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Effect of Biochar Amendment on the Growth and Photosynthetic Traits of Plants Under Drought Stress: A Meta-Analysis

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Abstract: Biochar, as a soil improvement additive, is widely applied in field practices due to its excellent performance in improving soil conditions and promoting plant growth under drought stress. A meta-analysis was conducted, analyzing 283 pairs of non-biochar-amendment (non-BA) controls and biochar amendment (BA) treatments under drought stress. This study aims to (1) evaluate the effects of biochar on gas exchange and carbon accumulation in plants under drought stress; and (2) quantify the factors influencing biochar's effects. The results showed that BA had a statistically significant positive impact on water use efficiency (*WUE*), yield, biomass, chlorophyll content, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*). The extent of these effects was influenced by plant type, degree of water stress, soil type, and the duration of BA application. The response to BA varied across plant types, with significant effects on the *WUE* of legumes (32.4–37.7%) compared to modest effects on eggplants and other vegetables (8.1–9.4%). BA was more effective in improving plant growth and *WUE* in soils with extremely coarse or fine textures than in those with medium particle sizes. The duration of BA application was also a critical factor; as the application duration increased, the improvement rates of yield, chlorophyll content, gws, and photosynthetic rate showed a decreasing trend, while *WUE* and biomass did not exhibit significant declines. However, Tr increased sharply over time. These findings highlight the potential of BA to enhance plant growth, *WUE*, and photosynthetic traits, while identifying the conditions under which these benefits can be maximized.

Keywords: biochar amendment; drought stress; meta-analysis; water use efficiency; crop growth

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1. Introduction

Nowadays, the rapid increase in population is demanding higher food output from agricultural production. Agriculture is the most water-intensive industry, accounting for more than 70% of total water consumption [1–3]. At the same time, population growth drives up the demand for industrial and domestic water [4]. Intense competition for water among various industries makes it impossible to increase food production by simply adding irrigation water input [5]. Furthermore, the likelihood of extreme arid climates occurring has increased [6,7]. It is expected that food production will be affected by varying degrees of drought over the long term [8]. Drought disrupts normal growth processes such as seed germination, heading, pollination, grain filling, and maturity, severely reducing crop yields [9–11]. When severe drought occurs during the critical water requirement period for crops, it may even result in significant grain abortion [12,13].

The limited supply of agricultural water poses a significant challenge to food security, making it essential to achieve higher water use efficiency (*WUE*) through new irrigation technologies (e.g., drip irrigation) and agronomic practices (e.g., mulching films or soil amendments) [14–16]. Biochar amendment has been proposed as a novel agricultural strategy to improve soil conditions, enhance long-term productivity, and increase nutrient and water use efficiency.

Biochar is a natural material derived from the pyrolysis of organic waste, such as plant straw and animal manure, under limited oxygen conditions at high temperatures (300–1000 °C). Its low density and large surface area endow biochar with superior adsorption capacity. When combined with soil, biochar effectively reduces soil bulk density and increases soil pH, cation exchange capacity (CEC), soil structure, and water retention capacity [17,18], directly enhancing crop yield and *WUE*. Under drought stress conditions, biochar can lower irrigation requirements by retaining precipitation or irrigation water and binding ions, thereby ensuring a steady supply of water and nutrients to crops [19,20]. This significantly reduces the sensitivity of plants to drought conditions.

Although biochar plays a positive role in agricultural practices, studies have reported varying effects. For instance, Gavili et al. [21] found that applying 100 tons·ha^{-1} of biochar decreased soybean biomass and yield compared to the control group, while [22] observed significant improvements in water use efficiency and leaf nitrogen use efficiency in Chenopodium quinoa. These inconsistent findings suggest that the effects of biochar are influenced by various factors.

Meta-analysis, a statistical method for analyzing data from independent experimental studies, is a valuable tool for systematically integrating factors that affect target variables. Initially developed for evidence-based medicine, meta-analysis has become widely used in ecology and environmental science. Its growing application in agricultural research makes it a promising approach for quantifying biochar's effects under drought stress [23–26].

This study aims to (1) quantify the effects of biochar on gas exchange and carbon accumulation in plants under drought stress; and (2) identify the factors influencing these effects. It is hoped that this research will provide a deeper understanding of the mechanisms by which biochar influences crop growth, offering practical guidance for its application in agricultural production.

2. Materials and Methods

2.1. Search Strategies

A meta-analysis was conducted to investigate the response of crop growth and photosynthetic traits to biochar under drought stress. Data were obtained from published studies and analyzed primarily to compare differences in water use efficiency (*WUE*), yield, biomass, chlorophyll content, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*) between biochar and non-biochar treatments. The literature was primarily sourced from Elsevier (Science Direct), Web of Science, Springer Link, and Google Scholar (up to September 2021) using the search keywords "drought" and "biochar" without additional restrictions on the search process. In total, 74 articles were reviewed.

2.2. Screening of Studies

The screening process was conducted in three subsequent steps (Figure 1). Step 1: review the title and abstract sections to exclude studies not related to biochar and drought. Step 2: examine the results and discussion sections to exclude studies in which water use efficiency (*WUE*), yield, biomass, chlorophyll content, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), or transpiration rate (*Tr*) could not be directly or indirectly extracted. Step 3: analyze the materials and methods sections to exclude studies where the basic experimental parameters could not be obtained.

