Positive Effects of Biochar on Pepper Growth, Yield, and Root Distribution under Water Stress Conditions

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ABSTRACT: The present study aimed to evaluate the effect of corncob waste-derived biochar (locally produced via slow pyrolysis – 500°C) on improved pepper plant growth, yield, and root growth and distribution. Sandy soil collected from the surface layer (0 – 30 cm depth) was used in this study. The sand was mixed with soft parts of corncob biochar at rates of 0, 0.25, 0.5, 1, and 2% (w/w). The mixture of each treatment was wetted to field capacity and incubated at room temperature (25±2 °C) for one month with rewetting every 7 days. The soil-biochar mixtures were underwent to physical and chemical analysis. The experimental design was carried out using a split-plot arrangement with randomized complete block design (RCBD) in three replicates for pot experiment inside open greenhouse. Four irrigation deficit (40, 60, 80, and 100% of ET_0) were assigned to the main factor. Biochar rates of 0.0, 0.25, 0.50, 1.0, and 2% (w/w) treatments were assigned to the submain factor. Two healthy seedlings, one month old, of green pepper (*Capsicum annuum* L.) cv. Hybrid 103 was planted in each pot on September 15, 2020. The agronomy practices were applied as recommended. The obtained results showed that all green pepper growth of shoot and root parameters were significantly affected by the irrigation deficit and applied biochar. Increasin The biochar rate 2% obtained the highest pepper root growth parameters. The interaction between water deficits and biochar application rates have a highly significant effect on Pepper fruit nutrient contents, where the highest values were attained at 2% biochar application and 100% of ET_0. Biochar addition on sandy soil showed improvement in growth, yield, and root distribution of green pepper plants grown under water sress. Through the enhancement of soil quality indices such organic matter, structure, water and nutrient holding capacity, and bioactivity. Therefore, the applied proper doses of good quality biochar combined with low inputs of mineral fertilizers can used as the one of the promising strategies for sustainability of sandy soil and maximize crop yied under drought condition.

***Keywords**: Biochar, pepper growth , root distribution, water stress, irrigation deficit*

INTRODUCTION

Pepper (Capsicum annuum L.), belonging to the Solanaceae family (de Souza et al., 2019), is one of the top ten most important vegetables in terms of market value and volume sold. This vegetable can be consumed either as mature green fruits or in an industrialized powder form (Silva et al., 2014). It is a plant that has high demands in terms of the chemical and physical characteristics of the soil, but it responds well to organic fertilization. The highest yields are obtained through the combination of organic fertilizers and minerals (Sediyama et al., 2009).

The International Biochar Initiative (IBI) defines biochar as a fine-grained organic material with a high carbon content. It is produced through the pyrolysis process, which involves the thermal degradation of biomass at temperatures ranging from 300 to 600 °C in the complete or partial absence of oxygen (Lehmann & Joseph, 2015; Oni et al., 2019). The biochar have a positive effect on plant growth, yield, and root distribution under water stress conditions

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Biochar widely used to improve soil health and increase crop yield under stress situations. The application of biochar improves soil organic matter, soil structure, soil aggregate stability, water and nutrient holding capacity, and the activity of beneficial microbes and fungi. This leads to an increase in tolerance to both damaging and abiotic stresses (Hou et al., 2023). Moreover, it has been discovered that the growth, physiology, and water usage efficiency of plants under water stress are all improved by the use of biochar in conjunction with reduced irrigation schedules (Hou et al., 2023). All things considered, applying biochar can be a useful strategy to mitigate the adverse effects of water stress on pepper yield, growth, and root development.

In recent years, the use of biochar in agricultural ecosystems has gained a lot of interest due to the potential benefits to both yield and the environment (Alkharabsheh et al., 2021; Liu et al., 2020). Biochar and fertilizers may be the primary methods for improving soil fertility, water consumption efficiency, and crop yield in regions with limited water resources by mitigating the negative effects of drought stress (Faloye et al., 2019).

In addition, the application of biochar enhances soil physical properties such as water-holding capacity, structure, porosity, bulk density, and fertility (Azeem et al., 2019; Baiamonte et al., 2021). Biochar increases soil water availability, which leads to a reduction in oxidative and osmotic stresses. This, in turn, improves plant growth and enhances water uptake by plants (Kul et al., 2021). The use of biochar indirectly improves soil water supply by altering soil structure and increasing water-holding capacity (Zhang et al., 2023). Biochar has the potential to enhance the quality of salt-affected sandy soil in arid conditions. This can lead to increased vegetative growth, yield, and water use efficiency (WUE) of tomato plants (Usman et al., 2016). The addition of biochar improved the quality of poor soil and enhanced vegetative growth traits, yield, and biomass of plants under conditions of salt and drought stress (Ali et al., 2017). The biochar rate of 4.8 t/ha increased the number of leaves, flowers, and fruit diameters of tomato . However, this increase was not enough to offset the decrease in fruit yield and the high levels of sodium ions that built up in the roots as a result of saline stress (Hazman et al., 2022). The biochar efficient depends on soil type, the amount of biochar added to the soil, and the physicochemical characteristics of the biochar. These characteristics are mainly determined by the type of feedstock and the pyrolysis conditions (Usman et al., 2016; Al-Wabel et al., 2013; Gabhi et al., 2020). The addition of biochar as an amendment has been proposed as a method to improve long-term productivity and enhance water and fertilizer use efficiency.

