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Assessing the impact of water stress and neem chip biochar application on soil properties, growth characteristics, and yield of *Cucumis sativus* L.

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Abstract

Modern agricultural farming faces significant challenges, particularly regarding efficient water use as water scarcity has become an increasingly pressing issue under changing climatic conditions. Biochar, an organic amendment, was explored to test whether it can improve water use efficiency and ultimately crop productivity. A glasshouse experiment arranged in a completely randomized design was used to determine the effect of neem-chip biochar on soil properties, growth characteristics, water use efficiency and cucumber yield under water stress conditions. It consisted of three levels of biochar (0, 15, and 30 ton ha^{-1}) and three levels of water stress (50%, 75%, and 100% Field Capacity), resulting in nine treatments and three replications. Water stress levels did not affect soil bulk density or porosity, whereas increasing levels of biochar significantly reduced bulk density ($F(2, 18) = 24.91$, $P < 0.001$) and increased porosity ($F(2, 18) = 16.58$, $P < 0.001$). Biochar effectively regulated soil pH, increasing it from 7.28 to 7.86. Incremental biochar doses raised soil organic carbon (SOC) from 17.22 to 20.78 g kg^{-1}, total nitrogen (TN) from 0.75 to 2.43 g kg^{-1}, available phosphorus (P) from 24.6 to 40.0 mg kg^{-1}, and exchangeable potassium (K) from 0.55 to 1.12 cmol kg^{-1}. Water stress and its interaction with biochar had a significant effect ($F(4, 18) = 3.37$, $P < 0.05$) on exchangeable K. Water stress notably impacted leaf development, vine elongation, and stem girth increase, with optimum water availability at 100% Field Capacity promoting greater growth and development. Furthermore, biochar statistically increased cucumber fruit yield (g $plant^{-1}$) under moderate water stress by 186% ($F(2, 18) = 9.42$, $P < 0.01$), with a higher water-use efficiency. This study showed that biochar application offers a great potential to improve the growth and yield of cucumber under moderate water stress conditions.

1. Introduction

Cucumbers (*Cucumis sativus* L.) play a pivotal role in global agriculture, serving as a significant source of food and revenue within the Cucurbitaceae family. With 97 genera and 1000 species, including watermelon, squash, and zucchini, the family thrives in diverse climates, characterized by large, fleshy fruits and climbing tendrils (Renner and Schaefer, 2016). Cucumber is a low-calorie vegetable (15 calories/100g) that is 95% water, an ideal hydrator, rich in antioxidants, potassium, vitamin K (Pandey et al., 2020), vitamins B and C, plus minerals like calcium, phosphorus, iron, and potassium (Dhanusri et al., 2023). In the modern era, cucumber farming has undergone a transformative evolution, embracing cutting-edge technologies to maximize productivity. Greenhouses, hydroponic systems, and vertical farming have become essential components of contemporary cucumber cultivation, enabling year-round production across diverse climates (Ampim et al., 2022). However, as cucumber farming modernizes, it faces challenges, particularly in water resource management. With cucumbers being notoriously thirsty plants, water-efficient practices become not just desirable, but essential, lest the flourishing cucumber fields of today wilt into a parched tomorrow.

Drought is an environmental stress that poses a threat to crop production worldwide. Its frequency and severity are expected to increase in many regions in the future due to decreased precipitation and increased evaporation resulting from global climate change (Dai et al., 2018). About two-thirds of the global population will be affected by increasing drought (Naumann et al., 2018), which threatens food security and forest health (Choat et al., 2018). The specter of water scarcity looms large in agricultural landscapes, leading to “water stress” in plants. Water stress results in significant declines in water potential and relative water content (RWC) and directly affects many aspects of plant physiology (Correia et al., 2006). Plant biochemical and physiological processes such as stomatal response, ROS

(Reactive Oxygen Species) scavenging, metabolic changes, respiration and photosynthesis are all affected when plants are subjected to water stress, and these collective responses lead to growth adjustment in plants as an adaptive response for survival (Khan et al., 2024). To mitigate the damage from ROS, plants respond by producing enzymatic antioxidants like superoxide dismutase (SOD), ascorbate peroxidase (APX), catalase (CAT), as well as non-enzymatic antioxidants like ascorbic acid and glutathione (Xu et al., 2008). It has been reported that application of biochar to soil stimulates enzymatic induction which eventually leads to the reduction of oxidative damage and promotes growth along with stress tolerance (Fareed et al., 2024).

Currently there is worldwide concern to improve yields of the agricultural crops under water stress without compromising the environmental quality. In the pursuit of water-efficient practices, biochar emerges as a promising solution to address the challenges posed by water scarcity in cucumber farming. Biochar is a carbon-rich product of the thermal degradation of organic wastes such as livestock manures, sewage sludge, crop residues, and composts, under anaerobic conditions. Its application is becoming popular to enhance crop production, particularly in soils under environmental stresses such as heavy metals, drought, or salinity (Yildirim et al., 2021). Although biochar lacks effective N content, it plays an important role in influencing soil nitrogen's effectiveness by directly or indirectly exerting influence on processes such as nitrification, mineralization and N fixation (Wang et al., 2023). Land application of biochar can permanently sequester C in the soil and reduce net emissions of greenhouse gases (Laird, 2008), increase crop production through improved nutrient availability and soil physical, chemical, and biological properties (Asai et al., 2009).

