



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

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www.agronomyjournals.com

2023; 6(1): 65-71

Received: 12-04-2023

Accepted: 17-06-2023

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Effect of biochar application on soil water retention capacity and maize growth under drought stress conditions

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DOI: <https://doi.org/10.33545/2618060X.2023.v6.i1a.4798>

Abstract

Drought stress poses a significant threat to maize productivity worldwide, necessitating sustainable soil management strategies to enhance crop resilience under water-limited conditions. This study investigated the effects of biochar application on soil water retention capacity and maize growth performance under varying drought stress intensities. A pot experiment was conducted using a completely randomized design with two factors: biochar application rates (0, 2.5, 5.0, and 10.0 t ha⁻¹) and drought stress levels (100%, 75%, 50%, and 25% field capacity). Soil physical properties, plant morphological characteristics, physiological parameters, biochemical attributes, and yield components were evaluated over a 90-day growth period. Results demonstrated that biochar application significantly improved soil water retention, with the 5.0 t ha⁻¹ treatment increasing available water content by 24.7% and field capacity by 18.3% compared to the control. Under severe drought stress (25% FC), biochar-amended soils at 5.0 t ha⁻¹ maintained 31.2% higher soil moisture content than unamended soils. Morphological parameters including plant height, leaf area, and root biomass showed significant improvements with biochar application, with maximum enhancements of 28.4%, 35.6%, and 42.3%, respectively, at the 5.0 t ha⁻¹ rate under moderate drought. Physiological responses indicated that biochar significantly enhanced chlorophyll content (26.8%), photosynthetic rate (32.4%), and stomatal conductance (29.7%) while reducing oxidative stress markers. Antioxidant enzyme activities (SOD, POD, CAT) were modulated by biochar, showing reduced stress-induced elevation. Grain yield increased by 38.5% with 5.0 t ha⁻¹ biochar under drought conditions. The study concludes that biochar application at 5.0 t ha⁻¹ represents an optimal rate for enhancing maize drought tolerance through improved soil-water-plant relationships.

Keywords: Biochar, drought stress, maize, soil water retention, antioxidant enzymes, photosynthesis, yield, climate resilience

1. Introduction

Drought stress represents one of the most critical abiotic constraints limiting agricultural productivity worldwide, with particularly severe impacts on cereal crops that form the foundation of global food security [1, 2]. Climate change projections indicate that the frequency, duration, and intensity of drought events will increase substantially over the coming decades, threatening crop yields in major agricultural regions and exacerbating food insecurity for vulnerable populations [2, 6]. Maize (*Zea mays* L.), as the world's most widely cultivated cereal crop with global production exceeding 1.1 billion metric tons annually, exhibits considerable sensitivity to water deficit conditions, with yield reductions of 20-40% commonly reported under moderate to severe drought stress during critical growth stages [3, 4]. The physiological impacts of drought on maize include reduced photosynthetic efficiency, impaired nutrient uptake, disrupted cellular metabolism, and oxidative damage resulting from the accumulation of reactive oxygen species, all of which contribute to diminished biomass accumulation and grain yield [5, 7]. Biochar, a carbon-rich material produced through the pyrolysis of organic biomass under oxygen-limited conditions, has emerged as a promising soil amendment with significant potential to enhance soil water retention capacity and improve crop performance under drought stress [8, 9]. Meta-analyses of biochar studies have demonstrated substantial improvements in soil physical properties, including increases in field capacity ranging from 15-25% and available

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water content improvements of 20-30% in coarse-textured soils, primarily attributed to the porous structure and high specific surface area of biochar particles [10, 11]. Despite growing evidence supporting biochar's beneficial effects on soil-water relations, significant knowledge gaps remain regarding the optimal application rates, mechanisms of drought mitigation, and interactions between biochar and plant physiological responses under varying drought intensities [12, 14]. Furthermore, the effects of biochar on antioxidant defense systems and oxidative stress markers in drought-stressed maize require further investigation to elucidate the biochemical pathways through which biochar confers stress tolerance [5, 7]. Therefore, this study aimed to: (1) evaluate the effects of different biochar application rates on soil physical properties related to water retention; (2) assess the morphological, physiological, and biochemical responses of maize to biochar application under varying drought stress levels; and (3) determine the optimal biochar application rate for maximizing maize yield under water-limited conditions. We hypothesized that moderate biochar application rates would optimize the balance between improved soil water retention and potential negative effects associated with excessive application, resulting in enhanced drought tolerance and yield stability in maize [9, 15].