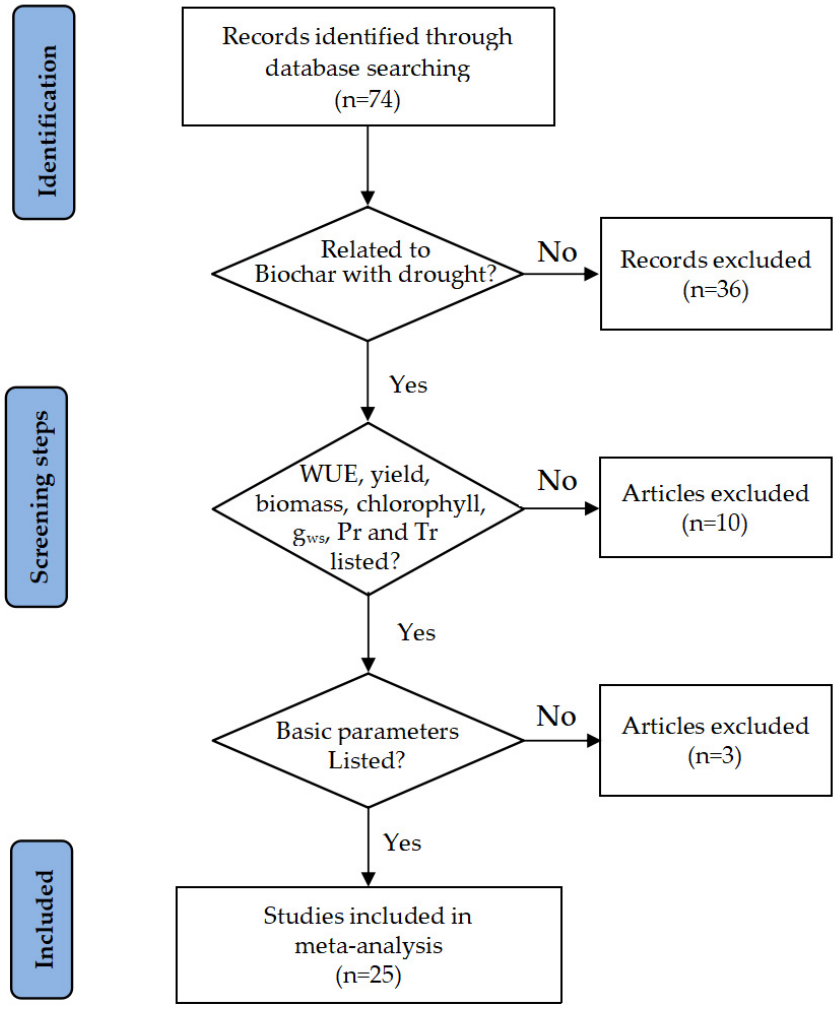

Figure 1. Flow diagram of studies included in review.

2.3. Data Extraction

All data were extracted using a standardized data-collection form. Information recorded included the authors, publication year, title, crop type, degree of water stress, mean values (for *WUE*, yield, biomass, chlorophyll, g_{ws}, *Pr*, and *Tr*), number of replicates, and standard errors for both the control and experimental groups. To maximize within-group homogenization, certain variables were categorized into sets based on published studies, as follows: crop type (according to actual types in practice); degree of water stress—including high water stress (HS), defined as water supply below 40% of crop requirements, moderate water stress (MS), with water supply between 40% and 70% of crop requirements, and no water stress (NS), where water supply exceeded 70% of crop requirements.

2.4. Data Analysis

In this research, the natural log of the response ratio was applied to quantify the effect size of the biochar in the given variable [27], as follows,

$$\mathrm{L\,nR} = \mathrm{Ln}\left(\frac{\overline{Ne}}{\overline{Nc}}\right)$$

where $\overline{Ne}$ means the mean value in the control group; and $\overline{Nc}$ means the mean value in the experimental group.

The variance of effect size (VarR) was calculated as below:

$$v(LnR) = \frac{STE_e}{n_e\overline{Ne}} + \frac{STE_c}{n_c\overline{Nc}}$$

where STE_e, STE_c, n_e, and n_c are the standard deviation of the experimental group and control group, and repetitions in the experimental group and control group, respectively.

The *lnR* was weighted as follows:

$$w(LnR) = \frac{1}{v(LnR)}$$

The overall mean effect sizes were estimated as follows:

$$Ln\overline{R} = \frac{\sum_{i=1}^{n}(LnR)_i \times w(LnR)_i}{\sum_{i=1}^{n} w(LnR)_i}$$

where $(LnR)_i$ and $w(LnR)_i$ mean the effect sizes and the weight of the effect sizes for the *i*th sample.

For studies where the standard error was missing, it was set to 1% of the value. A 95% bootstrap confidence interval (CI) with 4999 iterations was used to calculate the average effect size and 95% CI. If the 95% CI of the effect size overlaps with zero, the effect of biochar on the given variables is considered statistically significant; otherwise, the treatment effect is deemed insignificant. To simplify interpretation, the effect size (ES, %) was expressed as the percentage change, calculated as follows:

$$ES = \left(Ln\overline{R} - 1\right) \times 100\%$$

A positive value indicates a positive effect of biochar, while a negative value indicates a negative effect. A random-effects model was adopted for the analysis. Subgroup analysis was performed based on crop type and degree of water stress. The Begger funnel regression method was applied to assess potential publication bias within the entire dataset.

2.5. Data Treatment

Engauge Digitizer software 10.8(open-access software) was used to extract data from the figures. All analyses were performed using StataSE 12.0 (StataCorp, College Station, TX, USA). The forest plots were created using Origin Pro 8.5 (OriginLab Corporation, Northampton MA, USA). A p-value < 0.05 was considered statistically significant, except where otherwise specified.

3. Result

3.1. Overall

In this study, 25 papers (Table S1 and Figure 2) and 283 samples met the inclusion criteria for analysis, including 93 BA-to-control *WUE* comparisons, 156 BA-to-control yield comparisons, 119 BA-to-control biomass comparisons, 71 BA-to-control chlorophyll comparisons, 104 BA-to-control gws comparisons, 75 BA-to-control *Pr* comparisons, and 74 BA-to-control *Tr* comparisons. Among the dataset, 9 field experiments and 16 greenhouse experiments were included, with no significant differences observed between field and greenhouse sites. The soils studied included clay, clay–loam, silty-loam, sandy-loam, and loam, with the pH ranging from 4.19 to 8.6.