The application of biochar to soils can improve aggregate stability (Joseph et al., 2019; Odugbenro et al., 2020), water holding capacity (Karhu et al., 2011), soil health, fertilizer utilization and water use efficiency (Munoo et al., 2018), and in a few investigations, biochar application was found to mitigate the negative effect of water stress on plant growth (Abdou et al., 2024). Biochar contains organic nitrogen, potassium, and labile phosphorus in the bioavailable forms, which, when released to soils, enhance the supply of nutrients to roots for plant uptake, which enhances the growth and yield of crops under water stress (Khan et al., 2021). Although drought has been extensively studied in many crops, little research has been conducted to investigate the impact of different water stress levels on cucumber production when combined with biochar. As cucumber farming grapples with substantial water needs, effective water resource management becomes paramount. Hence, we hypothesized that incremental application of neem chip biochar would improve water-stress tolerance and affect cucumber growth and yield. Therefore, the objectives of this study were to determine the impact of different biochar application rates and water stress levels on some soil physical and chemical properties, and to evaluate the combined effects of biochar and water stress on the growth and yield of cucumber.

2. Materials and methods

2.1. Plant materials, Site and Experimental design

The experiment was conducted in the glasshouse of the Department of Soil Resources Management, Faculty of Agriculture, University of Ibadan, Nigeria. It lies between latitude 7° 27' 06" N and longitude 3° 53' 46" E and has an elevation of 234 m above sea level. The Experiment lasted from October to December, 2023. Cucumber (*Cucumis sativus* L.), Darina F1 Hybrid variety, was used as test crop. The cucumber seeds were sown to approximately 2 cm depth in 30 cm-height and 28 cm-diameter pots at 2 seeds per pot. After germination (four days after sowing) a uniform population of one seedling per pot was maintained.

The study was laid out in a completely randomized design (CRD) with 3 replications and 2 factors: water stress and biochar. The experiment consisted of 9 treatments containing all possible combinations of the three water stress levels (50, 75, and 100% FC) and three biochar application rates (0, 15, and 30 ton ha^{-1}). There were 27 experimental pots in total, each filled with 5 kg of soil and placed randomly on iron benches in the glasshouse. The experimental layout is shown in Fig. 1.

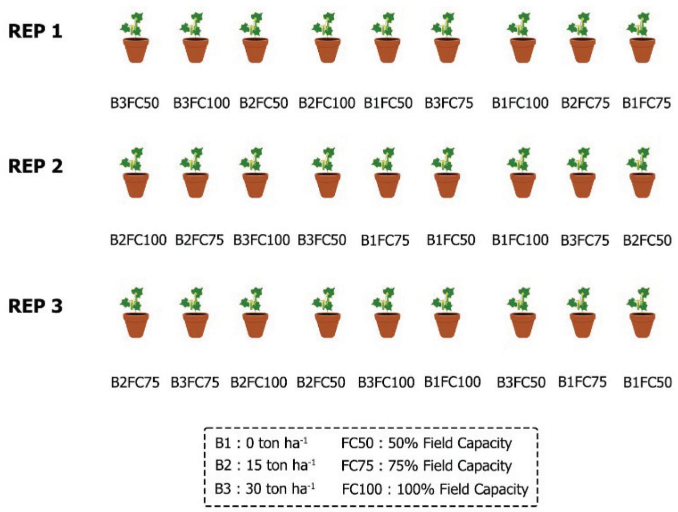

Fig. 1. A schematic representation of the experiment

2.2. Biochar production and application

The biochar feedstock used for this study was derived from Neem tree chips. These chips were initially dried in an oven at approximately 105°C for 24 hrs. Following drying, the neem chips were pyrolyzed in a metal kiln at 450°C for 2 hrs in the absence of oxygen. The carbonized material was allowed to cool at room temperature, and was ground using a grinder machine, sieved (2 mm), and subjected to analysis. Biochar was applied 4 weeks before sowing cucumber seeds at rates of 0 ton ha^{-1} (B1), 15 ton ha^{-1} (B2), and 30 ton ha^{-1} (B3), and thoroughly mixed with soil to a depth of approximately 15 cm in the pots. Information on the properties of biochar is shown in Table 1.

2.3. Water stress

To achieve the required water stress levels, the soil moisture content of the pot at field capacity was first calculated. For this purpose, a perforated pot with 5 kg of soil was saturated by placing it in a bowl of water for 24 h. After 24 h of capillary saturation, the pot was suspended for 72 h to allow gravimetric water to drain out, while the top of the pot was covered with a plastic sheet to prevent water loss due to evaporation. The pots were reweighed and the difference in weight from initial (before saturation) and final weight (72 h after suspension) was considered as moisture content at field capacity (FC). For 100% FC, the measured water was applied to 5 kg soil, while in case of 75 and 50% FC, 75 and 50% fraction of the 100% FC was added. To maintain the required water levels (100, 75, and 50% FC) during the experiment, the pots were weighed every 2 days, and water was added to each pot as needed to maintain each moisture level.

2.4. Soil sample collection for pot experiment

The soil used for the experiment was collected from an uncultivated area situated behind the Agronomy building at a depth of 0–15 cm. After collection, the soil was air-dried, ground, and sieved through a 2 mm sieve to remove twigs and gravel. Prior to conducting the experiment, the physical and chemical properties of the soil were determined. Soil samples were also collected at a depth of 0–10 cm after harvest to determine changes in soil physical (bulk density and porosity) and chemical (pH, soil organic carbon – SOC, total nitrogen – TN, available P, exchangeable K) properties.

