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The Mineral Biochar Alters the Biochemical and Microbial Properties of the Soil and the Grain Yield of *Hordeum vulgare* L. under Drought Stress

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Abstract: Biochar improves soil physical, biochemical, and microbial properties, leading to the amelioration of soil fertility, which, in turn, results in better growth and yield in crop plants. The current study aimed to evaluate whether using different levels of biochar can enhance soil characteristics and plant attributes. Accordingly, an experimental study was conducted in 2022 using a randomized complete block design with four replications (n = 4) in the experimental glasshouse of the University of Zanjan, in which two regimes of irrigation (D0, full irrigation as the control; D1, water scarcity was applied immediately after the flowering stage for two weeks) and four levels of natural mineral biochar (0% as the control treatment, 0.25, 0.5, and 1% of soil weight) were applied. The results indicated that drought substantially decreased the organic carbon content of the soil and the grain yield while increasing the available phosphorous, soil carbohydrate content, and microbial biomass of the soil. Biochar could considerably alter the means of the studied soil quality parameters and the barley grain yield. Adding biochar could be considered a valid strategy to increase the resistance of plants to drought.

Keywords: soil; organic carbon; available phosphorous; microbial biomass; grain yield; withholding irrigation

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1. Introduction

Barley (*Hordeum vulgare* L.) is the fourth most cultivated cereal and one of the most strategic crop plants produced almost all over the world as a source of staple food and animal feed [1]. It was reported that world barley production in the 2021–2022 cultivation season has decreased by 8.1% compared to 2020–2021 probably due to climate change and its repercussions, such as drought stress [2].

Food uncertainty is a comprehensive obstacle that has become a serious hazard worldwide, particularly in developing countries, due to overpopulation and dwindling accessibility of croplands, water, and other resources related to agriculture scopes [3–6]. Additionally, the amplification of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as atmospheric temperature and the evacuation of water resources, resulting from anthropogenic activities, have driven climate alteration, resulting in drought stress as one of the most important results of climate change [7–10]. Indeed, drought is defined as a situation in which the soil's total water capacity is between 12–20% for approximately 16 days, which differs from a water deficit in which the water capacity is less than 30% [7]. Under such circumstances, most plants cannot absorb abundant water, which is required for optimized growth [11]. Plant growth trends depend on soil conditions. Water availability directly affects plants' morphological, physiological, and biochemical attributes [12]. Therefore, water shortage is considered the most vital abiotic stress [13,14]. Reduced stomatal conductance, low transpiration rate, lack of biological nitrogen fixation, prevention of abscisic acid activity, absorption of macronutrients and micronutrients, the decline in chlorophyll concentration, low root elongation, high electrolyte leakage, and ethylene accumulation are some of the major consequences of water scarcity that affect plants' physiological responses [11,15–17]. Such destructive effects on plants cause a massive decrease in plant functions and yield attributes [18].

Drought is one of the most destructive stresses for wild plants and agronomic crops [4,5,17]. Drought stress affects crop yields, especially in arid and semi-arid regions of the world [8,10]. The intensity and frequency of drought periods are increasing due to climate change, as recently reported [19,20]. Scarce rainfall induces different physiological and metabolic responses in plants such as the closure of the stomata, resulting in reduced growth and a low photosynthetic rate [21]. The first biological mechanisms compromised by drought concern the reduction in cell expansion and cell divisions, two primary processes involved in plant growth [6,16]. If water stress continues, the impairment is more profound and conditions such as photosynthesis and cellular respiration influence critical processes, such as germination, emergence, leaf expansion, root and shoot development, dry matter accumulation, floral initiation, pollination, fertilization, seed growth and seed yield [16,22,23]. Indeed, water stress, by reducing the size and number of cells, leads to reduced leaf area and reduced plant height and stem development. Furthermore, a shortening of the period from floral initiation was observed, resulting in a lower yield in terms of seed production [17,24,25]. In addition to its effects on plants, drought can effectively change soil's microbial, biochemical, and physical properties, eventually leading to restriction in crop growth and production [4,6,26,27]. It was proposed that the negative impacts of drought on soil's microbial properties decrease the enzymatic activity of the soil and decrease nutrient cycling, soil fertility, and plant production [7,26,27]. It was proposed that the microbial population is decreased under drought because of restricted nutrient mineralization and respiration [7,28]. The destructive effects of water shortage on the microbial community and soil activity lead to lower enzymatic activity, lower nutrient uptake, and consequently, lower productivity [29]. For instance, the availability of some fertilizers may be affected by water shortages in the soil, consequently, disturbing nutrient uptake by plants, particularly carbon, nitrogen, and phosphorous [23,30]. Soil quality plays a critical role in the maintenance of high crop productivity. If the organic matter in the soil, such as organic carbon, is reduced, the sustainable production of farming activities is negatively affected [3]. This means that higher soil organic matter activates an appropriate soil microbial community, improves soil structure, increases beneficial nutrients, enhances crop water use efficiency, and increases productivity [31,32]. The overuse of chemical fertilizers, pesticides, and herbicides has diminished microbial activity and respiration, enzymatic activity, decomposition of various organic and inorganic materials, and soil productivity. Therefore, suitable soil management using healthy resources of fertilizers is a fundamental part of agricultural activities [30].

It was proposed that boosting soil properties and productivity requires healthy resources of amendments, such as organic substances, which can also be highly advantageous for mitigating the adverse effects of drought stress. Biochar, a product of biomass pyrolysis, is used as a carbon-rich material to elevate soil C sequestration and reduce CO_2 emissions [33–37]. Soil microorganisms use it as a C source, which increases the organic mass in the soil, leading to the reduced application of chemical fertilizer [38]. It was also reported that using biochar increases soil organic carbon, because of more sustainable soil aggregates [39]. Moreover, as biochar has considerable porosity, it provides an appropriate habitat for microorganisms, which causes a more effective decomposition of organic matter in the soil [40]. In addition, several researchers have reported that using biochar as a valuable soil conditioner improves soil water holding capacity, cation exchange capacity, soil texture stability, and soil aggregates [3,33–37,40–49].

Several experimental studies have argued how biochar affects soil properties and plant attributes under drought stress conditions. However, no single study has assessed the effect of mineral biochar (extracted from natural mines) on soil microbial activity and plant growth under drought stress. Therefore, this study was undertaken to determine the ameliorating effect of biochar on the adverse effects of drought on soil biochemical and physical characteristics and barley plant attributes. We hypothesized that the addition of biochar into the soil mitigates the detrimental impacts of drought stress on soil microbial activity and respiration, soil organic carbon, and other parameters. The results would determine the optimum level of biochar in alleviating the negative impacts of water shortages on soil and crops.

2. Materials and Methods

2.1. Site Description and Experimental Design

A pot study was conducted in the 2021–2022 cultivation season, in the experimental glasshouse of the University of Zanjan, Iran, using a randomized complete block design (n = 4). The experimental soil was sieved (2 mm) and oven-dried to evaluate its physiochemical parameters at the agricultural research center of Zanjan, Iran (Table 1). The physical and chemical properties of the experimental biochar are listed in Table 2. Barley (*Hordeum vulgare* L. var. Jolgeh) seeds were sown on 22 October 2021. The seeds were soaked in pots containing 10 kg of loamy sand soil (dry weight equivalent). Two regimes of irrigation, namely, non-stress conditions (full irrigation as a control treatment, D0) and withholding irrigation for two weeks at the flowering stage (D1) were applied as the main factors. Natural mineral biochar, a coal product, was mixed with the soil at the beginning of the experiment at four levels (B0, B0.25, B0.5, B1) with the soil amendment 0% (without biochar) as the control, 0.25%, 0.5%, and 1% *w*/*w*. Biochar was obtained from a natural mine in the Koohbanan region of Kerman Province, Iran. In fact, the used biochar in this experiment is a natural product that is extracted from the mine, and after it is ground and becomes powder, it becomes usable for any activity including agricultural activities. The recommended doses of NPK fertilizers (100, 60, 45 kg ha^{-1}, respectively) were used for barley based on the recommendations of the agricultural organization of Zanjan, Iran. The growth conditions in the glasshouse were as follows: 420 ppm of CO_2, relative humidity of 60% ± 5%, 16–21 °C (minimum–maximum), and natural light condition day/night cycle of 14/10 h photoperiod (using fluorescent lamps providing PAR). Each plastic pot (28 cm top diameter and 30 cm height) contained 10 kg of loamy, sandy soil (dry-weight equivalent). All pots were irrigated equally until the flowering stage, after which the drought stress treatment was initiated. Pots were weighed precisely several times during the drought period; their weight was recorded, a soil moisture curve was drawn, and sampling was performed when the soil water potential reached under 2 mega pascals.

