

Effects of Sustainable Input Applications on Plant Growth in Soil-based Greenhouse Cultivation of *Cucumis sativus* L.

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Abstract

In semi-arid conditions, sustainable soil amendments have recently gained attention for enhancing plant growth and product quality in protected vegetable cultivation. This study aimed to investigate the effects of biochar (BC) and arbuscular mycorrhizal inoculant (Endo Roots Soluble) (ERS)) applications on growth parameters (plant height, stem diameter, number of leaves), yield, photosynthetic activity, fruit quality characteristics (weight, fruit size, color, TSS), and macro- and micronutrient contents in leaves of cucumber (*Cucumis sativus* L.) grown in a fall greenhouse. The experiment was conducted in a randomized complete block design with four treatments and three replications. Results exhibited that both individual and combined applications of biochar and mycorrhiza significantly improved plant growth, yield, and quality parameters ($p < 0.05$; $p < 0.01$). The highest yield per plant and total yield da^{-1} were recorded in the BC treatment, with $3.461 \text{ kg plant}^{-1}$ and $9,385.47 \text{ kg da}^{-1}$, respectively. The highest values for plant height (189.73 cm), stem diameter (17.78 mm), and number of leaves (15.0) were observed in the BC + ERS treatment. Although not statistically significant, the BC + ERS treatment showed a 5.9% numerical increase in photosynthesis rate compared to the control. In the BC + ERS treatment, the highest nitrogen (N) content (8%) and iron (Fe) concentration ($150.51 \text{ mg kg}^{-1}$) were also recorded. Phosphorus (P) content was enhanced by mycorrhizal activity, reaching 1.50% in ERS and 1.46% in BC + ERS treatments. These findings highlight the promising role of biochar and mycorrhiza as soil amendments for developing resilient and sustainable vegetable production systems, particularly for fall planting in regions with limited arable land and water resources.

Keywords: Cucumber, Biochar, Mycorrhizal Fertilizer, Yield, Plant Nutrition, Growth

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INTRODUCTION

Cucumber (*Cucumis sativus* L.), a member of the Cucurbitaceae family (Pal et al, 2020), is one of the dominant greenhouse crops in the region due to its short growth cycle (Marcelis, 1992), high market demand (Kaur & Sharma, 2022), and multiple harvests per year. Greenhouse cultivation enables controlled, off-season production and offers protection from pests and environmental stressors (McCartney and Lefsrud., 2018; TÜİK, 2024).

Greenhouse design must align with local climatic conditions, production goals, materials, and economic feasibility (Argento et al., 2024). According to 2024 data, Turkey is a major producer of greenhouse vegetables. Tomatoes (4.15 million tons), peppers (1.06 million tons), cucumbers (1.03 million tons), and eggplants (368,000 tons) lead in protected vegetable production. Greenhouse areas, particularly plastic types, have expanded significantly, reaching over 776,000 decares nationwide (Statagri, 2024).

Protected cultivation enhances yield (Erdal et al., 2024), improves product quality (Topuz et al., 2024), and buffers against climatic variability. In Turkey, especially in the Mediterranean region, technologies such as automation, soilless culture, and renewable energy integration further support agricultural and food sustainability (Appolloni et al., 2024; Kumar et al., 2018; Azcón et al., 2015).

In Adıyaman, a semi-arid province, greenhouses are primarily used for early and late-season vegetable production, concentrated in Kahta, Besni, and Central districts with irrigation infrastructure. Cucumbers grown as a late-season crop are economically important, supplying local and nearby markets. However, snow damage in 2021 and the 2023 earthquakes disasters have disrupted agricultural activity. Local institutions including Adıyaman University and the GAP Administration have launched recovery programs supporting greenhouse reconstruction and sustainable practices.

Greenhouse-grown cucumbers can yield 2–3 times more than open-field crops, with greater land and water efficiency and enhanced fruit quality. Recently, sustainable inputs such as biochar and arbuscular mycorrhizal fungi have gained attention (Zhou et al., 2020).

Biochar, rich in carbon and nutrients, improves soil quality and supports plant growth while also offering resistance to pathogens (Kolton et al., 2011; Ogundeji et al., 2021; Gunes, 2022). It also contributes to environmental improvement, waste management, and renewable energy initiatives (Nasiri et al., 2023; Iijima et al., 2015; Keshavarz Afshar et al., 2016; Farhangi-Abri & Torabian, 2018; Hashem et al., 2019).

