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تأثير تعديلات التربة على نمو النبات والمغذيات الكبرى وكفاءة استخدام المياه للبامية (Abelmoschus esculentus) في التربة الرملية في ظل ظروف الإجهاد المائي

Effects of soil amendments on plant growth, macronutrient and water use efficiency of okra (Abelmoschus esculentus) in sandy soils under water-stressed conditions

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ملخص

تتميز التربة الرملية بضعف خصائصها الفيزيائية المتعلقة بقدرتها على الاحتفاظ بالماء والمغذيات الأساسية للنبات. وتتفاقم هذه المشكلة في المناطق القاحلة وشبه القاحلة التي تتميز بارتفاع درجات الحرارة وندرة المياه في الصيف. تناولت هذه الدراسة كيفية تأثير السماد العضوي (C) والفحم الحيوي (B) ومزيجهما (CB) على نمو البامية(Abelmoschus esculentus) ، وكفاءة استخدام المياه (WUE) ، وامتصاص المغذيات في التربة الرملية تحت نظامي ري: الري المجهد مائيًا (W1) والري الجيد (W2) احتوى السماد العضوي المضاف على ١٠,٢٤% من المواد العضوية، ونسبة عالية من المغذيات الكبرى، ودرجة قلوية (٨,٢٣)، بينما احتوى الفحم الحيوي على نسبة أعلى من النيتروجين (٥,٠٨%) والصوديوم (٤١,٤٠ ملي مكافئ/لتر) ورقم هيدروجينى منخفض (٤,٥٤). عزز السماد باستمرار الكتلة الحيوية للبامية ومساحة الورقة واستطالة الساق وامتصاص NPK عبر مستويي الري، محققًا ذروة الكتلة الحيوية الجافة الكلية (٩,٠٤ جم / نبات) و WUE (٠,٢٨ جم / لتر) تحت W2 مقارنة بالمعاملة الضابطة بدون إضافة أي تعديل (WUE = 0.08) جم / لتر. أظهر الفحم الحيوي وحده فوائد محدودة وانخفاض النمو تحتW1 ، ويعزى ذلك إلى الرقم الهيدروجينى الحمضى ومحتواه العالي من الصوديوم. أظهرت معاملة CB نتائج متوسطة، مع تآزر ملحوظ تحت W2 بلغت كفاءة استخدام العناصر الغذائية ذروتها مع السماد في W2 بنسبة ٧,٥٣٪ و ١٢٢٪ لكفاءة استخدام النيتروجين والبوتاسيوم على التوالي، بينما أعطى الفحم الحيوي تحت W1 أدنى القيم. تسلط النتائج الرئيسية الضوء على موثوقية السماد لتحسين أداء البامية في ظل توفر المياه المتغير، بينما كانت فعالية الفحم الحيوي محدودة بخصائصه. تؤكد النتائج على الدور الحاسم لاختيار التعديل وإدارة الري في تحسين إنتاجية التربة الرملية.

الكلمات المفتاحية: السماد العضوى ،الفحم الحيوى، إنتاجية المياه. الاجهاد المائى، إمتصاص العناصر الغذائية

Abstract:

Sandy soils are characterized by poor physical properties related to their ability to retain water and essential plant nutrients. This problem is exacerbated in arid and semi-arid regions characterized by high temperature and limited water in the summer. The objective of this study was to examine how compost (C), biochar (B), and their combination (CB) influenced okra (*Abelmoschus esculentus*) growth, water use efficiency (WUE), and nutrient uptake in sandy soil under two irrigation regimes: water-stressed (W1) and well-watered (W2) conditions. The applied compost contained 10.24% organic matter elevated micronutrients, and alkaline pH (8.23), whereas biochar had higher nitrogen (5.08%) and sodium (41.40 meq/l) but a low pH (4.54).

Compost increased the biomass of okra. ،leaf area, stem elongation, and NPK uptake across both irrigation levels, achieving peak total dry biomass (9.04 g/plant) and WUE (0.28 g/l) under W2 compared to control treatment with no amendment added (WUE = 0.08 g/l). Biochar alone exhibited limited benefits and reduced growth under W1, attributable to its acidic pH and high sodium content. The CB treatment showed intermediate results, with notable synergy under W2. Nutrient use efficiencies peaked with compost in W2 with 7.53%, 122% for nitrogen and potassium use efficiency, respectively, while biochar under W1 yielded the lowest values. These findings support the use of compost as an effective amendment to enhance okra growth and water use efficiency in sandy soils, particularly under water-limited conditions.