Table 1. Physical and chemical properties of the soil.

Unit	Fe mg/kg	Mn mg/kg	Zn mg/kg	Cu mg/kg	EC × 10^3 mS/cm	pH	O.C %	K mg/kg	S.P mg/kg	N %	Sand %	Silt %	Clay %
Quantity	2.79	4.20	0.38	0.28	1.20	8.17	0.12	181	5.6	0.012	72	16	12

Fe, Mn, Zn, Cu, EC, pH, O.C, K, S.P, and N represent iron, magnesium, zinc, copper, electrical conductivity, potential hydrogen, organic carbon, potassium, soluble phosphorus and nitrogen, respectively.

Table 2. Chemical properties of the biochar.

Unit	Pb mg/kg	N %	SP %	K %	O.C %	pH	EC × 10^3 mS/cm	Cd mg/kg	Cu mg/kg	Zn mg/kg	Mn mg/kg	Fe mg/kg
Quantity	0.58	1.38	0.15	0.13	13.85	6.4	1.23	0.02	0.56	1.74	3.42	4.15

Pb, N, SP, K, O.C, pH, EC, Cd, Cu, Zn, Mn, and Fe represent lead, nitrogen, soluble phosphorus, potassium, organic carbon, potential hydrogen, electrical conductivity, cadmium, copper, zinc, magnesium, and iron, respectively.

2.2. Soil Sampling and Measurements

At the end of the cultivation season, after harvesting grain yield, 250 g of soil sample from each treatment was collected in June 2022, transferred to the soil analysis laboratory in sealed plastic bags, and stored on dry ice immediately after collection. The studied soil parameters were determined and measured in the Soil Physics Laboratory of the University of Zanjan, Iran.

Determination of Soil Biochemical and Microbial Properties

In this experiment, the soil parameters included the organic carbon content of the soil (OC%), available phosphorous (AP), sulfuric acid carbohydrate (SAC), hot water soil carbohydrate (HWSC), microbial biomass (MB), the trend of soil microbial respiration (MR) on the 1st, 2nd, 5th, 12th, 19th, 26th, and 33rd days, and substrate-induced respiration (SIR) on the 1st, 2nd, 5th, and 12th days after sampling. The grain yield of the barley was measured at the end of the growing season. The OC was estimated using the Walkley and Black dichromate oxidation procedure [50], and AP was determined using the Olsen method [51]. The carbohydrate content was estimated in two types of soil extracts, that is, dilute acid-soluble extract using 1 g of soil mixed with 10 mL of 0.25 M H_2SO_4 and shaken in a plane rotary shaker for 16 h and hot water-soluble extract using 1 g of soil mixed with 10 mL of hot distilled water (85 °C) and heated for 2.5 h [51]. Each suspension was centrifuged (30 min at 3000 rpm), and 2 mL of the supernatant solution was used to determine the carbohydrate concentration using the phenol-sulfuric acid method described by Nielsen [52], using glucose as the calibration curve. The absorbance of each supernatant solution was measured using a spectrophotometer at 490 nm. The amount of CO_2 respired in NaOH was titrated against standardizing HCl at different intervals using phenolphthalein as the indicator [29]. Microbial biomass carbon was estimated by the fumigation–extraction method.

2.3. Statistical Analysis

Two-way ANOVA with Šidák multiple comparison tests was performed. Statistical analyses were performed using the GraphPad Prism 8 software (San Diego, CA, USA). Data are presented as mean ± S.E.M (standars error of mean), with the statistical significance level set at $p < 0.05$.

3. Results

The results of the present study illustrated significant effects of drought and biochar and their interaction ($p < 0.05$) on some of the studied soil factors, as well as the grain yield of barley. Regarding organic carbon (OC%), drought stress and biochar significantly affected this index. Drought decreased the OC compared with normal irrigation by 5.6% in non-amended soils. However, adding biochar both in normal irrigation and under drought stress improved the concentration of OC in the amended soil compared with the control (Figure 1). The application of 1% biochar to the soils significantly enhanced the OC more than all other biochar treatments. According to the results, the highest OC (27%) was observed under normal irrigation conditions with 1% mineral biochar, and the lowest value (17%) was detected in soil not amended with biochar and subjected to drought stress (Figure 1).

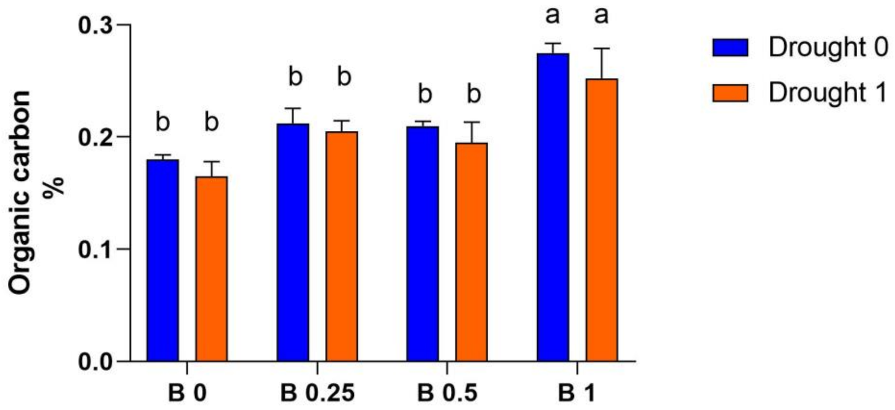

Figure 1. Effects of biochar and drought treatment on soil organic carbon (OC). Data are shown as mean ± S.E.M, and different letters denote statistically significant differences between experimental groups at the $p < 0.05$ level according to two-way ANOVA with Šidák multiple comparison test.

There were no significant effects for drought stress, biochar and their interaction on the available phosphorus content (Figure 2). However, drought stress increased the AP content in the absence of biochar; nonetheless, the application of mineral biochar even under drought conditions increased this parameter. The application of B0.25, B0.5, and B_1 levels in not stressed soils improved the AP compared to the control treatment. The highest AP value was obtained using 0.25% biochar (4.66 ppm) under normal irrigation and the lowest in the same level of biochar but in drought-exposed soils (Figure 2.)

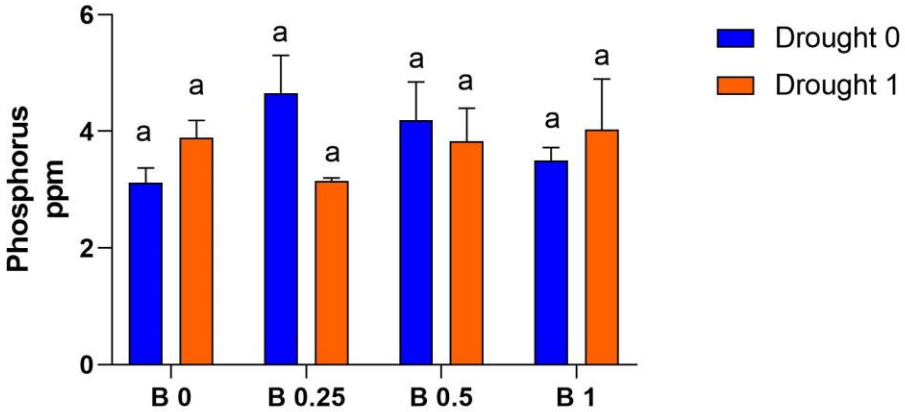

Figure 2. Effects of biochar and drought treatment on the concentration of soil available phosphorous (AP). Data are shown as mean ± S.E.M, and different letters denote statistically significant differences between experimental groups at the $p < 0.05$ level according to two-way ANOVA with Šidák multiple comparison test.

The response of hot water soil carbohydrates (HWSC) to the drought stress was not significant ($p < 0.05$). However, the application of biochar substantially increased the content of HWSC in the soil (Figure 3). We observed that although the effect of using B0.25 was not positive, increasing the level of biochar resulted in improved HWSC compared to soils without biochar. Moreover, drought stress increased the content of HWSC compared with the non-treated soils (D0-B0) treatment. Nonetheless, adding 1% biochar decreased HWSC in drought-treated soils. The highest HWSC (162.1 mg/kg soil) was detected in the D0-B1 treatment, and the lowest content (86.9 mg/kg soil) was observed in the D0-B0.25 treatment. In addition, withholding irrigation and biochar did not have any substantial effect on sulfuric acid carbohydrates (SAC), as shown in Supplementary Figure S1. However, it seems that amending soils with biochar in the soil somehow increased the SAC compared with the lack of biochar under drought-stress conditions.