Mycorrhizal inoculants improve nutrient uptake, photosynthesis, and fruit quality traits like sugar and vitamin C (Gülay et al., 2020). When combined with biochar, these fungi enhance microbial activity and nutrient availability, particularly in phosphorus-deficient soils (Lehmann & Joseph, 2015; Smith & Read, 2008).

This study aims to evaluate the effects of biochar and a commercial mycorrhizal product (ERS) on yield, fruit growth, some quality, and nutrient content (Nitrogen (N), Phosphorus (P), Potassium (K), Iron (Fe), Zinc (Zn), Manganese (Mn), Copper (Cu)) in greenhouse-grown cucumbers under semi-arid conditions. SPAD (Soil Plant Analysis Development meter) indicates chlorophyll and photosynthesis rate both crucial for assessing plant health. By assessing sustainable inputs under these conditions, this study contributes to more resilient and efficient agro production systems.

MATERIALS AND METHODS

Site description and Plant Material

This study was conducted between the months of August to November 2024 in a 1-decare plastic greenhouse constructed in Bozhöyük village of Adıyaman Province. The trial was carried out using the Malazgirt F₁ cucumber (*Cucumis sativus* L.) cultivar, grown *via* direct sowing. Seeds were sown on 26th August 2024 with an inter-row spacing of 90 cm and an intra-row spacing of 40 cm. A total of 396 plants were used in the experiment, with 33 plants per replication. Cultural practices such as hoeing and pest control were applied equally to all plots using commercial formulations. The geographic coordinates of the experimental site are 37.625749° N latitude and 38.295423° E longitude. The map image and the location of the greenhouse are presented in Figure 1. Soil samples from the 0–30 cm depth layer were analyzed for key parameters. The soil exhibited a slightly alkaline pH of 8.28. Electrical conductivity (EC) was measured at 599 $\mu\text{S}/\text{cm}$, indicating moderate salinity. Lime content was 42.21%, and the soil texture was classified as clay. Organic matter content was 1.72%. Available phosphorus (P) and potassium (K) were determined as 0.59 kg da^{-1} and 17.2 kg da^{-1} , respectively. Micronutrient analysis showed iron (Fe) at 6.20 mg kg^{-1} and zinc (Zn) at 0.22 mg kg^{-1} .



Figure 1. Overview of the greenhouse and experimental layout at the field site in Bozhöyük, Adıyaman.

Biochar Material Used in the Experiment

The biochar material used in this study was supplied by Tek Karbonlu Mangal Kömür Üretim A.Ş. This product was manufactured from 100% natural oak wood through a medium pyrolysis process at approximately 450 °C temperature using a moderate heating rate. The resulting material was in a fine powder form, characterized by a high surface area and porous structure, typical of charcoal-like organic soil amendments.

In the experiment, the biochar was incorporated into the soil mixture at application rates of 2% and 4%, which were adjusted according to previous literature (Zanutel et al., 2024; Grafmüller et al., 2022). It was specifically mixed into the top 10–15 cm of the soil surrounding the root zone. The application was carried out 15 days after planting, at a rate of 150 g per plant. This method aimed to maximize the water-holding capacity, nutrient retention, and promotion of beneficial soil microbiota. Additionally, this application strategy minimized potential losses of biochar due to degradation, drying, or wind dispersal.

Arbuscular Mycorrhizal Fungi (AMF) Inoculant Used in the Study

In this study, a commercially available product named Endo Roots Soluble (Organic Certified Fertilizer), containing arbuscular mycorrhizal fungi (AMF), was used. The formulation includes inocula of *Glomus intraradices*, *Glomus aggregatum*, *Glomus mosseae*, *Glomus clarum*, *Glomus monosporus*, *Glomus deserticola*, *Glomus brasilianum*, *Glomus etunicatum*, and *Gigaspora margarita*. The product was procured from Bioglobal Ltd. The AMF inoculant was applied via

drip irrigation at a rate of 50 g per plant, 15 and 20 days after sowing, in accordance with the manufacturer's recommendations.

In this study, biochar and arbuscular mycorrhizal fungi (ERS) were applied both individually and in combination. Additionally, all treatments were compared with a non-treated control group.

