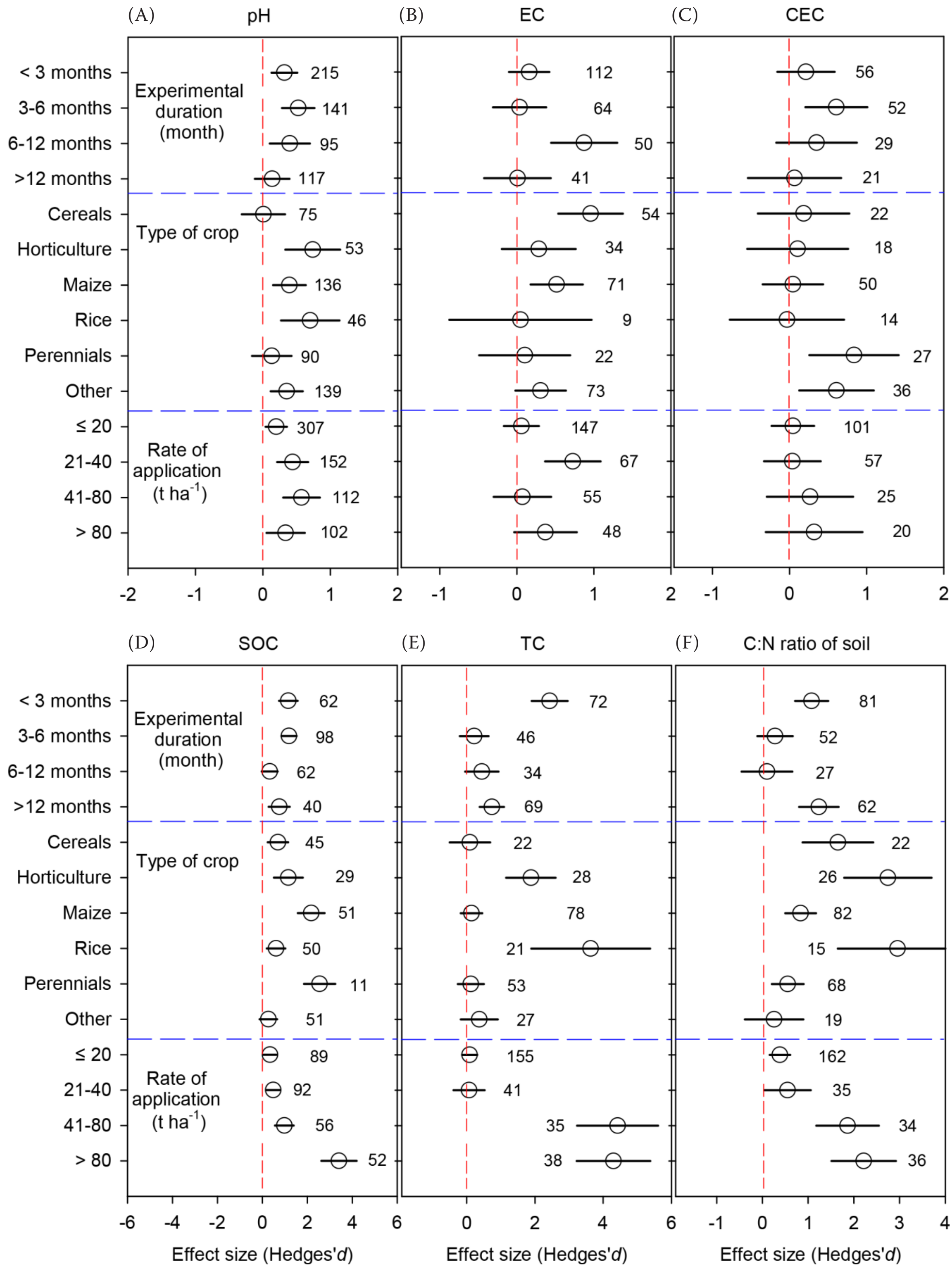

Figure 4. Effect size Hedges'*d* for the soil chemical properties (A) soil pH; (B) electrical conductivity (EC); (C) cation exchange capacity (CEC); (D) soil organic carbon (SOC); (E) soil total carbon (TC), and (F) soil carbon nitrogen ratio (C:N ratio) of soil under different management conditions (experiment duration, type of crop, and biochar application rate). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero. The numbers next to the bars are sample sizes for each variable

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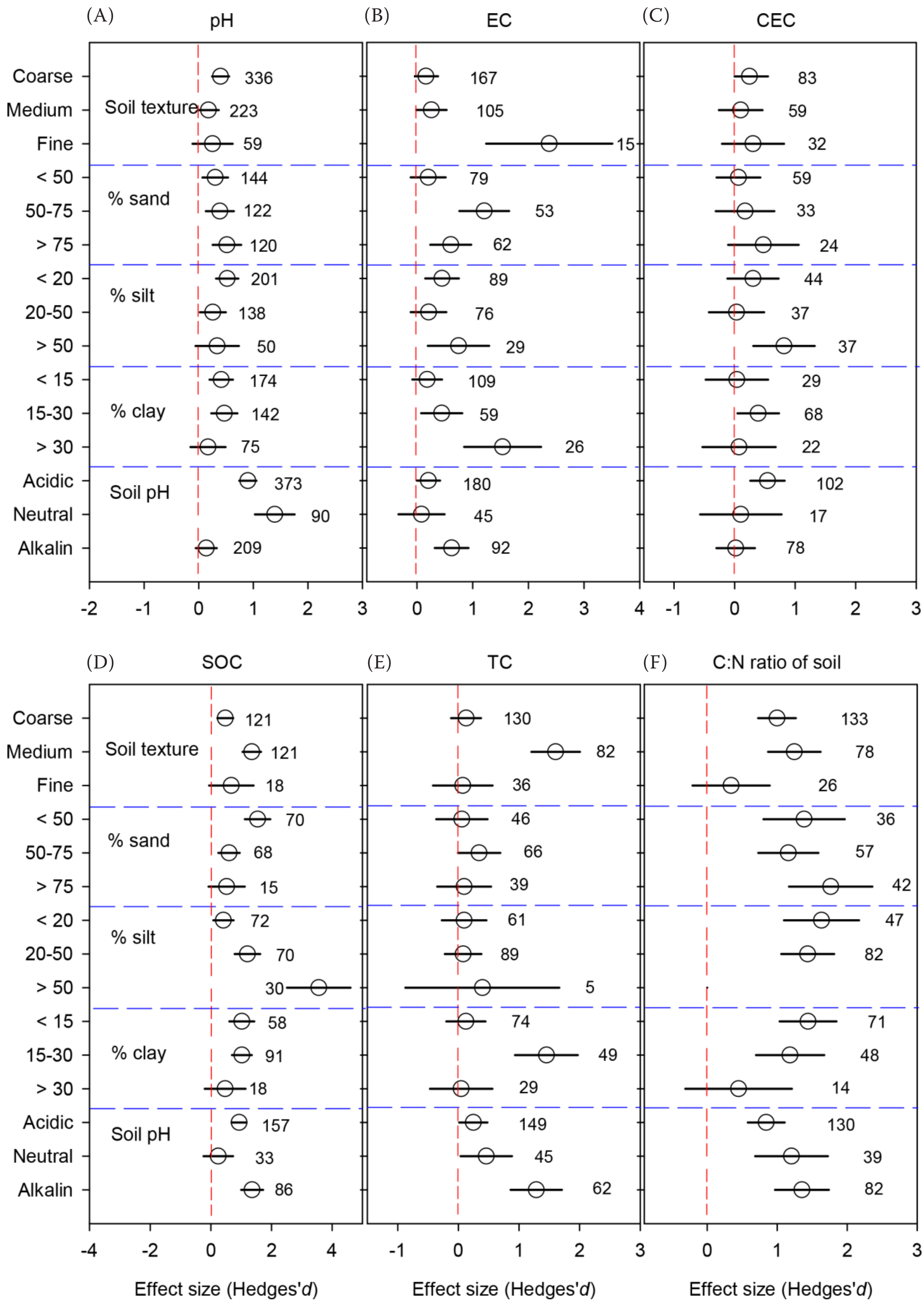