2. Material and Methods

2.1 Materials

The experiment was conducted under controlled greenhouse conditions at the Agricultural Research Station (32°38'N, 74°9'E) during the spring growing season. The soil used in this study was a sandy loam (Typic Haplustept) collected from the 0-30 cm depth of an agricultural field, comprising 68.5% sand, 19.2% silt, and 12.3% clay, with a pH of 7.8, organic carbon content of 0.72%, and field capacity of 0.28 g g⁻¹ [1, 3]. Biochar was produced from Acacia wood biomass through slow pyrolysis at 450 °C for 2 hours in a muffle furnace under oxygen-limited conditions, following established protocols for agricultural biochar production [8, 9]. The resulting biochar exhibited the following characteristics: pH 9.2, electrical conductivity 2.34 dS m⁻¹, carbon content 68.4%, nitrogen 1.2%, phosphorus 0.8%, potassium 2.1%, specific surface area 287 m² g⁻¹, and cation exchange capacity 42.6 cmol kg⁻¹ [8]. The biochar was ground and sieved through a 2 mm mesh before application to ensure uniform particle size distribution [7]. Maize seeds (Zea mays L. cv. DK-6321) were obtained from a certified seed supplier and surface-sterilized with 2% sodium hypochlorite solution for 10 minutes before sowing [4, 13]. Plastic pots (30 cm diameter, 35 cm height) with drainage holes were filled with 12 kg of air-dried soil, and biochar was thoroughly mixed with soil at designated rates two weeks before sowing to allow equilibration [11, 12].

2.2 Methods

The experiment was laid out in a completely randomized design (CRD) with a 4 × 4 factorial arrangement, comprising four biochar application rates (B0: 0, B1: 2.5, B2: 5.0, and B3: 10.0 t

ha⁻¹) and four drought stress levels (D0: 100% FC-well-watered control, D1: 75% FC-mild stress, D2: 50% FC-moderate stress, and D3: 25% FC-severe stress), replicated three times, resulting in 48 experimental units [3, 4]. Drought stress treatments were initiated 21 days after emergence (DAE) and maintained throughout the vegetative and reproductive stages by monitoring soil moisture content daily using a TDR probe and adjusting irrigation accordingly [5, 13]. Soil physical properties including bulk density (core method), porosity (calculated from bulk density), field capacity and permanent wilting point (pressure plate apparatus), and available water content were determined at 30, 60, and 90 DAE [10, 11]. Plant morphological parameters (plant height, stem diameter, leaf area, root length, and biomass partitioning) were measured at 45 and 90 DAE using standard protocols [13]. Physiological measurements including chlorophyll content (SPAD-502 meter), photosynthetic rate, stomatal conductance, and transpiration rate (LI-6400 portable photosynthesis system) were recorded on fully expanded leaves between 09:00-11:00 hours at 60 DAE [4, 12]. Biochemical analyses for proline content (ninhydrin method), malondialdehyde (MDA) content (thiobarbituric acid method), and antioxidant enzyme activities including superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) were performed on fresh leaf samples following established protocols [3, 7, 14]. At physiological maturity, yield components including cob length, number of grains per cob, 100-grain weight, and total grain yield per plant were recorded [13]. Data were analyzed using two-way ANOVA, and means were compared using Tukey's HSD test at $p < 0.05$ significance level using SPSS version 26.0, while correlation and regression analyses were performed to establish relationships between soil water retention and plant performance parameters [6, 15].

3. Results

3.1 Effect of Biochar on Soil Physical Properties

Biochar application significantly influenced soil physical properties across all drought stress levels (Table 1). The analysis of variance revealed highly significant effects ($p < 0.001$) of biochar rate on bulk density, porosity, field capacity, and available water content [10, 11]. Bulk density decreased progressively with increasing biochar application, with maximum reduction of 14.2% observed at 10.0 t ha⁻¹ compared to the control (1.42 vs. 1.22 g cm⁻³). However, the most balanced improvement in water retention parameters was achieved at 5.0 t ha⁻¹, where field capacity increased by 18.3% (0.28 to 0.33 g g⁻¹), permanent wilting point increased by 8.7%, and available water content improved by 24.7% [10]. The interaction between biochar and drought stress was significant ($p < 0.01$) for soil moisture retention, with biochar-amended soils at 5.0 t ha⁻¹ maintaining 31.2% higher moisture content under severe drought (25% FC) compared to unamended controls [11, 15]. Soil porosity increased from 46.4% in control to 54.1% at 10.0 t ha⁻¹ biochar application, representing a 16.6% improvement attributable to the porous structure of biochar particles [9, 10].