Key words: compost, biochar, water productivity. water stress, nutrient uptake

Introduction

Egypt has about 1 million square kilometers of land. However, only around 24,960 km² (about 4%) is farmed (Meguid, 2019). This small amount of farmland shows how Egypt's geography limits its farming ability (Sabahy et al., 2024). Egypt faces several challenges that hinder the growth of the agricultural sector and food security including land fragmentation (Meguid, 2019), urban sprout (Bratley and Ghoneim, 2018; Mohamed, 2017), and water scarcity (Gamal et al., 2024). Because of this, The Egyptian government is trying to improve the soil quality of the expanded sandy desert land to be suitable for cultivation. Reclaiming desert areas can greatly increase the amount of land used for growing crops (Shepherd, 2003; Subandi et al., 2019). However, sandy soils are characterized by poor nutrients and water holding capacity, which negatively affect soil productivity (Suganya and Sivasamy, 2007). Several studies highlighted the potential of soil amendments such as compost and biochar to address these limitations and improve soil quality. It facilitates the retention of key element cations such as calcium, potassium, and magnesium, contributing to improved soil fertility and nutrient availability (Abd El-Mageed et al., 2021; Oueriemmi et al., 2021; Rós et al., 2024; Tuesta et al., 2024; Zaid et al., 2024). Studies highlighted the biochar capability of enhancing soil water retention and reducing its bulk density, with improvements dependent on biochar type and particle size (Abd El-Mageed et al., 2021; Alghamdi et al., 2024; Bruun et al., 2023; Hou et al., 2025; Ndede et al., 2022; Suganya and Sivasamy, 2007; Torres et al., 2024).

On the other hand, okra plant (*Abelmoschus esculentus*) is a popular vegetable grown in the Middle East and North Africa region. It is rich in fundamental nutrients such as calcium, protein, and minerals, making it a valuable dietary supplement (Kumar et al., 2010; Singh, 2006). It can alleviate malnutrition, particularly in rural communities, by providing essential nutrient and improving dietary diversity (Massrie, 2025). Globally, it accounts for approximately 10.5 million tons in annual production (Wakchaure et al., 2023). As a summer crop that thrives at high temperatures, up to 34^{o}C (Hayamanesh et al., 2023), okra is often grown in arid and semi-arid regions. However, its productivity is significantly affected by abiotic stressors, particularly drought and heat (Abd El-Fattah et al., 2020). Drought stress is especially problematic in these regions, where limited root-zone water availability and high transpiration rates frequently coincided (Chaitanya et al., 2003). Therefore, enhancing soil nutrient and water retention capacities is crucial for improving okra productivity under harsh environmental conditions. The application of biochar and compost has been shown to significantly enhance okra growth and yield. Notably, the combination of biochar and arbuscular mycorrhizal fungi has been found to improve okra's tolerance to drought stress and boost growth parameters i.e., plant height and root dry weight (Jabborova et al., 2021). In another study, rice straw biochar improved both okra yield and water productivity by enhancing soil physical properties such as porosity and water holding capacity (Azman et al., 2024; Yakubu et al., 2020), as well as by improving Click or tap here to enter text.soil fertility (Lebrun et al., 2024). Further research has demonstrated the beneficial impact of compost application in mitigating drought stress on okra by improving soil fertility and physical properties (Azman et al., 2024; Ezeh and Adejumo, 2020; Jabborova et al., 2021; Lebrun et al., 2024; Trupiano et al., 2017).

Moreover, a synergetic effect of combined compost and biochar application has been observed, resulting in enhanced soil physical properties, improved nutrient availability and uptake (Anwar et al., 2021; Azman et al., 2024; Jabborova et al., 2021; Lebrun et al., 2024), and increased okra yield (Anwar et al., 2021).

Although compost and biochar are well known to improve soil quality, there remains a need to further investigate their effects on okra growth and nutrient use in sandy desert soils, where water-stress and high temperatures are predominant, especially during summer months. This represents a critical gap in optimizing soil management practices for okra cultivation in sandy soils for more sustainable food security. Threfore, this study aims to examine how soil amendments (compost, biochar, and their combination) affect the growth, water use efficiency, and nutrient use efficiency of okra in sandy soil under varying water availability.

Materials and methods

Study area

The experiment was conducted in the experimental farm of Aswan University, located at coordinates 24.26901 ^{o}N and 32.82657 ^{o}E. Figure 1 illustrates the minimum and maximum air temperatures recorded during the study period. On average, the minimum and maximum air temperatures were 27.95 ^{o}C and 43.42 ^{o}C, respectively, with no rainfall observed throughout the experiment.