Table 1
Properties of the studied soil and biochar produced from neem chips

Parameter	Soil	Biochar
pH (H_2O)	7.28	8.31
Organic Carbon (g kg^{-1})	17.0	244.5
Total Nitrogen (g kg^{-1})	0.75	5.17
Available Phosphorus (mg kg^{-1})	25.1	13.9
Potassium (cmol kg^{-1})	0.62	1.94
Calcium (cmol kg^{-1})	16.66	36.22
Magnesium (cmol kg^{-1})	6.51	8.20
Sand (g kg^{-1})	715	–
Silt (g kg^{-1})	192	–
Clay (g kg^{-1})	93	–
Textural Class	Loamy Sand	–

2.5. Soil Analyses

Soil TN was determined using the Kjeldahl digestion method (Infitek, KJA-X19C, Spokane WA) (Bremmer and Mulvancy, 1982). SOC was measured by potassium dichromate oxidation/colorimetric method (Wu et al., 2014). Soil pH was measured using a glass electrode pH meter (In-Situ Aqua TROLL 500 Multiparameter Sonde) with 1:1 soil-to-water ratio suspensions. Available P was determined by extracting phosphorus using ammonium fluoride (1N NH_4F) and hydrochloric acid (0.5N HCl) with potassium sulfate (K_2SO_4). Absorption was measured with a spectrophotometer using the Bray method (Bray and Kurtz 1945). The soil particle size distribution was determined by using a standard hydrometer after pre-treatment of samples with 1% solution of Calgon – sodium hexametaphosphate (Gee and Or, 2002). Exchangeable K^+, Ca^{2+} and Mg^{2+} were determined by extraction with 1N ammonium acetate (CH_3COONH_4) and their levels quantified using an atomic absorption spectrophotometer (AAS, Agilent 280Z AA, Santa Clara, USA) (Kacar, 1995). The soil properties are shown in Table 1.

Undisturbed soil samples, collected with the aid of core samplers (5 cm × 5 cm) were used to determine bulk density as described by Hillel (1982) and porosity was calculated from bulk density, as specified by Odugbenro et al. (2023).

2.6. Agronomic parameters, yield parameters, and water use efficiency (WUE)

Data were collected on crop growth and yield parameters. Growth attributes were monitored at 2-week intervals for 8 weeks, starting from 4 weeks after planting (WAP). The growth parameters measured were the number of leaves (counted), vine length (measured with a meter rule), and stem girth (measured with a vernier caliper, 0–150 mm, Mitutoyo Digital Caliper, Japan). For the yield parameters, the number of fruits per pot was taken by counting the number of fruits per treatment, while fresh fruit weight (g $plant^{-1}$) was measured using a sensitive weighing balance.

The water use efficiency was determined by dividing fresh cucumber fruit yield per pot (g) by the cumulative volume of water provided (Litre) over the entire planting season, as specified by Zhang et al. (2020).

$$\text{Water Use Efficiency (g L}^{-1}\text{)} = \frac{\text{Fresh fruit yield}}{\text{Cumulative volume of water provided}}$$

2.7. Statistical analysis

The data collected on agronomic properties were subjected to one-way Analysis of Variance (ANOVA) using the SPSS 19 package, whereas two-way ANOVA was used to examine the significance of water stress and biochar on soil physical and chemical properties using GenStat Release 8th Edition. Treatment means were compared using Tukey HSD Test and the least significant difference (LSD) at 5% probability level.

3. Results

3.1. Soil bulk density and porosity

Biochar treatment significantly ($F(2, 18) = 24.91$, $P < 0.001$) reduced soil bulk density in comparison to the control (no biochar, B1) at 50% and 100% FC (Fig. 2). The trend observed was B1 (0 ton biochar ha^{-1}) > B2 (15 ton ha^{-1}) > B3 (30 ton ha^{-1}) for all the water stress levels, with the lowest bulk density (0.93 Mg m^{-3}) found in B3 at 50% FC, which was 21.7% less than the unamended control at 100% FC. However, the different soil water levels did not significantly affect bulk density. Conversely, soil porosity increased with increasing biochar application when compared to the unamended soil (Fig. 3). Analysis of treatment effects showed significant ($F(2, 18) = 16.58$, $P < 0.001$) differences at 50% and 100% FC. The highest soil porosity value (65.0%) was recorded with B3 at 50% FC, indicating an increase of 13.4% compared to B1 at 75% FC, which had the lowest porosity value. The statistical analysis result showed that the water stress levels as well as the interaction between biochar and water stress had no significant effect on soil porosity.

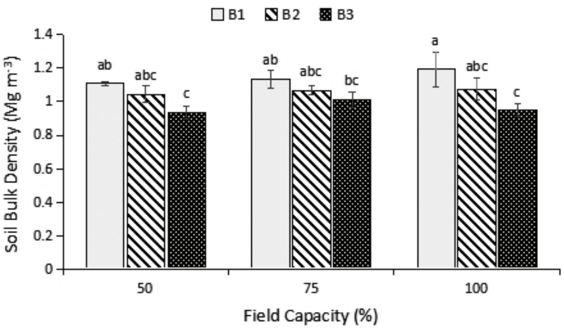

Fig. 2. Effect of biochar on soil bulk density under different water stress levels. B1: 0 ton ha^{-1} of biochar; B2: 15 ton ha^{-1} of biochar; B3: 30 ton ha^{-1} of biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters indicate significant differences

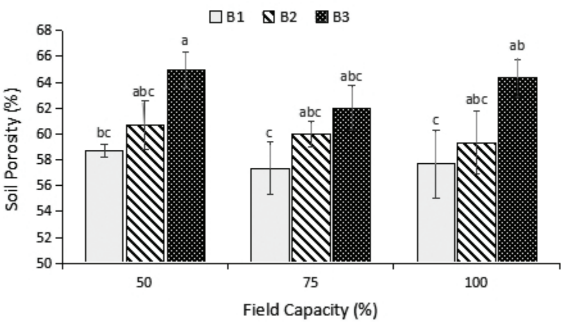

Fig. 3. Effect of biochar on soil porosity under different water stress levels. B1: 0 ton ha^{-1} of biochar; B2: 15 ton ha^{-1} of biochar; B3: 30 ton ha^{-1} of biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters indicate significant differences

3.2. Soil chemical properties

Biochar significantly ($F(2, 18) = 35.75$, $P < 0.001$) raised pH with increasing level of application at all water stress levels (Fig. 4). The highest pH (7.86) was recorded with B3 at 75% FC, representing ~8% increase when compared to the unamended control (7.28) at 50% FC, where pH was lowest. Statistical analysis result confirmed that water stress levels did not have a significant ($P > 0.05$) effect on soil pH.