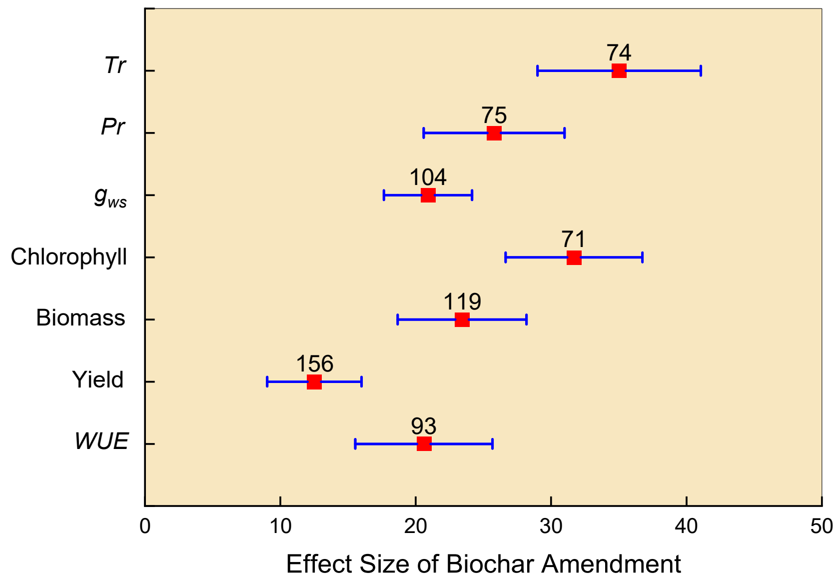

Figure 2. Summary for the effect size of the biochar amendment (BA) on *WUE*, yield, biomass, chlorophyll, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*).

Averaged across a wide range of environmental conditions, BA significantly increased *WUE*, biomass, chlorophyll content, g_{ws}, and *Pr* by 20.6% (95% CI: 15.54–25.67%), 23.42% (95% CI: 18.66–28.17%), 31.69% (95% CI: 26.63–36.75%), 20.90% (95% CI: 17.65–24.16%), and 25.79% (95% CI: 20.59–31.00%), respectively. Yield and *Tr* showed the smallest and largest increases in effect size, at 12.51% and 35.02%, respectively. Overall, all growth and photosynthetic indicators exhibited positive responses to BA to varying degrees.

3.2. Response Affected by Plant Type

There are significant differences in the responses to the BA among different plants at $p < 0.001$ (Figure 3). For *WUE*, there were three improvement echelons. The BA groups for faba bean and soybean, located in the first echelon with 37.7% and 32.4% yield, increased compared to the control group. In addition, a 16.7–20.4% increase in the *WUE* of wheat, maize, and cowpea positioned them in the middle echelon. Eggplant, pumpkin, and chenopodium quinca only possessed 8.1%, 8.2%, and 9.4% of the increasing contribution in *WUE* and were in the third echelon. The effect size of the *WUE* increase in the first echelon was significantly higher than that in the third echelon; however, the middle echelon did not show significant differences with the other two echelons in *WUE* change. In terms of the yield, it was found that the BA contributed to crop yield increases from 7.1% to 25.1% in all groups compared with the control group, except for soybean, which displayed a 15.8% decrease in the yield. Faba bean did not show a significant yield-increase effect because of the overlap of the error bars and the zero-ES line. Regarding biomass, most of the cabbage seedlings had the most positive response to the BA with a 74.8% increase, which was twice as much as the rest of the crops. Additionally, broad bean, eggplant, maize, okra, quercus castaneifoli, rapeseed, and wheat had significant increases in biomass (11.0%, 20.4%, 20.7%, 11.9%, 34.0%, 21.9%, and 27.4%) in the BA treatment compared to the control group without BA. Biomass of the soybean increased by 7.4% when comparing the BA group with the non-BA group but the increase trend was not obvious. Also, it was found that the chlorophyll and *Tr* of the Chenopodium quinoa decreased by 17.2% and 18.2% after adding BA, respectively. For the rest of the plants, both the chlorophyll and *Tr* increased significantly, with the exception of the chlorophyll of okra. In addition, both the g_{ws} and *Pr* in the BA treatment were significantly higher than those in the control treatment.