Figure 5. Effect size Hedges'*d* for the soil chemical properties (A) soil pH; (B) electrical conductivity (EC); (C) cation exchange capacity (CEC); (D) soil organic carbon (SOC); (E) soil total carbon (TC), and (F) soil carbon nitrogen ratio (C:N ratio) under different soil properties (soil texture and initial soil pH). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero. The numbers next to the bars are sample sizes for each variable

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Impacts of biochar pyrolysis conditions on the effects of biochar application. Biochar from different feedstocks significantly effects on soil chemical properties. Wood biochar and manure biochar produced the strongest effects on soil pH and EC, respectively, while sewage sludge biochar had the most significant effect on SOC, TC, and C:N ratio (Figure 6). Overall, the effects on soil pH, SOC, and the C:N ratio were generally positive regardless of all the biochar pyrolysis temperatures. The highest effects on TC and soil EC were observed at when biochar pyrolysis temperatures were ≤ 400 °C and 401–500 °C, respectively. Meanwhile, biochar pyrolysis temperature of 501–600 °C generated the strongest effects for SOC and the soil C:N ratio (Figure 6).

Impacts of biochar properties on the effects of biochar application. A biochar pH value > 8.0, carbon content > 50%, nitrogen content > 0.5%, hydrogen content < 3%, and C:N ratio < 30, significantly increased the soil pH, respectively (Figure 7A). The magnitude of increase in soil EC was significant when biochar pH was 6.0–8.0, carbon content was < 75%, nitrogen was > 0.5%, oxygen was 10–20%, all hydrogen content conditions, and the C:N ratio of biochar was < 30 and between 50–100 (Figure 7B). In comparison, soil CEC was not noticeably affected by biochar properties, with the exception of the carbon content of biochar between 50–75%, nitrogen > 1%, and the C:N ratio of biochar 30–50 and > 500 (Figure 7C). The effect of biochar application on SOC was significantly positive under all biochar pH, carbon, nitrogen, oxygen (except for 10–20%), hydrogen, and C:N ratios (except for > 500) (Figure 7D). The effect of biochar application on TC was significantly positive when the biochar pH value was higher than 6.0, nitrogen was between 0.5–1%, all oxygen and hydrogen content groups, and the biochar C:N ratio was > 30 (Figure 7E). The biochar pH, carbon, nitrogen (except for > 1%), oxygen, hydrogen, and biochar C:N ratio (except for > 50) exhibited an overall effect on the soil C:N ratio (Figure 7F).

Correlation analysis among mean effect sizes of differences in soil chemical properties. Significant positive correlations were found among any two effect sizes of soil pH, TC, and SOC (Figure 8). A significant positive correlation was also found between effect sizes of TC and the soil C:N ratio, as well as the effect sizes of soil pH and CEC. The effect sizes of the soil C:N ratio was negatively related to EC (Figure 8). However, there were no significant relationships between any two effect sizes of TC, EC, and CEC. In addition, no significant relationships were found for the soil C:N ratio with soil pH and SOC (Figure 8).

Key drivers of changes in soil chemical properties. We conducted an aggregated boosted tree (ABT) analysis to compare the relative importance of management conditions, soil properties, biochar pyrolysis conditions, and biochar properties on the soil chemical properties. Overall, 71.6–81.6% of the variance in soil pH, EC, CEC, SOC, TC, and the C:N ratio could be explained by the first four factors that were different for each soil chemical property (Figure 9). Moreover, the initial soil pH (31.6%), biochar application rate (27.0%), and biochar pH (12.1%) were important in explaining the variation of soil pH (Figure 9A); the biochar application rate (25.5%), soil pH (16.4%), biochar pH (15.4%), and biochar carbon (14.0%) were important for soil EC (Figure 9B); the sand content (31.6%), silt content (15.7%), and experimental duration (15.5%) were important for soil CEC (Figure 9C); the initial soil pH (26.2%), pyrolysis temperature (19.3%), biochar application rate (19.0%), and biochar carbon (14.2%) were important for SOC (Figure 9D); the biochar application rate (48.0%) and biochar carbon (15.4%) were important for TC (Figure 9E); and the biochar application rate (36.3%) and biochar carbon (26.2%) were also important for the C:N ratio of soil (Figure 9F). Together, these results suggest that the biochar application rate, initial soil pH, and sand content in the soil were the major drivers of the change in soil chemical properties in biochar amended soils.

DISCUSSIONS

In this meta-analysis that used data from published experiments conducted worldwide, we found that biochar amendment can significantly improve soil chemical properties, and biochar addition can increase pH, EC, CEC, SOC, TC, and the C:N ratio of agricultural soil (Figure 2 and Table 1). Moreover, when biochar was added to soils, the soil chemical properties changed in a way that was related to experimental conditions, soil properties, pyrolysis conditions, and biochar properties (Figure 3).

Effects of biochar on soil pH. Soil pH is an important indicator of soil properties, and it has a great influence on soil fertility and crop growth (Šimek and Cooper 2002). Our meta-analysis showed that the use of biochar as a soil amendment significantly (P < 0.01) increased soil pH (Figure 2, Table 1), depending on experimental duration, soil texture, initial soil