The application of biochar to soil significantly increased SOC compared with the unamended control (Fig. 5a). At 50% FC, SOC was significantly ($F(2, 18) = 47.50$, $P < 0.001$) higher with B2 and B3 than with the control (B1). At 75% and 100% FC, the SOC content was about 10% higher with B3 than B1 but did not differ from B2. The different water stress levels had no significant effect on SOC. Also, the interaction between water stress and biochar showed no significant effect on SOC.

Biochar application resulted in higher soil TN content compared to the unamended control (Fig. 5b). Across all water stress levels, the highest TN levels were recorded with B3 and was lowest with B1 (no biochar application). At 75% FC, TN was about 2-fold higher ($F(2, 18) = 20.88$, $P < 0.01$) with B2 and B3 than with B1. Statistical analysis result showed that the different water stress levels had a significant ($F(2, 18) = 7.71$, $P < 0.01$) effect on TN. However, their interactive effects were not significant.

Soil available P was positively influenced by increasing biochar dose at 100% FC, where available P was about 60% higher ($F(2, 18) = 9.88$, $P = 0.001$) with B2 and B3 than with

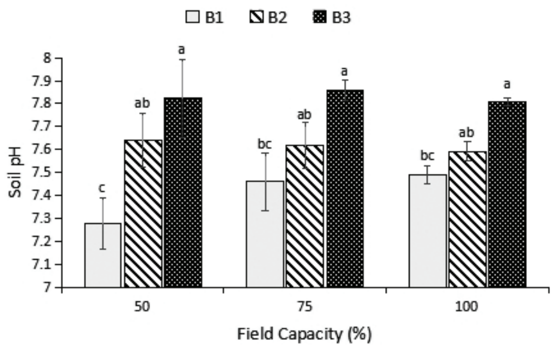

Fig. 4. Effect of biochar on soil pH under different water stress levels. B1: 0 ton ha^{-1} of biochar; B2: 15 ton ha^{-1} of biochar; B3: 30 ton ha^{-1} of biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters indicate significant differences

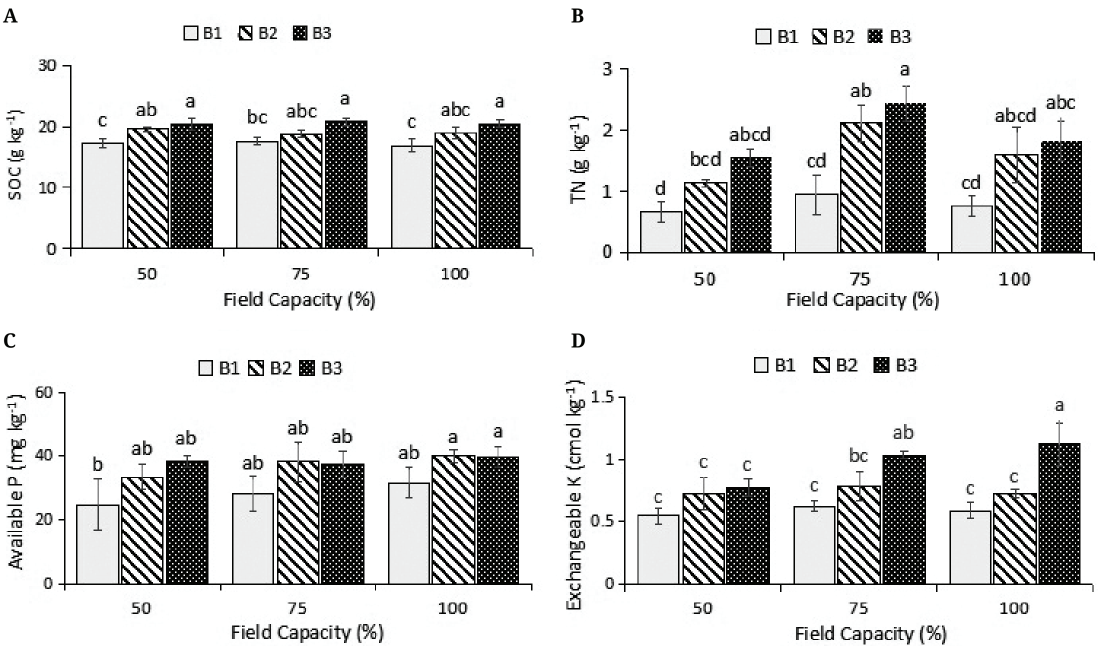

Fig. 5. Effect of biochar on (a) SOC (b) TN (c) Available P and (d) Exchangeable K under different water stress levels. B1: 0 ton ha^{-1} of biochar; B2: 15 ton ha^{-1} of biochar; B3: 30 ton ha^{-1} of biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters indicate significant differences

B1 (Fig. 5c). However, according to the variance analysis, the differences among the three water levels and the interactive effects between biochar and water stress were not significant ($P > 0.05$).