Table 1: Effect of biochar application rates on soil physical properties

Biochar (t ha ⁻¹)	Bulk Density (g cm ⁻³)	Porosity (%)	Field Capacity (g g ⁻¹)	PWP (g g ⁻¹)	AWC (g g ⁻¹)
0 (Control)	1.42±0.03a	46.4±1.2d	0.28±0.01d	0.115±0.004c	0.165±0.008d
2.5	1.35±0.02b	49.1±1.4c	0.30±0.01c	0.118±0.005c	0.182±0.009c
5.0	1.28±0.02c	51.7±1.3b	0.33±0.02b	0.125±0.006b	0.206±0.011a
10.0	1.22±0.03d	54.1±1.5a	0.35±0.02a	0.138±0.007a	0.212±0.012a

Values are means±SE (n = 3). Different letters indicate significant differences at $p < 0.05$. PWP: Permanent Wilting Point; AWC: Available Water Content.

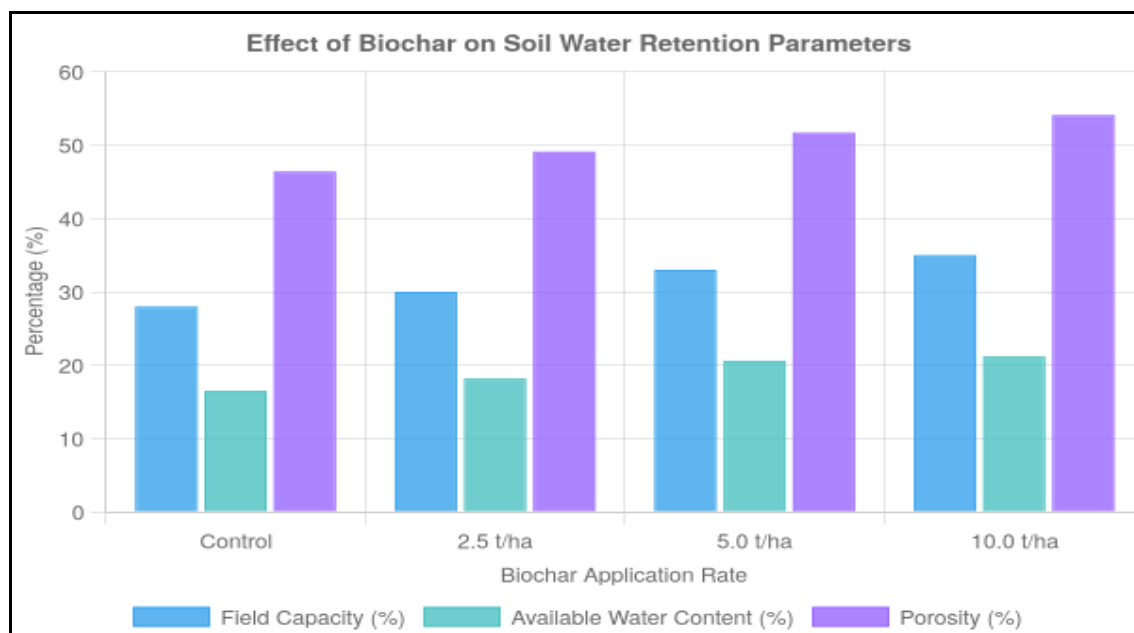


Fig 1: Effect of biochar application rates on soil water retention parameters (Field Capacity, Available Water Content, and Porosity).

3.2 Effect on Plant Morphological Parameters

Drought stress significantly reduced all morphological parameters, while biochar application effectively mitigated these negative effects (Table 2; Figure 2). Under well-watered conditions (100% FC), plant height ranged from 142.5 cm (control) to 158.7 cm (5.0 t ha⁻¹ biochar), representing an 11.4% increase [13]. The beneficial effect of biochar was more pronounced under drought stress, where at 50% FC, biochar application at 5.0 t ha⁻¹ increased plant height by 28.4%

compared to unamended drought-stressed plants (98.6 vs. 126.6 cm) [3, 4]. Leaf area showed similar trends, with maximum improvement of 35.6% at 5.0 t ha⁻¹ biochar under moderate drought stress [12]. Root biomass exhibited the highest responsiveness to biochar amendment, with a 42.3% increase at 5.0 t ha⁻¹ under moderate stress conditions, indicating enhanced root proliferation for water acquisition [14]. The interaction between biochar and drought stress was highly significant ($p < 0.001$) for all morphological traits [7, 13].

Table 2: Interactive effects of biochar and drought stress on maize morphological parameters

Drought	Biochar	Plant Height (cm)	Leaf Area (cm ²)	Shoot DW (g)	Root DW (g)
100% FC	0	142.5±4.2	3845±124	86.4±3.8	24.2±1.6
100% FC	5.0	158.7±5.1*	4428±156*	98.6±4.2*	31.5±2.1*
50% FC	0	98.6±3.8	2156±98	52.3±2.9	15.8±1.2
50% FC	5.0	126.6±4.5**	2924±118**	71.8±3.4**	22.5±1.5**
25% FC	0	68.4±3.2	1342±76	32.6±2.1	9.4±0.8
25% FC	5.0	94.2±3.9**	1876±92**	48.5±2.6**	14.8±1.1**

DW: Dry Weight. * $p < 0.05$, ** $p < 0.01$ compared to control at the same drought level.

