



Article Response of Plant Root Growth to Biochar Amendment: A Meta-Analysis

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Abstract: Biochar is widely used in agriculture to improve soil fertility and plant growth. However, a comprehensive assessment of how biochar amendment affects plant root growth is lacking. This study investigated the change in plant root biomass in response to biochar application, including impact factors such as the biochar feedstock and application rate, plant type, and soil pH. The Science Direct, Web Of Science, and Scopus databases were employed to search for literature published before 2021. The published papers with at least three replicates of biochar-amended treatments and a control at the same site were selected for meta-analysis. Our results showed that 165 (81.3%) of 203 datasets from 47 published studies indicated positive effects of biochar amendment on root growth with a mean relative increase of 32%. The feedstocks of biochar and its rate of application were the main factors that determined its effects on plant root growth. The increment of root biomass following biochar amendment was the greatest for trees (+101.6%), followed by grasses (+66.0%), vegetables (+26.9%), and cereals (+12.7%). The positive effects mainly depended on feedstock sources, with the highest positive effect (+46.2%) for gramineous, followed by woody plants (+25.8%) and green wastes (+21.1%). Linear regression analysis and SEM (Structural equation modeling) analysis showed that total nitrogen (TN) and available phosphorus (AK) are one of the most important factors affecting the increase of root biomass. These results suggest that biochar can be considered an effective amendment to improve root growth and soil fertility. Biochar feedstock sources, application rates, and plant types should be considered to assess the potential benefits of biochar for root growth and soil quality.

Keywords: biochar; root growth; soil; meta-analysis

1. Introduction

Biochar is a carbon-rich material produced by high-temperature pyrolysis (usually 300–700 °C) [1] of biological materials under anoxic conditions [2]. It is widely used in agriculture to improve soil fertility [3], repair soil polluted by heavy metals and pesticide residues [4], and improve crop yield and quality [5]. These benefits stem from its rich carbon content, well-developed pore structure, large specific surface area, richness in oxygen-containing functional groups, and a high degree of aromatization [6].

Both positive and negative effects of biochar amendment on root growth have been widely reported in pot or field experiments [7–11]. Ali et al. [12] found that it increased wheat root biomass regardless of the application level, while others have found that it has no [13] or even a negative [14] effect on root growth, as observed in soil microbial



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). and root biomass studies [15,16]. Zhu et al. [13] reported that the application of wood biochar has a positive effect on corn root biomass, while the application of bamboo leaf, tobacco stalk, and wheat straw biochars inhibit the root growth of corn seedlings [17]. In another study, the underground biomass of horse tamarind (*Leucaena leucocephala*) increased, while that of maize decreased [18]. This might be related to the different nutrient requirements of different plant species. In a previous study, the addition of biochar to the soil in a subtropical region enhanced K and P bioavailability, which in turn improved rice grain yield [19]. Bista et al. [20] reported that biochar application increased the root biomass of wheat, particularly in treatments without fertilizer. The inconsistent results (biochar has different effects on plant root growth) could be due to differences in the biochar characteristics, soil types, and plant types in individual studies. In addition, a comprehensive study analyzing the main factors that determine the effect of biochar application on root growth may be useful for guiding agricultural management.

Soil condition is the main factor that determines root growth [21]. As a soil amendment, biochar can improve soil fertility and soil quality [22–24]. Biochar can increase the content of soil organic matter (SOM) [25]. In recent years, the increase of soil organic carbon (SOC) in biochar-amended soil has been well documented [26], and the report by Sun et al., [27] has shown that compared with B0 (no biochar), the SOC content presented an 18.8% and 8.2% increase with B60 (60 Mg ha⁻¹ biochar) and B90 (90 Mg ha⁻¹ biochar) (p < 0.05), respectively. In addition, Wang et al. [28] found that biochar amendments can modify fertilizer nitrogen (N) availability in soil and crop N uptake. Biochar can also affect soil P cycling, by altering P chemical forms, changing soil P sorption and desorption capacities, and influencing the microbial population size, enzyme activities, mycorrhizal associations and microbial production of metal-chelating organic acids [29]. Yan et al. [23] found that the available soil K increased with biochar application, and increased further on increasing the rate of biochar application. Thus, biochar can effectively promote plant growth [30,31]. However, there were also some studies that reported little effect of biochar on soil nutrients [32] or negative effects, such as Sun et al. [27] who showed that compared with B0 (no biochar), the SOC content presented a 14.0% decrease with B30 (30 Mg ha⁻¹ biochar). The inconsistency could be attributed to biochar feedstocks and characteristics [33], the application ratio of biochar [34], plant types [35] and soil properties [36].

Therefore, this study used a meta-analysis to explore: (1) the effect size of biochar amendment on root biomass; (2) the main factors that influence the response of plant root biomass to biochar amendment.