The objectives of the present paper were to:

1) Beneficial use of solid agricultural wastes turned to biochar,

2) Study of the role of biochar in improving plant growth and yield under water stress conditions, and

3) Study of the role of biochar in root distribution under water stress conditions.

MATERIALS AND METHODS

Soil sample

The soil sample used in the present study was collected from the surface layer (0 – 30 cm depth) at the El-Shagaa Village, Nubaria region, Behiera Governorate.

The soil was air-dried and passed through a 2.0 mm sieve. Some physical and chemical properties of the soil sample are reported in Table (1). The soil properties were performed according to the procedures outlined in **(Carter and Gregorich, 2008).**

Biochar sample

The biochar material used in the present study was obtained from the Biochar Production Unit associated with the project "Development of Biochar Technology Production from Agricultural Residues and its Application to Some Solve Existing Environmental Problems in the Egyptian Community" Central Laboratory for Agricultural Climate, Albossaly, and financially supported by the Academy of Scientific Research and Technology, Egypt.

The biochar was produced from soft parts of corncob by pyrolysis at a high temperature (500 °C) using the fabricated stove for this purpose under limited oxygen (Figure 1)

Table (1). Soil physical and chemical analysis of soil used in the present study

Parameters	Values
Particle-size distribution (%)	
Sand	94.00
Silt	5.00
Clay	1.00
Textural class	Sand
EC, dS/m (1:1, water extract)	0.477
pH (1:1, water suspension)	7.67
Organic carbon (%)	1.38
$CaCO_3$ (%)	2.50
Soluble cations (meq/l)	
Ca^{2+}	1.753
Mg^{2+}	1.550
Na^{+}	0.803
K^{+}	0.351
Soluble anions (meq/l)	
$CO_3^{=}$+HCO_3^{-}	0.352
Cl^{-}	2.533
$SO_4^{=}$	1.863
Available Nutrients (mg/kg)	
N	52.1
P	15.08
K	351.67

Figure (1). Picture of the Soft Corncob biochar used in the present study

The biochar was subjected to chemical analysis and the result is illustrated in Table (2) according to (Carter and Gregorich, 2008).

Table (2). Chemical analysis of soft Corncob Biochar

Parameters	Soft Biochar
EC (1:10, water extract), dS/m	2.556
pH (1:10, water suspension)	7.50
Organic carbon, %	37.00
CEC, me/100 g	10.385
Soluble nutrients, %	
N	0.044
P	0.017
K	0.403
Ca	0.160
Mg	0.115
Na	0.390
Total Elements, %	
N	0.945
P	0.980
K	1.350
Ca	1.340
Mg	1.360
Na	0.800

Soil-Biochar mixture preparation

The sandy soil was mixed with biochar at rates of 0, 0.25, 0.5, 1.0, and 2% (w/w). The mixture was wetted to field capacity and incubated at room temperature (25±2°C) for one month with rewetting every 7 days. At the end of the incubation time, the soil-biochar mixtures were air-dried and pass-through a 2.0 mm sieve and stored for pot experiment.

Pot Experiment setup

The pot experiment was carried out as a split plot in Randomized Complete Block Design (RCBD), with three replications in the open greenhouse of the Central Laboratory for Agricultural Climate (CLAC), Albossaly, Beheira Government. There were two studied factors. The main factor is the irrigation deficit (five treatments, 40, 60, 80, and 100% of potential evapotranspiration, ET0). The sub-factor is biochar rates of 0.0, 0.25, 0.50, 1.0, and 2% (w/w) treatments. There were 60 pots with a capacity of 15 kg (diameter=20 cm and height=30 cm). The green pepper (Capsicum annuum L.) cv. Hybrid 103 (2 seedlings per pot, four weeks old) was sown on September 30, 2020. The agronomy practices were applied as recommended. The irrigation was applied every two days according to the calculated crop evapotranspiration with the Penman-Montith equation **(Allen et al., 1998).** The well-ground biochar passed through a 0.5 mm sieve was mixed in the pots before one week of seed sowing. At harvesting time on Feb 24, 2021, the plants were collected manually. Harvested plants from each pot were separated into roots and shoots and they were weighed separately.

Plant measured parameters

1- **Vegetative growth parameters** included: stem length(cm), No. of branches, stem fresh weight(g), stem dry weight(g), shoot water content (%), total fresh weight (g)
2- **Root measurements included:** root length (RL, cm), root width (RW, cm), root fresh weight (RFW, g), root dry weight (RDW, g), root water content (RWC, %), and root volume density(RD

Laboratory soil analysis:

The soil samples were taken from each pot after harvesting and analyzed for the following properties:

Soil pH was determined in the 1:1, soil: water suspension using a pH meter **(Jackson, 1973).**

Electrical conductivity (EC): The soil: water extract, 1:1 (w/v) was measured using a conductivity meter according to **(Jackson 1973)**.

Soil Organic Carbon (SOC) was determined using the modified Walkley-Blacks titration method (**Carter and Gregorich, 2008**). The soil organic matter content (OM) was calculated using the suitable constant (1.724).