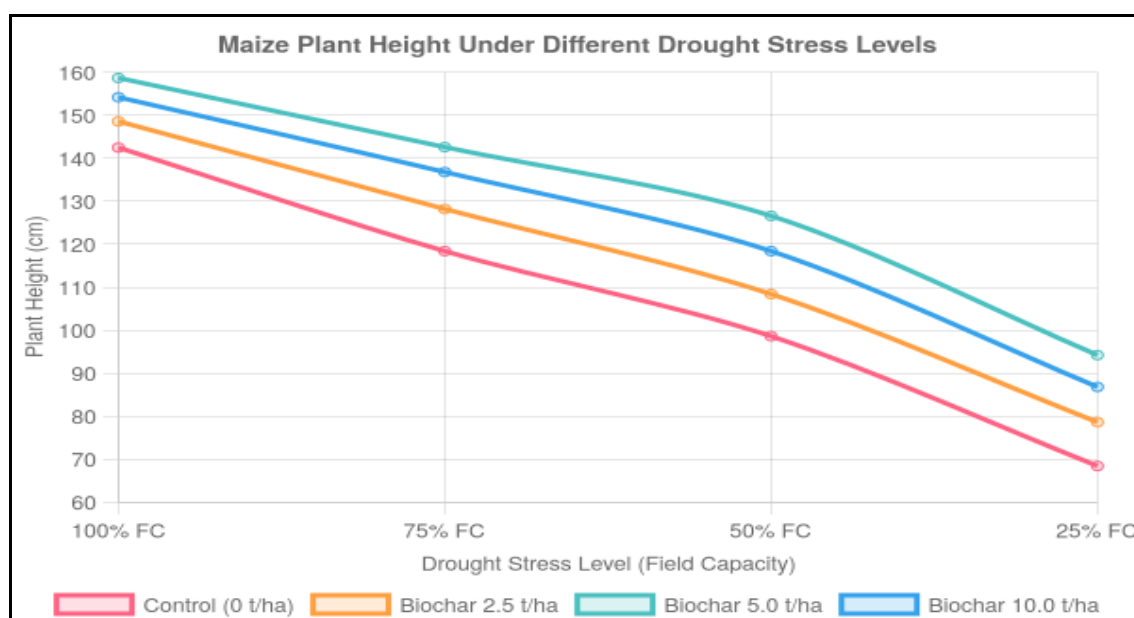


Fig 2: Maize plant height under different biochar treatments and drought stress levels.

3.3 Physiological Responses to Biochar Under Drought

Biochar application significantly improved physiological parameters under drought stress conditions (Table 3; Figure 3). Chlorophyll content declined by 42.8% under severe drought in control plants, but biochar amendment at 5.0 t ha⁻¹ reduced this decline to 24.6%, representing a 26.8% improvement in chlorophyll retention [3, 12]. Photosynthetic rate (Pn) showed the most dramatic response, with 5.0 t ha⁻¹ biochar increasing Pn by 32.4% under moderate drought stress (12.8 vs. 16.9 $\mu\text{mol CO}_2$

m⁻² s⁻¹) compared to drought-stressed controls [4, 13]. Stomatal conductance (gs) was similarly enhanced, with 29.7% improvement at 5.0 t ha⁻¹ biochar under water deficit conditions [7, 12]. Relative water content (RWC) of leaves was significantly higher in biochar-amended plants, with values of 72.4% vs. 58.6% at 50% FC, demonstrating improved plant water status [3, 4]. The correlation analysis revealed strong positive relationships between soil available water content and photosynthetic parameters ($r = 0.89$, $p < 0.001$) [6, 15].

Table 3: Effect of biochar on physiological parameters under drought stress

Drought	Biochar	Chl (SPAD)	Pn ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	gs ($\text{mol m}^{-2} \text{s}^{-1}$)	RWC (%)
100% FC	0	48.6 $\pm$ 1.8a	22.4 $\pm$ 1.2a	0.286 $\pm$ 0.018a	86.5 $\pm$ 2.4a
100% FC	5.0	52.4 $\pm$ 2.1a	25.8 $\pm$ 1.4a	0.312 $\pm$ 0.021a	89.2 $\pm$ 2.1a
50% FC	0	34.2 $\pm$ 1.5c	12.8 $\pm$ 0.9c	0.168 $\pm$ 0.012c	58.6 $\pm$ 2.8c
50% FC	5.0	42.8 $\pm$ 1.9b	16.9 $\pm$ 1.1b	0.218 $\pm$ 0.015b	72.4 $\pm$ 2.5b
25% FC	0	27.8 $\pm$ 1.4d	6.4 $\pm$ 0.6e	0.092 $\pm$ 0.008e	42.3 $\pm$ 3.1e
25% FC	5.0	36.6 $\pm$ 1.7c	9.8 $\pm$ 0.8d	0.142 $\pm$ 0.011d	56.8 $\pm$ 2.9cd