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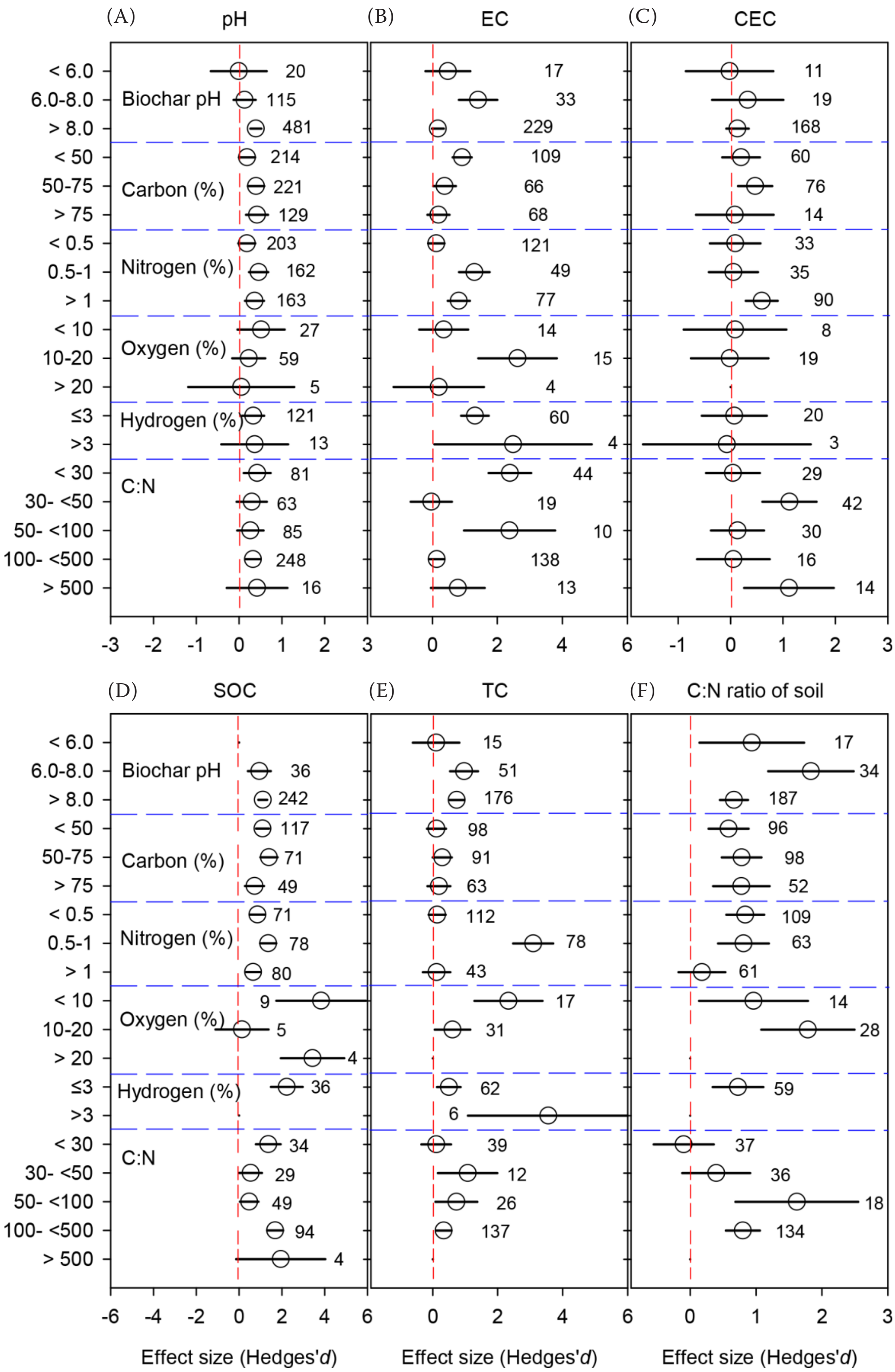

Figure 6. Effect size Hedges'*d* for the soil chemical properties (A) soil pH; (B) electrical conductivity (EC); (C) cation exchange capacity (CEC); (D) soil organic carbon (SOC); (E) soil total carbon (TC), and (F) soil carbon nitrogen ratio (C:N ratio) to biochar addition in agriculture soil under different pyrolysis conditions (feedstock and pyrolysis temperature). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero. The numbers next to the bars are sample sizes for each variable

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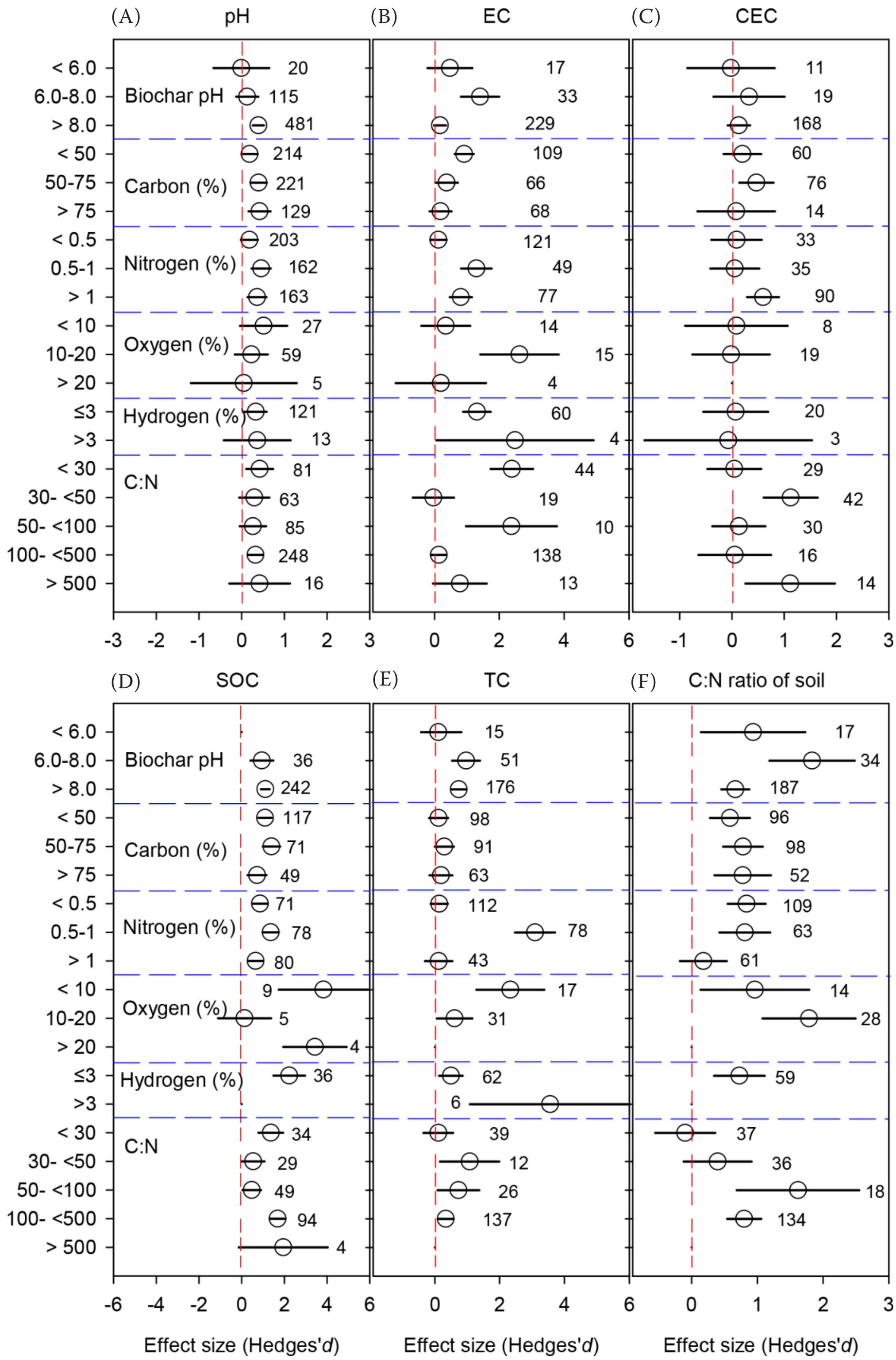

Figure 7. Effect size Hedges'*d* for the soil chemical properties (A) soil pH; (B) electrical conductivity (EC); (C) cation exchange capacity (CEC); (D) soil organic carbon (SOC); (E) soil total carbon (TC), and (F) soil carbon nitrogen ratio (C:N ratio) to biochar addition in agriculture soil under different biochar properties (biochar pH, carbon, nitrogen, oxygen, hydrogen, and C:N ratio of biochar). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero. The numbers next to the bars are sample sizes for each variable