Soluble cations (meq/l): soluble Ca and Mg were determined by titration using EDTA titer according to the methods outlined in **Carter and Gregorich(2008).** Na and K were determined by flame photometry according to the methods outlined in **Jackson (1973).**

Soluble anions (meq/l): Soluble HCO3, CL, and SO4 were determined according to the methods outlined in **(Carter and Gregorich 2008).**

Total calcium carbonates (%), were determined according to the methods outlined in **Carter and Gregorich (2008).**

Soil available nitrogen content (mg/kg): available N was determined in soil extract by using the Neseler method described by **(Jackson, 1973).**

Soil available phosphorus content (mg/kg): Available phosphorus extracted according to **(Olsen et al., 1954)** and determined using method **(Jackson, 1973).**

Soil available potassium content (mg/kg): available K extracted by ammonium acetate (1N of pH 7.0) and determined by flame photometry **(Jackson, 1973).**

Laboratory plant analysis:

At harvesting time, the fruit sample was cut into small pieces and then dried at 70C° in an electric oven for 48 hrs. The dried material was grounded in a plant mill. The grounded powder was digested with sulfuric acid + hydrogen peroxide **(Lowther, 1980).** The digestion extract was subjected to nutrient determination according to the methods outlined in Carter and Gregorich (2008).

Root nutrients content: such as N, P, K, Ca, and Mg as % (dry matter) and protein content (%).

Protein content: protein content (%) was calculated by multiply the nitrogen content by 5.75.

Leaf chlorophyll content (mg/100 g FW)

Chlorophyll content was determined in fresh leaves to estimate chlorophyll a and b, respectively **(Arnon, 1956, Richardson *et al.*, 2002) as follows:**

Chl a = (17.7 A663 – 2.63 A645) *(10/w)

Chl b = (22.9 A645 – 4.68 A663) *(10/w)

Total chlorophyll = Chl a + Chl b

Where: A645 and A663 are the absorptions at 645 and 663 nm wavelength, w is the leaf sample weight and 10 is the volume of the measured solution.

III.9. Statistical analysis

The data were first tabulated in Microsoft Excel and analyzed using STATISTIX 10 (Statistix, 2019). Means were separated using the Least significant difference Test (LSD) at a 5% probability level of significance (**Snedecor and Cochran, 1989**).

RESULTS AND DISCUSSION

Biochar characteristics

Scanning electron micrograph (SEM) images are very useful to obtain accurate details about the surface structure of biochar. The comparison of the images between soft and hard biochars might then allow us to understand morphological changes during the carbonization stage **(Özçimen and Ersoy–Mericboyu, 2010)**. The SEM pictures of soft biochar produced at 500˚C are given in Plate (1). The surfaces of BC were imaged with many hollow channels in diameters of around 29 and 95 nanometers for soft biochar. These porous structures of the biochar are likely to provide a high internal surface area and adsorption ability for elements and increase the ability for water retention. The structural difference may reflect the specific surface area and the adsorptio

capacity of water.

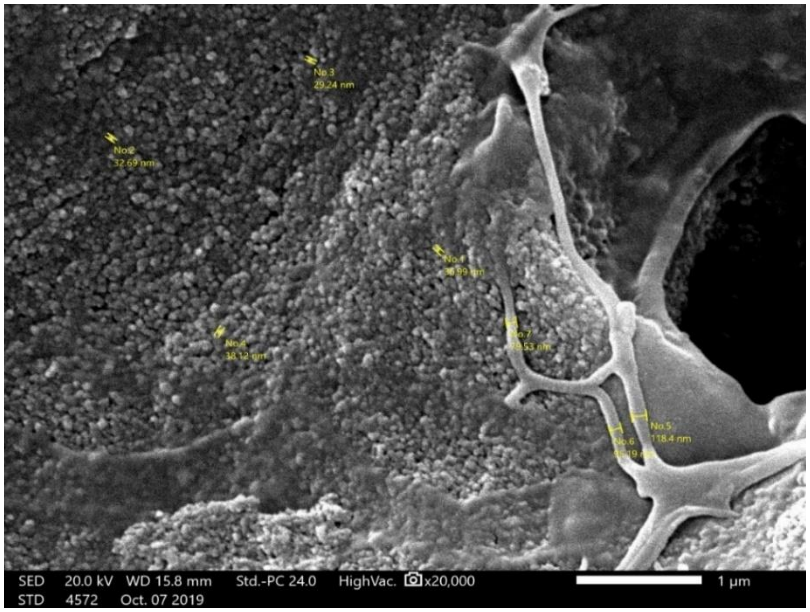

Plate (1). SEM micrograph of Soft corncob biochar

The functional groups identified from the FTIR spectra for the soft and hard biochar samples are illustrated in Figure (2). The spectra of soft biochar demonstrated many bands at 3318 cm–1 (amides group), 2924 cm–1 (aromatic group), 1597 cm–1 (carboxyl group), 1432 cm-1(nitro group), 793 cm-1(thiocarbonyl), and 551 cm-1(alkyl group) as shown in Figure 2.