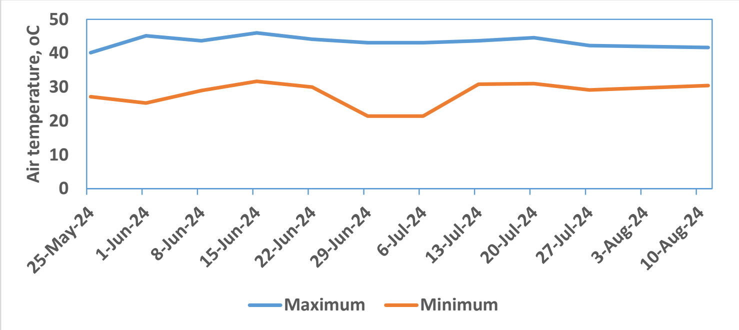


Figure 1. Average minimum and maximum air temperature (ºC) in the study area during the cultivation season

Experiment setup

A pot experiment was conducted to examine the effect of soil amendments and irrigation scheduling on okra (*Abelmoschus esculentus*) during its vegetative growth stage. Six kilograms of prewashed sand soil (99.34% sand) with a bulk density of 1.7 g/cm^3 was used to fill the pots. Soil amendments included compost at two rates (20 g/kg and 40 g/kg, representing 50% and 100%) and biochar at two rates (2 g/kg and 3 g/kg). The experiment followed a factorial completely randomized design, with two factors: First, soil amendment treatments consisted of control treatment (T) where no soil amendment added, compost at 40 g/kg soil (C), biochar at 3 g/kg soil (B), and combined compost (20 g/kg) + biochar (2 g/kg soil (CB). Second, irrigation scheduling for irrigation triggered by visible signs of plant water stress (temporal wilting, W1) and daily irrigation (W2). The experiment was conducted in four replicates. All treatments received basal fertilization with 1.26 g nitrogen (N) and 0.25 g phosphorus (P) per pot, along with foliar potassium (K) application at 4 g/l concentration.

The experiment started on May 25, 2024, with okra seeds sown in prepared pots. Initially, all pots were irrigated uniformly with 300 ml of water until seedling emergence. After 30 days, irrigation schedules (W1 and W2) were implemented, with 1L of water applied per irrigation event until harvest on August 11, 2024. The specific irrigation intervals for each treatment are illustrated in Figure 2.

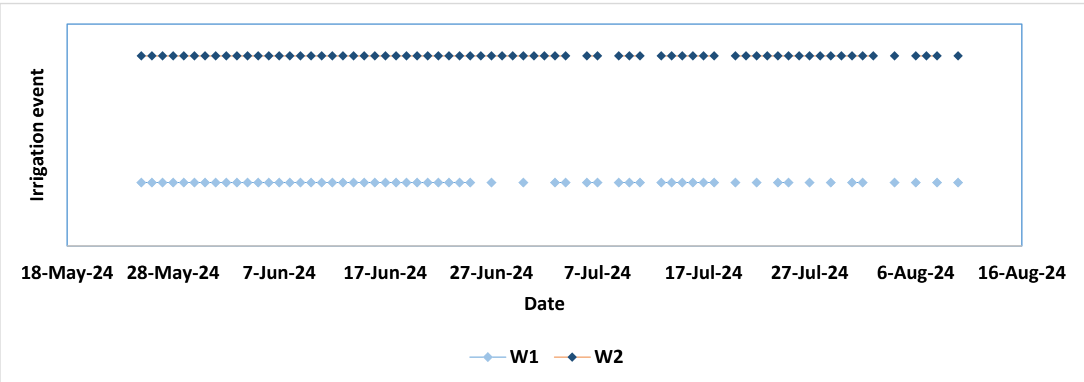


Figure 2. Irrigation intervals under treatments W1 (stress-based) and W2 (daily)

At harvest, plant growth parameters including number of leaves, leaf area, and stem length were recorded. Leaf area (LA) was determined using the method described by (Pandey and Singh, 2011). In this method, each leaf was traced onto a sheet of paper, and the tracing was then cut out and weighed. A separate piece of the same type of paper with a known area was also weighed to calculate the weight-per-unit area ratio. Leaf area was then estimated using the formula:

$$LA = \frac{Weight\ of\ tracing}{Weight\ per\ unit\ area}$$

Plant parts (stems, leaves, and roots) were separated, oven-dried at 70°C, and weighed to determine dry biomass. Leaf and stem NPK concentrations were analyzed using the Kjeldahl method for nitrogen, spectrophotometry for phosphorus, and flame photometry for potassium, following (Cotteine, 1980). Soil properties before and after cultivation, as well as characteristics of compost and biochar, were assessed based on methods outlined by (Stakman and Vanderhast, 1962).

Water use efficiency (WUE) was calculated as the total dry biomass (g) divided by the total volume of water applied (L).

Nutrient use efficiency for nitrogen, phosphorus, and potassium was calculated using the formula as described by (Nadeem et al., 2022; van de Wiel et al., 2016).

$$Nutrient\ use\ efficiency = \frac{Nutrient\ content\ in\ shoot}{Soil\ nutrient\ concentration} \times 100$$

Statistical analysis and data visualization were conducted using a completely randomized design in R, employing the *agricolae*, *ggplot2*, *gtsummary*, *dplyr*, *and tidyverse* package.