Biochar application significantly increased exchangeable K at 75% and 100% FC levels ($F(2, 18) = 41.95$, $P < 0.001$). At both soil water levels, exchangeable K was about 40% to 2-fold higher with B3 than the control (Fig. 5d). A statistically significant ($F(2, 18) = 6.12$, $P < 0.01$) difference among water stress levels was also observed for exchangeable K, where it was about 30% to 40% greater at 75% and 100% FC than at 50% FC only with B3.

3.3. Growth parameters of cucumber

At 4 weeks after planting (WAP), water stress had a significant ($F(2, 18) = 12.02$, $P < 0.001$) effect on the number of leaves. The number of leaves in cucumber did not differ at 100% or 75% FC irrespective of the biochar rates but was about 30% greater with B2 than B1 at 50% FC (Table 2). At 6 WAP,

Table 2
Effect of biochar on the number of cucumber leaves under different water stress levels

FC Level (%)	Biochar	Weeks After Planting		
		4	6	8
50	B1	8.67 ± 3.06c	13.00 ± 3.61b	13.30 ± 0.58d
	B2	11.30 ± 0.58ab	12.67 ± 0.58b	13.70 ± 0.58cd
	B3	10.33 ± 0.58bc	12.30 ± 1.53b	14.00 ± 1.73cd
75	B1	11.00 ± 1.00abc	14.00 ± 1.73ab	14.30 ± 0.58cd
	B2	9.67 ± 0.58bc	13.30 ± 0.58ab	15.30 ± 0.58cd
	B3	11.00 ± 1.00abc	13.30 ± 2.31ab	16.70 ± 2.89bc
100	B1	13.30 ± 1.15a	15.30 ± 2.08ab	15.30 ± 0.58cd
	B2	12.00 ± 1.00ab	14.30 ± 0.58ab	19.00 ± 2.08ab
	B3	13.30 ± 0.58a	16.70 ± 0.58a	21.70 ± 2.89a

Explanations: B1 – 0 ton ha^{-1} biochar; B2 – 15 ton ha^{-1} biochar; B3 – 30 ton ha^{-1} biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters in the same column indicate significant differences. n = 3 ± S.E.

a significant ($F(2, 18) = 5.56$, $P < 0.05$) effect of water stress on number of leaves was observed. The number of leaves did not differ under each soil moisture level but was higher with B3 at 100% FC than all treatments at 50% FC. At 8 WAP, significant effects of both biochar ($F(2, 18) = 8.19$, $P < 0.01$) and water stress ($F(2, 18) = 19.49$, $P < 0.001$) on the number of leaves of cucumber were recorded. Biochar application at 100% FC was about 20% to 30% greater in leaves number with B3 and B2 than B1.

At 4 WAP, vine length was not influenced by biochar rates under each soil water level (Table 3). However, water stress had a significant effect ($F(2, 18) = 7.25$, $P < 0.01$) on vine length. Vine length at 100% FC was about 20% to 40% higher with B2 and B3 than B2 and B1 at 50% FC. At 6 WAP, the effect of biochar on cucumber vine length was significant ($F(2, 18) = 9.59$, $P < 0.01$), where it was about 40% greater with B3 than B1 at 100% FC and by about 60% different at 75% FC. At 8 WAP, both biochar ($F(2, 18) = 12.23$, $P < 0.001$) and water stress ($F(2, 18) = 4.93$, $P < 0.05$) had significant effects on vine length; values were about 25% to 60% greater with B3 than B1 at all soil water levels

At 4 WAP, biochar ($F(2, 18) = 19.68$, $P < 0.001$) and water stress ($F(2, 18) = 9.97$, $P = 0.001$) significantly impacted cucumber stem girth; values were about 20% to 30% higher with B3 than B2 or B1 under all soil water levels (Table 4). At 6 WAP, a significant ($F(2, 18) = 8.41$, $P < 0.01$) effect of biochar on stem girth was observed. Cucumber stem girth was about 30%

Table 3
Effect of biochar on cucumber vine length (cm) under different water stress levels

FC Level (%)	Biochar	Weeks After Planting		
		4	6	8
50	B1	63.67 ± 11.02b	114.67 ± 11.02b	119.33 ± 3.16c
	B2	74.67 ± 14.00b	138.00 ± 14.00b	150.67 ± 5.03bc
	B3	81.33 ± 10.82ab	145.67 ±4.08ab	150.33 ± 8.89ab
75	B1	79.00 ± 9.02ab	116.00 ± 5.51b	142.33 ± 8.14bc
	B2	86.33 ± 13.80ab	146.00 ± 7.85ab	162.00 ± 7.28bc
	B3	89.33 ± 7.54ab	189.00 ± 2.08a	214.67 ± 6.81a
100	B1	86.00 ± 5.24ab	133.67 ± 6.16b	135.67 ± 7.63bc
	B2	104.33 ± 8.54a	155.00 ± 8.54ab	171.67 ± 7.63ab
	B3	106.00 ± 1.52a	191.67 ± 1.53a	213.00 ± 3.64a

Explanations: B1 – 0 ton ha^{-1} biochar; B2 – 15 ton ha^{-1} biochar; B3 – 30 ton ha^{-1} biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters in the same column indicate significant differences. n = 3 ± S.E.