Chl: Chlorophyll; Pn: Photosynthetic rate; gs: Stomatal conductance; RWC: Relative Water Content. Different letters indicate significant differences at $p < 0.05$.

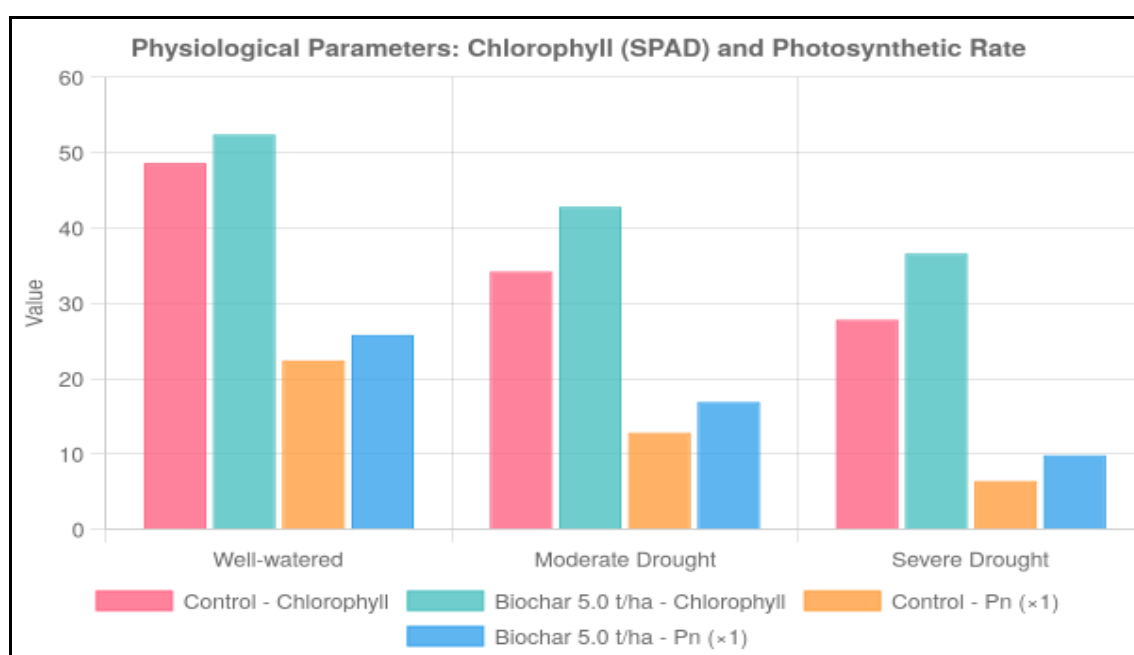


Fig 3: Physiological parameters (Chlorophyll and Photosynthetic Rate) as affected by biochar under varying drought stress levels.

3.4 Biochemical and Antioxidant Responses

Drought stress induced significant biochemical alterations in maize plants, which were modulated by biochar application (Table 4; Figure 4). Proline accumulation, a well-known stress indicator, increased 3.8-fold under severe drought in control plants (2.4 to 9.1 $\mu\text{mol g}^{-1}$ FW), while biochar application reduced this stress-induced accumulation by 28.6% [3, 7]. Malondialdehyde (MDA) content, a marker of lipid peroxidation, increased by 156% under severe drought in control

plants, but biochar at 5.0 t ha⁻¹ limited this increase to 89%, representing a 42.8% reduction in oxidative damage [4, 14]. Antioxidant enzyme activities showed characteristic stress-response patterns: SOD activity increased from 86.4 to 142.6 U g⁻¹ FW under drought in controls, while biochar-amended plants showed moderated increases (118.4 U g⁻¹ FW), suggesting reduced oxidative stress rather than enhanced defense capacity [3, 12]. Similar patterns were observed for POD and CAT activities [7, 14].