Results and discussion

Experimental soil and amendments' characterization

Table 1 represents the chemical composition of the used compost, biochar as soil amendments as well as the sandy soil media used for cultivation. The compost had a relatively high organic matter content (10.24%) and moderate electrical conductivity (EC) of 2.39 dS/m, indicating its potential to enhance soil fertility and water-holding capacity. In contrast, the biochar contained no measurable organic matter but exhibited a significantly higher nitrogen content (5.80%) compared to compost (1.34%) and sandy soil (0.01%). Biochar also showed elevated levels of potassium (16.20 meq/l) and sodium (41.40 meq/l), suggesting its capacity to supply essential cations, though care must be taken regarding its high sodium concentration.

Table 1. Soil and amendments' chemical analyses at the beginning of the experiment.

Parameters	Compost	Biochar	Sandy soil	Parameters	Compost	Biochar	Sandy soil
Organic Matter (%)	10.24		0.24	Cations (meq/l)			
pH (1:2.5)	8.23	4.54	8.76	Ca^{2+}	15.00	1.50	3.50
EC (dS/m)	2.39	0.59	0.38	Mg^{2+}	9.00	1.00	1.50
N (%)	1.34	5.80	0.01	Na+	22.80	41.40	4.90
P (%)	0.14	0.17	0.00	K^{+}	0.96	16.20	0.28
K (%)	0.74	0.10	0.01	Anions (meq/l)			

Cu (mg/kg)	85.40	55.00	0.03	CO_3^-			
Fe (mg/kg)	14000.00	438.80	5.02	HCO_3^-	2.00	0.50	0.50
Mn (mg/kg)	432.00	155.00	0.43	Cl^-	27.00	7.40	2.25
Zn (mg/kg)	42.60	49.80	0.33	SO_4^{2-}	18.76	9.40	1.03

The sandy soil used in the experiment was characterized by low nutrient content, minimal organic matter (0.24%), and low EC (0.38 dS/m) primarily thanks to the prewashing process conducted to the soil before being used as a cultivation media. Both compost and soil pH were alkaline (8.23 and 8.76, respectively) while biochar was acidic (pH 4.54), which might influence nutrient availability when amendments are applied. Micronutrient analysis revealed that compost was particularly rich in iron (14,000 mg/kg) and manganese (432 mg/kg), while biochar had moderate levels of micronutrients such as zinc and copper.

The cation and anion content further emphasized the nutrient enhancement potential of compost and biochar. Compost provided high levels of calcium and magnesium, while biochar was notably higher in chloride and sulphate than compost. Overall, these results indicate that both compost and biochar could substantially improve the chemical properties of sandy soils, each offering distinct contributions to nutrient supply and soil conditioning.

Effect of water stress and soil amendments on okra growth parameters

Table 2 presents the dry mass (± standard error) of okra stem, leaves, roots, and total biomass under two irrigation regimes: daily irrigation (W1) and stress-triggered irrigation (W2), across four soil amendment treatments: control (T), compost (C), biochar (B), and compost + biochar (CB). The effect of applied treatments on total fresh biomass, leaves' area (LA) and number, as well as stem length is shown in Figure 3. Compared to water-stressed treatment (W1), well-watered conditions (W2) resulted in significantly greater stem elongation, higher leaf count, increased LA, and enhanced fresh and dry biomass in okra ($P<0.05$).

The obtained results highlight the superior efficacy of compost (C) in promoting plant growth under both irrigation regimes. Under limited irrigation (W1), compost yielded significantly higher biomass in all plant components than other treatments, with a total dry biomass of 3.71±0.53g. This indicates that C treatment significantly ($P<0.05$) enhanced vegetative growth of okra under periodic water stress. In contrast, the B and CB treatments did not result in improvements in biomass over the control under W1 conditions; all three treatments (T, B, CB) recorded statistically similar and low total dry biomass, ranging from 0.65 to 0.82g. This indicated limited benefit from biochar, whether applied alone or in combination with compost, under water-stressed conditions.

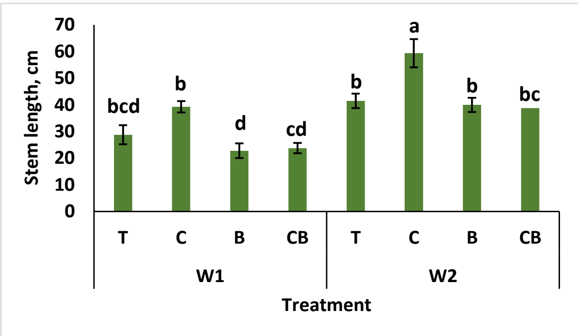
Table 2. Okra stem, leaves, root, and total dry mass ± standard error for each applied treatment under stress-triggered irrigation (W1) and daily irrigation (W2).