Measurement of Plant Growth and Yield Parameters

Measurements were conducted in October 2024 using standard procedures. Leaf number was determined by manually counting all visible leaves on each plant. Stem diameter (mm) was measured approximately 2 cm above the soil surface using a digital caliper, while plant height (m) was measured from the soil surface to the tip of the main shoot using a measuring tape. Fruit weight (g) was recorded using a digital scale, and fruit diameter (width) and length (height) were measured with a standard ruler. All measurements were performed in three replicates for each treatment, with five plants and fruits sampled per replicate. For yield calculations, mature fruits were harvested from plants representing each replicate and treatment. Total fruit weight per plot was summed to calculate yield per decare (kg da^{-1}), and this value was divided by the number of plants per plot to obtain yield per plant (kg plant^{-1}).

Photosynthesis, chlorophyll content and TSS (%)

Photosynthesis rate was measured using a portable plant photosynthesis meter (EARS miniPPM 300), and leaf chlorophyll content was assessed using a SPAD meter (SPAD-502, Minolta, Japan), with results expressed as SPAD values. Both SPAD and photosynthesis measurements were conducted between 9:00 and 11:00 AM in October 2024. Total soluble solids (TSS) content of cucumber fruits was determined using a digital refractometer (Atago 3840 PAL, Atago Co., Ltd., Japan) at room temperature ($\sim 20\text{--}25^\circ\text{C}$).

Macro- and Micro- Nutrient Content Analysis

Cucumber leaf samples were dried at 65°C until reaching constant weight, then ground to a fine powder. Two grams of the dried samples were weighed and ashed in a muffle furnace at 550°C for 4 hours. The resulting ash was dissolved in a mixture of nitric and hydrochloric acid (HNO_3/HCl) and diluted with distilled water to prepare solutions suitable for analysis by atomic absorption spectrophotometry (AAS). Total N content was determined using the Kjeldahl method (Kjeldahl, 1883; Saéz Plaza et al., 2013). Phosphorous (P) was analyzed by the vanadomolybdo-phosphoric yellow colorimetric method following wet digestion with a nitric-perchloric acid mixture (Kaçar and Kovancı, 1982). K, Fe, Zn, Mn, and Cu concentrations were measured using flame or graphite furnace atomic absorption spectrometry (Kaçar, 1972).

Statistical Analyses

All statistical analyses were conducted using IBM SPSS Statistics 26.0 software. One-way analysis of variance (ANOVA) was performed to determine the effects of treatments. For variables showing significant differences ($p \leq 0.05$), Duncan's Multiple Range Test (DMRT) and Least Significant Difference (LSD) tests were applied at the 5% significance level to compare means. Descriptive statistics (mean, standard deviation, and 95% confidence intervals) were also calculated. Mean separation results were indicated by letters in the tables, and different letters denote statistically significant differences among treatments.

RESULTS AND DISCUSSION

This study investigated the effects of soil amendment practices, specifically mycorrhizal inoculation and biochar application, on cucumber production. Table 1 presents the effects of different soil amendment applications on yield, fruit color parameters, photosynthetic activity, and chlorophyll content in cucumber plants. The results indicated that soil amendments had a statistically significant effect on both yield per plant and yield per decare ($p < 0.01$). The highest yield per plant (3.461 kg) was observed in the Biochar (BC) treatment, representing approximately a 162% increase compared to the control group (1.322 kg). The highest overall yield ($9,385.47 \text{ kg da}^{-1}$) was recorded in the BC treatment, corresponding to a 163.1% increase relative to the control ($3,566.27 \text{ kg da}^{-1}$). The ERS treatment alone produced a yield of $8,054.23 \text{ kg da}^{-1}$, while ERS + BC yielded $7,844.76 \text{ kg da}^{-1}$, ranking second and third, respectively. The ERS+BC treatment significantly increased yield per plant and total yield compared to the control and single applications, highlighting the synergistic effects of combined biochar and microbial amendment (Figure 2A, 2B). These results confirm that the use of soil amendments (Zhang et al., 2020)—especially integrated applications—plays a critical role in maximizing cucumber productivity (Wang et al., 2021).

Regarding fruit color parameters, the L^* value (lightness) varied significantly among treatments ($p < 0.05$), ranging from 26.80 to 28.46. The highest L^* value was recorded in the BC treatment (28.46), while the lowest was observed in the control group (26.80), indicating that biochar application contributed to increased fruit brightness. The a^* values (green–red axis) were negative across all treatments, indicating a dominant green hue in the fruit. Statistically significant differences were found for this parameter ($p < 0.01$). The most negative a^* value (-8.08) was observed in the BC treatment, suggesting a stronger green color intensity.