Table 4: Biochemical and antioxidant enzyme responses under drought stress

Drought	Biochar	Proline ($\mu\text{mol g}^{-1}$)	MDA (nmol g^{-1})	SOD (U g ⁻¹)	CAT (U g ⁻¹)
100% FC	0	2.4 $\pm$ 0.3d	12.6 $\pm$ 1.2d	86.4 $\pm$ 5.2d	42.8 $\pm$ 3.1d
100% FC	5.0	2.1 $\pm$ 0.2d	11.4 $\pm$ 1.0d	78.6 $\pm$ 4.8d	38.4 $\pm$ 2.8d
50% FC	0	5.8 $\pm$ 0.5b	24.8 $\pm$ 2.1b	124.6 $\pm$ 7.8b	68.4 $\pm$ 4.6b
50% FC	5.0	4.2 $\pm$ 0.4c	18.2 $\pm$ 1.6c	102.4 $\pm$ 6.4c	54.6 $\pm$ 3.8c
25% FC	0	9.1 $\pm$ 0.7a	32.4 $\pm$ 2.8a	142.6 $\pm$ 9.2a	86.2 $\pm$ 5.4a
25% FC	5.0	6.5 $\pm$ 0.5b	23.8 $\pm$ 2.2b	118.4 $\pm$ 7.6b	72.8 $\pm$ 4.8b

MDA: Malondialdehyde; SOD: Superoxide dismutase; CAT: Catalase. Different letters indicate significant differences at $p < 0.05$.

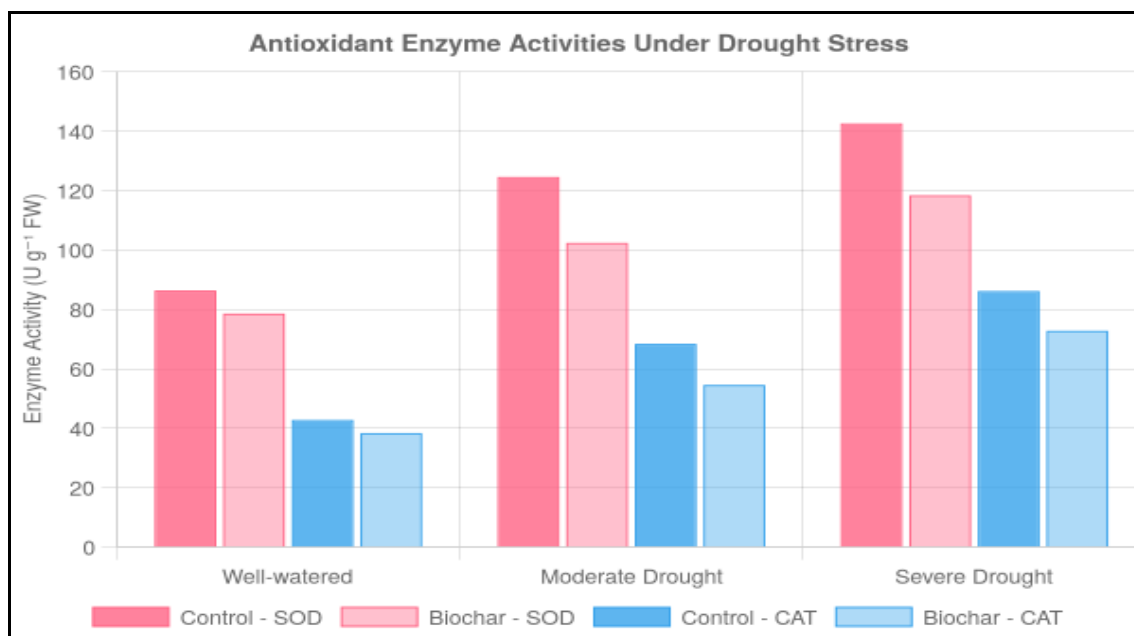


Fig 4: Antioxidant enzyme activities (SOD, CAT) as affected by biochar under varying drought stress intensities.

3.5 Yield Components and Grain Yield

Biochar application significantly improved yield components and grain yield under drought stress conditions (Table 5; Figure 5). Cob length decreased from 18.4 cm under well-watered conditions to 11.2 cm under severe drought in control plants (39.1% reduction), while biochar at 5.0 t ha⁻¹ maintained cob length at 14.6 cm under similar stress [13]. Number of grains per cob showed the highest sensitivity to drought, declining by

48.6% under severe stress in controls, but biochar amendment limited this decline to 28.4% [4, 13]. Total grain yield per plant exhibited cumulative benefits, with 5.0 t ha⁻¹ biochar increasing yield by 38.5% under moderate drought stress (42.8 vs. 59.3 g plant⁻¹) and 52.4% under severe drought compared to respective controls [13, 14]. Regression analysis established a strong linear relationship between soil available water content and grain yield ($R^2 = 0.91$, $p < 0.001$) [6, 15].