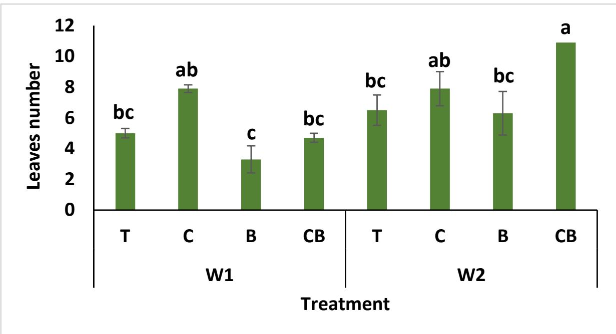
Water level	**Soil amendment**	**Dry mass, g**			
		Stem	**Leaves**	**Root**	**Total**
W1	T	$0.25±0.03^{c}$	$0.32±0.02^{cd}$	$0.17±0.04^{c}$	$0.73±0.09^{de}$
	C	$1.29±0.13^{b}$	$1.68±0.16^{b}$	$0.75±0.26^{bc}$	$3.71±0.53^{bc}$

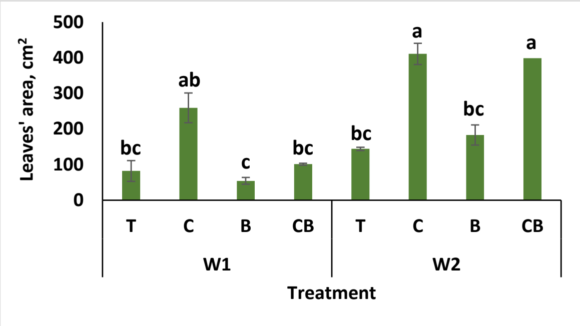
	B	0.23±0.03^{c}	0.23±0.09 ^{d}	0.20±0.13 ^{c}	0.65±0.25 ^{e}
	CB	0.230.07^{c}	0.40±0.17 ^{cd}	0.18±0.07 ^{c}	0.82±0.31 ^{de}
W2	T	0.71±0.07 ^{bc}	0.98±0.12 ^{bcd}	0.60±0.11 ^{bc}	2.29±0.26 ^{cde}
	C	3.68±0.37 ^{a}	3.78±0.42 ^{a}	1.59±0.20 ^{a}	9.04±0.64 ^{a}
	B	0.85±0.17 ^{bc}	1.34±0.35 ^{bc}	0.60±0.10 ^{bc}	2.79±0.61 ^{cd}
	CB	1.48±0.14 ^{b}	2.87±0.15 ^{a}	1.40±0.32 ^{ab}	5.75±0.53 ^{b}

* Where T is control treatment (no amendment), C is compost, B is biochar, and CB is compost+biochar. Different small letters refer to significant differences between treatments at $p < 0.05$.

Under well-watered conditions (W2), all treatments showed a significant increase in biomass (P<0.05) compared to their performance under W1. This effect was particularly observed in the C and CB treatments. The C treatment recorded the highest total dry biomass (9.04±0.64g), nearly tripling its performance under W1. The CB treatment also performed significantly better under W2 (5.75±0.53g), suggesting a synergistic interaction between compost and biochar when water is not a limiting factor. Nevertheless, no significant difference was observed between the CB treatment under W2 and the CB treatment under W1 conditions.







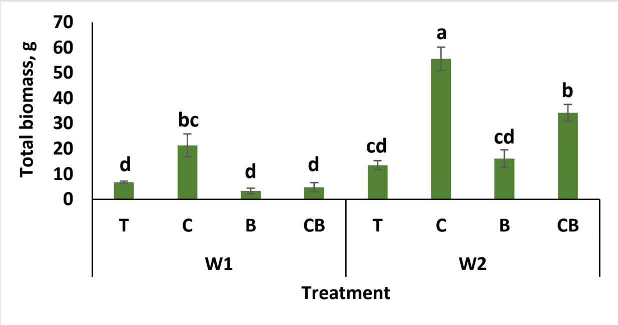


Figure 3. Average okra growth parameters and standard error under different applied soil amendment and water regime treatments. Different small letters refer to significant difference between treatments (P<0.05). Where T is control treatment (no amendment), C is compost, B is biochar, and CB is compost+biochar.