The b^* values (yellow–blue axis) also showed significant variation among treatments ($p < 0.01$), ranging from 11.62 to 17.93, with the highest value recorded under BC application. This indicates a greater tendency toward yellow hues in biochar-treated fruits. No statistically significant differences were detected in hue angle among treatments ($p > 0.05$), with values ranging from 114.57 to 117.31, suggesting that soil amendments did not substantially alter the primary hue of the cucumber fruits.

The chroma values (color saturation) differed significantly across treatments ($p < 0.01$), with the highest chroma observed in the BC group (19.68) and the lowest in the ERS group (13.11). This result reflects that biochar enhanced the vibrancy and saturation of fruit coloration.

For photosynthesis rate (%), although numerical differences were observed among treatments (ranging from 57.21% to 60.60%), these differences were not statistically significant ($p > 0.05$). The ERS + BC treatment showed the highest value, while the control had the lowest, indicating a numerical increase of 5.9%, albeit not statistically confirmed.

In contrast, significant differences were observed in SPAD values, which indicate chlorophyll content ($p < 0.01$). The highest SPAD reading (52.40) was found in the ERS + BC treatment, while the lowest (34.67) was measured in the control group. This corresponds to an approximate 51.2% increase in chlorophyll content due to the combined application. SPAD values, indicating relative chlorophyll content, were also significantly enhanced under ERS+BC, suggesting improved photosynthetic potential (Figure 2E). The ERS and BC treatments alone also improved SPAD values to 43.67 and 39.80, respectively, confirming their positive effect on leaf chlorophyll accumulation.

The effects of different soil amendment applications on cucumber agronomic performance parameters were summarized in Table 2. Significant differences were observed among treatments for leaf number, stem diameter, plant height, fruit weight, fruit diameter, fruit length, and total soluble solids (TSS) content ($p \leq 0.05$ or $p \leq 0.01$).

The highest leaf number (15.0) and stem diameter (17.78 mm) were recorded under the combined ERS + BC application, indicating superior vegetative growth. Plant height was greatest in the BC treatment (189.73 cm), closely followed by the ERS + BC (188.93 cm) and ERS (173.60 cm) treatments, all of which were significantly taller than the control group (153.73 cm). A notable increase in stem diameter and plant height was observed in response to biochar and microbial combinations, particularly in ERS+BC treatment (Figure 2C, 2D).

Regarding fruit characteristics, the heaviest fruits were produced by the ERS treatment (144.09 g), whereas the largest fruit diameter (3.2 cm) and length (18.3 cm) were also achieved under this treatment. Both parameters were significantly higher than those in the control group (fruit diameter: 2.8 cm, fruit length: 16.0 cm). The BC treatment resulted in the highest TSS content (3.21%), significantly exceeding the control (2.96%).

These findings collectively demonstrate that combined and individual soil amendments positively influence cucumber growth and fruit quality traits, with ERS + BC promoting vegetative development, ERS enhancing fruit size and weight, and BC improving TSS. The control treatment consistently showed the lowest values across these parameters.

Table 3 presents the macro- and micro-nutrient contents in dried cucumber leaves under different soil amendment treatments, with all measured nutrients showing statistically significant differences among treatments ($p < 0.01$). The highest total nitrogen content was observed in the ERS + BC treatment (8.0%), significantly exceeding other treatments. Phosphorus content peaked in the ERS treatment (1.50%), while potassium content reached its maximum value of 3.77% in the BC treatment.

The ERS + BC treatment led to significant improvements in both macro- and micronutrient concentrations, particularly nitrogen, phosphorus, potassium, and iron, with a pronounced enhancement observed in iron levels (Figure 2F; Table 3). Iron concentration reached its highest level under the ERS + BC treatment, registering $150.51 \text{ mg kg}^{-1}$, while zinc and copper concentrations were highest in the ERS treatment, with values of 30.18 mg kg^{-1} and 30.21 mg kg^{-1} , respectively. Manganese content was most elevated in the BC treatment (13.55 mg kg^{-1}), significantly surpassing other groups.

These results indicate that combined and individual applications of biochar and mycorrhizal biofertilizers positively influence the nutrient accumulation in cucumber leaves. The synergy of soil amendments and microbial biostimulants effectively enhances the nutritional status of the plants, which is likely to contribute to improved growth and yield performance.