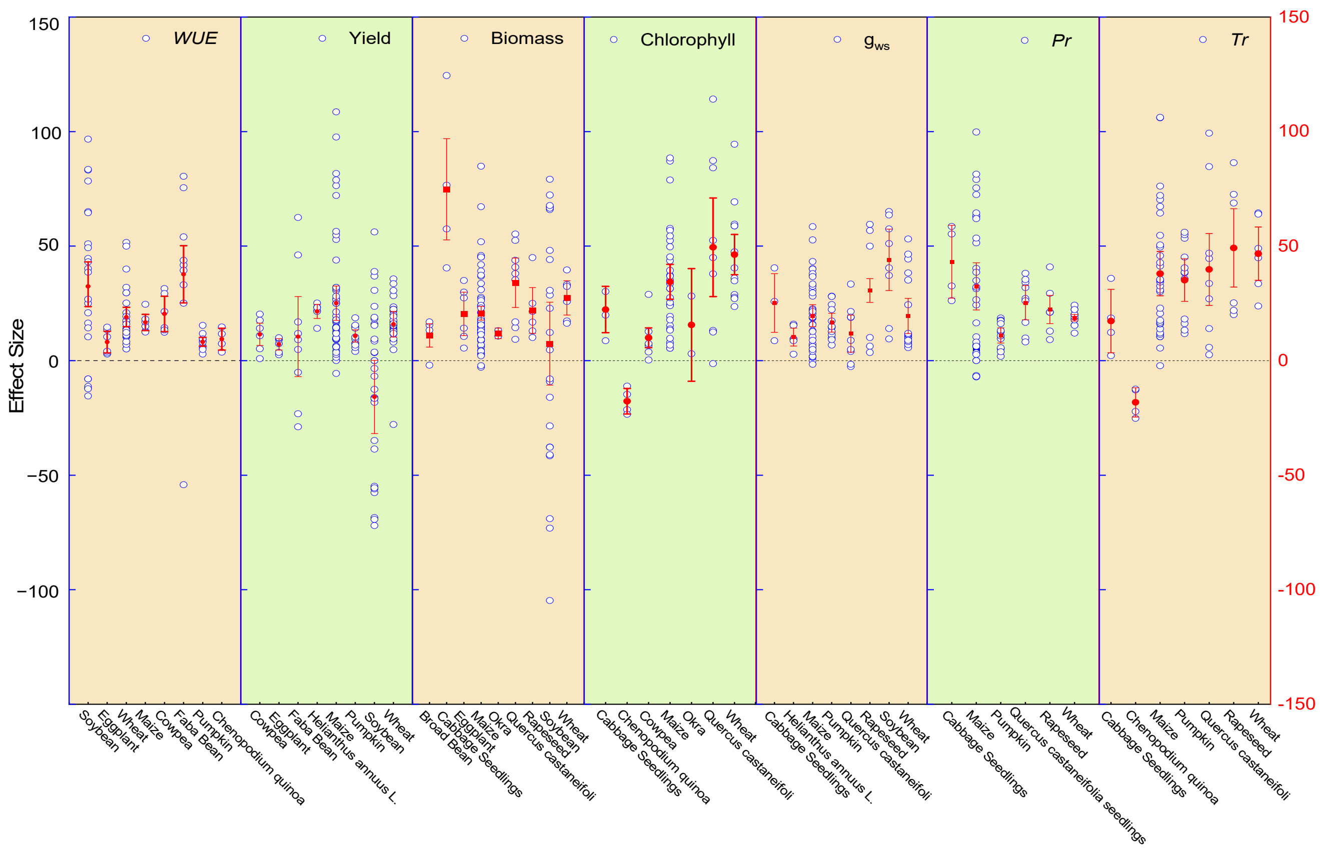

Figure 3. Summary of reported mean effect sizes of biochar amendment (BA) on the *WUE*, yield, biomass, chlorophyll, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*) corresponding to each type of crop. Blue hollow circles stand for observations, red solid marks stand for means values and error bar.

3.3. Response Affected by Stress Degree

The responses of *WUE*, yield, biomass, chlorophyll, g_{ws}, *Pr*, and *Tr* to BA varied depending on the degree of water stress (Figure 4). Under MS conditions, *WUE* showed the most pronounced response to BA, with a 22.6% increase, followed by NS (22.2%) and HS (17.9%). Biomass also exhibited the highest increase under MS conditions (29.8%), with increases of 23.5% and 18.8% under HS and NS conditions, respectively.

For other indicators, including yield, chlorophyll, g_{ws}, *Pr*, and *Tr*, it was observed that the effect sizes of the BA group compared to the non-BA group decreased as water stress conditions were alleviated. BA significantly enhanced the observed values for yield (33.0%), chlorophyll (43.7%), g_{ws} (45.6%), *Pr* (62.0%), and *Tr* (57.5%) under HS conditions. Furthermore, the effect size of BA under HS conditions was 182% and 309% greater than those under MS and NS conditions, respectively.

3.4. Response Affected by Soil Type

The subgroup analysis indicated that the type of planting soil influenced the degree of BA response across all growth indicators (Table 1). When planting in clay, clay–loam, and sandy-loam soils, *WUE* showed large effect sizes of 26.4%, 19.8%, and 30.0%, respectively. The smallest effect size for *WUE* (6.9%) occurred in silty-loam soil, while under loam soil conditions, the effect size was also relatively small at 8.1%.

For yield, the effect sizes decreased as the soil texture became increasingly coarse. A substantial increase of 32.7% in yield was observed with BA treatment under sandy-loam planting conditions. Biomass changes associated with texture variation followed a pattern similar to *WUE*, with the smallest effect size (5.2%) observed in silty-loam soil.

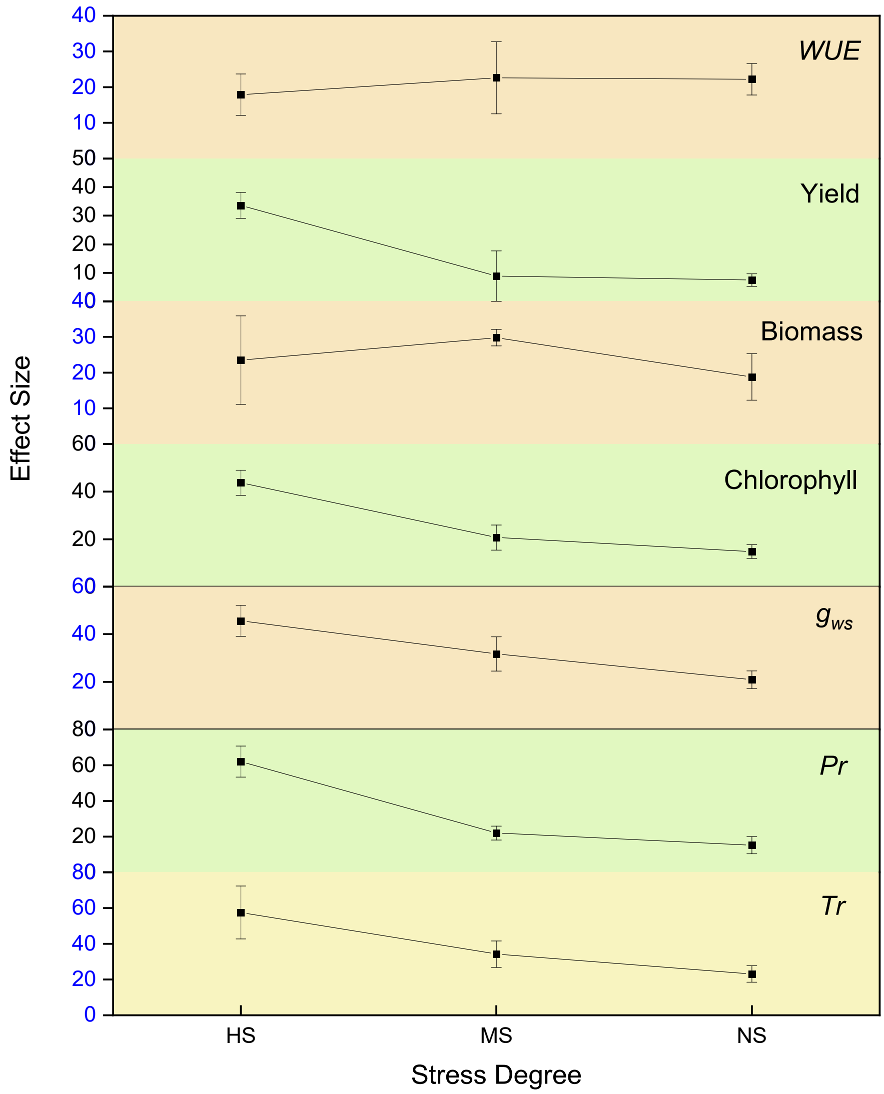

Figure 4. Summary of reported mean effect sizes of biochar amendment (BA) on *WUE*, yield, biomass, chlorophyll, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*) corresponding to different drought stress degrees (HS-high water stress; MS-moderate water stress; NS-no water stress).