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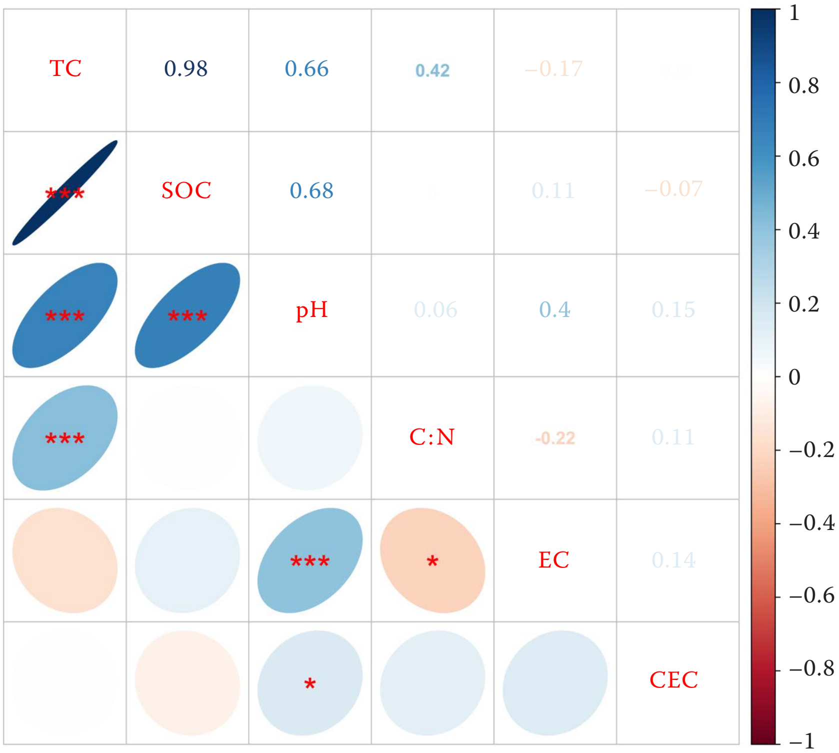

Figure 8. Coefficients and *P*-values of the correlations among mean effect sizes of soil pH, electrical conductivity (EC), cation exchange capacity (CEC), soil organic carbon (SOC), soil total carbon (TC) and soil carbon nitrogen ratio (C:N ratio) measurements for the tested studies. Asterisks highlight significant *P*-values (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$)

pH, biochar pyrolysis conditions, biochar pH, or the biochar application rate (Figure 3, Figures 4A–7A). Biochar pH depends on feedstock materials and pyrolysis conditions and determines its effect on soil pH (Lehmann and Joseph 2009, Shaaban et al. 2018). In general, biochar pH ranges from 5.9 to 12.3, with an average of 8.9 (Ahmad et al. 2014). The potential of biochar ameliorating soil acidity is related to its alkalinity (Shaaban et al. 2018) and application rate (Purakayastha et al. 2019). Biochar generally has a higher pH than the soil to which it was applied (Liang et al. 2016, El-Naggar et al. 2019); thus, as the application rate increases, the soil pH also increases (Molnár et al. 2016, Laird et al. 2017). This is likely because calcium, magnesium, potassium, and sodium base ions exist in biochar in the form of oxides and soluble carbonates, which dissolve in water and become alkaline, thus neutralising soil acidity (Tan et al. 2017). Moreover, the initial soil pH is important in determining the effect of biochar on soil pH.

Due to biochar's alkaline nature, acidic soils responded better to biochar applications compared to neutral and alkaline soils (Farhangi-Abriz et al. 2021). Since various biochar field trials are performed on acidic soils, applying an acid-neutralising material such as biochar is the most effective practice to increase yield and nutrient availability in such soils. Moreover, applying acidic biochar to alkaline soils may improve soil pH, while neutral biochar might decrease the soil pH of alkaline soils (Hailegnaw et al. 2019). Because most biochars are alkaline, limited information is available on biochar application to alkaline soils (Yu et al. 2019). Therefore, the effects of soil pH changes on plant growth in alkaline soils caused by biochar application need to be examined. Furthermore, it should be noted that the effect of biochar on improving soil pH progressively diminishes as time passes (Molnár et al. 2016). Within 12 months, biochar application increases soil pH, yet after more than 12 months, the effect on soil pH is not significant (Figure 4). Oxidation and leaching processes may reduce the biochar effects and pH with time. This was demonstrated by Slavich et al. (2013) in a study showing decreasing effects of biochar made from animal manure over a few cropping seasons. As the effect of biochar on improving soil pH will weaken over time, the application period of biochar should be considered when using biochar to improve acidic soil.

Effects of biochar on soil EC and CEC. Soil soluble salt is directly proportional to EC, so changes in soil soluble salt can be inferred from changes in the EC value of soil solutions (Corwin and Lesch 2005). When biochar is applied, the soil EC value significantly in-

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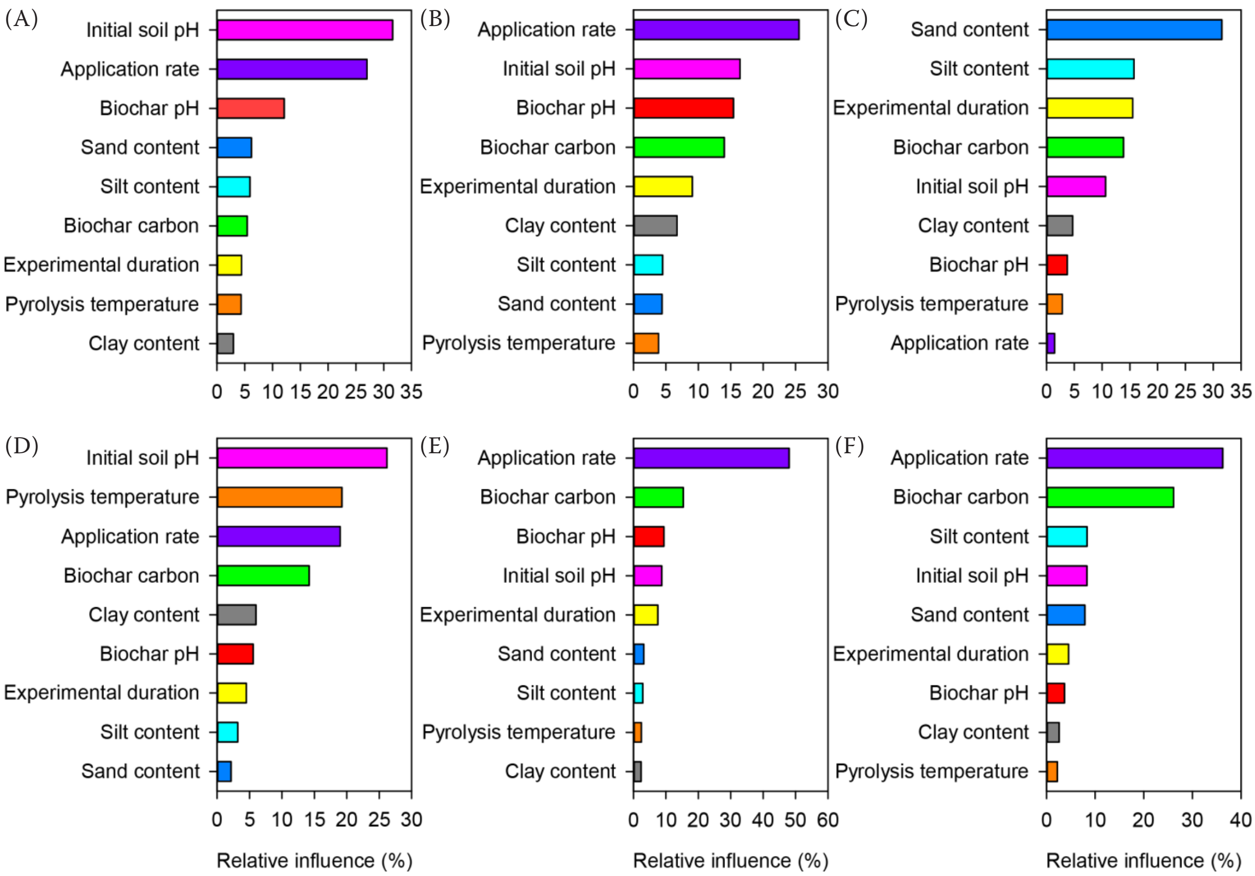