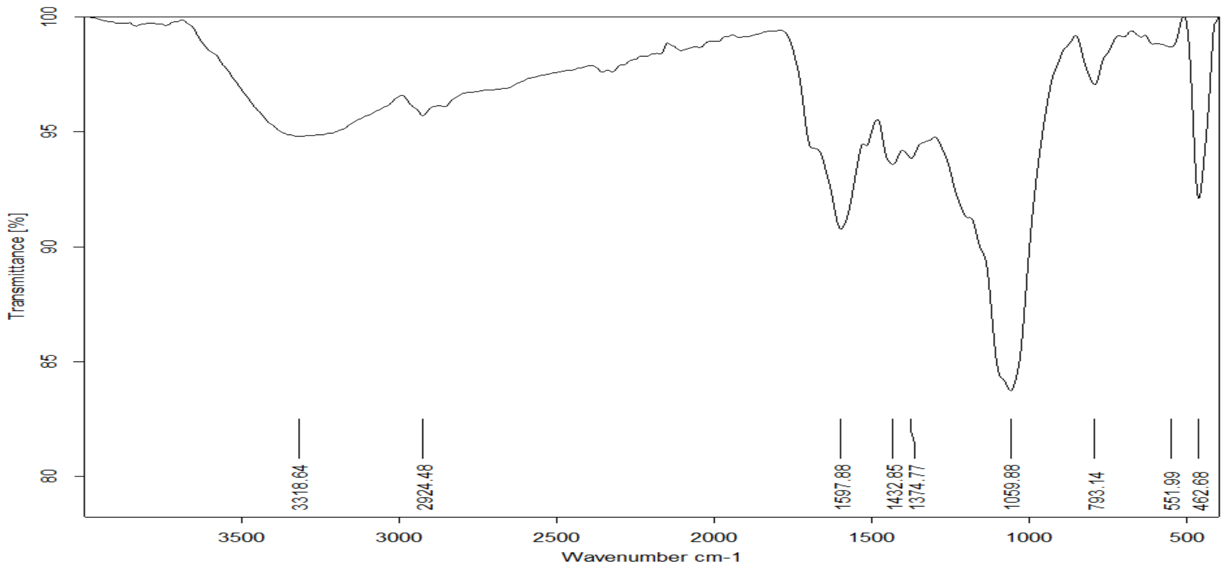

Figure (2). FTIR Spectra of soft corncob biochar

The energy-dispersive X-ray microanalysis (EDX) of the soft biochar is described in Figure (3). For EDX quantification of these features, an accelerating voltage of 10 kV was used since this was enough to generate all elemental peaks of interest. To optimize the chemical analysis of elements in biochar present in the samples, the analyzer mode in the INCA software was used to find the optimal choice of accelerating voltage. In Figure (3), the synthesized spectrum for an accelerating voltage of 4 kV is seen. It is clear that with a lower accelerating voltage, the carbon peak is much stronger compared to the other peaks. A lower accelerating voltage is preferred. Table (3) shows the approximate chemical analysis of soft biochar.

Table (3). The EDX elemental analysis of soft corncob biochar samples

Elements	Soft Biochar Mass %	Atom %
C	61.77	69.49
O	34.52	29.15
Mg	0.25	0.14
Si	0.45	0.22
P	0.28	0.12
K	1.42	0.49
Ca	0.81	0.27
Fe	0.16	0.04
Cu	0.34	0.07
Total	**100.00**	**100.00**

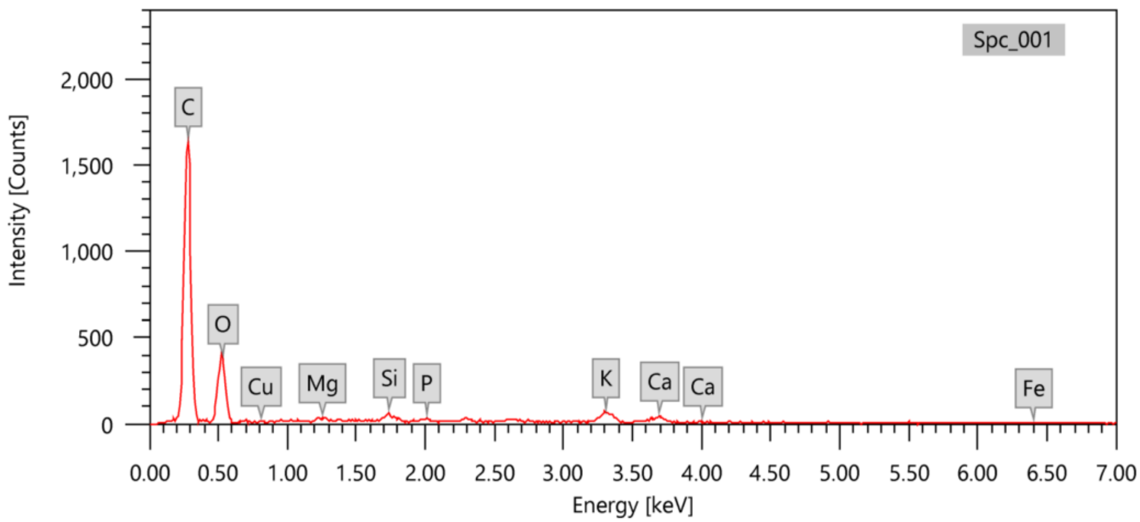

Figure (3). EDX spectra of soft corncob biochar sample

IV.2. Effect of irrigation and biochar on Pepper plant growth

Plant growth

Table (4) illustrates the effect of both irrigation and biochar application on pepper growth parameters.