For chlorophyll, the effect size of BA on clay–loam soil was 137.3% higher than that on sandy-loam soil. However, other planting conditions lacked relevant data due to missing values. For gws and *Pr*, values under loam soil conditions were also unavailable. The minimum increase in g_{ws} (11.2%) occurred with BA treatment in clay–loam soil, while the maximum increase (25.1%) was observed in sandy-loam soil. For *Pr*, as soil texture became coarser, the effect size gradually declined from 49.2% to 30.3%. The effect sizes for *Pr* were 19.8%, 25.3%, and 11.0% under clay, clay–loam, and silty-loam soil conditions, respectively.

3.5. Response Affected by Application Duration

The duration of BA application influenced the responses of growth and physiological indicators. As the application duration increased, the effect size of BA on *WUE* increased slightly, at a rate of less than 0.004% per day (Figure 5). A similar trend was observed for biomass, which increased at a rate of 0.035% per day.

Table 1. Mean effect size of the *WUE*, yield, biomass, chlorophyll, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*) corresponding to various soil types. Data shown are for all observations.

Soil Type		Clay	Clay–Loam	Silty-Loam	Loam	Sandy-Loam
WUE	Mean	26.4	19.8	6.9	8.1	30
	n	21	8	21	6	25
	95% CI	24.6–28.1	16.1–23.4	1.1–12.6	3.4–12.8	19.0–41.1
Yield	Mean	15	10.9	10.8	7.1	32.7
	n	21	27	12	6	27
	95% CI	8.2–21.7	8.8–13.0	8.1–13.5	4.6–9.5	−90.8
Biomass	Mean	48.2	16.1	5.2	20.4	24.2
	n	15	18	2	6	22
	95% CI	39.6–56.9	7.7–24.4	−31.6	10.9–29.9	13.2–35.1
Chlorophyll	Mean	--	51.5	--	--	21.7
	n	--	15	--	--	10
	95% CI	--	38.9–64.0	--	--	15.9–27.5
g_{ws}	Mean	16	11.2	16.6	--	25.1
	n	18	15	12	--	14
	95% CI	13.8–18.2	08.7–13.6	12.5–20.8	--	18.5–31.7
Pr	Mean	49.2	39.8	35.2	--	30.3
	n	6	8	12	--	8
	95% CI	32.1–66.3	24.1–55.5	25.9–44.5	--	18.1–42.5
Tr	Mean	19.8	25.3	11	--	--
	n	18	9	12	--	--
	95% CI	18.3–21.3	16.6–20.3	07.7–14.4	--	--

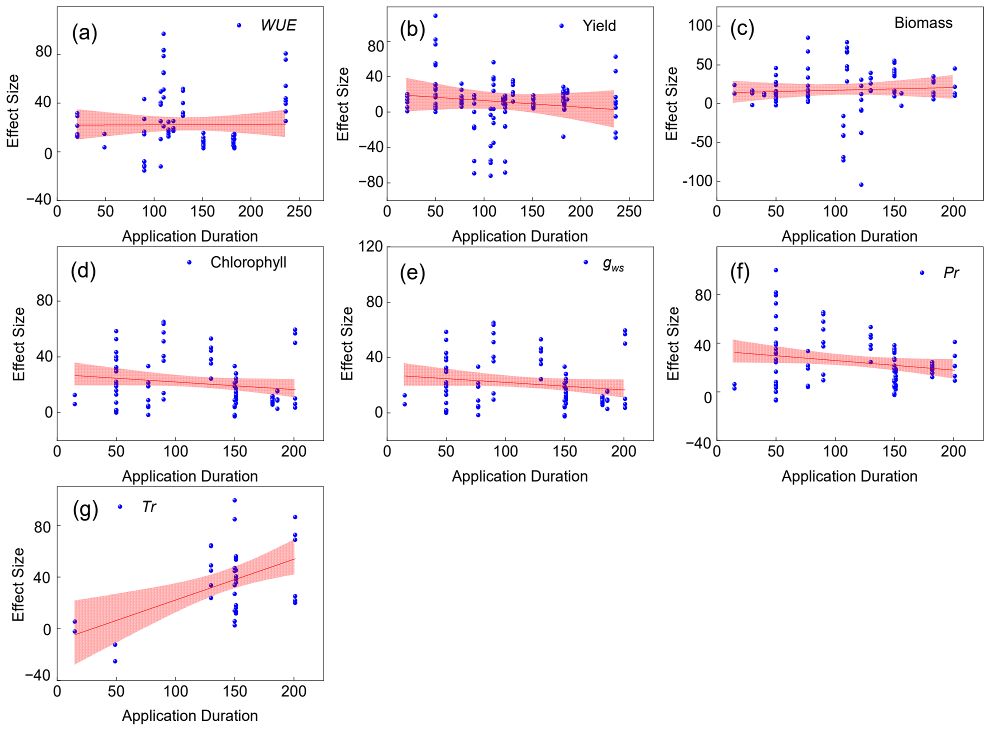

Figure 5. Summary of reported mean effect size of the biochar amendment (BA) on *WUE*, yield, biomass, chlorophyll, stomatal conductance (g_{ws}), photosynthetic rate (*Pr*), and transpiration rate (*Tr*) corresponding to BA application duration, which were marked by **(a)**, **(b)**, **(c)**, **(d)**, **(e)**, **(f)** and **(g)**, respectively. The red area represents the 95% confidence interval. Data shown are for all observations.

In contrast, an opposite trend was observed for yield, chlorophyll, g_{ws}, and *Pr*, as all of them showed a decreasing response with prolonged BA application. The rates of decrease were 0.075% per day for yield, 0.054% per day for chlorophyll, 0.054% per day for g_{ws}, and 0.078% per day for *Pr*. *Tr*, on the other hand, showed a strongly positive response to the application duration, with the highest increase rate of 0.316% per day.