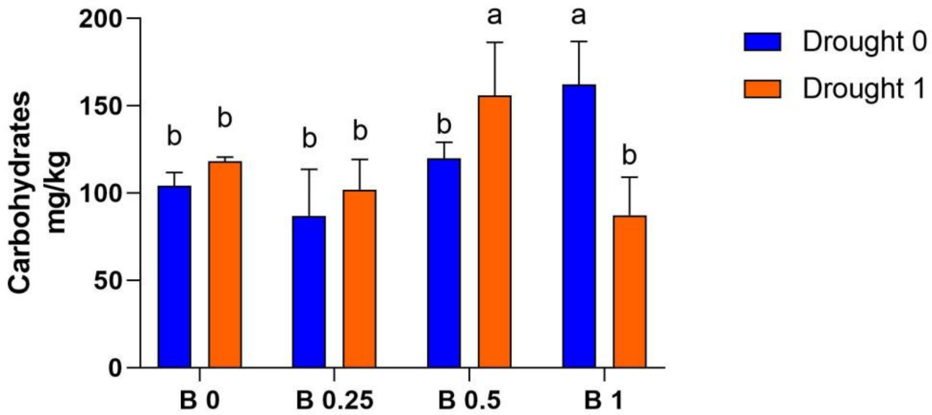

Figure 3. Effects of biochar and drought treatment on the concentration of soil carbohydrates (extracted with hot water). Data are shown as mean ± S.E.M, and different letters denote statistically significant differences between experimental groups at the $p < 0.05$ level according to two-way ANOVA with Šidák multiple comparison test.

The effects of drought and biochar on microbial biomass (MB) were significant ($p < 0.01$, Figure 4). The overall MB content, regardless of the biochar level, was increased by 385.1% in drought-treated soil compared with normal irrigation. Interestingly, the MB was greater in drought-stressed, non-amended soil (D1-B0), and the opposite was true in D0-B1 treatment. The MB in D1-B0 was greater than non-stressed, non-amended soil (D0-B0) but it was greater in D0-B1 than D1-B1. The biochar increased the MB in the B1 treatment in normal irrigated soils 2560% in comparison to the control treatment (without biochar in normal irrigation). In addition, drought increased MB compared to normal irrigation, but the effect was not significant (Figure 4). The highest MB (94.7 mg C/100 g soil) was observed in normal irrigation conditions due to the application of 1% of biochar into the soil, while the lowest MB (3.56 mg C/100 g soil) was detected in normal irrigation conditions because of not using biochar.

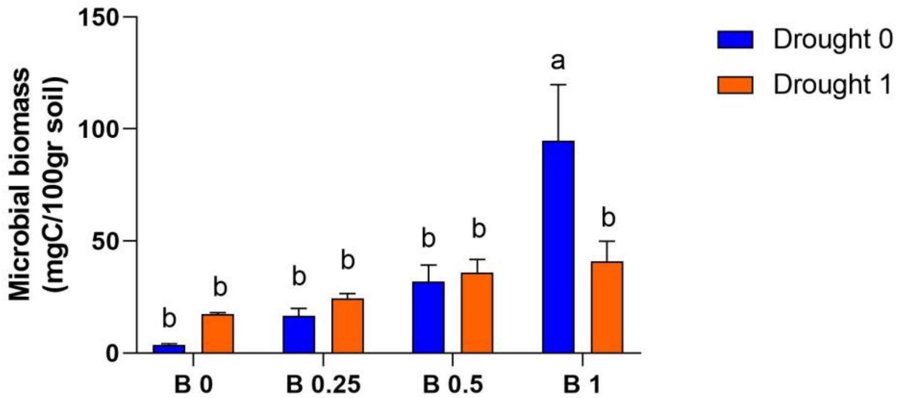

Figure 4. Effects of biochar and drought treatment on the soil microbial biomass. Data are shown as mean ± S.E.M, and different letters denote statistically significant differences between experimental groups at the $p < 0.05$ level according to two-way ANOVA with Šidák multiple comparison test.

MR and SIR were significantly affected by biochar application and drought stress (Figures 5 and 6). In this experiment, it was found that MR and SIR decreased slightly under both normal irrigation and drought conditions. On the 33rd day, MR values in soils amended with different levels of biochar were significantly greater in soils under normal irrigation conditions than in drought stressed soil (Figure 5).

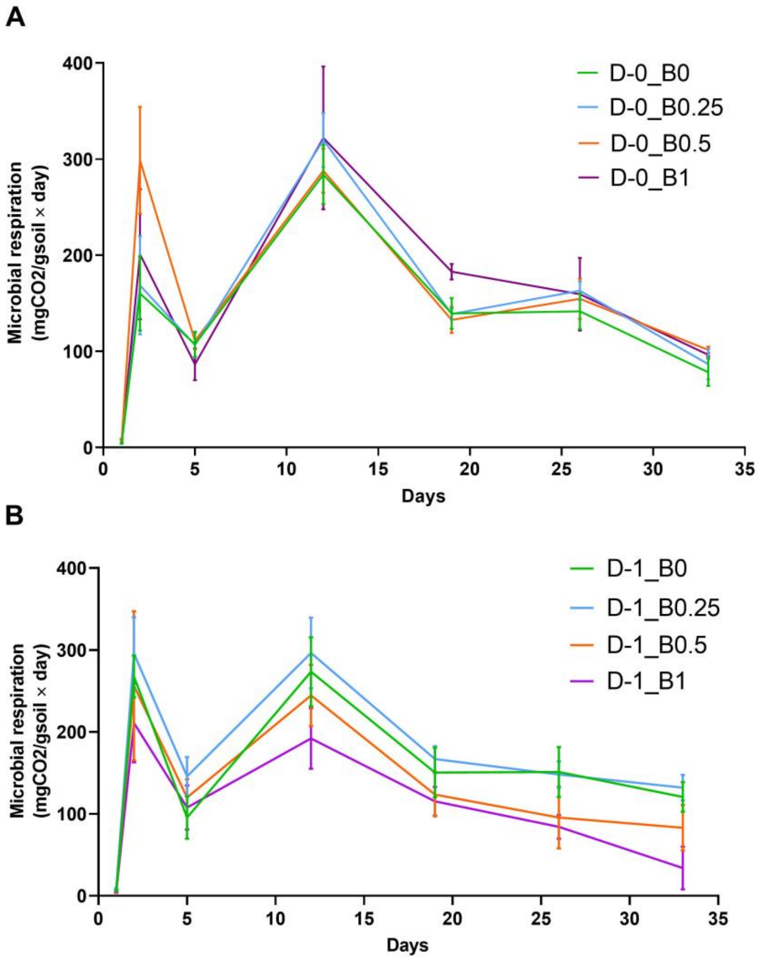

Figure 5. The alterations of microbial respiration of the soil affected by the application of mineral biochar in normal irrigation conditions (**A**) and under drought stress (**B**). D-0 corresponds to control groups with full irrigation; D-1 refers to the experimental groups in which watering was suspended for two weeks in the flowering stage. B0, B0.25, B0.5, B1 correspond to biochar 0% (control group), 0.25%, 0.5%, and 1% w/w, respectively.

Furthermore, we observed that the addition of substrate (glucose) to the soil effectively increased SIR up to five days. After 5 days, however, SIR started to decline. On the 12th day, SIR slightly decreased in both irrigation conditions compared to at 5 days. After 12 days. The SIR in irrigated soils was significantly higher in soil amended with 0.5% biochar than the other biochar treatment. In drought stressed soil, however, the SIR was significantly greater in both 0.25% and 0.5% biochar than in non-amended soil and that amended with 1% biochar (Figure 6).

At the end of the cultivation season, grain yield was estimated. Although withholding irrigation significantly reduced the grain yield, the application of biochar both in normal irrigation and in drought-stressed soils significantly increased the yield (Figure 7). Drought reduced the overall grain yield by 69%, regardless of biochar level, compared with normal irrigation. Nevertheless, amending the soils with 0.25%, 0.5%, and 1% of biochar increased the grain yield under normal irrigation conditions by 74.5%, 38.1%, and 20.7%, respectively, compared to the non-amended soils. The highest grain yield (8.43 g/pot) was observed in soils amended with 0.25% mineral biochar under normal irrigation conditions, and the lowest (1.5 g/pot) was observed under drought-stressed plants grown in soils without biochar (Figure 7).