2. Materials and Methods

2.1. Literature Search

The Web Of Science (https://www.webofscience.com/wos/alldb/basic-search, accessed on 1 November 2021), Science Direct (https://www.sciencedirect.com, accessed on 1 November 2021), and Scopus (https://www.scopus.com/search/form.uri?display=basic#basic, accessed on 1 November 2021) were employed to search peer-reviewed articles published before 2021. The keywords used for the online literature search were "biochar" and "root." The meta-analysis included studies with at least three replicates of biochar-amended and control treatments at the same site (i.e., the same experimental conditions) [37] A total of 203 individual observations from 47 peer-reviewed articles were included in our analysis (Table S1).

2.2. Data Collection

From each study, we extracted the mean root biomass, standard deviations, and the number of replicates for both biochar-amended and control treatments. If the articles only reported the standard errors, then the standard errors were converted to standard deviations. The plant type, soil properties [pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), available potassium (AK)], experimental conditions (field/pot), biochar application rates and characteristics (feedstock, pH) were extracted

when available. Engauge Digitizer software (version 11.1, Mark Mitchell) was used to extract data that were presented with the figures in original papers. The biochar feedstocks were grouped as gramineous plants (n = 76), green waste (n = 37), and woody plants (n = 61). The biochar pH values were grouped as 6–8 (n = 31), 8–10 (n = 71), and 10–12 (n = 60). The application rates were grouped as <20 Mg ha⁻¹ (n = 83), 20–40 Mg ha⁻¹ (n = 50), and >40 Mg ha⁻¹ (n = 39). The plant types were grouped as cereals (n = 84), vegetables (n = 39), fruits (n = 8), grasses (n = 34), and trees (n = 15). The soil pH levels were grouped as 3–5 (extremely acidic, n = 11), 5–7 (acidic, n = 73), and 7–9 (alkaline, n = 79).

2.3. Data Meta-Analysis

The effect size of each soil response variable was determined by calculating the ln-transformed response ratio RR = ln (Xt/Xc), where Xt is the measured change in the response variable following biochar treatment and Xc is the value measured in the untreated soil (control) [38].

We used MetaWin 2.1 for the meta-analysis [39], selected a random classification effect model to calculate weighted average effects, and used the self-help sampling method (999 times) to calculate the 95% confidence interval (CI) of the average effect of different groups. The means of effect sizes among different levels were considered significant at α = 0.05 when the 95% CIs were non-overlapping [7,40].

The percent changes in plant root biomass are presented in Figures 3–7. The effect size (ln (RR)) and exponentially transformed 95% CI were used to calculate the percentage change in root biomass [6].

$$Percentage change = [exp(lnRror95\%CI) - 1] \times 100$$
(1)

Forest plots were made by Prism 7.0 using meta-analysis data, the map was made by ArcMap 10.8. In addition, other statistical analyses were conducted in R v.4.0.3.

3. Results

3.1. Biochar Effects on Root Biomass, Soil Organic Carbon (SOC), and Soil Nutrients

The search identified 47 papers and 203 datasets. The papers were mainly from China and Europe (Italy, Germany, Spain, France, Ireland, and Denmark), Canada, the United States, Pakistan, Colombia, Egypt, Australia, and some other countries (Figure 1). Overall, 165 (81.3%) of the 203 datasets showed positive effects on root growth (Figure 2), and the root biomass increased by 32.2% (95%CI: 27.4–33.3%). Some soil properties were related to the improvement of soil fertility. On average, biochar application significantly increased soil organic carbon (SOC) by 102.3%, total nitrogen (TN) by 46.2%, available phosphorus (AP) by 33.0%, and available potassium (AK) by 311.5% (Figure 3).

3.2. The Chemical Characteristics of Biochars and Soils

The properties of biochar from different feedstocks are different. On average, the total carbon (TC) of the three biochars (gramineous plants, green waste, and woody plants) are 561.3, 502.2, and 661.2, the total nitrogen (TN) of the three biochars are 7.2 g, 12.2, and 3.4 g kg⁻¹, the total phosphorus (TP) of the three biochars are 4.9, 1.6, and 1.2 g kg⁻¹, and the total potassium (TK) of the three biochars are 37.3, 5.8, and 9.7 g kg⁻¹, respectively (Figure 4). Properties of soils under different vegetations studied are also different. On average, the soil organic carbon (SOC) of the five vegetations (cereal, fruit, grass, tree, vegetable) are 14.9, 32.8, 15.7, 13.1, and 15.2 g kg⁻¹, the soil total nitrogen (TN) of the five vegetations are 1.9, 1.3, 1.7, 1.2, and 1.0 g kg⁻¹, and the soil total phosphorus (TP) of the five vegetations are 0.2, 0.3, 0.6, 0.2, and 0.1 g kg⁻¹, respectively (Figure 5).



Figure 1. Site location of experiments used in this study.