Table 4
Effect of biochar on cucumber stem girth (mm) under different water stress levels

FC Level (%)	Biochar	Weeks After Planting		
		4	6	8
50	B1	2.18 ± 0.00d	3.71 ± 0.01bc	4.23 ± 0.07c
	B2	2.89 ± 0.03bc	4.24 ± 0.02abc	4.64 ± 0.03abc
	B3	2.89 ± 0.00bc	4.88 ± 0.09ab	4.64 ± 0.04abc
75	B1	2.28 ± 0.05cd	3.24 ± 0.12c	4.34 ± 0.11bc
	B2	2.98 ± 0.03b	4.88 ± 0.09ab	5.03 ± 0.05abc
	B3	3.32 ± 0.02b	5.09 ± 0.05ab	5.62 ± 0.07ab
100	B1	2.88 ±0.04bc	3.81 ± 0.11bc	4.45 ± 0.03bc
	B2	3.05 ± 0.00b	5.62 ± 0.06a	5.62 ± 0.07ab
	B3	4.01 ± 0.05a	5.19 ± 0.08ab	5.83 ± 0.09a

Explanations: B1 – 0 ton ha^{-1} biochar; B2 – 15 ton ha^{-1} biochar; B3 – 30 ton ha^{-1} biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level, while different letters in the same column indicate significant differences. n = 3 ± S.E.

greater with B2 than B1 at 100% FC, and about 40% greater with B3 or B2 than B1 at 75% FC. At 8 WAP, biochar had a significant ($F(2, 18) = 5.48$, $P < 0.05$) effect on stem girth; values were about 30% higher with B3 than B1 at 100% FC.

3.4. Cucumber yield

Biochar rates and different water stress levels affected the number of fruits and weight of cucumber in different ways (Table 5). At 100% FC, treatment with B2 and B3 recorded the highest number of fruits per plant and fruit weight at harvest. The number of fruits and weight were significantly higher than B1 ($F(2, 18) = 7.00$ and $F(2, 18) = 9.42$, respectively; $P < 0.01$). Cucumber plants subjected to moderate water stress also recorded a greater fruit yield than those subjected to severe water stress. The fruit weight at harvest increased by 147% in plants with B2 at 75% FC while those with B3 at 100% FC increased by 141.8%, compared to the control (B1) at the same water stress level.

Table 5
Effect of biochar on yield of cucumber under different water stress levels

FC Level (%)	Biochar	No. of fruits	Fruit weight (g plant^{-1})
50	B1	1.00±0.00	110±2.00
	B2	1.00±0.00	123±4.16
	B3	1.33±0.58	217±8.51
75	B1	1.00±0.00	97±5.77
	B2	1.67±0.58	240±6.56
	B3	1.67±0.58	277±7.02
100	B1	1.00±0.00	153±6.00
	B2	2.00±0.58	303±13.50
	B3	2.00±0.00	370±12.00
$LSD_{0.05}$	Biochar	0.3301***	81.9**
	FC Level	0.3301**	81.9**
	Biochar × FC	0.5718ns	141.8ns

Explanations: B1 – 0 ton ha^{-1} biochar; B2 – 15 ton ha^{-1} biochar; B3 – 30 ton ha^{-1} biochar; LSD: Least Significant Difference; *** Very Highly Significant; ** Highly Significant; ns: not significant; n = 3 ± S.E.

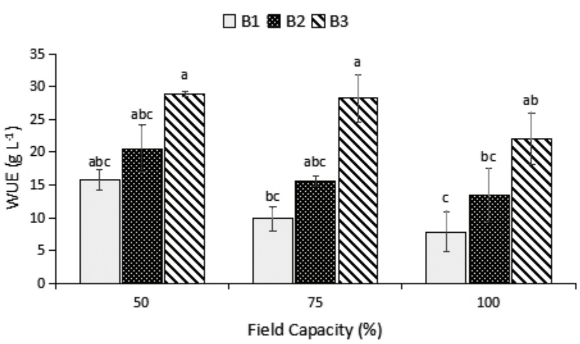

Fig. 6. Effect of biochar on WUE under different water stress levels. B1: 0 ton ha^{-1} of biochar; B2: 15 ton ha^{-1} of biochar; B3: 30 ton ha^{-1} of biochar. According to Tukey HSD, values with the same letter are not significantly different at the 0.05 probability level while different letters indicate significant differences

3.5. Water use efficiency (WUE)

The result of WUE of cucumber under different biochar application rates and water stress levels is shown in Fig. 6. Biochar rate had significant ($F(2, 18 = 29.92$, $P < 0.001$) effect on WUE, with 15 and 30 ton ha^{-1} raising the WUE of cucumber plants under 50% water stress by 30% and 84%, respectively. The effect of water stress on WUE was also significant ($F(2, 18 = 3.91$, $P < 0.05$). However, the interactive effects between biochar and water stress on WUE were not significant ($P > 0.05$). Additionally, under water stress, WUE was increased by 26% and 98% when subjected to 75% FC and 50% FC, respectively.

4. Discussion

4.1. Effect of biochar and water stress on soil physical properties

Soil bulk density is the ratio of dry soil to its total volume, and it exhibits an inverse relationship with soil porosity which is the amount of pores found between soil particles that are responsible for holding air and water. In the present study, increasing rate of biochar application reduced bulk density and increased soil porosity (Fig. 2 and Fig. 3, respectively). This reduction in bulk density following biochar application is in consonance with previous studies (Li et al., 2018; Odugbenro et al., 2023). Jin et al. (2024) also reported an increase in soil porosity following a one-off biochar application. Although water stress did not have a significant effect on soil bulk density and porosity, our results showed that treatments with the highest biochar application rate (B3) recorded the greatest reduction in soil bulk density and greatest improvement in porosity across the water stress levels. This contrasts with the findings of Jin et al. (2018), who reported that drought stress significantly ($P < 0.05$) affected soil bulk density and porosity. The observed increase in soil porosity and decrease in bulk density following increased biochar application may be attributed to increased microporosity, reduced soil compaction, and improved soil structure (Toková et al., 2020). This phenomenon enhances the physical structure of amended soils by improving aeration, water storage and soil quality, thereby ultimately promoting favourable conditions for cucumber growth and development.