4. Discussion

The addition of biochar improves the physical properties of soil. Keabetswe [28] has shown that biochar enhances the soil's ability to retain volumetric moisture content. This trend is particularly evident in the 0–30-centimeter soil layers with and without biochar treatment. Owing to the bonding and adhesion properties of organic materials in biochar, biochar can strengthen soil aggregate stability and increase pore space, thereby improving soil moisture retention [29,30]. In arid conditions, maintaining soil moisture is crucial for crop growth. For sandy and coarse-textured soils, biochar-amended soils exhibit improved water retention [31]. Biochar reduces water flow in sandy soils by enhancing the binding of sand particles, increasing soil cohesion, and absorbing moisture. For fine-textured soils, the addition of biochar significantly promotes water penetration and drainage (i.e., saturation conductivity) and may significantly improve moisture dynamics in viscous soils [32,33]. Blanco-Canqui [34] showed that biochar has little effect on medium-textured soils (e.g., loam), suggesting that medium soil particle sizes between sand and clay are the least responsive to biochar amendment. In contrast, we found that BA significantly increased the *WUE*, yield, and biomass accumulation in extremely coarse and very fine soils, whereas the corresponding improvements in medium-grained soils were significantly reduced (Table 1). This indicates that the improvement of soil conditions by biochar is particularly beneficial for enhancing yield and *WUE*.

Biochar absorbs plant hormones and alters the balance of plant hormones. Harmful compounds such as high concentrations of phenolic acids can be adsorbed, thereby modulating the metabolism of indole-3-acetic acid (IAA) to ensure root system development [35]. BA activates the synthesis of abscisic acid (ABA) and IAA, thereby inducing root growth and enhancing plant root resistance to drought stress and pathogen defense [36,37]. BA significantly increases soil pH, which alters the soil's chemical environment near the roots, changes the ion balance in the soil, and may affect the biochemical properties of the roots, leading to an increase in xylem pH [38,39]. Consequently, this increase in pH may induce higher ABA concentrations in the leaves, causing stomatal closure and reducing gws. However, our analysis found that BA resulted in increased stomatal conductance. The most probable explanation is that biochar helps maintain optimal moisture and nutrient conditions in the soil, even in arid conditions, thereby sustaining normal photosynthetic rates under reduced water availability [40,41]. Our results further show that the more severe the drought, the greater the increases in chlorophyll content, g_{ws}, *Pr*, and *Tr*. This suggests that the photosynthetic characteristics of plants respond positively to biochar as drought stress intensifies.

Biochar attracts adsorbed inorganic nitrogen species through static electricity, thereby reducing the availability of applied nitrogen fertilizers [42]. As the duration of biochar application increases, this effect becomes more significant. For example, at 40 days of application, biochar increased the chlorophyll content in the leaves by 17.34%; however, after 151 days, the chlorophyll content decreased by 1.92%, and at 182 days, biochar application resulted in a 21.08% reduction in leaf chlorophyll content (Figure 5d). In addition, biochar significantly enhances photosynthesis and promotes plant biomass accumulation, which may lead to chlorophyll dilution in leaves [43]. Chlorophyll content serves as a reliable indicator of nitrogen (N) content in plants. Therefore, biochar additives represent a promising strategy to enhance nitrogen retention and alleviate environmental impacts in the context of excessive nitrogen (N) fertilizer use [44].

The results showed that biochar generally played an active role in improving water use efficiency (*WUE*), as reported in numerous studies [45–48]. Changes in the *WUE* neither appeared to be sensitive to drought stress, nor did it exhibit a strong response to the duration of biochar application (Figure 5g). In fact, biochar significantly increases plant yield (Figure 2). However, the overall improvement in plant properties associated with biochar, such as enhanced plant moisture status and greater leaf gas exchange rates, resulted in increased moisture evaporation, particularly as the duration of biochar application extended. Thus, the interaction between yield and transpiration rate (*Tr*) may reasonably explain the observed stability of *WUE*. Coupled with high temperatures during dry conditions, which can exacerbate plant water loss and ineffective soil water evaporation [49], biochar's ability to maintain stable *WUE* demonstrates its significant role in stabilizing plant water relations under drought conditions. In addition, our research showed that the application of biochar greatly improved the *WUE* of legumes but not eggplant. A possible explanation is that vegetables like eggplant require substantial irrigation, and biochar's compensation effect may not fully offset the losses caused by drought stress; however, owing to limited data availability, this hypothesis requires further investigation using a broader range of vegetable crops.

In summary, biochar enhances crop production as an effective method of carbon sequestration. It represents an important strategy to improve soil water and gas conditions while increasing yield. However, this study has potential limitations. Variations in feedstock types and production processes lead to differences in biochar properties and efficacy, which require further quantification [50].

5. Conclusions

We conducted a meta-analysis involving 25 papers with 283 non-BA-to-BA comparisons. The results showed that when encountering drought stress, there were statistically significant increases of 12.51%, 20.6%, 23.42%, 31.69%, 20.90%, 25.79%, and 35.02% in the *WUE*, yield, biomass, chlorophyll, g_{ws}, *Pr*, and *Tr*, respectively. These benefits were most pronounced with vegetables growing in clay and sandy-loam soils, which require large amounts of water. Especially when confronted with high drought stress, BA exhibited huge potential to enhance yield and photosynthesis across all the tested crops. The main advantages of BA treatment include its ability to sequester carbon and its environmentally friendly features, and thus it can be applied at a large scale in the future.

In this paper, a quantitative analysis based on currently available data from the published literature was conducted. However, confidence in the results of this study may be constrained by data representativeness and the scale of the sampled studies. Thus, more efforts are needed to include further experimental details to extend the compatibility and complementary traits of biochar itself, and to determine suitable environmental factors, land management, and relevant socioeconomic aspects to further the practical guidelines.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14122952/s1, Table S1: Basic Information of Biochar.

Author Contributions: W.Z.: conceptualization, methodology, software implementation, the literature review and analysis, validation, and manuscript drafting. W.N.: methodology, supervision, and manuscript review and editing. H.L.: investigation. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, upon reasonable request.

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Conflicts of Interest: We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript.