However, the B treatment consistently produced the lowest total biomass under W1, with no significant difference from the control, highlighting limited effectiveness. The limited effectiveness of biochar in improving plant growth parameters compared to compost may be due to its high sodium concentration (41.40 meq/l) and low pH (4.54). Elevated sodium levels in biochar can increase soil salinity, thereby intensify the adverse effects of water stress (W1) and impede plant development (Ibrahim et al., 2021; Rezaie et al., 2019). Excessive sodium can also induce toxicity in plants by disrupting nutrient uptake mechanisms and inducing physiological stress (Ahmad et al., 2024; Gao et al., 2024; Hafeez et al., 2019; Ibrahim et al., 2021). In addition, a pH value below 5 indicates acidic conditions, which can result in nutrient imbalances and reduced availability of key macronutrients such as nitrogen, phosphorus, and potassium (Dai et al., 2017; Du et al., 2024).

Response of WUE to soil amendments and water stress

Figure 4 presents the impact of different soil amendment treatments on water use efficiency (WUE) in okra under water-stressed (W1) and well-watered (W2) conditions. The WUE was significantly higher (P<0.05) under well-watered conditions compared to water-stressed conditions. Soil amendments played a crucial role in maximizing WUE, with all treatments outperforming the control (T) in both irrigation regimes. Among the amendments, compost consistently achieved the highest WUE, followed by compost-biochar combination (CB), while biochar alone showed the least improvement. The control treatment, with no amendments, exhibited the lowest WUE for okra in sandy soil.

Under W1 conditions, C treatment improved WUE by 4.67 times (0.14 g/l) compared to control treatment of no amendment added (WUE = 0.03 g/l), highlighting its effectiveness in enhancing biomass production per unit of water under water stress. The CB treatment showed a moderate increase in WUE (0.05 g/l) compared to the control but less efficient than the compost alone. The study of (Zahra et al., 2021) also found that the combined application of biochar and compost significantly improved WUE of maize yield under low irrigation levels, suggesting a synergistic effect.

In contrast, biochar had the lowest WUE under W1 (0.02 g/l), performing similarly to the control with no significant differences between both treatments. The reduced vegetative growth observed under W1 (Table 2 and Figure 3) may be linked to biochar-induced soil acidity and elevated sodium levels, which likely exacerbated water stress effects (Du et al., 2024; Gao et al., 2024; Rezaie et al., 2019) resulting in lower WUE.

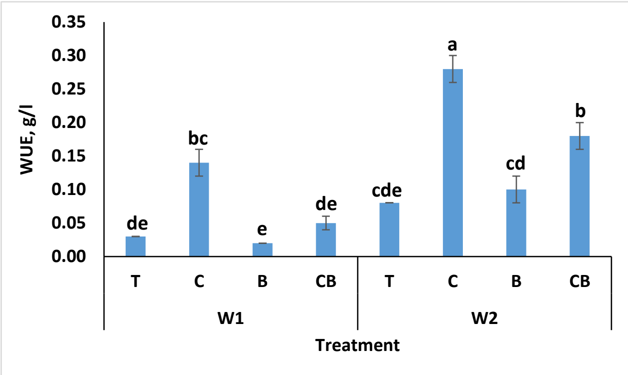


Figure 4. Okra water use efficiency (WUE) and standard error under water-stressed (W1) and well-watered (W2) conditions. Different small letters refer to significant difference between treatments (P<0.05). Where T is control treatment, C is compost, B is biochar and CB is compost + biochar

Under W2 conditions, all treatments exhibited improved WUE compared to W1. Compost again recorded the highest WUE (0.28 g/l), with CB showing a slight but significant increase (0.18 g/l), indicating a potential synergistic effect between compost and biochar under adequate water supply (Zahra et al., 2021). Biochar displayed marginal improvement over its W1 performance (WUE = 0.10 g/l) but remained the least effective among the applied soil amendments. The enhanced growth parameters (Figure 3) and WUE (Figure 4) under well-watered conditions may be due to salt leaching, which likely improved soil properties through continuous irrigation and biochar amendment (Sun et al., 2019; Xiao and Meng, 2020).

The significantly (P<0.05) lower performance of biochar compared to compost might be attributed to its high sodium content, which can increase malondialdehyde levels-a stress indicator-and reduce okra growth and yield (Ding et al., 2021), ultimately lowering WUE. While some studies report biochar’s potential to enhance WUE under deficit irrigation and saline conditions (Abd El-Mageed et al., 2021; Alkhasha et al., 2019; Hou et al., 2025), others note that excessive biochar application, particularly with high sodium content, can elevate soil salinity and negatively impact crop yield and WUE (Rezaei and Razzaghi, 2018). This aligns with findings by (Ibrahimi and Alghamdi, 2022), who observed that biochar high carbon content and large particle size may not significantly improve soil water retention. Additionally, biochar application under saline conditions did not enhance yields due to elevated salinity (Alghamdi et al., 2023), possibly explaining its minimal WUE improvement over the control in sandy soils.