Figure 9. The relative influence of experimental condition, soil properties, biochar pyrolysis condition and biochar properties factors on the soil chemical properties ((A) soil pH; (B) electrical conductivity (EC); (C) cation exchange capacity (CEC); (D) soil organic carbon (SOC); (E) soil total carbon (TC), and (F) soil carbon nitrogen ratio (C:N ratio)) based on aggregated boosted tree model by analysis using the "dismo" package of R 4.0.2

creases (Table 1, Figure 3), which may be caused by the soluble ash it contains, thus improving the soil base saturation (Liang et al. 2006). Our results indicated that the biochar application rate (25.5%) is important in explaining the variation of EC (Figure 9B). The biochar made from different raw materials exhibits different EC, between 0.4 and 3.2, which is higher than soil's. However, some studies showed that soil EC was negatively correlated (Alotaibi and Schoenau 2016) or not correlated (Abujabhah et al. 2016b) with the amount of biochar applied. This is mainly because biochar increases the soil porosity and increases the leaching of water-soluble nutrient ions to the deep soil, and thus reduces the content of soluble ions in the soil.

CEC is used to estimate the ability of soil to adsorb, retain, and exchange cations and is, therefore, an important indicator of soil quality. A higher CEC indicates a high nutrient fixation capacity, which is beneficial for plant growth. When in contact with the soil, the active groups on the biochar surface, such as -COOH or -OH, react with metal cations in the soil and form metal ion complexes, resulting in electrostatic adsorption (Tan et al. 2017). These functional groups are negatively charged; thus, biochar has a high CEC, which increases soil CEC (Figure 2). Tan et al. (2017) indicated that soil CEC increased by 0.92 cmol/kg when the biochar addition ratio was 1:100 and continues to increase with biochar addition compared to the no biochar addition soil. However, the effect of biochar on soil CEC is related to biochar feedstock materials, biochar production conditions, and soil type (Figure 3C). The probable mechanisms have been extensively discussed (Liang et al. 2006, Lehmann and Joseph 2009, Hagner et al. 2016, Shaaban et al. 2018). Our meta-analysis indicated that biochar significantly improves the CEC of low CEC and acidic soils, but has no significant

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effect on CEC for alkaline soils with high CEC or soils with high organic matter content (Figure 5C). This may be because biochar is rich in functional groups, it has a high adsorption capacity and can absorb mineral elements (Lehmann and Joseph 2009, Ahmad et al. 2014, Laghari et al. 2015).

It should be noted that biochar can increase soil CEC, particularly in sandy-textured soils (Figure 9). In addition, the duration of biochar application and type of crop also affects the effect of biochar on soil CEC. It is acknowledged that a positive correlation between soil clay content and CEC exists (Ersahin et al. 2006, Gao et al. 2021). With biochar amendment, the CEC of coarse soils increased compared to non-coarse textured soils (Figure 5C). This may be due to the loose structure of sandy soil, which makes it easy for biomass charcoal to pass. Therefore, the abundant functional groups on biochar surfaces and their larger surface areas can be used to increase soil cation exchange capacity, absorb more nutrient ions, avoid nutrient loss, and effectively improve soil fertility and fertiliser utilisation efficiency. Consistently, Burrell et al. (2016) and Razzaghi et al. (2020) showed in their experimental and statistical data models that coarse-textured soils could be improved structurally by biochar application. The CEC of agricultural soils gives an overall idea of their fertility status and water holding capacity (Obalum et al. 2013), thus, low-CEC soils lose nutrient ions with rainfall or irrigation water due to its weak adsorption capacity (Gregory and Nortcliff 2013).

Effects of biochar on SOC, TC, and the C:N ratio. Our results indicated that the effect of biochar on SOC, TC, and the C:N ratio of soil depended on soil pH, biochar properties, application amounts, experimental duration, and type of crop (Table 1, Figure 3). Several other studies have confirmed an increase in soil carbon and the C:N ratio by the addition of biochar (Agegnehu et al. 2017, Tan et al. 2017, Shaaban et al. 2018). Moreover, our study indicated that soil pH is important for explaining the variation of SOC (26.2%), whereas the biochar application rate is important for explaining the variation of soil TC (48.0%) or the C:N ratio (36.3%) (Figure 9).

SOC, the main energy source and key trigger for nutrient availability, is a major soil factor affecting plant growth. Its formation is a long-term process involving soil retention of exogenous organic materials, affected by climate, management practices, and soil properties. Biochar has high chemical and microbiological stability in soils due to its high carbon content, complex aromatised structure, and inherent chemical inertness. Therefore, it may change the composition of soil organic matter to increase the total SOC content. Applying biochar with a high C:N ratio results in microbial nitrogen immobilisation and carbon substrate input in soil (Kirkby et al. 2014); therefore, decreased soil microbial activities due to the high biochar C:N ratio would reduce soil greenhouse gas fluxes and increase SOC (Cleveland and Liptzin 2007, Kirkby et al. 2014). Biochar with moderate alkalinity would enhance SOC mineralisation, while that with extremely high or low pH values would cause macronutrient deficiencies. Applying biochar in acidic soils enhances its consumption by microorganisms for balanced soil pH conditions, which may trigger a vigorous priming effect on native SOC mineralisation (Foereid et al. 2011, Jones et al. 2011). Otherwise, adding biochar to neutral or alkaline soils would inhibit soil carbon mineralisation due to enhanced soil pH (Liu et al. 2019a).

Our study showed that the biochar application is the most influential variable of biochar effect on SOC among all variables. Biochar comprises highly concentrated aromatic ring structures, with hydroxyl, carboxyl, carbonyl groups, and lactone structures on their surfaces, thereby increasing soil carbon content (Lyu et al. 2018, Faloye et al. 2019). Moreover, the porous biochar structure can increase the stability of soil organic carbon against biodegradation, thereby reducing its mineralisation rate (Liu et al. 2019b). Due to abundant surface morphological structures, biochar can adsorb soil carbon onto its outer surfaces, reducing the availability of soil organic carbon and inhibiting the degradation of adsorbed carbon, thus indirectly increasing the carbon content of soil (Hartley et al. 2016, Tan et al. 2017, Yu et al. 2019).

Overall, our results showed that the effect size (Hedges'd) of the biochar was greatest for SOC (0.50), the C:N ratio of soil (0.44), soil pH (0.39), TC (0.35), EC (0.21), and CEC (0.20). Among the various factors examined using the ABT analysis, 71.6–81.6% of the variance in soil pH, EC, CEC, SOC, TC, and the C:N ratio could be explained by the first four factors that were different for each soil chemical properties. In conclusion, our study suggests that improving soil chemical properties by adding biochar is affected not only by biochar application and biochar properties but also by local soil environmental factors, especially soil pH and soil texture. Improving agricultural soil properties by adding biochar requires not only

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a particular type and implementation of management practices, but also the local environmental factors that should be considered when proposing a land management plan. Furthermore, there is an urgent need for long-term agriculture studies examining changes in soil chemical properties in order to improve our understanding of the potential of applications of biochar in global agriculture and soil environments.