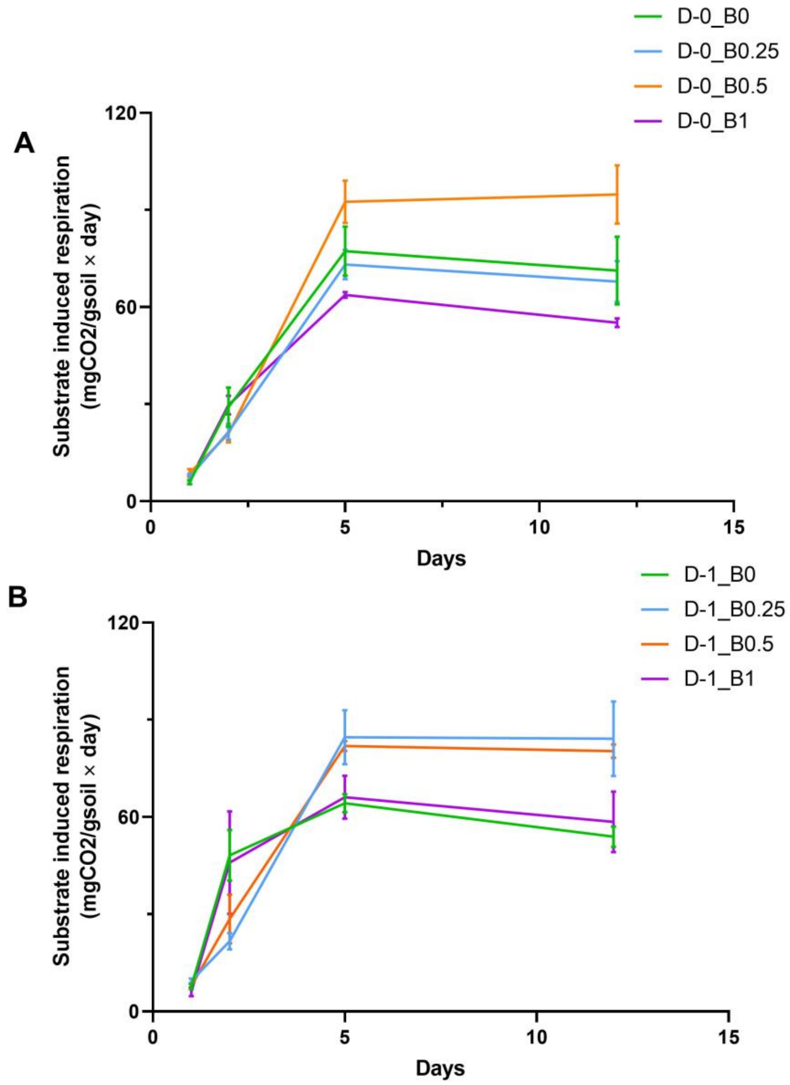

Figure 6. The effects of mineral biochar on substrate-induced respiration in normal irrigation (**A**) and drought-stressed soil (**B**). D-0 corresponds to control groups with full irrigation; D-1 refers to the experimental groups in which watering was suspended for two weeks in the flowering stage. B0, B0.25, B0.5, B1 correspond to biochar 0% (control group), 0.25%, 0.5%, and 1% w/w, respectively.

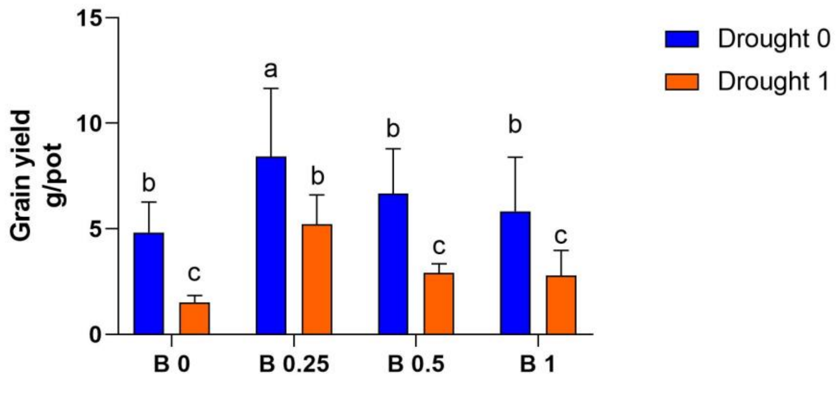

Figure 7. The effects of mineral biochar and drought on grain productivity (grams per pot) of barley plants. Data are shown as mean ± S.E.M, and different letters denote statistically significant differences between experimental groups at the $p < 0.05$ level according to two-way ANOVA with Šidák multiple comparison test.

4. Discussion

4.1. Soil Organic Carbon Content

The present study showed that biochar considerably increased OC under normal and withholding irrigation conditions. Such a result is aligned with many previous reports [37,45,48,53]. Biochar is a carbon-rich substance that directly elevates the OC content and improves the physical, biochemical, and microbial properties [41]. Biochar is reported to increase soil OC content because it has a stable structure that reduces surface OC oxidation and degradation of microbial communities and prevents carbon mineralization [48,54,55]. Consequently, using biochar in the soil increases OC in a short time, sustainably benefiting soil organic carbon [41]. In addition, drought decreased OC content in the absence of biochar. Similarly, Deng and colleagues reported that drought caused a remarkable reduction in OC content in the soil because it lowered water availability for microorganisms, which, in turn, reduced the plant litter input into the soil [56,57]. Other researchers have also reported a negative effect of drought stress on soil organic carbon content [58,59].

4.2. Soil Available Phosphorus

Our results showed that the effects of drought and biochar on the AP were insignificant. However, drought slightly increased the AP, which is consistent with the results of Li et al. [46] and Xiao et al. [60]. In this study, we found that adding biochar at some levels increased AP both under normal irrigation and drought stress compared to the non-amended soil, but the effect was greater under normal irrigation compared to drought-stressed soil. Other authors have reported similar results regarding the impact of using biochar in improving the AP content of the soil under drought stress [3,11,30,42,61]. It appears that although the initial pH of biochar is an important factor in changing the soil pH, as a whole, biochar enhances soil pH and consequently reduces Al and Fe availability, improving the soil's AP. In reality, biochar decreases soil exchangeable acidity, Al, and H and increases the soil exchangeable K, Na, Ca, Mg, and CEC [62]. The slight effect of biochar on improving AP could be probably due to the rapid absorption of phosphorus by the plants or to the phosphorus mineralization by soil microorganisms, as noted previously by other authors [13,33]. Moreover, biochar increases soil AP through interaction with soil in the short term such as through adsorption and desorption, dissolution, precipitation, and redox reactions [63].

4.3. Soil Carbohydrate

Soil carbohydrate levels were significantly affected by biochar treatment. Carbohydrates comprise approximately 15% of soil organic matter and are the major source of available soil organic carbon [37]. Similar to the results of the present study, many authors reported that adding biochar improved soil carbohydrate content and increased the soil organic matter [35,64,65]. Moreover, biochar is believed to enhance soil physical structure and improve the quality and quantity of soil aggregates, resulting in higher organic carbon and carbohydrates in the soil [66]. Furthermore, it was claimed that the appropriate specific surface area of biochar increases the microbial communities as it offers a suitable great habitat for them [67,68].

4.4. Soil Microbial Biomass

Our study indicated that the microbial biomass increased owing to the application of biochar, which agrees with the findings of Jabborova and colleagues [44]. Numerous researchers have reported that biochar improves microbial biomass under drought and normal irrigation conditions [26,36,61,69]. It was proven that biochar addition improves the activity of certain enzymes, such as protease and alkaline esterase in the soil, which enhances the soil nutrient availability required for plant growth both under normal and drought conditions [44,70]. The increase in MB with the addition of biochar in this study is consistent with the results reported by other researchers [45,48]. It seems that the increase in the MB in response to the addition of biochar is due to the effect of biochar on microbial community growth, which is accelerated due to using biochar and inhibiting organic matter degradation [41]. In addition, it was reported that a higher quantity of biochar in the soil accelerates the soil respiration rate, improving nutrient cycling and nutrient absorption and enhancing crop yield [34,41,49,71–74].

4.5. Microbial Respiration and Substrate Induced Respiration of the Soil

The lowest levels of microbial respiration were observed under water-stressed soils, as reported by several authors [26,71,75,76]. The microbial decomposition of soil plays a critical role in soil microbial respiration [41]. Moreover, it was claimed that in addition to temperature, one of the most vital factors for microbial activity in the soil is adequate moisture of the soil [41,71,74,77]. Water shortage reduces the soil microbial biomass and organic matter, leading to lower soil respiration [78]. However, any change in soil's microbial community has a negative effect on the microbial activity, microbial respiration, and enzymatic activity of the soil [71,79]. In this study, biochar application promoted microbial respiration and substrate-induced respiration under both normal and drought irrigation conditions. Additionally, the respiration rate in the soil samples including mineral biochar decreased much more slowly during measurement. This may be because biochar increases the respiration rate of the soil or maintains respiration at a higher level because it contains a large amount of organic matter. Indeed, soil microorganisms break down organic matter, causing an increase in the processes associated with microbial respiration. All these findings agree with those reported by other authors [34,41,73,80]. Furthermore, increased soil respiration impacts carbon decomposition processes leading to increased carbon mineralization [49]. Our data confirmed that biochar application increased soil organic carbon, increasing labile carbon mineralization.