In recent times, sustainable production techniques that prioritize human health and environmental protection have necessitated the transition of predominantly small family farms from traditional practices to modern, integrated plant management systems. Within this framework, the application of appropriate cultivation methods and fertilization programs plays a crucial role in plant growth and product quality. The study observed that bio-inputs such as mycorrhizal fertilizer and biochar supported the growth and yield parameters of cucumber plants. Eifediyi and Remison (2010) emphasized that organic-based fertilizers positively influenced growth and yield in cucumber compared to other fertilizer combinations. This finding highlights the necessity of promoting organic-based fertilizers through integrated applications within sustainable agricultural systems. Similarly, Kumar et al., (2018) reported that long-term biochar applications increased yield in pepper, aligning with the results of the present study. This research underscores the critical role of integrated treatments, particularly ERS+BC, in enhancing cucumber yield under semi-arid conditions. Jeffery et al. (2017) noted that biochar increased yields by approximately 25% in tropical climates but exhibited limited efficacy in temperate zones. In contrast, the more than 160% yield increase observed here suggests that the effectiveness of biochar-based applications is strongly dependent on local environmental factors such as soil pH and climatic conditions. These yield improvements are consistent with findings from Asri et al. (2011) and Eifediyi and Remison (2010).

Consistent with Yarış et al. (2008) and Asri et al. (2011), significant differences were also found in fruit color parameters a^* (green intensity) and b^* (yellowness) in this study. The lowest a^* value (-8.08) and highest b^* value (17.93) was recorded under the BC treatment ($p < 0.01$), indicating that biochar application positively influenced pigment development and fruit coloration.