References

1. Deepa, R.; Anandhi, A.; Alhashim, R. Volumetric and impact-oriented water footprint of agricultural crops: A review. *Ecol. Indic.* **2021**, *130*, 108093. [CrossRef]
2. Fitton, N.; Alexander, P.; Arnell, N.; Bajzelj, B.; Calvin, K.; Doelman, J.; Gerber, J.; Havlik, P.; Hasegawa, T.; Herrero, M.; et al. The vulnerabilities of agricultural land and food production to future water scarcity. *Glob. Environ. Change* **2019**, *58*, 101944. [CrossRef]
3. Unesco. *United Nations World Water Assessment Programme: The United Nations World Water Development Report 2020: Water and Climate Change*; Unesco: Paris, France, 2020.
4. Rushforth, R.R.; Ruddell, B.L. The vulnerability and resilience of a city's water footprint: The case of flagstaff, Arizona, USA. *Water Resour. Res.* **2016**, *52*, 2698–2714. [CrossRef]
5. Alexandratos, N.; Bruinsma, J. *World Agriculture towards 2030/2050: The 2012 Revision*; FAO: Rome, Italy, 2012.
6. Hamal, K.; Sharma, S.; Pokharel, B.; Shrestha, D.; Talchabhadel, R.; Shrestha, A.; Khadka, N. Changing pattern of drought in nepal and associated atmospheric circulation. *Atmos. Res.* **2021**, *262*, 105798. [CrossRef]
7. Li, L.; Zhang, Y.-J.; Novak, A.; Yang, Y.; Wang, J. Role of biochar in improving sandy soil water retention and resilience to drought. *Water* **2021**, *13*, 407. [CrossRef]
8. Aliyari, F.; Bailey, R.T.; Arabi, M. Appraising climate change impacts on future water resources and agricultural productivity in Agro-urban river basins. *Sci. Total Environ.* **2021**, *788*, 147717. [CrossRef]
9. Danish, S.; Zafar-Ul-Hye, M.; Mohsin, F.; Hussain, M. Acc-deaminase producing plant growth promoting rhizobacteria and biochar mitigate adverse effects of drought stress on maize growth. *PLoS ONE* **2021**, *16*, e0250286. [CrossRef]
10. Farooq, M.; Gogoi, N.; Barthakur, S.; Baroowa, B.; Bharadwaj, N.; Alghamdi, S.S.; Siddique, K.H.M. Drought stress in grain legumes during reproduction and grain filling. *J. Agron. Crop Sci.* **2017**, *203*, 81–102. [CrossRef]
11. Zhang, L.; Li, C.; Liu, Y.; Sun, Z.; He, Y.; Wen, D.; Wang, Y.; Chen, X.; Cai, H.; Li, G. Participation of urea-N absorbed on biochar granules among soil and tobacco plant (*Nicotiana tabacum* L.) And its potential environmental impact. *Agric. Ecosyst. Environ.* **2021**, *313*, 107371. [CrossRef]
12. Nussbaumer, A.; Meusburger, K.; Schmitt, M.; Waldner, P.; Gehrig, R.; Haeni, M.; Rigling, A.; Brunner, I.; Thimonier, A. Extreme summer heat and drought lead to early fruit abortion in European beech. *Sci. Rep.* **2020**, *10*, 5334. [CrossRef]
13. Turc, O.; Tardieu, F. Drought affects abortion of reproductive organs by exacerbating developmentally driven processes via expansive growth and hydraulics. *J. Exp. Bot.* **2018**, *69*, 3245–3254. [CrossRef] [PubMed]
14. Singh, M.; Saini, R.K.; Singh, S.; Sharma, S.P. Potential of integrating biochar and deficit irrigation strategies for sustaining vegetable production in water-limited regions: A review. *Hortscience* **2019**, *54*, 1872–1878. [CrossRef]
15. Wang, J.; Du, G.; Tian, J.; Jiang, C.; Zhang, Y.; Zhang, W. Mulched drip irrigation increases cotton yield and water use efficiency via improving fine root plasticity. *Agric. Water Manag.* **2021**, *255*, 106992. [CrossRef]
16. Yuan, Z.; Zhang, R.; Wang, B.; Gao, B.; Ayana, G.; Abera, D.; Ashraf, M.; Li, F. Film mulch with irrigation and rainfed cultivations improves maize production and water use efficiency in Ethiopia. *Ann. Appl. Biol.* **2019**, *175*, 215–227. [CrossRef]
17. Fehmi, J.S.; Rasmussen, C.; Gallery, R.E. Biochar and woodchip amendments alter restoration outcomes, microbial processes, and soil moisture in a simulated semi-arid ecosystem. *Restor. Ecol.* **2020**, *28*, S355–S364. [CrossRef]
18. Githinji, L. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Arch. Agron. Soil Sci.* **2014**, *60*, 457–470. [CrossRef]
19. Qian, Z.; Tang, L.; Zhuang, S.; Zou, Y.; Fu, D.; Chen, X. Effects of biochar amendments on soil water retention characteristics of red soil at south China. *Biochar* **2020**, *2*, 479–488. [CrossRef]
20. Zhao, X.; Hu, M. Capillary forces between particles: Role of biochar in improving water retention capacity of soil. *Arab. J. Geosci.* **2021**, *14*, 1769. [CrossRef]
21. Gavili, E.; Moosavi, A.A.; Kamgar Haghighi, A.A. Does biochar mitigate the adverse effects of drought on the agronomic traits and yield components of soybean? *Ind. Crops Prod.* **2019**, *128*, 445–454. [CrossRef]
22. Kammann, C.I.; Linsel, S.; Gößling, J.W.; Koyro, H. Influence of biochar on drought tolerance of *Chenopodium quinoa* Willd and on soil–plant relations. *Plant Soil* **2011**, *345*, 195–210. [CrossRef]
23. Stanley, T.D.; Jarrell, S.B. Meta-regression analysis: A quantitative method of literature surveys. *J. Econ. Surv.* **1989**, *3*, 161–170. [CrossRef]
24. Du, Y.D.; Zhang, Q.; Cui, B.J.; Sun, J.; Wang, Z.; Ma, L.H.; Niu, W.Q. Aerated irrigation improves tomato yield and nitrogen use efficiency while reducing nitrogen application rate. *Agric. Water Manag.* **2020**, *235*, 106152. [CrossRef]
25. Gao, H.; Yan, C.; Liu, Q.; Ding, W.; Chen, B.; Li, Z. Effects of plasticmulching and plastic residue on agricultural production: A meta-analysis. *Sci. Total Environ.* **2019**, *651*, 484–492. [CrossRef] [PubMed]
26. Zhang, J.; Jiang, H.; Song, X.; Jin, J.; Zhang, X. The responses of plant leaf CO_2/H_2O exchange and water use efficiency to drought: A meta-analysis. *Sustainability* **2018**, *10*, 5512. [CrossRef]