Irrigation deficit was highly significantly affected the pepper growth parameters such as stem length, No. of branches, stem fresh weight, stem dry weight, stem water content, total fresh weight, chlorophyll a, b and total chlorophyll. All pepper growth parameters were significantly increased as the irrigation deficit increased. The relative values of pepper growth parameters as compared to the 100% of ET0 were 84.28, 90.78, and 94.82% for stem length, 71.59, 83.83, and 86.14% for No. of branches, 69.89, 82.46, and 83.83% for stem fresh weight, 82.51, 86.69, and 99.24% for stem dry weight, 95.60, 99.04, and 96.71 for stem water content,71.09, 85.22, and 87.15% for total fresh weight, 31.57, 52.72, and 70.53% for chlorophyll (a) content, 55.82, 70.56, and 85.12% for chlorophyll (b) content, and 46.42, 63.65, and 79.46% for total chlorophyll content.

Biochar application rates significantly increased the pepper growth parameters. Increasing the biochar rate to 2% significantly increased the pepper growth parameters. The increases in pepper growth parameters at 2% biochar application were 66.19, 100.39, 51.41, 45.00, 1.68, 61.49, 39.78, 19.18, and 25.78%, for stem length, No. of branches, stem fresh weight, stem dry weight, stem water content, total fresh weight, chlorophyll (a) content, chlorophyll (b) content, and total chlorophyll content, respectively as compared with 0% biochar application rate as control (Table 5).

The interaction effect for irrigation deficit and biochar rates was highly significant and the best treatment was attained at 100% of ET0 and 2% of biochar rate.

The present study has reported positive effects of biochar on pepper growth, such as improved nutrient availability, and enhanced soil fertility. However, there is also debate and conflicting findings regarding the optimal biochar application rate and its long-term effects on pepper growth (**Smith et al., 2015)**. Future research should focus on determining the ideal biochar type and application method for maximizing pepper yield. Applying biochar can lessen the detrimental impacts of water stress on pepper development. By increasing soil nutrient availability and water retention, biochar enhances plant performance in general.

According to recent findings (**Johnson et al., 2018**), applying biochar greatly improves soil fertility by raising the nutrient content and soil organic carbon. Furthermore, the study shows that using biochar promotes better pepper plant development and yield. These findings imply that using biochar to improve soil fertility and boost pepper production can be a successful tactic.

Biochar is widely applied as an amendment to improve soil quality and fertility. As an example, BC proved its efficiency in ameliorating soil structure (Baiamonte, et al., 2015), increasing crop productivity (Schmidt, et al., 2015), affecting pH, enhancing ionic exchange capacity, porosity, surface area, bulk density, water-holding capacity (WHC), nutrient use efficiency, as well as increasing phosphorus and nitrogen availability to plant nutrition **(Kammann, et al., 2015; Alkharabsheh, et al., 2021).**

It has been discovered that pepper plant yield and vegetative growth are positively impacted by the use of biochar. The application of biochar has been demonstrated in many studies to improve pepper plant growth, productivity, and nutrient uptake (**Al-Harbia** et al., 2020). For instance, a study on the effects of biochar on tomato and pepper plants grown on soilless media discovered that the development of pepper plants in biochar-treated pots was greatly boosted, increasing leaf area, canopy dry weight, node count, and yields of buds, flowers, and fruit **(Graber et al., 2010).** Also, the biochar increases the efficiency of nutrient uptake and decreases nutrient loss in leachates, both of which can lead to increased plant growth and yield (**Lévesque et al., 2020**). It's crucial to remember that a variety of factors, including the biochar type, the rate at which it is applied, and the soil conditions, might affect how successful biochar is (**Jaaf et al., 2022**).

The extent of changes in soil properties depends on the characteristics of both biochar and soil to which it is to be applied **(Joseph et al., 2021**). Biochar application to soil has its in*fl*uence on the wettability of soil, water in*fi*ltration, water retention, aggregation, and stability thereby helping in combating erosion, mitigating drought and nutrient loss, and enhancing groundwater quality.

The following are some of the main conclusions of this section:

- Pepper plant development was markedly improved in biochar-treated pots; this resulted in increased leaf area, canopy dry weight, node count, and yields of fruit, buds, and flowers.
- Several pepper vegetative development and yield characteristics were significantly impacted by the combination of biochar and irrigation.
- The application of biochar increased the stem height, no. of branches, and fruit production of pepper plants.
- Compared to unaltered controls, pepper plant development in biochar-treated pots was significantly improved, with a system-wide rise in the majority of measured plant parameters.

According to **Jaaf et al. (2022)**, Red pepper (Capsicum annuum L.) growth and some chemical properties of a silty-clay soil showed varying impacts on plant growth parameters upon application of biochar derived from corncob and poultry litter; poultry litter, either alone or in combination with biochar, increased soil macro- and micronutrient concentrations and improved most of the red pepper growth parameters.