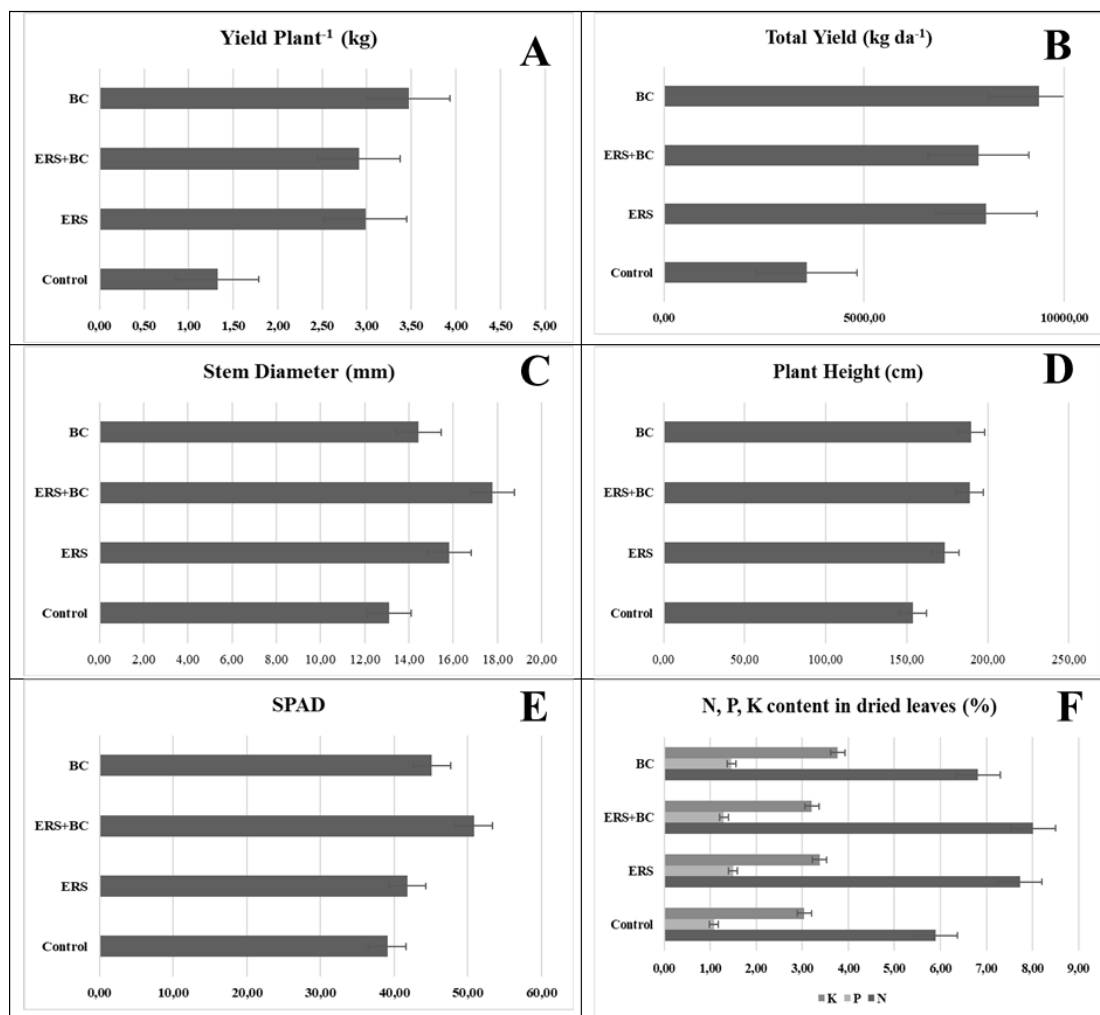


Figure 2. Effects of soil amendment treatments on morphological, physiological and nutritional parameters in cucumber plants. Panels represent (A) yield plant⁻¹ (g), (B) total yield (kg da⁻¹), (C) stem diameter (mm), (D) plant height (cm), (E) SPAD values, and (F) N, P, K content in dried leaves.

Bolat and Kara (2017), Çelik et al. (2019), and Şahin et al. (2024) reported that biochar and mycorrhizal treatments enhanced nutrient uptake, thereby supporting leaf number and seedling development. Similarly, the highest leaf number and stem diameter values were observed under the ERS + BC combination in this study. These increases can be attributed to biochar's effect on improving soil water retention capacity and mycorrhiza's enhancement of nutrient uptake efficiency in the root zone (Sun et al., 2024). The beneficial effects of biochar and mycorrhizal applications on soil health and nutrient uptake have been emphasized in multiple studies. While Bolat and Kara (2017) documented improved nutrient absorption with biochar, Seyed Sharifi et al. (2017) reported significant enhancement of phosphorus uptake by mycorrhiza in basil but noted limited effects of biochar on this parameter. Increased organic matter content in the rhizosphere supports the symbiotic relationship between mycorrhiza and plants, thus promoting nutrient uptake (Azcón-Aguilar & Barea, 1996, 2015; Güneş, 2022).

Organic fertilizer applications have been reported to improve soil structure, increase water holding capacity, and reduce erosion risk, contributing to healthier plant development (Fageria, 2012). In this context, the ERS + BC treatment in our study notably enhanced the content and balanced distribution of nutrients such as K, Mn, and Cu. Ye et al. (2020) reported increased yield when biochar was applied alongside mineral fertilizers, consistent with the elevated nutrient levels observed in this study.

Furthermore, Kumar et al., (2018) highlighted that long-term biochar application increased pepper yield and soil organic matter content. This attribute of biochar, which stabilizes carbon in the soil and reduces greenhouse gas emissions, also underscores its value as an environmentally friendly and cost-effective soil amendment (Zhang et al., 2017; Yang et al., 2019; Xiang et al., 2020; Creamer & Gao, 2016; Güneş, 2022).

Table 1. Effects of Different Soil Amendment Applications on Yield, Fruit Color, Photosynthetic Activity and Chlorophyll Content of Cucumber

	Yield Parameters		Color Parameters				Photosynthesis & Chlorophyll Parameters			
	Yield Plant ⁻¹ (kg)	Yield (ton da ⁻¹)	L	a	b	Hue	Chrom a	Photosynthesis rate (%)	R	SPAD
1	1.322 d	3,566.27 d	26.80 b	-6.93 b	13.67 bc	117.16	15.40 cb	57.21	34.67 d	39.0 d
2	2.973 b	8,054.23 b	26.98 b	-5.98 ab	11.62 c	117.31	13.11 c	59.66	43.67 b	41.8 c
3	2.909 c	7,844.76 c	28.36 a	-7.56 ab	15.33 b	116.65	17.12 b	60.60	52.40 a	50.8 a
4	3.461 a	9,385.47 a	28.46 a	-8.08 a	17.93 a	114.57	19.68 a	58.97	39.80 c	45.1 b
	**	**	*	**	**	NS	**	NS	**	**
F	4422.982	4429.384	3.967	6.952	10.181	1.502	10.507	2.403	75.524	269.132

1: Control 2:ERS 3:ERS+BC 4: BC

*, ** indicates significance at ($p \leq 0.05$) and ($p \leq 0.01$), respectively and NS: Not-significance

Means followed by different letters are significantly different according to Duncan's Multiple Range Test.