4.6. Grain Yield

Water shortage is one of the most critical hindrances affecting the yield and productivity of barley crops. Based on the two-way ANOVA, withholding irrigation significantly decreased the grain yield in the plants of non-amended soil. However, the barley grain yield was significantly increased in soils amended with the different biochar levels compared to that in non-amended soil. Other studies have also reported that using different levels of biochar increased the yield of other crops grown under normal irrigation and drought conditions [2,81–85]. It is claimed that drought stress results in premature flowering, quick completion of the growing season, less seed production, fewer seeds, and less thousand-seed weight, eventually leading to lower economic yield [86]. Analogously, in agreement with our results, other scientists have reported the beneficial effect of biochar in increasing the grain yield in maize [46], Chinese cabbage [43], wheat [87], and rice [88]. Thus, the use of biochar increases water retention, microbial activity, carbohydrate content, and microbial biomass, all parameters that improve plant growth and production [46,89]. Furthermore, biochar increases nutrient availability, uptake transformation, and utilization efficiency for plants, leading to higher rates of photosynthesis, which, in turn, results in increased production [80,89,90].

5. Conclusions

In conclusion, our results strongly confirm the efficiency of using biochar in enhancing soil quality, fertility, and plant productivity. Specifically, the application of biochar had stimulating effects on the soil microbial biomass and respiration, as well as the organic carbon content of the soil, which eventually led to enhanced grain yield. The adding of mineral biochar can be advantageous under both normal irrigation and drought conditions in improving soil microbial and biochemical properties, leading to improved production. However, there was no significant impact on some soil attributes in soils amended with biochar, suggesting that mineral biochar does not always have a positive effect. Other studies have used different mixtures, types, and concentrations of biochar with results that are not always clear and definitive [91–93]. It is conceivable that the use of more heterogeneous soil mixtures together with biochar can improve the yields of the studied plants [94–96]. However, it is necessary to conduct further experimental studies to determine the best type of biochar (mineral or organic) and the optimal level.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12030559/s1, Figure S1: Concentration of soil carbohydrate (extracted with sulfuric acid) affected by the application of mineral biochar under drought stress. Data are shown as mean ± S.E.M, and different letters denote statistically significant differences between experimental groups at the $p < 0.05$ level according to two-way ANOVA with Šidák multiple comparison test.

Author Contributions: Conceptualization, S.N., B.A. and A.T.; methodology, M.A.D., A.E.-K. and L.V.Z.; formal analysis, S.N. and A.M.; data curation, S.N. and A.M.; writing—original draft preparation, S.N., B.A. and A.T.; writing—review and editing, A.M.; supervision, A.M.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The extra data and materials used in this study will be made available by the authors upon request as much as possible.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Meints, B.; Cuesta-Marcos, A.; Fisk, S.; Ross, A.; Hayes, P. Food Barley Quality Improvement and Germplasm Utilization. In *Exploration, Identification and Utilization of Barley Germplasm*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 41–73. [CrossRef]
2. Saddiq, M.S.; Wang, X.; Iqbal, S.; Hafeez, M.B.; Khan, S.; Raza, A.; Iqbal, J.; Maqbool, M.M.; Fiaz, S.; Qazi, M.A.; et al. Effect of Water Stress on Grain Yield and Physiological Characters of Quinoa Genotypes. *Agronomy* **2021**, *11*, 1934. [CrossRef]
3. Ali, L.; Manzoor, N.; Li, X.Q.; Naveed, M.; Nadeem, S.M.; Waqas, M.R.; Khalid, M.; Abbas, A.; Ahmed, T.; Li, B.; et al. Impact of Corn Cob-Derived Biochar in Altering Soil Quality, Biochemical Status and Improving Maize Growth under Drought Stress. *Agronomy* **2021**, *11*, 2300. [CrossRef]
4. Bayati, P.; Karimmojeni, H.; Razmjoo, J.; Pucci, M.; Abate, G.; Baldwin, T.C.; Mastinu, A. Physiological, Biochemical, and Agronomic Trait Responses of Nigella sativa Genotypes to Water Stress. *Horticulturae* **2022**, *8*, 193. [CrossRef]
5. Biareh, V.; Shekari, F.; Sayfzadeh, S.; Zakerin, H.; Hadidi, E.; Beltrao, J.G.T.; Mastinu, A. Physiological and Qualitative Response of *Cucurbita pepo* L. to Salicylic Acid under Controlled Water Stress Conditions. *Horticulturae* **2022**, *8*, 79. [CrossRef]
6. Naservafaei, S.; Sohrabi, Y.; Moradi, P.; Mac Sweeney, E.; Mastinu, A. Biological Response of *Lallemantia iberica* to Brassinolide Treatment under Different Watering Conditions. *Plants* **2021**, *10*, 496. [CrossRef]
7. Bogati, K.; Walczak, M. The Impact of Drought Stress on Soil Microbial Community, Enzyme Activities and Plants. *Agronomy* **2022**, *12*, 189. [CrossRef]
8. Aghajanlou, F.; Mirdavoudi, H.; Shojaee, M.; Mac Sweeney, E.; Mastinu, A.; Moradi, P. Rangeland Management and Ecological Adaptation Analysis Model for Astragalus curvirostris Boiss. *Horticulturae* **2021**, *7*, 67. [CrossRef]
9. Mirdavoudi, H.; Ghorbanian, D.; Zarekia, S.; Soleiman, J.M.; Ghonchepur, M.; Sweeney, E.M.; Mastinu, A. Ecological Niche Modelling and Potential Distribution of Artemisia sieberi in the Iranian Steppe Vegetation. *Land* **2022**, *11*, 2315. [CrossRef]
10. Moradi, P.; Aghajanloo, F.; Moosavi, A.; Monfared, H.H.; Khalafi, J.; Taghiloo, M.; Khoshzaman, T.; Shojaee, M.; Mastinu, A. Anthropic Effects on the Biodiversity of the Habitats of Ferula gummosa. *Sustainability* **2021**, *13*, 7874. [CrossRef]
11. Danish, S.; Zafar-ul-Hye, M.; Fahad, S.; Saud, S.; Brtnicky, M.; Hammerschmiedt, T.; Datta, R. Drought Stress Alleviation by ACC Deaminase Producing Achromobacter xylosoxidans and Enterobacter cloacae, with and without Timber Waste Biochar in Maize. *Sustainability* **2020**, *12*, 6286. [CrossRef]
12. Hanaka, A.; Ozimek, E.; Reszczynska, E.; Jaroszuk-Scisel, J.; Stolarz, M. Plant Tolerance to Drought Stress in the Presence of Supporting Bacteria and Fungi: An Efficient Strategy in Horticulture. *Horticulturae* **2021**, *7*, 390. [CrossRef]
13. Danish, S.; Zafar-ul-Hye, M.; Hussain, M.; Shaaban, M.; Nunez-Delgado, A.; Hussain, S.; Qayyum, M.F. Rhizobacteria with ACC-Deaminase Activity Improve Nutrient Uptake, Chlorophyll Contents and Early Seedling Growth of Wheat under PEG-Induced Osmotic Stress. *Int. J. Agric. Biol.* **2019**, *21*, 1212–1220. [CrossRef]
14. Anjum, S.A.; Wang, L.C.; Farooq, M.; Hussain, M.; Xue, L.L.; Zou, C.M. Brassinolide Application Improves the Drought Tolerance in Maize Through Modulation of Enzymatic Antioxidants and Leaf Gas Exchange. *J. Agron. Crop Sci.* **2011**, *197*, 177–185. [CrossRef]
15. Taghvaei, M.; Nasrolahizadehi, A.; Mastinu, A. Effect of Light, Temperature, Salinity, and Halopriming on Seed Germination and Seedling Growth of Hibiscus sabdariffa under Salinity Stress. *Agronomy* **2022**, *12*, 2491. [CrossRef]