Figure 2. Distribution of relative increments of root biomass after biochar application.



Figure 3. Box-plot showing (**a**) soil organic carbon (SOC), (**b**) total nitrogen (TN), (**c**) available phosphorus (AP), and (**d**) available potassium (AK) content in soils before and after biochar treatment. The upper and lower sides of the box plot are 75% and 25% quantiles, respectively. The line in the middle of the box represents the median of the data. The points outside the whiskers represent outliers beyond 1.5 times the inter quantile range.



Figure 4. Boxplot showing (**a**) total carbon (TC), (**b**) total nitrogen (TN), (**c**) total phosphorus (TP), and (**d**) total potassium (TK) content in biochar from different feedstocks. The upper and lower sides of the box plot are 75% and 25% quantiles. The line in the middle of the box represents the median of the data. The points outside the whiskers represent outliers beyond 1.5 times the inter quantile range.



Figure 5. Box-plot showing (**a**) soil organic carbon (SOC), (**b**) total nitrogen (TN), and (**c**) total phosphorus (TP) content in soils under different vegetations studied. The upper and lower sides of the box plot are 75% and 25% quantiles. The line in the middle of the box represents the median of the data. The points outside the whiskers represent outliers beyond 1.5 times the inter quantile range.

3.3. Effects of the Biochar Application Rate and Properties (Feedstock, pH) on Root Biomass

The effect sizes of biochar application on root biomass were significantly different with different biochar feedstocks. The greatest increase (46.2%) was observed with gramineous plant biochar (95%CI: 38.1–54.9%), compared to 21.1% (95%CI: 13.4–29.4%) for woody plant biochar and 25.8% (95%CI: 15.8–36.6%) for green waste biochar (Figure 6a).



Figure 6. Forest plots showing the effects of (**a**) biochar produced from a range of feedstocks, (**b**) biochar pH value, (**c**) biochar application rates, (**d**) biochar on different plant types, (**e**) biochar applications to soils with a range of pH values. A forest plot presenting percent changes in root biomass. The total number of replicates (*n*), included in each grouping are shown in parentheses.

On average, biochar at pH values of 6–8, 8–10 and 10–12 increased root biomass by 32.4% (95%CI: 22.0–43.8%), 38.1% (95%CI: 30.5–46.2%) and 27.7% (95%CI: 20.4–35.4%), respectively (Figure 6b). In addition, the effect sizes of biochar application on root biomass were not significantly different among biochars with different pH values.

The effect sizes of biochar application on root biomass were significantly different with different application rates. The greatest increase was 46.6% (95%CI: 38.7–55.0%) observed

in the >40 Mg ha⁻¹ group, followed by 23.3% (95%CI: 15.1–32.1%) in the 20–40 Mg ha⁻¹ group and 18.3% (95%CI: 9.2–28.1%) in the <20 Mg ha⁻¹ group (Figure 6c).

3.4. Effects of Biochar Addition on Root Biomass Varied with the Plant Type

The effect sizes of biochar application on root biomass were significantly different with different plant types. Overall, the greatest increase in the root biomass was 101.6% (95%CI: 73.0–134.8%) achieved with trees, followed by 66.0% (95%CI: 52.0–81.1%) and 60.5% (95%CI: 28.1–101.2%) for grasses and fruits, respectively. The lower increments of 26.9% (95%CI: 17.5–36.8%), and 12.7% (95%CI: 6.9–18.6%) were observed with vegetables and cereals (Figure 6d).

3.5. Effects of Biochar Addition on Root Biomass According to the Soil pH

Overall, biochar increased root growth by 30.6%, and no significant differences were observed according to the soil pH (Figure 4e). When the soil pH was 3–5, 5–7, and 7–9, plant root biomass increased by 25.2% (95%CI: 5.9–48.1%), 29.9% (95%CI: 22.6–37.6%), and 32.2% (95%CI: 24.8–40.1%), respectively (Figure 6e).

4. Discussion

4.1. Biochar Improved Soil Nutrients and Promoted Root Growth

Our meta-analysis showed that biochar promoted plant root growth, and its application significantly improved SOC, TN, AP, and AK (Figure 3). Consistent with our analysis, Zhang et al. [34] reported that biochar improved citrus fruit indexes (peel, edibility, acidity ratio of soluble solids to acid, and soluble solid) by enhancing the soil pH, organic matter, and nutrients. In our research, the linear regression analysis showed that SOC (R = 0.32, *p* = 0.12), TN (R = 0.83, *p* < 0.01), AP (R = 0.34, *p* = 0.09) and AK (R = 0.45, *p* < 0.05) were positively correlated with the increase in root biomass (Figure 5a–d). In general, biochar improves soil nutrients and promotes root growth [24,37]. Previous research reported that biochar promoted crop growth by improving soil nutrients [27,41]. Biochar application can significantly increase soil total nitrogen (TN) and available phosphorus (AP) [34] as we revealed. In addition, Cui et al. [24] also found that biochar promotes root growth by increasing soil K availability. In this research, SEM (Structural equation modeling analysis) showed that the most important factor affecting the increase of root biomass was TN (Figure 6e). Changes in the biological, as well as physical properties of soil as a result of biochar amendment, could affect the root response. Peeyush et al. [42] reported that biochar enhanced the physical properties of soil (such as infiltration rate, maximum water holding capacity, aggregate stability, and mean weight diameter) leading to an increased crop yield and maximum monetary returns under subtropical conditions. In addition, biochar also increased the total soil fungal density and changed the proportional abundance of bacterial and fungal taxa by changing the soil's physicochemical properties [43].