4.2. Effect of biochar and water stress on soil chemical properties

Soil pH after biochar application followed the trend B3>B2>B1 at the three water levels. Our finding is consistent with the study conducted by Zhou et al., (2024) which reported a significant increase in soil pH following the application of corn straw, wheat straw and rice straw biochars. The alkalinity of biochar stems from its feedstock and production process, which contains alkaline compounds such as calcium carbonate (lime) and potassium carbonate that increase soil pH (Sohi et al., 2010). This may also be due to the negatively charged functional groups (-COOH and -OH) on biochar's surface, which combine with free H^+ in the soil, leading to an increase in soil pH (Ran et al., 2023). This gives biochar the potential to neutralize soil acidity. Furthermore, the strong reactivity of highly alkaline biochar in soil solutions speed up the release of pH-dependent charges from the surfaces of minerals such as kaolinite, iron and aluminium oxides, as well as organic compounds, therefore leading to pH increase (Bornø et al. 2018). Water stress, on the other hand, did not significantly (P > 0.05) influence soil pH. Silva et al. (2023) also demonstrated that pH of soil planted to maize was not affected by different levels of drought stress.

SOC improves soil structure, aeration and crop yield. Biochar is rich in carbon and in our study, its application to soil significantly increased organic carbon. Odugbenro et al. (2019) and Joseph et al. (2020) also reported increases in soil organic carbon following biochar application to soil. Addition of organic substances, such as rice straw to soil significantly increases carbon emissions due to biodegradation (Zhang et al., 2020). By contrast, biochar is a non-degradable C-rich material that increases SOC without influencing emissions mainly because it does not decompose (Yin et al., 2021).

Soil TN recorded significant increase across the water stress levels following biochar application. One possible explanation for the observed increase in total nitrogen is biochar's inherent properties. For example, some inorganic forms of N are adsorbed onto biochar because of its porous structure, thereby decreasing ammonium (NH_4^+) and nitrate (NO_3^-) losses from soil, potentially allowing nutrient retention for plant uptake (Haider et al., 2017). Biochar has high cation and anion exchange capacity (CEC and AEC). The changed cation and anion exchange capacities of soils after biochar application also further influences N retention (Mandal et al., 2018). Soil TN was significantly (P < 0.01) reduced by decreasing water level. Soil nitrogen cycles are particularly sensitive to water deficit conditions (Deng et al., 2021) due to the inhibition of nitrification which affects the response of soil microorganisms to environmental conditions such as temperature and soil moisture content (Bogati and Walczak, 2022). Additionally, the intracellular osmolytes excreted by microorganisms upon re-wetting dry soil increases the pool of soil TN and other available nutrients for efficient plant uptake (Soinne et al., 2010)

In our study, we observed that soil available P content increased in biochar-amended soils. Neem stem biochar is moderately low in phosphorus. However, pyrolysis conserves much of this phosphorus, making it readily available upon incorporation into the soil (Adekiya et al., 2025). Furthermore, biochar minimizes phosphorus leaching through sorption and adsorption while increasing P retention (Anyebe et al., 2025). The greatest available P contents were recorded at 100% FC. One plausible explanation for this is that lower soil moisture content (50% and 75% FC) could have impeded the movement and availability of phosphorus, despite the biochar's potential to increase soil phosphorus. P moves in the soil through gaseous means, unlike N which moves through mass flow (in soil water). Here, the low microbial activity due to low soil water may limit P availability due to reduced P mineralization. P may also be adsorbed to biochar or other organic materials in the dry soil, limiting its release into solution. It could then be released upon rewetting the soil. Zhou et al. (2020) posited that the mechanism responsible for increase in available P with biochar application at 100% FC is as a result of the effect that biochar has on some soil factors affecting P availability such as soil pH, Al^{3+}, Fe^{3+}, Ca^{2+} and dissolved organic carbon content. Also, at this soil water content, microbial activities are quite effective. Mineralization is actively occurring and controls P mineralization and availability.

Biochar and water stress significantly improved soil exchangeable K. According to the two-way ANOVA, a significant ($F(4, 18) = 3.37$, $P < 0.05$) interaction between biochar and water stress levels was recorded, which showed reduction in exchangeable K as water deficit condition increased. This is an indication that the effectiveness of biochar in increasing soil exchangeable K is dependent on the soil moisture content. Many studies have reported positive effect of biochar on soil exchangeable K (Singh et al., 2018; Asri, 2022).

4.3. Effect of biochar and water stress on the growth parameters of cucumber

The study's results suggest that water stress plays a critical role in masking the potential benefits of biochar. High water stress at 50% FC might limit leaf production so severely that any benefits conferred by biochar are negated, which explains the lack of significant differences in leaf number across biochar doses at this stress level throughout the study (Shao et al., 2008). The time-dependent nature of biochar effects is also a key consideration. Biochar's influence on plant growth is not always immediate, as changes in soil microbial communities and nutrient cycling processes require time to establish following application (Hagemann et al., 2016). Previous research indicates that the beneficial effects of biochar on plant growth can become apparent over several weeks or even months (Joseph et al., 2021), aligning with the lack of significant differences at the earliest time point of 2 WAP (results not shown). The positive effect of biochar particularly with B3 on leaf number under mild (75% FC) and optimal (100% FC) water conditions at 4 and 8 WAP was more pronounced, potentially due to improvements in water retention and nutrient availability. This finding is consistent with the results of Yildirim et al. (2021) who observed an increased leaf number in cabbage following 10% biochar application at 100% irrigation. The specific observations at four weeks suggest that the significant differences seen with the B3 at 75% and 100% FC, compared to the control, indicate a positive effect of biochar on leaf number under these water conditions at this stage. This may reflect a threshold effect where a higher application rate (B3) is necessary to overcome moderate water stress (75% FC) and stimulate leaf production.