16. Yousefi, A.R.; Rashidi, S.; Moradi, P.; Mastinu, A. Germination and Seedling Growth Responses of Zygophyllum fabago, Salsola kali L. and Atriplex canescens to PEG-Induced Drought Stress. *Environments* **2020**, *7*, 107. [CrossRef]
17. Yousefvand, P.; Sohrabi, Y.; Heidari, G.; Weisany, W.; Mastinu, A. Salicylic Acid Stimulates Defense Systems in Allium hirtifolium Grown under Water Deficit Stress. *Molecules* **2022**, *27*, 3083. [CrossRef]
18. Zafar-ul-Hye, M.; Danish, S.; Abbas, M.; Ahmad, M.; Munir, T.M. ACC Deaminase Producing PGPR Bacillus amyloliquefaciens and Agrobacterium fabrum along with Biochar Improve Wheat Productivity under Drought Stress. *Agronomy* **2019**, *9*, 343. [CrossRef]
19. Zarei, A.R.; Mahmoudi, M.R. Evaluation of the Effect of Changes in Climatic Variables at Different Levels on the Rate of Potential Evapotranspiration in Arid and Semi-Arid Regions. *Pure Appl. Geophys.* **2022**, *180*, 421–437. [CrossRef]
20. Yan, X.Y.; Zhang, Q.; Ren, X.Y.; Wang, X.Y.; Yan, X.M.; Li, X.Q.; Wang, L.; Bao, L.L. Climatic Change Characteristics towards the "Warming-Wetting" Trend in the Pan-Central-Asia Arid Region. *Atmosphere* **2022**, *13*, 467. [CrossRef]
21. Khaleghnezhad, V.; Yousefi, A.R.; Tavakoli, A.; Farajmand, B.; Mastinu, A. Concentrations-dependent effect of exogenous abscisic acid on photosynthesis, growth and phenolic content of *Dracocephalum moldavica* L. under drought stress. *Planta* **2021**, *253*, 127. [CrossRef]
22. Chaichi, M.; Nemati, A.; Dadrasi, A.; Heydari, M.; Hassanisaadi, M.; Yousefi, A.R.; Baldwin, T.C.; Mastinu, A. Germination of *Triticum aestivum* L.: Effects of Soil-Seed Interaction on the Growth of Seedlings. *Soil Syst.* **2022**, *6*, 37. [CrossRef]
23. Zangani, E.; Afsahi, K.; Shekari, F.; Mac Sweeney, E.; Mastinu, A. Nitrogen and Phosphorus Addition to Soil Improves Seed Yield, Foliar Stomatal Conductance, and the Photosynthetic Response of Rapeseed (*Brassica napus* L.). *Agriculture* **2021**, *11*, 483. [CrossRef]
24. Jam, B.J.; Shekari, F.; Andalibi, B.; Fotovat, R.; Jafarian, V.; Najafi, J.; Uberti, D.; Mastinu, A. Impact of Silicon Foliar Application on the Growth and Physiological Traits of *Carthamus tinctorius* L. Exposed to Salt Stress. *Silicon-Neth* **2022**, *15*, 1235–1245. [CrossRef]
25. Fawad, M.; Khan, M.A.; Wahid, F.; Khan, H.; Gul, B.; Khattak, A.M.; Jamal, A.; Mastinu, A. Irrigation Scheduling and Weed Management: A Sustainable Approach for Managing Broomrape and Other Weeds in Tomato Crop. *Horticulturae* **2022**, *8*, 676. [CrossRef]
26. Abdul Rahman, N.S.N.; Abdul Hamid, N.W.; Nadarajah, K. Effects of Abiotic Stress on Soil Microbiome. *Int. J. Mol. Sci.* **2021**, *22*, 9036. [CrossRef]
27. Siebielec, S.; Siebielec, G.; Klimkowicz-Pawlas, A.; Galazka, A.; Grzadziel, J.; Stuczynski, T. Impact of Water Stress on Microbial Community and Activity in Sandy and Loamy Soils. *Agronomy* **2020**, *10*, 1429. [CrossRef]
28. Motamedi, M.; Zahedi, M.; Karimmojeni, H.; Motamedi, H.; Mastinu, A. Effect of rhizosphere bacteria on antioxidant enzymes and some biochemical characteristics of *Medicago sativa* L. subjected to herbicide stress. *Acta Physiol. Plant.* **2022**, *44*, 84. [CrossRef]
29. Nguyen, L.T.T.; Osanai, Y.; Anderson, I.C.; Bange, M.P.; Tissue, D.T.; Singh, B.K. Flooding and prolonged drought have differential legacy impacts on soil nitrogen cycling, microbial communities and plant productivity. *Plant Soil* **2018**, *431*, 371–387. [CrossRef]
30. Zaheer, M.S.; Ali, H.H.; Soufan, W.; Iqbal, R.; Habib-ur-Rahman, M.; Iqbal, J.; Israr, M.; El Sabagh, A. Potential Effects of Biochar Application for Improving Wheat (*Triticum aestivum* L.) Growth and Soil Biochemical Properties under Drought Stress Conditions. *Land* **2021**, *10*, 1125. [CrossRef]
31. Dai, P.G.; Cong, P.; Wang, P.; Dong, J.X.; Dong, Z.R.; Song, W.J. Alleviating Soil Acidification and Increasing the Organic Carbon Pool by Long-Term Organic Fertilizer on Tobacco Planting Soil. *Agronomy* **2021**, *11*, 2135. [CrossRef]
32. Lu, J.J.; Li, S.P.; Liang, G.P.; Wu, X.P.; Zhang, Q.; Gao, C.H.; Li, J.H.; Jin, D.S.; Zheng, F.J.; Zhang, M.N.; et al. The Contribution of Microorganisms to Soil Organic Carbon Accumulation under Fertilization Varies among Aggregate Size Classes. *Agronomy* **2021**, *11*, 2126. [CrossRef]
33. Foster, E.J.; Hansen, N.; Wallenstein, M.; Cotrufo, M.F. Biochar and manure amendments impact soil nutrients and microbial enzymatic activities in a semi-arid irrigated maize cropping system. *Agric. Ecosyst. Environ.* **2016**, *233*, 404–414. [CrossRef]
34. Gao, Y.; Li, T.X.; Fu, Q.; Li, H.; Liu, D.; Ji, Y.; Li, Q.L.; Cai, Y.P. Biochar application for the improvement ofwater-soil environments and carbon emissions under freeze-thaw conditions: An in-situ field trial. *Sci. Total Environ.* **2020**, *723*, 138007. [CrossRef]
35. Khademalrasoul, A.; Naveed, M.; Heckrath, G.; Kumari, K.G.I.D.; de Jonge, L.W.; Elsgaard, L.; Vogel, H.J.; Iversen, B.V. Biochar Effects on Soil Aggregate Properties Under No-Till Maize. *Soil Sci.* **2014**, *179*, 273–283. [CrossRef]
36. Li, M.; Cai, L. Biochar and Arbuscular Mycorrhizal Fungi Play Different Roles in Enabling Maize to Uptake Phosphorus. *Sustainability* **2021**, *13*, 3244. [CrossRef]
37. Saffari, N.; Hajabbasi, M.A.; Shirani, H.; Mosaddeghi, M.R.; Mamedov, A.I. Biochar type and pyrolysis temperature effects on soil quality indicators and structural stability. *J. Environ. Manag.* **2020**, *261*, 110190. [CrossRef]
38. Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockaday, W.C.; Crowley, D. Biochar effects on soil biota—A review. *Soil Biol. Biochem.* **2011**, *43*, 1812–1836. [CrossRef]
39. Onweremadu, E.U.; Onyia, V.N.; Anikwe, M.A.N. Carbon and nitrogen distribution in water-stable aggregates under two tillage techniques in Fluvisols of Owerri area, southeastern Nigeria. *Soil Tillage Res.* **2007**, *97*, 195–206. [CrossRef]
40. Masto, R.E.; Kumar, S.; Rout, T.K.; Sarkar, P.; George, J.; Ram, L.C. Biochar from water hyacinth (*Eichornia crassipes*) and its impact on soil biological activity. *Catena* **2013**, *111*, 64–71. [CrossRef]
41. Zhang, R.; Qu, Z.; Liu, L.; Yang, W.; Wang, L.; Li, J.; Zhang, D. Soil Respiration and Organic Carbon Response to Biochar and Their Influencing Factors. *Atmosphere* **2022**, *13*, 2038. [CrossRef]