Acknowledgement. We would like to convey our special thanks to various authors and organisations for their various contributions to the data used in this meta-analysis review. The authors gratefully acknowledge researchers at the Shaanxi Provincial Land Engineering Construction Group, for their help with the field experiments.

REFERENCES

Abujabhah I.S., Bound S.A., Doyle R., Bowman J.P. (2016a): Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. Applied Soil Ecology, 98: 243–253.

Abujabhah I.S., Doyle R., Bound S.A., Bowman J.P. (2016b): The effect of biochar loading rates on soil fertility, soil biomass, potential nitrification, and soil community metabolic profiles in three different soils. Journal of Soils and Sediments, 16: 2211–2222.

Adams C., Soares K. (1997): The Cochrane Collaboration and the Process of Systematic Reviewing. Advances in Psychiatric Treatment, 3: 240–246.

Agegnehu G., Nelson P.N., Bird M.I. (2016): The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. Science of The Total Environment, 569–570: 869–879.

Agegnehu G., Srivastava A.K., Bird M.I. (2017): The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Applied Soil Ecology, 119: 156–170.

Ahmad M., Rajapaksha A.U., Lim J.E., Ming Z., Bolan N., Mohan D., Vithanage M., Lee S.S., Ok Y.S. (2014): Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere, 99: 19–33.

Ajayi A.E., Horn R. (2016): Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. Soil and Tillage Research, 164: 34–44.

Alotaibi K.D., Schoenau J.J. (2016): Application of two bioenergy byproducts with contrasting carbon availability to a prairie soil: three year crop response and changes in soil biological and chemical properties. Agronomy, 6: 13.

Arft A.M., Walker M.D., Gurevitch J., Alatalo J.M., Bret-Harte M.S., Dale M., Diemer M., Gugerl F., Henry G.H.R., Jones M.H., Hollister R.D., Jónsdóttir I.S., Laine K., Lévesque E., Marion G.M., Molau U., Molgaard P., Nordenhäll U., Raszhivin V., Robinson C.H., Starr G., Stenström A., Stenström M., Totland O., Turner P.L., Walker L.J., Webber P.J., Welker J.M., Wookey P.A. (1999): Responses of tundra plants to experimental warming: meta-analysis of the international tundra experiment. Ecological Monographs, 69: 491–511.

Bayabil H.K., Stoof C.R., Lehmann J.C., Yitaferu B., Steenhuis T.S. (2015): Assessing the potential of biochar and charcoal to improve soil hydraulic properties in the humid Ethiopian Highlands: the Anjeni watershed. Geoderma, 243–244: 115–123.

Bera T., Collins H.P., Alva A.K., Purakayastha T.J., Patra A.K. (2016): Biochar and manure effluent effects on soil biochemical properties under corn production. Applied Soil Ecology, 107: 360–367.

Borchard N., Schirrmann M., Cayuela M.L., Kammann C., Wrage-Mönnig N., Estavillo J.M., Fuertes-Mendizábal T., Sigua G., Spokas K., Ippolito J.A., Novak J. (2019): Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: a meta-analysis. Science of The Total Environment, 651: 2354–2364.

Borchard N., Siemens J., Ladd B., Möller A., Amelung W. (2014): Application of biochars to sandy and silty soil failed to increase maize yield under common agricultural practice. Soil and Tillage Research, 144: 184–194.

Burrell L.D., Zehetner F., Rampazzo N., Wimmer B., Soja G. (2016): Long-term effects of biochar on soil physical properties. Geoderma, 282: 96–102.

Case S.D.C., McNamara N.P., Reay D.S., Whitaker J. (2012): The effect of biochar addition on N_2O and CO_2 emissions from a sandy loam soil – the role of soil aeration. Soil Biology and Biochemistry, 51: 125–134.

Cayuela M.L., Aguilera E., Sanz-Cobena A., Adams D.C., Abalos D., Barton L., Ryals R., Silver W.L., Alfaro M.A., Pappa V.A., Smith P., Garnier J., Billen G., Bouwman L., Bondeau A., Lassaletta L. (2017): Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on a meta-analysis of available measurement data. Agriculture, Ecosystems and Environment, 238: 25–35.

Cayuela M.L., van Zwieten L., Singh B.P., Jeffery S., Roig A., Sánchez-Monedero M.A. (2014): Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agriculture, Ecosystems and Environment, 191: 5–16.

Chen D., Liu X.Y., Bian R.J., Cheng K., Zhang X.H., Zheng J.F., Joseph S., Crowley D., Pan G.X., Li L.Q. (2018): Effects of biochar on availability and plant uptake of heavy metals – a meta-analysis. Journal of Environmental Management, 222: 76–85.

Cheng J.Z., Lee X.Q., Gao W.C., Chen Y., Pan W., Tang Y. (2017): Effect of biochar on the bioavailability of difenoconazole and microbial community composition in a pesticide-contaminated soil. Applied Soil Ecology, 121: 185–192.

https://doi.org/10.17221/522/2021-PSE

Cleveland C.C., Liptzin D. (2007): C:N:P stoichiometry in soil: is there a "redfield ratio" for the microbial biomass? Biogeochemistry, 85: 235–252.

Corwin D.L., Lesch S.M. (2005): Apparent soil electrical conductivity measurements in agriculture. Computers and Electronics in Agriculture, 46: 11–43.

Dai Y.H., Zheng H., Jiang Z.X., Xing B.S. (2020): Combined effects of biochar properties and soil conditions on plant growth: a meta-analysis. Science of The Total Environment, 713: 136635.

De la Rosa J.M., Paneque M., Miller A.Z., Knicker H. (2014): Relating physical and chemical properties of four different biochars and their application rate to biomass production of *Lolium perenne* on a Calcic Cambisol during a pot experiment of 79 days. Science of The Total Environment, 499: 175–184.

Deal C., Brewer C.E., Brown R.C., Okure M.A.E., Amoding A. (2012): Comparison of kiln-derived and gasifier-derived biochars as soil amendments in the humid tropics. Biomass and Bioenergy, 37: 161–168.

Edeh I.G., Mašek O., Buss W. (2020): A meta-analysis on biochar's effects on soil water properties – new insights and future research challenges. Science of The Total Environment, 714: 136857.

El-Naggar A., Lee S.S., Rinklebe J., Farooq M., Song H., Sarmah A.K., Zimmerman A.R., Ahmad M., Shaheen S.M., Ok Y.S. (2019): Biochar application to low fertility soils: a review of current status, and future prospects. Geoderma, 337: 536–554.

Ersahin S., Gunal H., Kutlu T., Yetgin B., Coban S. (2006): Estimating specific surface area and cation exchange capacity in soils using fractal dimension of particle-size distribution. Geoderma, 136: 588–597.

Faloye O.T., Alatise M.O., Ajayi A.E., Ewulo B.S. (2019): Effects of biochar and inorganic fertilizer applications on growth, yield and water use efficiency of maize under deficit irrigation. Agricultural Water Management, 217: 165–178.

Farhangi-Abriz S., Torabian S., Qin R., Noulas C., Lu Y., Gao S. (2021): Biochar effects on yield of cereal and legume crops using meta-analysis. Science of the Total Environment, 775: 145869.