Cucumber vines are structured to climb objects in order to increase their exposure to photosynthetic radiation. Reduced soil moisture could limit plant cell division and hence, impede vine elongation (Rahil and Qanadillo, 2015). Our results showed that biochar addition to soil at the appropriate dose could mitigate the negative effects of moderate water stress by improving water retention and nutrient availability (El-Naggar et al., 2019). The findings underscore the complex interactions between biochar application, water availability, and plant growth dynamics, suggesting that biochar's benefits are more pronounced under less severe water stress and over extended periods.

Biochar application significantly increased cucumber stem girth. Result from this experiment showed that water availability is an important factor influencing cucumber growth and development. Severe water stress at 50% FC limited plant growth to the extent that biochar's potential benefits were negligible, explaining the absence of significant differences in stem girth at 6 and 8 WAP at this water stress level. A reduction in plant growth in deficit soil-water treatments has been observed previously and can be explained by reduced water uptake, which leads to stomatal closure, and reduced nutrient diffusion to the roots (Avolio and Koerner, 2025; Erinle et al., 2025). In contrast, under mild and optimal water conditions (75% and 100% FC), biochar's positive influence on stem girth became more evident. This indicates that water quantity is the primary factor affecting cucumber stem girth under combined biochar and water application. This result is similar to the findings of Zhang et al. (2020) which reported that increased biochar application rate promoted the growth of tomato stem girth under moderate deficit of water but no obvious effect was recorded under heavy deficits.

4.4. Effect of biochar and water stress on the yield of cucumber and WUE

Biochar and water stress affected cucumber development and yield. The obtained results showed that increasing biochar application under 100% FC and 75% FC produced a better yield in terms of cucumber fruit number and weight per pot. This suggests that biochar has the capacity to enhance fruit production under optimal water and moderate water deficit conditions. The mechanisms behind this enhancement can be attributed to the biochar's porous structure which acts like a sponge, enhancing soil water retention and providing a stable source of water for plants (Karhu et al., 2011). This is particularly beneficial for fruit development, potentially mitigating the effects of water stress that the unamended plants might experience. Furthermore, biochar serves as a nutrient reservoir, slowly releasing essential nutrients into the soil over time. This gradual nutrient release supports increased fruit production by providing necessary nutrients for flower formation, fruit set, and fruit growth. A previous study reported that sugarcane waste biochar application increased cucumber production and water use efficiency under limited irrigation scenarios (Abdou et al., 2024).

Water use efficiency is an indicator of how well water is used to produce a crop. It is an important characteristic that indicates crop productivity, which is a nexus between water and nutrient cycling in agroecosystems (Li et al., 2018). The WUE of cucumber plants increased by 84% when they were subjected to water stress at 50% FC and supplemented with 30 ton ha^{-1} biochar. This is also in comparison with cucumber plants subjected to 75% FC and 100% FC (Fig. 6). The increase in WUE with water stress could be imputed to a decline in transpiration rate and stomatal closure in response to drought stress (Murtaza et al., 2024). Furthermore, several authors (Nasiri et al., 2024; Zhang et al., 2020) have reported increase in WUE following biochar application to soils. The mechanism ascribed to this could be through biochar's ability to improve the soil's water holding capacity, which allows the soil to retain more water from irrigation or rainfall in semi-arid rain-fed regions.

The long-term biochar application, especially under water stress, is expected to significantly improve soil's water and nutrient retention and availabilty, and promote plant drought tolerance by increasing porosity, reducing bulk density, improving water-nutrient synergy and enhancing microbial activity and nutrient cycling. Applying biochar over a relatively long time will build a resilient soil that better manages water, thereby sustaining plant health and productivity even when water is limited.

5. Conclusions

In this research, an experiment was conducted to determine the effects of biochar application and water availability on the growth characteristics and yield of cucumber, as well as on soil physical and chemical properties, in a glasshouse. Based on the findings, it is concluded that water stress has no significant effect on soil physical properties: soil bulk density and porosity. However, increasing neem-chip biochar application could significantly reduce bulk density and increase porosity. Neem-chip biochar could regulate soil pH and improve soil total N, organic C, available P and exchangeable K. Optimal water availability is crucial for maximizing yield as water stress influenced leaf development, plant growth and fruit production negatively. However, neem-chip biochar when applied at 30 ton ha^{-1} could reduce the negative effect of water stress at 75% FC by optimizing plant growth and yield. Therefore, neem-chip biochar at 30 ton ha^{-1} can be used to improve soil fertility, water use efficiency and yield of cucumber where water supply is moderately limited. The short-term experimental trial in a screenhouse setting and the use of only one soil type were considered limitations to this research, as they are inadequate to provide information on the adaptation of cucumber plants to water stress under varying soil types over a long period of time. We suggest that further experiments should be conducted in the field on various biochar doses using cucumber and other test crops in order to ascertain the best dose for mitigating the negative effect of drought stress, so that this technology can be employed sustainably.

Availability of data and material

The data and materials that support the findings of this study are available upon reasonable request from the corresponding author.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

George O. Odugbenro – Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Writing – original draft. **Yusuf O. Omotosho** – Data curation, Investigation, Writing – review & editing. **Kolapo O. Oluwasemire** – Validation, Writing – review & editing. All authors read and approved the final manuscript.

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