27. Hedges, L.V.; Gurevitch, J.; Curtis, P.S. The meta-analysis of response ratios in experimental ecology. *Ecology* **1999**, *80*, 1150–1156. [CrossRef]
28. Keabetswe, L.; Shao, G.C.; Cui, J.; Lu, J.; Stimela, T. Integrated effects of biochar and deficit irrigation subjected at various growth stages on tomato yield and water use efficiency. *J. Anim. Plant Sci.* **2019**, *29*, 1352–1361.
29. Akhtar, S.S.; Li, G.; Andersen, M.N.; Liu, F. Biochar enhances yield and quality of tomato under reduced irrigation. *Agric. Water Manag.* **2014**, *138*, 37–44. [CrossRef]
30. Maryam, T.; Rabi, H.M.; Amjad, T.A.; Ripendra, A.; Ali, F. Soil hydrostructural parameters under various soil management practices. *Agric. Water Manag.* **2024**, *292*, 108633. [CrossRef]
31. Ajayi, A.E.; Horn, R. Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. *Soil Tillage Res.* **2016**, *164*, 34–44. [CrossRef]
32. Guo, M. Application of biochar for soil physical improvement. *Agric. Environ. Appl. Biochar* **2016**, *63*, 101–122.
33. Castellini, M.; Giglio, L.; Niedda, M.; Palumbo, A.; Ventrella, D. Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil Tillage Res.* **2015**, *154*, 1–13. [CrossRef]
34. Blanco-Canqui, H. Biochar and soil physical properties. *Soil Sci. Soc. Am. J.* **2017**, *81*, 687–711. [CrossRef]
35. Marschner, H. *Marschner's Mineral Nutrition of Higher Plants*; Academic Press: Cambridge, MA, USA, 2011.
36. Gu, Y.; Hou, Y.; Huang, D.; Hao, Z.; Wang, X.; Wei, Z.; Jousset, A.; Tan, S.; Xu, D.; Shen, Q.; et al. Application of biochar reduces *Ralstonia solanacearum* infection via effects on pathogen chemotaxis, swarming motility, and root exudate adsorption. *Plant Soil* **2017**, *415*, 269–281. [CrossRef]
37. Pei, J.; Li, J.; Fang, C.; Zhao, J.; Nie, M.; Wu, J. Different responses of root exudates to biochar application under elevated CO_2. *Agric. Ecosyst. Environ.* **2020**, *301*, 107061. [CrossRef]
38. Guo, L.; Bornø, M.L.; Niu, W.; Liu, F. Biochar amendment improves shoot biomass of tomato seedlings and sustains water relations and leaf gas exchange rates under different irrigation and nitrogen regimes. *Agric. Water Manag.* **2021**, *245*, 106580. [CrossRef]
39. Liu, X.; Wei, Z.; Manevski, K.; Liu, J.; Ma, Y.; Andersen, M.N.; Liu, F. Partial root-zone drying irrigation increases water-use efficiency of tobacco plants amended with biochar. *Ind. Crop Prod.* **2021**, *166*, 113487. [CrossRef]
40. Laghari, M.; Mirjat, M.S.; Hu, Z.; Fazal, S.; Xiao, B.; Hu, M.; Chen, Z.; Guo, D. Effects of biochar application rate on sandy desert soil properties and sorghum growth. *Catena* **2015**, *135*, 313–320. [CrossRef]
41. Li, N.; Yao, N.; Li, Y.; Chen, J.; Liu, D.; Biswas, A.; Li, L.; Wang, T.; Chen, X. A meta-analysis of the possible impact of climate change on global cotton yield based on crop simulation approaches. *Agric. Syst.* **2021**, *193*, 103221. [CrossRef]
42. Nguyen, T.T.N.; Xu, C.-Y.; Tahmasbian, I.; Che, R.; Xu, Z.; Zhou, X.; Wallace, H.M.; Bai, S.H. Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. *Geoderma* **2017**, *288*, 79–96. [CrossRef]
43. Loladze, I. Rising atmospheric CO_2 and human nutrition: Toward globally imbalanced plant stoichiometry? *Trends Ecol. Evol.* **2002**, *17*, 457–461. [CrossRef]
44. Zhang, X.; Lv, P.; Xu, C.; Huang, X.; Rademacher, T. Dryness decreases average growth rate and increases drought sensitivity of Mongolia oak trees in north China. *Agric. For. Meteorol.* **2021**, *308–309*, 108611. [CrossRef]
45. Alkhasha, A.; Al-Omran, A.; Louki, I. Impact of deficit irrigation and addition of biochar and polymer on soil salinity and tomato productivity. *Can. J. Soil Sci.* **2019**, *99*, 380–394. [CrossRef]
46. Batool, A.; Taj, S.; Rashid, A.; Khalid, A.; Qadeer, S.; Saleem, A.R.; Ghufran, M.A. Potential of soil amendments (biochar and gypsum) in increasing water use efficiency of *Abelmoschus esculentus* L. *Moench Front. Plant Sci.* **2015**, *6*, 733. [CrossRef] [PubMed]
47. Ghori, S.A.; Gul, S.; Tahir, S.; Sohail, M.; Batool, S.; Shahwani, M.N.; Bano, G.; Butt, M.-U. Wood-derived biochar influences nutrient use efficiency of heavy metals in spinach (*Spinacia oleracea*) under groundwater and wastewater irrigation. *J. Environ. Eng. Landsc. Manag.* **2019**, *27*, 144–152. [CrossRef]
48. Xiao, Q.; Zhu, L.X.; Shen, Y.F.; Li, S.Q. Sensitivity of soil water retention and availability to biochar addition in rainfed semi-arid farmland during a three-year field experiment. *Field Crop Res.* **2016**, *196*, 284–293. [CrossRef]
49. Bodner, G.; Nakhforoosh, A.; Kaul, H. Management of crop water under drought: A review. *Agron. Sustain. Dev.* **2015**, *35*, 401–442. [CrossRef]
50. Ghorbani, M.; Amirahmadi, E. Biochar and soil contributions to crop lodging and yield performance—A meta-analysis. *Plant Physiol. Biochem.* **2024**, *215*, 109053. [CrossRef]