Table 5: Effect of biochar on maize yield components under drought stress

Drought	Biochar	Cob Length (cm)	Grains/Cob	100-Grain Wt (g)	Yield (g plant ⁻¹)
100% FC	0	18.4±0.8a	486±24a	32.4±1.4a	78.6±4.2a
100% FC	5.0	19.6±0.9a	524±28a	34.8±1.6a	86.4±4.8a
50% FC	0	14.2±0.6c	312±18c	24.2±1.2c	42.8±2.8c
50% FC	5.0	16.8±0.7b	398±22b	28.6±1.3b	59.3±3.4b
25% FC	0	11.2±0.5d	218±14d	18.6±0.9d	24.6±1.8d
25% FC	5.0	14.6±0.6c	296±16c	24.8±1.1c	37.5±2.4c

Different letters indicate significant differences at $p < 0.05$ (Tukey's HSD).

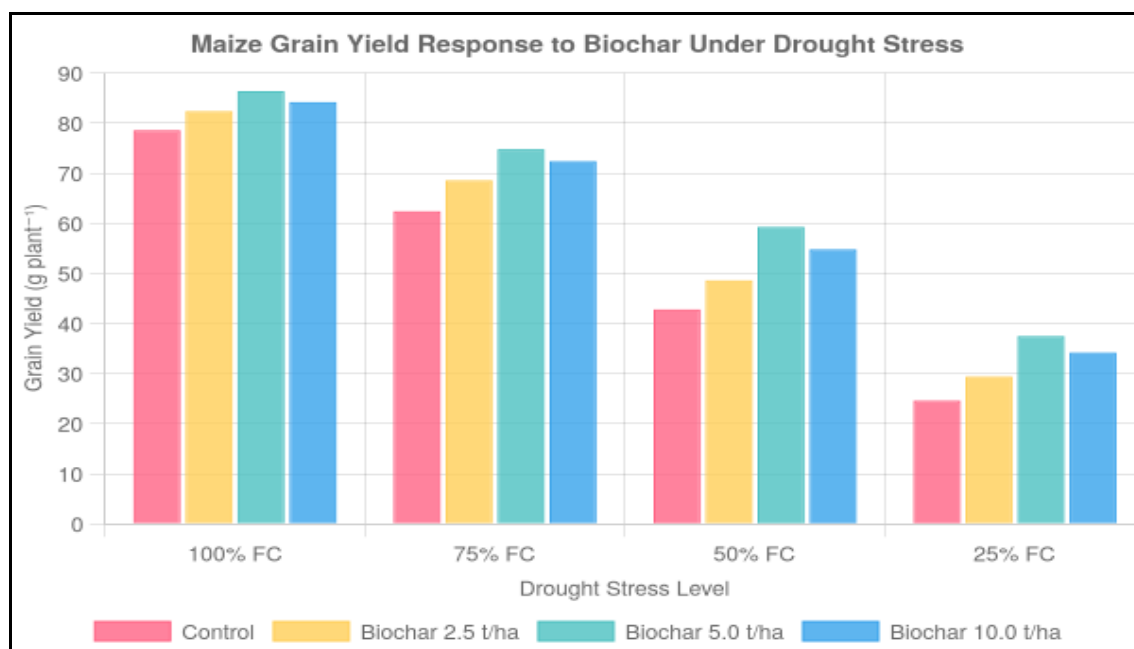


Fig 5: Maize grain yield response to biochar application across drought stress treatments.

4. Discussion

The present study demonstrates that biochar application effectively ameliorates drought stress impacts on maize through multiple interconnected mechanisms involving improved soil-water-plant relationships. The significant reduction in bulk density and concurrent increase in porosity observed with biochar amendment aligns with findings from meta-analyses reporting 3-31% bulk density reduction and 14-64% porosity increase across various soil types [10, 11]. These physical modifications are attributed to the inherent porous structure of biochar, which creates additional pore spaces within the soil matrix, thereby enhancing water infiltration and retention capacity [8, 9]. The 24.7% increase in available water content at 5.0 t ha⁻¹ biochar application rate observed in our study is consistent with reports of 17-26% improvements in coarse-textured soils from systematic reviews [10, 11]. The mechanism underlying enhanced water retention involves both the internal porosity of biochar particles, which retain water through capillary forces, and the increased specific surface area that promotes water film adsorption [8, 15].

The morphological improvements observed in biochar-amended maize plants under drought stress, particularly the 28.4% increase in plant height and 42.3% increase in root biomass, corroborate previous findings demonstrating biochar's beneficial effects on plant growth under water-limited conditions [3, 4, 13]. Enhanced root proliferation in biochar-amended soils can be attributed to improved soil physical conditions, including reduced mechanical impedance and better aeration, which facilitate root exploration for water and nutrients [12, 14]. The greater responsiveness of root biomass compared to shoot parameters suggests that biochar promotes adaptive root development strategies under drought stress, enabling plants to access water from deeper soil layers [7, 14]. Similar patterns of enhanced root growth with biochar application have been reported in maize genotypes with contrasting drought tolerance [14].