Table 2. Effects of Biochar and ERS Applications on Agronomic Characteristics and Fruit Quality Parameters of Cucumber

	Agronomic Performance Parameters						TSS (%)
	Leaf Numbers	Stem Diameter (mm)	Plant Height (cm)	Fruit Weight (g)	Fruit Diameter (cm)	Fruit Length (cm)	
1	9 c	13.12 d	153.73 c	103.764 c	2.8 c	16.0 c	2.96 b
2	14.7 a	15.82 b	173.60 b	144.085 a	3.2 a	18.3 a	2.97 b
3	15.0 a	17.78 a	188.93 a	129.135 b	3.1 a	16.8 b	2.98 b
4	13.3 b	14.44 c	189.73 a	125.582 b	3.0 b	17.0 b	3.21 a
	**	**	**	**	*	*	**
F	153.471	56.960	223.197	153.741	18.365	87.790	17.331

1: Control 2:ERS 3:ERS+BC 4: BC

*, ** indicates significance at ($p \leq 0.05$) and ($p \leq 0.01$), respectively and NS: Not-significance

Means followed by different letters are significantly different according to Duncan's Multiple Range Test.

Table 3. Mineral Element Content in Dried Leaves of Cucumber Plants

	Content of Nutrient Macro and Micro Elements of Dried Cucumber Leaves						Cu (mg kg ⁻¹)
	N (%)	P (%)	K (%)	Fe (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Mn (mg kg ⁻¹)	
1	5.9 d	1.08 c	3.04 d	90.6 c	20.77 c	7.63 d	20.88 c
2	7.7 b	1.50 a	3.38 b	116.45 b	30.18 a	11.03 b	30.21a
3	8.0 a	1.29 b	3.20 c	150.51 a	27.15 b	8.93 c	27.11 b
4	6.8 c	1.46 a	3.77 a	92.64 c	29.82 a	13.55 a	30.04 a
	**	**	**	**	**	**	**
F	1233.627	117.438	779.900	860.017	31.046	844.381	32.451

1: Control 2:ERS 3:ERS+BC 4: BC

*, ** indicates significance at ($p \leq 0.05$) and ($p \leq 0.01$), respectively and NS: Not-significance

Means followed by different letters are significantly different according to Duncan's Multiple Range Test.

CONCLUSION

Biochar is considered a promising tool for sustainable soil health management, contributing significantly to the improvement of soil structure and the support of nutrient cycling, particularly in the short period. However, due to uncertainties regarding the long-term persistence of biochar effects reported in the literature, long-term field trials conducted under diverse environmental conditions are of paramount importance.

The potential of biochar in enhancing soil health, nutrient management, and mitigating climate change should be carefully optimized within the framework of sustainable agriculture goals, while also considering its economic feasibility. In this context, the benefits derived from alternative applications such as biochar must be evaluated alongside plant growth parameters (e.g., plant height, stem diameter, leaf number) and productivity levels, which is critical for the development of resilient production systems.

Mycorrhizal biofertilizers have also been recognized as microorganisms that establish symbiotic relationships with plant roots, promoting plant growth, enhancing nutrient uptake efficiency, and improving microbial activity in the rhizosphere. When applied together with biochar, these symbiotic microorganisms benefit from a more favorable habitat around the roots, resulting in synergistic effects on plant development.

Consequently, under semi-arid climatic conditions, within greenhouse environments and regions with limited vegetable production areas, this study demonstrated that mycorrhiza and biochar applications positively affected growth parameters such as plant height, stem diameter, and leaf number, as well as yield and quality traits in cucumber. Thus, these applications can be considered effective and feasible strategies for sustainable greenhouse vegetable cultivation.

Compliance with Ethical Standards

Peer Review

This article has been peer-reviewed by independent experts in the field using a double-blind review process.

Conflict of Interest

The author declares that there is no conflict of interest.

Author Contribution

The author solely conceived, designed, and conducted the study, analyzed the data, and wrote the manuscript.

Ethics Committee Approval

Ethical approval was not required for this study.

Consent to Participate / Publish

Not applicable.

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Data Availability

Not applicable.

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