Overall, the research points to biochar as a good soil supplement for pepper cultivation, with the potential to positively impact pepper vegetative development and yield. It's crucial to remember that a variety of factors, including the type of biochar, the rate at which it is applied, and the soil conditions, might affect how successful biochar is. The results of the present study are compatible with those obtained by **Graber et al.(2010); Lévesque et al.(2020); Al-Harbia et al. (2020); and Jaaf et al. (2022).**

Table (4). Vegetative growth of pepper plant as affected by irrigation deficit and biochar

Irrigation regime, % of ET_0	Biochar application, %	Stem length cm	No. of branches	Stem fresh weight g	Stem dry weight g	Stem water content %	Total fresh weight g	Chlorophyll a mg/100g	Chlorophyll b mg/100g	Total Chlorophyll mg/100g
40	0	12.80	2.33	7.83	1.92	75.53	15.67	35.80	135.40	171.20
	0.25	20.00	2.33	9.83	1.93	80.34	18.17	45.30	143.80	189.10
	0.5	21.83	3.00	11.00	2.13	80.61	20.83	57.40	155.80	213.20
	1	25.33	3.67	15.67	2.38	84.79	27.17	65.80	163.80	229.60
	2	28.33	4.17	16.83	2.48	85.25	28.83	72.50	174.90	247.40
60	0	12.50	2.67	12.00	1.88	84.31	21.33	73.80	176.80	250.60
	0.25	24.50	2.50	14.17	2.12	85.06	23.67	85.20	184.80	170.00
	0.5	24.67	2.83	14.50	2.28	84.25	26.67	92.50	196.80	289.30
	1	27.33	4.67	15.17	2.50	83.52	28.83	100.40	205.80	306.20
	2	27.67	5.50	16.33	2.62	83.98	32.17	110.30	213.90	324.20
80	0	20.83	2.33	13.17	2.12	83.92	19.33	107.80	217.30	325.10
	0.25	21.67	3.83	14.17	2.40	83.06	23.67	116.30	224.80	341.10
	0.5	23.17	4.00	14.50	2.72	81.26	26.50	121.70	235.90	357.60
	1	24.00	4.00	15.67	2.85	81.81	32.00	130.60	244.80	375.40
	2	32.17	4.50	15.83	2.98	81.16	34.17	141.90	257.00	398.90
100	0	23.67	3.00	13.67	2.07	84.88	25.50	154.70	259.40	414.10
	0.25	23.83	3.83	15.17	2.23	85.27	27.83	166.50	267.90	434.40
	0.5	26.00	4.00	17.00	2.25	86.76	30.33	175.30	278.50	453.80
	1	27.17	4.33	20.00	3.10	84.50	35.00	184.00	285.90	470.70
	2	27.83	6.50	21.67	3.52	83.77	37.00	195.40	294.40	489.80

Table (5). Main effects of irrigation, biochar, and their interaction on pepper vegetative growth

Treatments	Stem length Cm	No. of branches	Stem fresh weight g	Stem dry weight g	Stem water content %	Total fresh weight g	Chlorophyl a mg/100g	Chlorophyll b mg/100g	Total Chlorophyll mg/100g
The main effect of irrigation (% of ET_0)									
40	21.66	3.10	12.23	2.17	81.30	22.13	55.36	154.74	210.10
60	23.33	3.63	14.43	2.28	84.22	26.53	92.44	195.62	288.06
80	24.37	3.73	14.67	2.61	82.24	27.13	123.66	235.96	359.62
100	25.70	4.33	17.50	2.63	85.04	31.13	175.34	277.22	452.56
LSD 0.05	0.51**	0.07**	0.14**	0.05**	0.34**	0.39**	1.73**	2.26**	3.97**
The main effect of Biochar (%)									
0	17.45	2.58	11.67	2.00	82.16	20.46	93.02	197.22	290.25
0.25	22.50	3.13	13.33	2.17	83.43	23.33	103.32	205.32	308.65
0.5	23.92	3.46	14.25	2.35	83.22	26.08	111.72	216.75	328.47
1	25.96	4.17	16.63	2.71	83.65	30.75	120.40	225.08	345.47
2	29.00	5.17	17.67	2.90	83.54	33.04	130.02	235.05	365.08
LSD 0.05	0.58**	0.08**	0.25**	0.05**	0.46**	0.39**	1.24**	1.91**	1.99**
Irrigation X Biochar interaction									
LSD 0.05	1.15**	0.16**	0.46**	0.09**	0.88**	0.79**	2.79**	4.09ns	5.30ns

Root growth characteristics

The effect of both irrigation and biochar application on pepper root growth parameters are illustrated in Table (6).

Irrigation regimes highly significantly affected the pepper root growth parameters such as root length, root width, root fresh weight, root dry weight, root water content, and root volume density. All pepper root growth parameters were significantly increased as the irrigation regime increased from 40 to 100% of ET0. The relative values of pepper root growth parameters as compared to the 100% of ET0 were 86.41, 87.46, and 98.59%, for root length, 71.59, 83.83, and 60.45, 84.68, and 99.35% for root width, 72.63, 88.77, and 91.49% for root fresh weight, 87.03, 88.61, and 93.35% for root dry weight, 93.85, 96.18, and 98.61% for root water content, and 72.41, 88.97, and 91.03% for root volume density.