42. Bayu, D.; Tadesse, M.; Amsalu, N. Effect of biochar on soil properties and lead (Pb) availability in a military camp in South West Ethiopia. *Afr. J. Environ. Sci. Technol.* **2016**, *10*, 77–85. [CrossRef]
43. Chun, J.-H.; Kang, Y.-G.; Lee, J.-H.; Yun, Y.-U.; Oh, T.-K.; Yoon, M.-H. The combined effect of nitrogen and biochar amendments on the yield and glucosinolate contents of the Chinese cabbage. *J. King Saud Univ. Sci.* **2022**, *34*, 101799. [CrossRef]
44. Jabborova, D.; Annapurna, K.; Al-Sadi, A.M.; Alharbi, S.A.; Datta, R.; Zuan, A.T.K. Biochar and Arbuscular mycorrhizal fungi mediated enhanced drought tolerance in Okra (*Abelmoschus esculentus*) plant growth, root morphological traits and physiological properties. *Saudi J. Biol. Sci.* **2021**, *28*, 5490–5499. [CrossRef] [PubMed]
45. Laird, D.A.; Fleming, P.; Davis, D.D.; Horton, R.; Wang, B.; Karlen, D.L. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* **2010**, *158*, 443–449. [CrossRef]
46. Li, C.; Zhao, C.; Zhao, X.; Wang, Y.; Lv, X.; Zhu, X.; Song, X. Beneficial Effects of Biochar Application with Nitrogen Fertilizer on Soil Nitrogen Retention, Absorption and Utilization in Maize Production. *Agronomy* **2022**, *13*, 113. [CrossRef]
47. Li, L.; Zhang, Y.J.; Novak, A.; Yang, Y.C.; Wang, J.W. Role of Biochar in Improving Sandy Soil Water Retention and Resilience to Drought. *Water* **2021**, *13*, 407. [CrossRef]
48. Yang, S.; Chen, X.; Jiang, Z.; Ding, J.; Sun, X.; Xu, J. Effects of Biochar Application on Soil Organic Carbon Composition and Enzyme Activity in Paddy Soil under Water-Saving Irrigation. *Int. J. Environ. Res. Public Health* **2020**, *17*, 333. [CrossRef]
49. Zhou, G.; Zhou, X.; Zhang, T.; Du, Z.; He, Y.; Wang, X.; Shao, J.; Cao, Y.; Xue, S.; Wang, H.; et al. Biochar increased soil respiration in temperate forests but had no effects in subtropical forests. *For. Ecol. Manag.* **2017**, *405*, 339–349. [CrossRef]
50. Drover, D.P.; Manner, H. Comparison between Walkley-Black and a Dry Combustion Method for Determining Organic Carbon in a Humic Brown Soil, Papua-New-Guinea. *Commun. Soil Sci. Plant Anal.* **1975**, *6*, 495–500. [CrossRef]
51. Adesodun, J.K.; Mbagwu, J.S.C.; Oti, N. Structural stability and carbohydrate contents of an ultisol under different management systems. *Soil Tillage Res.* **2001**, *60*, 135–142. [CrossRef]
52. Nielsen, S.S. Phenol-Sulfuric Acid Method for Total Carbohydrates. In *Food Analysis Laboratory Manual*, 1st ed.; Nielsen, S.S., Ed.; Springer: Boston, MA, USA, 2010; pp. 47–53. [CrossRef]
53. Whalley, W.R.; Clark, L.J.; Gowing, D.J.G.; Cope, R.E.; Lodge, R.J.; Leeds-Harrison, P.B. Does Soil Strength Play a Role in Wheat Yield Losses Caused by Soil Drying? *Plant Soil* **2006**, *280*, 279–290. [CrossRef]
54. Nguyen, B.T.; Lehmann, J.; Kinyangi, J.; Smernik, R.; Riha, S.J.; Engelhard, M.H. Long-term black carbon dynamics in cultivated soil. *Biogeochemistry* **2008**, *89*, 295–308. [CrossRef]
55. Liang, B.; Lehmann, J.; Solomon, D.; Sohi, S.; Thies, J.E.; Skjemstad, J.O.; Luizão, F.J.; Engelhard, M.H.; Neves, E.G.; Wirick, S. Stability of biomass-derived black carbon in soils. *Geochim. Cosmochim. Acta* **2008**, *72*, 6069–6078. [CrossRef]
56. Deng, L.; Peng, C.; Zhu, G.; Chen, L.; Liu, Y.; Shangguan, Z. Positive responses of belowground C dynamics to nitrogen enrichment in China. *Sci. Total Environ.* **2018**, *616–617*, 1035–1044. [CrossRef]
57. Deng, L.; Peng, C.H.; Kim, D.G.; Li, J.W.; Liu, Y.L.; Hai, X.Y.; Liu, Q.Y.; Huang, C.B.; Shangguan, Z.P.; Kuzyakov, Y. Drought effects on soil carbon and nitrogen dynamics in global natural ecosystems. *Earth-Sci. Rev.* **2021**, *214*, 103501. [CrossRef]
58. Ren, C.; Zhao, F.; Shi, Z.; Chen, J.; Han, X.; Yang, G.; Feng, Y.; Ren, G. Differential responses of soil microbial biomass and carbon-degrading enzyme activities to altered precipitation. *Soil Biol. Biochem.* **2017**, *115*, 1–10. [CrossRef]
59. Hoover, D.L.; Rogers, B.M. Not all droughts are created equal: The impacts of interannual drought pattern and magnitude on grassland carbon cycling. *Glob. Chang. Biol.* **2016**, *22*, 1809–1820. [CrossRef]
60. Xiao, L.; Min, X.X.; Liu, G.B.; Li, P.; Xue, S. Effect of plant-plant interactions and drought stress on the response of soil nutrient contents, enzyme activities and microbial metabolic limitations. *Appl. Soil Ecol.* **2023**, *181*, 104666. [CrossRef]
61. Hashem, A.; Kumar, A.; Al-Dbass, A.M.; Alqarawi, A.A.; Al-Arjani, A.F.; Singh, G.; Farooq, M.; Abd Allah, E.F. Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. *Saudi J. Biol. Sci.* **2019**, *26*, 614–624. [CrossRef]
62. Geng, N.; Kang, X.; Yan, X.; Yin, N.; Wang, H.; Pan, H.; Yang, Q.; Lou, Y.; Zhuge, Y. Biochar mitigation of soil acidification and carbon sequestration is influenced by materials and temperature. *Ecotoxicol. Environ. Saf.* **2022**, *232*, 113241. [CrossRef]
63. Zhang, M.; Riaz, M.; Zhang, L.; El-desouki, Z.; Jiang, C. Biochar Induces Changes to Basic Soil Properties and Bacterial Communities of Different Soils to Varying Degrees at 25 mm Rainfall: More Effective on Acidic Soils. *Front. Microbiol.* **2019**, *10*, 1321. [CrossRef] [PubMed]
64. Spaccini, R.; Mbagwu, J.S.C.; Igwe, C.A.; Conte, P.; Piccolo, A. Carbohydrates and aggregation in lowland soils of Nigeria as influenced by organic inputs. *Soil Tillage Res.* **2004**, *75*, 161–172. [CrossRef]
65. Ouyang, L.; Wang, F.; Tang, J.; Yu, L.; Zhang, R. Effects of biochar amendment on soil aggregates and hydraulic properties. *J. Soil Sci. Plant Nutr.* **2013**, *13*, 991–1002. [CrossRef]
66. Soinne, H.; Hovi, J.; Tammeorg, P.; Turtola, E. Effect of biochar on phosphorus sorption and clay soil aggregate stability. *Geoderma* **2014**, *219*, 162–167. [CrossRef]
67. Ippolito, J.A.; Stromberger, M.E.; Lentz, R.D.; Dungan, R.S. Hardwood Biochar Influences Calcareous Soil Physicochemical and Microbiological Status. *J. Environ. Qual.* **2014**, *43*, 681–689. [CrossRef]
68. Khadem, A.; Raiesi, F. Responses of microbial performance and community to corn biochar in calcareous sandy and clayey soils. *Appl. Soil Ecol.* **2017**, *114*, 16–27. [CrossRef]
69. Jabborova, D.; Wirth, S.; Kannepalli, A.; Narimanov, A.; Desouky, S.; Davranov, K.; Sayyed, R.Z.; El Enshasy, H.; Malek, R.A.; Syed, A.; et al. Co-Inoculation of Rhizobacteria and Biochar Application Improves Growth and Nutrientsin Soybean and Enriches Soil Nutrients and Enzymes. *Agronomy* **2020**, *10*, 1142. [CrossRef]