Fedrowitz K., Koricheva J., Baker S.C., Lindenmayer D.B., Palik B., Rosenvald R., Beese W., Franklin J.F., Kouki J., Macdonald E., Messier C., Sverdrup-Thygeson A., Gustafsson L. (2014): Can retention forestry help conserve biodiversity? A meta-analysis. Journal of Applied Ecology, 51: 1669–1679.

Foereid B., Lehmann J., Major J. (2011): Modeling black carbon degradation and movement in soil. Plant and Soil, 345: 223–236.

Gao S., DeLuca T.H., Cleveland C.C. (2019): Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: a meta-analysis. Science of The Total Environment, 654: 463–472.

Gao Y., Shao G.C., Yang Z., Zhang K., Lu J., Wang Z.Y., Wu S.Q., Xu D. (2021): Influences of soil and biochar properties and amount of biochar and fertilizer on the performance of biochar in improving plant photosynthetic rate: a meta-analysis. European Journal of Agronomy, 130: 126345.

Giagnoni L., Maienza A., Baronti S., Vaccari F.P., Genesio L., Taiti C., Martellini T., Scodellini R., Cincinelli A., Costa C., Mancuso S., Renella G. (2019): Long-term soil biological fertility, volatile organic compounds and chemical properties in a vineyard soil after biochar amendment. Geoderma, 344: 127–136.

Gregory P.J., Nortcliff S. (2013): Soil Conditions and Plant Growth. 1st Edition. Oxford, Blackwell Publishing Ltd. ISBN: 9781405197700

Gurevitch J., Koricheva J., Nakagawa S., Stewart G. (2018): Meta-analysis and the science of research synthesis. Nature, 555: 175–182.

Hagner M., Kemppainen R., Jauhiainen L., Tiilikkala K., Setälä H. (2016): The effects of birch (*Betula* spp.) biochar and pyrolysis temperature on soil properties and plant growth. Soil and Tillage Research, 163: 224–234.

Hailegnaw N.S., Mercl F., Pračke K., Száková J., Tlustoš P. (2019): Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. Journal of Soils and Sediments, 19: 2405–2416.

Hall D.J.M., Bell R.W. (2015): Biochar and compost increase crop yields but the effect is short term on sandplain soils of Western Australia. Pedosphere, 25: 720–728.

Hartley W., Riby P., Waterson J. (2016): Effects of three different biochars on aggregate stability, organic carbon mobility and micronutrient bioavailability. Journal of Environmental Management, 181: 770–778.

Hedges L.V., Olkin I. (1985): Statistical Methods for Meta-Analysis. New York, Academic Press.

Hedges L.V., Gurevitch J., Curtis P.S. (1999): The meta-analysis of response ratios in experimental ecology. Ecology, 80: 1150–1156.

Herath H.M.S.K., Camps-Arbestain M., Hedley M. (2013): Effect of biochar on soil physical properties in two contrasting soils: an Alfisol and an Andisol. Geoderma, 209–210: 188–197.

Hijmans R.J., Phillips S., Leathwick J., Elith J. (2017): Species distribution modelling with R. R package "Dismo". Available at: https://cran.r-project.org/web/packages/dismo/vignettes/sdm.pdf (accessed March 13, 2018)

Jeffery S., Meinders M.B.J., Stoof C.R., Bezemer T.M., van de Voorde T.F.J., Mommer L., van Groenigen J.W. (2015): Biochar application does not improve the soil hydrological function of a sandy soil. Geoderma, 251–252: 47–54.

Jeffery S., Verheijen F.G.A., Kammann C., Abalos D. (2016): Biochar effects on methane emissions from soils: a meta-analysis. Soil Biology and Biochemistry, 101: 251–258.

Jiang Y., Carrijo D., Huang S., Chen J., Balaine N., Zhang W.J., van Groenigen K.J., Linquist B. (2019): Water management to mitigate the global warming potential of rice systems: a global meta-analysis. Field Crops Research, 234: 47–54.

Jien S., Wang C. (2013): Effects of biochar on soil properties and erosion potential in a highly weathered soil. Catena, 110: 225–233.

https://doi.org/10.17221/522/2021-PSE

Jindo K., Sánchez-Monedero M.A., Hernández T., García C., Furukawa T., Matsumoto K. (2012): Biochar influences the microbial community structure during manure composting with agricultural wastes. Science of The Total Environment, 416: 476–481.

Jones D.L., Murphy D.V., Khalid M., Ahmad W., Edwards-Jones G., DeLuca T.H. (2011): Short-term biochar-induced increase in soil CO_2 release is both biotically and abiotically mediated. Soil Biology and Biochemistry, 43: 1723–1731.

Kätterer T., Roobroeck D., Andrén O., Kimutai G., Karltun E., Kirchmann H., Nyberg G., Vanlauwe B., Röing De Nowina K. (2019): Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. Field Crops Research, 235: 18–26.

Kirkby C.A., Richardson A.E., Wade L.J., Passioura J.B., Batten G.D., Blanchard C., Kirkegaard J.A. (2014): Nutrient availability limits carbon sequestration in arable soils. Soil Biology and Biochemistry, 68: 402–409.

Laghari M., Mirjat M.S., Hu Z.Q., Fazal S., Xiao B., Hu M., Chen Z., Guo D. (2015): Effects of biochar application rate on sandy desert soil properties and sorghum growth. Catena, 135: 313–320.

Laird D.A., Novak J.M., Collins H.P., Ippolito J.A., Karlen D.L., Lentz R.D., Sistani K.R., Spokas K., Van Pelt R.S. (2017): Multi-year and multi-location soil quality and crop biomass yield responses to hardwood fast pyrolysis biochar. Geoderma, 289: 46–53.

Lebrun M., Miard F., Nandillon R., Scippa G.S., Bourgerie S., Morabito D. (2019): Biochar effect associated with compost and iron to promote Pb and As soil stabilization and *Salix viminalis* L. growth. Chemosphere, 222: 810–822.

Lehmann J., Joseph S. (2009): Biochar for environmental management: an introduction. In: Lehmann J., Joseph S. (eds.): Biochar for Environmental Management Science and Technology. UK, Earthscans, 1–12. ISBN: 9780367779184

Li M.F., Wang J., Guo D., Yang R.R., Fu H. (2019): Effect of land management practices on the concentration of dissolved organic matter in soil: a meta-analysis. Geoderma, 344: 74–81.

Li X.X., Chen X.B., Weber-Siwirska M., Cao J.J., Wang Z.L. (2018): Effects of rice-husk biochar on sand-based rootzone amendment and creeping bentgrass growth. Urban Forestry and Urban Greening, 35: 165–173.

Liang B., Lehmann J., Solomon D., Kinyangi J., Grossman J., O'Neill B., Skjemstad J.O., Thies J., Luizão F.J., Petersen J., Neves E.G. (2006): Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70: 1719–1730.

Liang C.F., Gascó G., Fu S.L., Méndez A., Paz-Ferreiro J. (2016): Biochar from pruning residues as a soil amendment: effects of pyrolysis temperature and particle size. Soil and Tillage Research, 164: 3–10.

Lin Z.B., Liu Q., Liu G., Cowie A.L., Bei Q.C., Liu B.J., Wang X.J., Ma J., Zhu J.G., Xie Z.B. (2017): Effects of different biochars on *Pinus elliottii* growth, N use efficiency, soil N_2O and CH_4 emissions and C storage in a subtropical area of China. Pedosphere, 27: 248–261.