Biochar application rates significantly increased the pepper root growth parameters. Increasing the biochar rate by 2% significantly increased the pepper root growth parameters. The increases in pepper root growth parameters were 62.12, 100, 74.97, 103.08, -4.12, and 73.04%, for root length, root width, root fresh weight, root dry weight, root water content, and root volume density, respectively as compared with 0% biochar application rate as control (Table 7).

The interaction effect for irrigation regimes and biochar rates was highly significant the best treatment was attained at 100% of ET0 and 2% of biochar rate, except for root fresh weight, root dry weight, root water content, and root volume density which the maximum values were attained at 80% of ET0 and 1.0% biochar rate.

Water stress negatively impacts plant and root growth, resulting in reduced biomass and altered root architecture. Deficit irrigation can promote root and plant growth while preserving water resources. It works by applying controlled water stress during particular growth stages. To enhance crop yield under conditions of restricted water availability. In irrigated crops, the application of water management techniques, such as deficit irrigation, can successfully encourage root growth. It highlights how crucial it is to take root development into account when planning irrigation systems to maximize plant water uptake and total crop output. The present results confirmed by **Johnson & Brown (2015) and Johnson et al. (2018)**

Plant water use and root growth can be greatly impacted by varying the frequency of irrigation. It implies that using regular, moderate irrigation will increase the effectiveness of how well plants use water and encourage the establishment of deeper roots, which will improve plant health and drought resistance.

Plant productivity, root system expansion, and increased crop yields are all achieved through efficient irrigation procedures. to address the issues of water scarcity and transition to sustainable farming practices. Nutrient uptake and plant resilience are enhanced by irrigation practices that maintain soil moisture levels within a root zone. The findings highlight how important it is to arrange irrigation schedules appropriately, accounting for factors such as plant species, soil composition, and climate to ensure that roots have access to enough water without suffering from waterlogging or drought stress. Although some studies indicate that there is no appreciable variation in plant root depth, biochar can enhance soil fertility and root development. This argument is put forth critically, with some authors arguing that it could depend on factors such as the kind of soil and the method by which biochar is applied.

The results show that by extending and increasing the biomass of the roots, adding biochar to the soil can enhance nutrient uptake and water retention. Moreover, it has been found that biochar alters root growth by increasing the emergence of roots.

Table (6) Pepper root characteristics as affected by irrigation and biochar for pepper root characteristics

Irrigation regimes, % of ET0	Biochar application, %	Root length cm	Root Width cm	Root fresh weight g	Root dry weight g	Root water content %	Root volume density g/cm3
0	0	8.67	7.67	7.83	1.67	78.76	8.33E-04
	0.25	11.67	8.17	8.33	2.65	68.25	9.00E-04
	0.5	12.88	8.83	9.83	2.97	69.88	1.03E-03
	1	18.50	10.17	11.50	3.12	72.88	1.20E-03
	2	22.10	11.33	12.00	3.37	71.97	1.27E-03
60	0	12.00	10.50	9.33	1.82	80.55	1.00E-03
	0.25	14.83	12.83	9.50	2.02	78.77	1.00E-03
	0.5	15.50	12.83	12.67	3.13	74.25	1.30E-03
	1	16.00	13.17	13.67	3.50	74.40	1.47E-03
	2	16.33	15.33	15.83	3.53	77.68	1.70E-03
80	0	13.67	10.17	6.17	1.57	74.60	6.67E-04
	0.25	16.00	10.50	9.50	2.50	73.74	1.00E-03
	0.5	17.50	12.50	12.00	2.58	78.47	1.27E-03
	1	17.83	14.17	16.33	3.93	75.93	1.73E-03
	2	19.17	19.50	18.33	4.15	77.36	1.93E-03
100	0	15.17	10.17	11.83	2.32	80.42	1.27E-03
	0.25	15.67	12.83	12.67	2.50	80.29	1.33E-03
	0.5	15.83	13.83	13.33	3.20	76.02	1.40E-03
	1	15.00	17.67	15.00	3.85	74.35	1.60E-03
	2	22.67	21.33	15.33	3.93	74.35	1.63E-03

Table (7). Main effects of irrigation, biochar, and their interaction on pepper root characteristics

Irrigation regimes, % of ET_0	Biochar application, %	Root length cm	Root width cm	Root fresh weight g	Root dry weight	Root water content	Root volume density g/cm^3
The main effect of irrigation							
40		14.75	9.23	9.90	2.75	72.35	1.05E-03
60		14.93	12.93	12.10	2.80	77.13	1.29E-03
80		16.83	15.27	12.47	2.95	76.02	1.32E-03
100		17.07	15.17	13.63	3.16	77.09	1.45E-03
LSD 0.05		0.37**	1.89**	0.26**	0.11**	0.83**	0.0001494**
The main effect of Biochar							
	0	12.38	9.63	8.79	1.84	78.58	9.42E-04
	0.25	14.54	11.08	10.00	2.42	75.26	1.06E-03
	0.5	15.42	12.00	11.83	2.97	74.65	1.25E-03
	1	17.08	13.79	14.13	3.60	74.39	1.50E-03
	2	20.07	19.26	15.38	3.75	75.34	1.63E-03
	LSD 0.05	0.34**	1.90**	0.22**	0.07**	0.90**	0.000109**
Irrigation X Biochar interaction							
	LSD 0.05	0.71**	4.27**	0.47**	0.17**	1.80**	0.0002446**

IV.3. Effect of irrigation and biochar on Pepper fruit yield and characteristics

Fruit yield

Pepper fruit yield and characteristics as affected by irrigation regimes and biochar application rates are illustrated in Table (8).