70. Qin, M.S.; Zhang, Q.; Pan, J.B.; Jiang, S.J.; Liu, Y.J.; Bahadur, A.; Peng, Z.L.; Yang, Y.; Feng, H.Y. Effect of arbuscular mycorrhizal fungi on soil enzyme activity is coupled with increased plant biomass. *Eur. J. Soil Sci.* **2020**, *71*, 84–92. [CrossRef]
71. Liu, L.; Estiarte, M.; Bengtson, P.; Li, J.; Asensio, D.; Wallander, H.; Penuelas, J. Drought legacies on soil respiration and microbial community in a Mediterranean forest soil under different soil moisture and carbon inputs. *Geoderma* **2022**, *405*, 115425. [CrossRef]
72. Ölinger, R.; Beck, T.; Heilmann, B.; Beese, F. Soil Respiration. In *Methods in Soil Biology*; Springer: Berlin/Heidelberg, Germany, 1996; pp. 93–110. [CrossRef]
73. Sackett, T.E.; Basiliko, N.; Noyce, G.L.; Winsborough, C.; Schurman, J.; Ikeda, C.; Thomas, S.C. Soil and greenhouse gas responses to biochar additions in a temperate hardwood forest. *GCB Bioenergy* **2015**, *7*, 1062–1074. [CrossRef]
74. Schindlbacher, A.; Wunderlich, S.; Borken, W.; Kitzler, B.; Zechmeister-Boltenstern, S.; Jandl, R. Soil respiration under climate change: Prolonged summer drought offsets soil warming effects. *Glob. Chang. Biol.* **2012**, *18*, 2270–2279. [CrossRef]
75. Schimel, J.P. Life in Dry Soils: Effects of Drought on Soil Microbial Communities and Processes. *Annu. Rev. Ecol. Evol. Syst.* **2018**, *49*, 409–432. [CrossRef]
76. Meisner, A.; Jacquiod, S.; Snoek, B.L.; ten Hooven, F.C.; van der Putten, W.H. Drought Legacy Effects on the Composition of Soil Fungal and Prokaryote Communities. *Front. Microbiol.* **2018**, *9*, 294. [CrossRef]
77. Sun, S.; Lei, H.; Chang, S.X. Drought differentially affects autotrophic and heterotrophic soil respiration rates and their temperature sensitivity. *Biol. Fertil. Soils* **2019**, *55*, 275–283. [CrossRef]
78. Hinojosa, M.B.; Laudicina, V.A.; Parra, A.; Albert-Belda, E.; Moreno, J.M. Drought and its legacy modulate the post-fire recovery of soil functionality and microbial community structure in a Mediterranean shrubland. *Glob. Chang. Biol.* **2019**, *25*, 1409–1427. [CrossRef]
79. Ficken, C.D.; Warren, J.M. The carbon economy of drought: Comparing respiration responses of roots, mycorrhizal fungi, and free-living microbes to an extreme dry-rewet cycle. *Plant Soil* **2019**, *435*, 407–422. [CrossRef]
80. Liu, S.W.; Zhang, Y.J.; Zong, Y.J.; Hu, Z.Q.; Wu, S.; Zhou, J.; Jin, Y.G.; Zou, J.W. Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: A meta-analysis. *GCB Bioenergy* **2016**, *8*, 392–406. [CrossRef]
81. Hussain, T.; Hussain, N.; Tahir, M.; Raina, A.; Ikram, S.; Maqbool, S.; Fraz Ali, M.; Duangpan, S. Impacts of Drought Stress on Water Use Efficiency and Grain Productivity of Rice and Utilization of Genotypic Variability to Combat Climate Change. *Agronomy* **2022**, *12*, 2518. [CrossRef]
82. Wu, B.J.; Lin, X.; Ali, M.F.; Wang, D. Development of an irrigation regime for winter wheat to save water resources by avoiding irrigation at anthesis stage. *J. Agron. Crop Sci.* **2023**, *209*, 188–203. [CrossRef]
83. Guo, J.; Qu, L.; Wang, L.; Lu, W.; Lu, D. Effects of post-silking drought stress degree on grain yield and quality of waxy maize. *J. Sci. Food Agric.* **2022**, *103*, 1530–1540. [CrossRef]
84. Iseghohi, I.; Abe, A.; Meseka, S.; Mengesha, W.; Gedil, M.; Menkir, A. Effects of drought stress on grain yield, agronomic performance, and heterosis of marker-based improved provitamin-A maize synthetics and their hybrids. *J. Crop Improv.* **2021**, *36*, 239–259. [CrossRef]
85. Saikumar, S.; Varma, C.M.K.; Saiharini, A.; Kalmeshwer, G.P.; Nagendra, K.; Lavanya, K.; Ayyappa, D. Grain yield responses to varied level of moisture stress at reproductive stage in an interspecific population derived from Swarna/O. glaberrima introgression line. *NJAS-Wagening. J. Life Sci.* **2016**, *78*, 111–122. [CrossRef]
86. Duvnjak, J.; Lončarić, A.; Brkljačić, L.; Šamec, D.; Šarčević, H.; Salopek-Sondi, B.; Španić, V. Morpho-Physiological and Hormonal Response of Winter Wheat Varieties to Drought Stress at Stem Elongation and Anthesis Stages. *Plants* **2023**, *12*, 418. [CrossRef] [PubMed]
87. Dong, Z.J.; Li, H.B.; Xiao, J.N.; Sun, J.L.; Liu, R.L.; Zhang, A.P. Soil multifunctionality of paddy field is explained by soil pH rather than microbial diversity after 8-years of repeated applications of biochar and nitrogen fertilizer. *Sci. Total Environ.* **2022**, *853*, 158620. [CrossRef] [PubMed]
88. Thomas, S.C.; Gale, N. Biochar and forest restoration: A review and meta-analysis of tree growth responses. *New For.* **2015**, *46*, 931–946. [CrossRef]
89. Phares, C.A.; Atiah, K.; Frimpong, K.A.; Danquah, A.; Asare, A.T.; Aggor-Woananu, S. Application of biochar and inorganic phosphorus fertilizer influenced rhizosphere soil characteristics, nodule formation and phytoconstituents of cowpea grown on tropical soil. *Heliyon* **2020**, *6*, e05255. [CrossRef]
90. Liu, Y.X.; Lu, H.H.; Yang, S.M.; Wang, Y.F. Impacts of biochar addition on rice yield and soil properties in a cold waterlogged paddy for two crop seasons. *Field Crop. Res.* **2016**, *191*, 161–167. [CrossRef]
91. Simiele, M.; Argentino, O.; Baronti, S.; Scippa, G.S.; Chiatante, D.; Terzaghi, M.; Montagnoli, A. Biochar Enhances Plant Growth, Fruit Yield, and Antioxidant Content of Cherry Tomato (*Solanum lycopersicum* L.) in a Soilless Substrate. *Agriculture* **2022**, *12*, 1135. [CrossRef]
92. Iacomino, G.; Sarker, T.C.; Ippolito, F.; Bonanomi, G.; Vinale, F.; Staropoli, A.; Idbella, M. Biochar and Compost Application either Alone or in Combination Affects Vegetable Yield in a Volcanic Mediterranean Soil. *Agronomy* **2022**, *12*, 1996. [CrossRef]
93. Achakzai, A.G.; Gul, S.; Buriro, A.H.; Khan, H.; Mushtaq, A.; Bano, A.; Agha, S.; Kamran, K.; Ponya, Z.; Ismail, T. Biochar-fertilizer mixture: Does plant life history trait determine fertilizer application rate? *Environ. Pollut. Bioavailab.* **2023**, *35*, 2170282. [CrossRef]
94. Honvault, N.; Houben, D.; Lebrun, M.; Vedere, C.; Nobile, C.; Guidet, J.; Kervroedan, L.; Aubertin, M.L.; Rumpel, C.; Faucon, M.P.; et al. Positive or neutral effects of biochar-compost mixtures on earthworm communities in a temperate cropping system. *Appl. Soil Ecol.* **2023**, *182*, 104684. [CrossRef]

95. Vedere, C.; Lebrun, M.; Biron, P.; Planchais, S.; Bordenave-Jacquemin, M.; Honvault, N.; Firmin, S.; Savoure, A.; Houben, D.; Rumpel, C. The older, the better: Ageing improves the efficiency of biochar-compost mixture to alleviate drought stress in plant and soil. *Sci. Total Environ.* **2023**, *856*, 158920. [CrossRef]
96. Jia, H.J.; Chu, D.P.; You, X.W.; Li, Y.Q.; Huang, C.J.; Zhang, J.L.; Zeng, X.N.; Yao, H.; Zhou, Z.F. Biochar improved the composting quality of seaweeds and cow manure mixture and altered the microbial community. *Front. Microbiol.* **2022**, *13*, 4622. [CrossRef]