Liu C., Wang H.L., Li P.H., Xian Q.S., Tang X.G. (2019a): Biochar's impact on dissolved organic matter (DOM) export from a cropland soil during natural rainfalls. Science of The Total Environment, 650: 1988–1995.

Liu X., Mao P.N., Li L.H., Ma J. (2019b): Impact of biochar application on yield-scaled greenhouse gas intensity: a meta-analysis. Science of The Total Environment, 656: 969–976.

Lyu H.H., Gao B., He F., Zimmerman A.R., Ding C., Huang H., Tang J.C. (2018): Effects of ball milling on the physicochemical and sorptive properties of biochar: experimental observations and governing mechanisms. Environmental Pollution, 233: 54–63.

Meng J., Tao M.M., Wang L.L., Liu X.M., Xu J.M. (2018): Changes in heavy metal bioavailability and speciation from a Pb-Zn mining soil amended with biochars from co-pyrolysis of rice straw and swine manure. Science of the Total Environment, 633: 300–307.

Minasny B., McBratney A.B., Brough D.M., Jacquier D. (2011): Models relating soil pH measurements in water and calcium chloride that incorporate electrolyte concentration. European Journal of Soil Science, 62: 728–732.

Molnár M., Vaszita E., Farkas É., Ujaczki É., Fekete-Kertész I., Tolner M., Klebercz O., Kirchkeszner C., Gruiz K., Uzinger N., Feigl V. (2016): Acidic sandy soil improvement with biochar – a microcosm study. Science of The Total Environment, 563–564: 855–865.

Mukherjee A., Lal R., Zimmerman A.R. (2014): Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. Science of the Total Environment, 487: 26–36.

Mukherjee A., Zimmerman A.R. (2013): Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar-soil mixtures. Geoderma, 193–194: 122–130.

Norini M.-P., Thouin H., Miard F., Battaglia-Brunet F., Gautret P., Guégan R., Le Forestier L., Morabito D., Bourgerie S., Motelica-Heino M. (2019): Mobility of Pb, Zn, Ba, As and Cd toward soil pore water and plants (willow and ryegrass) from a mine soil amended with biochar. Journal of Environmental Management, 232: 117–130.

Obalum S.E., Watanabe Y., Igwe C.A., Obi M.E., Wakatsuki T. (2013): Improving on the prediction of cation exchange capacity for highly weathered and structurally contrasting tropical soils from their fine-earth fractions. Communications in Soil Science and Plant Analysis, 44: 1831–1848.

Omondi M.O., Xia X., Nahayo A., Liu X.Y., Korai P.K., Pan G.X. (2016): Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma, 274: 28–34.

Pandey V., Patel A., Patra D.D. (2016): Biochar ameliorates crop productivity, soil fertility, essential oil yield and aroma profiling in basil (*Ocimum basilicum* L.). Ecological Engineering, 90: 361–366.

Peake L.R., Reid B.J., Tang X.G. (2014): Quantifying the influence of biochar on the physical and hydrological properties of dissimilar soils. Geoderma, 235–236: 182–190.

https://doi.org/10.17221/522/2021-PSE

Pranagal J., Oleszczuk P., Tomaszewska-Krojańska D., Kraska P., Różyło K. (2017): Effect of biochar application on the physical properties of Haplic Podzol. Soil and Tillage Research, 174: 92–103.

Purakayastha T.J., Bera T., Bhaduri D., Sarkar B., Mandal S., Wade P., Kumari S., Biswas S., Menon M., Pathak H., Tsang D.C.W. (2019): A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: pathways to climate change mitigation and global food security. Chemosphere, 227: 345–365.

Razzaghi F., Obour P.B., Arthur E. (2020): Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma, 361: 114055.

Sandhu S.S., Ussiri D.A.N., Kumar S., Chintala R., Papiernik S.K., Malo D.D., Schumacher T.E. (2017): Analyzing the impacts of three types of biochar on soil carbon fractions and physiochemical properties in a corn-soybean rotation. Chemosphere, 184: 473–481.

Shaaban M., Van Zwieten L., Bashir S., Younas A., Núñez-Delgado A., Chhajro M.A., Kubar K.A., Ali U., Rana M.S., Mehmood M.A., Hu R.G. (2018): A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution. Journal of Environmental Management, 228: 429–440.

Šimek M., Cooper J.E. (2002): The influence of soil pH on denitrification: progress towards the understanding of this interaction over the last 50 years. European Journal of Soil Science, 53: 345–354.

Slavich P.G., Sinclair K., Morris S.G., Kimber S.W.L., Downie A., Van Zwieten L. (2013): Contrasting effects of manure and green waste biochars on the properties of an acidic ferralsol and productivity of a subtropical pasture. Plant and Soil, 366: 213–227.

Stefaniuk M., Oleszczuk P., Różyło K. (2017): Co-application of sewage sludge with biochar increases disappearance of polycyclic aromatic hydrocarbons from fertilized soil in long term field experiment. Science of The Total Environment, 599–600: 854–862.

Tan Z.X., Lin C.S.K., Ji X.Y., Rainey T.J. (2017): Returning biochar to fields: a review. Applied Soil Ecology, 116: 1–11.

Unger R., Killorn R., Brewer C.E. (2011): Effects of soil application of different biochars on selected soil chemical properties. Communications in Soil Science and Plant Analysis, 42: 2310–2321.

Vaccari F.P., Maienza A., Miglietta F., Baronti S., Di Lonardo S., Giagnoni L., Lagomarsino A., Pozzi A., Pusceddu E., Ranieri R., Valboa G., Genesio L. (2015): Biochar stimulates plant growth but not fruit yield of processing tomato in a fertile soil. Agriculture, Ecosystems and Environment, 207: 163–170.

Verhoeven E., Six J. (2014): Biochar does not mitigate field-scale N_2O emissions in a Northern California vineyard: an assessment across two years. Agriculture, Ecosystems and Environment, 191: 27–38.

Wang D.Y., Fonte S.J., Parikh S.J., Six J., Scow K.M. (2017): Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. Geoderma, 303: 110–117.

Wong J.T.F., Chen X.W., Deng W.J., Chai Y.M., Ng C.W.W., Wong M.H. (2019): Effects of biochar on bacterial communities in a newly established landfill cover topsoil. Journal of Environmental Management, 236: 667–673.

Yao Q., Liu J.J., Yu Z.H., Li Y.S., Jin J., Liu X.B., Wang G.H. (2017): Changes of bacterial community compositions after three years of biochar application in a black soil of northeast China. Applied Soil Ecology, 113: 11–21.

Yu H.W., Zou W.X., Chen J.J., Chen H., Yu Z., Huang J., Tang H.R., Wei X.Y., Gao B. (2019): Biochar amendment improves crop production in problem soils: a review. Journal of Environmental Management, 232: 8–21.

Zhang W.S., Liang Z.Y., He X.M., Wang X.Z., Shi X., Zou C., Chen X. (2019): The effects of controlled release urea on maize productivity and reactive nitrogen losses: a meta-analysis. Environmental Pollution, 246: 559–565.

Zheng J.F., Han J.M., Liu Z.W., Xia W.B., Zhang X.H., Li L.Q., Liu X.Y., Bian R.J., Cheng K., Zheng J.W., Pan G.X. (2017): Biochar compound fertilizer increases nitrogen productivity and economic benefits but decreases carbon emission of maize production. Agriculture, Ecosystems and Environment, 241: 70–78.

Received: December 16, 2021
Accepted: May 23, 2022
Published online: June 1, 2022