Nutrient uptake and use efficiency

The uptake of essential macronutrients (N, P, and K) in leaves and stems of okra plant under different tested treatments irrigation levels and soil amendments' application is demonstrated in Table 3. In addition, the effect of the applied treatments on okra nutrient use efficiency is shown in Table 4.

The interaction between soil amendments and water availability further highlighted the efficiency of compost. Under W2, compost led to the highest NPK uptake in both leaves and stems surpassing the CB treatment. Even under W1, compost maintained a significantly (P<0,05) higher nutrient uptake than other treatments. In contrast, biochar under W1 consistently resulted in the lowest nutrient uptake values. These findings emphasize the critical role of compost in maximizing nutrient absorption under both favorable and adverse water conditions. Nutrient use efficiency in okra, encompassing nitrogen (NUE), phosphorus (PUE), and potassium (KUE), was assessed based on nutrient uptake relative to the externally applied fertilizers during the vegetative growth phase, excluding the contributions of nutrients inherently present in compost and biochar. The results revealed that both irrigation regime and soil amendments significantly (P<0.05) affected nutrient use efficiency.

Well-watered (W2) conditions consistently enhanced NPK uptake compared to water-stressed (W1) conditions across all treatments. The C treatment significantly improved NPK uptake in both okra leaves and stems, outperforming all other amendments. Nitrogen uptake in okra leaves was the highest with C treatment, followed by the CB treatment, then the B treatment, with the T treatment registering the lowest values. These trends were similarly reflected in phosphorus and potassium uptake.

Table 3. Effect of water and soil amendments on okra nutrient uptake in leaves and stem. Different small letters refer to significant differences between treatments.

Water level	Soil amendment	N uptake, mg/plant		P uptake, mg/plant		K uptake, mg/plant	
		Leaves	Stem	Leaves	Stem	Leaves	Stem
W1	T	3.5±0.33^{d}	1.07±0.26^{c}	0.79±0.19^{cd}	0.30±0.03^{b}	6.36±1.62^{d}	6.91±0.69^{b}
	C	22.41.98^{c}	10.68±1.10^{bc}	3.55±0.57^{bc}	1.34±0.22^{b}	27.14±1.50^{bc}	15.69±1.61^{b}
	B	4.42.06^{d}	3.09±0.99^{bc}	0.48±0.13^{d}	0.19±0.01^{b}	2.54±1.22^{d}	2.10±0.45^{b}
	CB	8.3±4.16^{d}	2.48±1.08^{bc}	0.73±0.27^{cd}	0.21±0.08^{b}	4.04±1.75^{d}	1.82±0.85^{b}
W2	T	8.1±1.10^{d}	3.27±0.82^{bc}	2.83±0.32^{bcd}	1.21±0.29^{b}	28.79±4.02^{bc}	19.64±2.46^{b}
	C	62.0±3.30^{a}	31.49±8.43^{a}	8.80±1.14^{a}	4.48±0.75^{a}	42.65±4.69^{a}	98.75±11.71^{a}
	B	26.7±4.99^{c}	12.44±0.76^{bc}	2.22±0.57^{cd}	0.73±0.18^{b}	14.88±4.75^{cd}	9.48±1.98^{b}
	CB	42.5±3.88^{b}	16.95±1.06^{ab}	5.69±0.43^{b}	1.70±0.25^{b}	31.42±0.68^{b}	18.77±1.91^{b}

* Where T is control treatment (no amendment), C is compost, B is biochar, and CB is compost+biochar. Different small letters refer to significant differences between treatments at p < 0.05.

The interaction between soil amendments and water availability further highlighted the efficiency of compost. Under W2, compost led to the highest NPK uptake in both leaves and stems, surpassing the CB treatment. Even under W1, compost maintained a significantly

(P<0.05) higher nutrient uptake than other treatments. In contrast, biochar under W1 consistently resulted in the lowest nutrient uptake values. These findings emphasize the critical role of compost in maximizing nutrient absorption under both favorable and adverse water conditions.

Nutrient use efficiency in okra, encompassing nitrogen (NUE), phosphorus (PUE), and potassium (KUE), was assessed based on nutrient uptake relative to the externally applied fertilizers during the vegetative growth phase, excluding the contributions of nutrients inherently present in compost and biochar. The results revealed that both irrigation regime and soil amendments significantly (P<0.05) affected nutrient use efficiency.

Table 4. Nitrogen (N), phosphorus (P), and potassium (K) use efficiency and standard error in okra plant under water stress (W1) and well-watered conditions (W2). Different small letters refer to significant differences between treatments.