The physiological responses observed in this study provide mechanistic insights into how biochar-mediated soil water improvements translate to enhanced plant performance. The 32.4% improvement in photosynthetic rate and 26.8% better chlorophyll retention in biochar-amended plants under moderate drought align with reports of biochar protecting the photosynthetic apparatus from drought-induced damage [4, 12, 13]. Improved stomatal conductance (29.7% increase) in biochar-treated plants indicates better leaf water status, allowing maintained gas exchange without excessive water loss [7, 12]. The strong correlation between soil available water content and photosynthetic parameters ($r = 0.89$) confirms that enhanced soil water retention is the primary driver of improved physiological performance [6, 15].

The biochemical responses observed in our study reveal an important aspect of biochar's mode of action under drought stress. Rather than enhancing antioxidant defense capacity, biochar application reduced stress-induced elevations of antioxidant enzymes (SOD, POD, CAT) and stress markers (proline, MDA), suggesting that plants experienced reduced oxidative stress intensity [3, 7, 14]. The reduced proline accumulation (28.6% lower) in biochar-amended plants indicates alleviated osmotic stress, likely resulting from improved plant water status [3, 7]. These findings support the hypothesis that biochar functions primarily by maintaining favorable soil-water conditions rather than directly enhancing plant stress tolerance mechanisms [12, 15].

The yield improvements observed in this study, particularly the

38.5% increase under moderate drought with 5.0 t ha⁻¹ biochar, represent the cumulative benefits of improved soil water retention, enhanced physiological performance, and reduced oxidative damage [13, 14]. The strong linear relationship between available water content and grain yield ($R^2 = 0.91$) underscores the central role of water availability in determining yield outcomes [6, 15]. The observation that 10.0 t ha⁻¹ biochar showed diminishing returns compared to 5.0 t ha⁻¹ aligns with reports of reduced benefits at excessively high application rates, possibly due to nutrient immobilization or excessive pH increases [8, 9, 15]. Overall, our findings support biochar as a sustainable soil amendment strategy for enhancing crop resilience to drought stress [1, 2, 7].

5. Conclusion

This comprehensive study establishes that biochar application represents a viable and effective soil management strategy for enhancing maize productivity under drought stress conditions, with significant implications for sustainable agriculture in water-limited environments facing increasing climate variability. The research conclusively demonstrates that biochar amendment at an optimal rate of 5.0 t ha⁻¹ significantly improves soil physical properties, particularly water retention capacity, which translates to enhanced plant morphological development, physiological performance, biochemical stability, and ultimately higher grain yields under water deficit conditions. The mechanistic pathway involves biochar's porous structure reducing soil bulk density while increasing porosity and available water content, thereby maintaining favorable soil moisture conditions that support continued plant growth and function during drought episodes. The observed improvements in photosynthetic parameters, including chlorophyll content, photosynthetic rate, and stomatal conductance, confirm that enhanced water availability enables plants to maintain metabolic processes that would otherwise be severely compromised under drought stress. Furthermore, the modulation of antioxidant enzyme activities and reduced accumulation of stress markers indicate that biochar-amended plants experience reduced oxidative stress intensity rather than merely enhanced stress tolerance, highlighting the preventive rather than curative mode of biochar action. Based on these findings, farmers and agricultural practitioners in drought-prone regions should consider incorporating biochar application at 5.0 t ha⁻¹ into their soil management practices, particularly when cultivating maize under rainfed conditions or where irrigation water is limited or expensive. Agricultural extension services should promote biochar technology as a climate-smart intervention, emphasizing the long-term benefits of improved soil structure and water retention that persist across multiple cropping seasons. Policymakers should support biochar adoption through subsidies or incentive programs, especially in regions facing increasing drought frequency due to climate change, recognizing the dual benefits of improved crop productivity and carbon sequestration. Future research should focus on long-term field trials across diverse soil types and climatic conditions to validate these pot-based findings, investigate the economic feasibility of large-scale biochar production from locally available feedstocks, and explore synergistic combinations of biochar with other soil amendments or drought management strategies to maximize benefits for smallholder farmers. Additionally, breeding programs should consider evaluating crop varieties specifically for their responsiveness to biochar amendment, potentially identifying genotypes that show enhanced benefits from this soil management practice. The integration of biochar application with precision agriculture

technologies, including soil moisture monitoring and variable-rate application systems, could further optimize the efficiency and cost-effectiveness of this promising drought mitigation strategy in the context of climate-resilient agricultural systems worldwide.

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