4.2. Factors Influencing the Effects of Biochar on Root Growth

The feedstocks of biochar and its rate of application were the main factors that determined its effects on plant root growth [29,44]. The kind of feedstock is one of the main factors determining the physical and chemical properties of biochar [6,29]. We found that the effects on root biomass of biochar from gramineous plants were significantly higher than those of other kinds of biochar (Figure 6a). This might be related to its higher P and K content compared to biochars produced from green waste and wood (Figure 4). Tefanko and Leszczynska [45] compared 20 types of biochar and found biochar produced from straw had higher nutrient contents, particularly P and K, and this supports our findings, that biochar promoted root growth by increasing soil AP and AK (Figure 7c,d).



Figure 7. Relationships between the relative increase of (**a**) soil organic carbon (SOC) to root biomass, (**b**) total nitrogen (TN) to root biomass, (**c**) available phosphorus (AP) to root biomass, (**d**) available potassium (AK) to root biomass (BM), and (**e**) their structural equation model.

The increment in root biomass increased with an increasing rate of biochar application (Figure 4c). Previous studies have reported that increasing biochar application rates leads to increased soil organic matter, nitrogen, phosphorus, and other nutrients, thereby promoting root growth [6,46]. In a study of the effects of straw biochar application rates (0, 10, 20, 30, 40, and 50 Mg ha⁻¹) on the yield of corn, Feng et al. [47] found that the yield increased with the application rate. However, the economic benefits (input–output ratio) should be considered and the amount of biochar should be selected accordingly.

The effects of biochar on root growth varied with the plant type (Figure 4d). Different plants have different root morphologies and nutrient requirements [48]. The soil nutrients varied with the plants in the studies we collected (Figure 5). Compared with SOC, we found that the N content in the soil of trees was deficient (Figure 5). Biochar application can obviously improve the TN in the soil (Figure 3). It can provide a certain amount of nitrogen by affecting the soil content of mineral nitrogen and reducing nitrogen leaching loss. Studies [49] have shown that straw returning and adding biochar can improve soil pH, enhance soil water and fertilizer retention capacity, improve soil conditions, and significantly affect the mineral nitrogen content of soil. Zhou et al. [50] pointed out that proper addition of biochar can greatly reduce soil nitrogen leaching. Thus, trees respond to biochar application more than any other plant type. The surface of biochar is rich in oxygen-containing functional groups, and the anions of these weak acid functional groups react with H^+ to form neutral molecules [51]. At the same time, the previously adsorbed exchangeable base cations are released into the solution, which is the main mechanism for biochar to improve soil pH [52]. Soil pH is a main abiotic factor affecting the soil environment [53] and it also affects soil fertility and crop growth [54]. Indeed, soil pH may be the main factor affecting the stability of biochar [55], but little is known about the effect of biochar on plant growth under different soil pH conditions. Biochar promotes plant growth more obviously at a lower soil pH [46,56,57]. However, we found no significant difference in the promotion effects of biochar on crop roots at different soil pH values (Figure 6e). In this research, only 11 data sets were collected for low pH soils (pH 3–5) (n = 11), and most of the biochar feedstocks were wood and green waste [20,58–60], and the promotion effects of these two feedstocks were lower than those of gramineous biochar (Figure 6a). So, the effects of biochar on root growth with various soil pH values should be further studied in the future.

5. Conclusions

Our research indicated that biochar promoted root growth by increasing soil nutrients such as TN and AK. The biochar produced by gramineous plants had the greatest promotion effect, which was significantly higher than that of green waste and woody plant biochars. This might be related to its higher K content compared to biochars produced from green waste and wood. The promotion effects for trees and grass were larger than those for vegetables and cereals. Biochar application can obviously improve the TN, AP and AK in the soil, supplement a certain amount of N, P and K, and promote growth. Overall, many other factors influenced the effects of biochar on root growth, and thus the effect of other factors, such as the physical characteristics of biochar, heating time and temperature, should be further studied.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/ 10.3390/agronomy11122442/s1, Table S1: Literature used in meta-analysis.

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