Water level	Soil amendment	Use efficiency, %		
		N	P	K
W1	T	0.37 ± 0.03^{e}	0.44 ± 0.08^{cd}	10.62 ± 0.88^{c}
	C	2.79 ± 0.22^{cd}	1.82 ± 0.15^{bc}	28.84 ± 6.16^{bc}
	B	0.38 ± 0.10^{e}	0.27 ± 0.06^{d}	3.71 ± 1.31^{c}
	CB	1.17 ± 0.33^{de}	0.37 ± 0.14^{cd}	4.69 ± 1.74^{c}
W2	T	0.92 ± 0.15^{e}	1.62 ± 0.18^{bcd}	39.24 ± 5.57^{b}
	C	7.53 ± 0.42^{a}	5.31 ± 0.61^{a}	122 ± 8.96^{a}
	B	3.15 ± 0.38^{c}	1.18 ± 0.28^{cd}	19.48 ± 5.25^{bc}
	CB	4.78 ± 0.40^{b}	2.96 ± 0.26^{b}	40.14 ± 2.00^{b}

* Where T is control treatment (no amendment), C is compost, B is biochar, and CB is compost+biochar. Different small letters refer to significant differences between treatments at p < 0.05.

Well-watered treatment (W2) led to enhanced NUE, PUE, and KUE compared to their water-stressed (W1) conditions. Compost was the most effective soil amendment for improving nutrient use efficiency across all measured parameters, followed by the compost-biochar mixture. The control (T) and biochar only (B) treatments exhibited significantly lower nutrient use efficiency values. In terms of interactive effects, compost applied under W2 yielded the highest efficiencies (NUE = 7.53%, PUE = 5.31%, and KUE = 122%). This demonstrates the high capacity of improving nutrient uptake and use efficiency under well-watered conditions. The CB treatment also performed well under W2, indicating a complementary role of biochar when combined with compost. Under W1 conditions, compost maintained relatively high efficiencies (NUE = 2.79%, PUE = 1.82%, and KUE = 28.84%), reinforcing its value as a resilient soil amendment. Conversely, biochar under W1 recorded the lowest nutrient use efficiencies (NUE = 0.38%, PUE = 0.27%, and KUE = 3.71%), highlighting its limited effectiveness under drought stress due to its acidity and high content of sodium as explained earlier.

The significantly enhanced plant nutrient uptake and use efficiency observed with compost, compared to biochar, can be attributed to multiple factors. First, compost substantially improves plant nutrient status by increasing the availability of essential macronutrients such as NPK and micronutrients (Manirakiza and Şeker, 2020; Sarwar et al., 2025), whereas biochar may temporarily immobilize certain nutrients due to its strong adsorption capacity (Rodríguez-Vila et al., 2022). Additionally, the alkaline nature of compost (Table 1) helps maintain an optimal pH (6.0-6.5), maximizing macronutrients availability while preventing micronutrient deficiencies associated with high alkaline conditions (Ferrarezi et al., 2022). Furthermore, compost reduces sodium concentration in soil, which is beneficial for plant growth under salt stress conditions (Sarwar et al., 2025). On contrary, the elevated sodium content in biochar can exacerbate soil salinity, impairing plant growth and nutrient acquisition (Hou et al., 2023; Rezaei and Razzaghi, 2018; Soothar et al., 2021).

Conclusions

This study illustrates the critical influence of organic soil amendments on okra growth parameters in sandy soils under varying water regimes. The aim is to recommend the best soil amendment suitable to improve plant nutrient uptake and increase water use efficiency (WUE) under water-stressed and well-watered conditions. Compost emerged as the most effective soil amendment, consistently enhancing plant growth, nutrient uptake, and WUE across both water-stressed and well-watered conditions. Its superior performance stems from optimal organic matter content, favorable pH, and balanced nutrient composition, which collectively improved plant tolerance to drought.

Biochar application alone showed limited effectiveness under water stress, potentially due to its elevated sodium levels and acidic pH that may exacerbate soil salinity. While the compost and biochar combination displayed synergistic benefits under well-watered conditions, its advantages were less pronounced than compost alone.

The results position compost as reliable amendment for sandy soil cultivation, particularly in water-scarce environment. Biochar's utility appears more context-dependent, warranting careful consideration of soil conditions and irrigation management.

Based on the observed results, in areas with similar soil properties and environmental conditions, it is recommended to apply compost as a soil amendment at a rate of ~12.5 kg per hectare of sandy soil at a depth of 18 cm when planting okra. However, the presented research study struggled with certain limitations such as the biochar used was derived from food waste, resulting in a high sodium concentration and low pH. These properties negatively influenced the availability of macro-nutrients, highlighting that the effects of biochar are highly dependent on its specific characteristics and source material. Further investigations should focus on the diverse effects of biochar chemical and physical properties on improving soil water retention and plant water use efficiency. Additional research is recommended at the on-farm level across various soil types (e.g., sandy, calcareous, clay) to better assess the impact of the proposed amendments on soil properties and okra growth under different irrigation regimes and water stress conditions.

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