Irrigation regimes highly significantly affected the pepper fruit yield such as No. of fruits, fruit weight, mean fruit weight, fruit length, and fruit diameter. All pepper fruit yield parameters were significantly increased as the irrigation regime increased from 40 to 100% of ET0. The relative values of pepper fruit yield parameters as compared to the 100% of ET0 were 58.06, 82.80, and 94.62%, for No. of fruits, 52.00, 83.83, and 92.82 for fruit yield, 88.61, 90.51, and 96.31% for mean fruit weight, 68.31, 81.92, and 92.25% for fruit length, 57.01, 64.02, and 77.10% for fruit diameter,

Biochar application rates significantly increased the pepper fruit yield parameters. Increasing the biochar rate to 2% significantly increased the pepper fruit yield parameters. The increases in pepper fruit yield parameters were 50.82, 206.49, 101.91, 11.59, and 41.98%, for No. of fruits, fruit weight, mean fruit weight, fruit length, and fruit diameter., respectively as compared to 0% biochar application rate as control (Table 9).

Table (8). Pepper fruit characteristics as affected by irrigation, biochar, and their interaction

Irrigation regimes, % of ET_0	Biochar application, %	No. of Fruits	Fruit weight g	Mean fruit weight g	Fruit length cm	Fruit diameter Cm
40	0	3.9	24.14	6.16	7.70	0.98
	0.25	4.9	36.81	7.45	8.11	1.08
	0.5	5.4	40.93	7.60	8.43	1.35
	1	6.1	47.07	7.71	9.54	1.30
	2	6.5	85.34	13.10	9.89	1.39
60	0	6.2	38.68	6.20	9.97	1.16
	0.25	7.1	52.05	7.30	10.21	1.37
	0.5	8.0	70.67	8.79	10.32	1.38
	1	8.4	76.31	9.12	10.86	1.49
	2	9.0	103.94	11.53	11.00	1.48
80	0	7.2	35.78	4.97	11.32	1.48
	0.25	7.7	57.85	7.52	11.45	1.56
	0.5	8.9	78.03	8.81	11.89	1.75
	1	9.6	99.32	10.39	12.12	1.68
	2	10.5	147.22	13.95	12.21	1.79
100	0	6.9	53.74	7.75	12.42	1.62
	0.25	9.3	80.30	8.65	12.63	1.90
	0.5	9.7	87.71	9.02	12.86	2.09
	1	9.9	98.47	9.97	12.89	2.34
	2	10.8	130.33	12.05	13.10	2.77

The interaction effect for irrigation regimes and biochar rates was highly significant and the best treatment was attained at 100% of ET0 and 2% of biochar rate.

The present results are compatible with those recorded by Laird et al. (2010) and Jeffery et al. (2011), who stated that applying biochar can greatly enhance the chemical properties of the soil, including raising pH, improving nutrient availability, and encouraging the build-up of organic matter. Crop productivity and nutrient uptake are positively impacted by these soil quality improvements. However, depending on the particular soil and the properties of the biochar, the efficiency of the material may differ.

Table (9). Main effects of irrigation, biochar, and their interaction on pepper fruit characteristics

Irrigation regimes, % of ET_0	Biochar application, %	No. of Fruits	Fruit weight g	Mean fruit weight g	Fruit length cm	Fruit diameter Cm
The main effect of irrigation						
40		5.4	46.86	8.40	8.73	1.22
60		7.7	68.33	8.58	10.47	1.37
80		8.8	83.64	9.13	11.79	1.65
100		9.3	90.11	9.48	12.78	2.14
LSD 0.05		0.09**	3.05**	0.14**	0.05**	0.07**
The main effect of Biochar						
0		6.1	38.08	6.27	10.35	1.31
0.25		7.3	56.75	7.73	10.60	1.48
0.5		8.0	69.33	8.55	10.88	1.64
1		8.5	80.29	9.29	11.35	1.70
2		9.2	116.71	12.66	11.55	1.86
LSD 0.05		0.09**	3.31**	0.22**	0.07**	0.04**
Irrigation X Biochar interaction						
LSD 0.05		0.18**	6.64**	0.42**	0.14**	0.09**

Fruit nutrients content

Pepper fruit nutrient contents as affected by irrigation regimes and biochar application rates are illustrated in Table (10).

Irrigation regimes highly significantly affected the pepper fruit nutrient contents such as N, P, K, Ca, and Mg. All pepper fruit nutrient contents were significantly increased as the irrigation regime increased from 40 to 100% of ET0. The relative values of pepper fruit nutrients content as compared to the 100% of ET0 were 81.62, 82.26, and 97.28%, N, 64.01, 71.86, and 79.47% for P, 91.39, 97.09, and 99.59% for K, 66.19, 81.92, and 96.66% for Ca, 72.63, 75.16, and 83.82% for Mg (Table 11),

Biochar application rates significantly increased the pepper fruit nutrient contents. Increasing the biochar rate to 2% significantly increased the pepper fruit nutrient contents. The increases in pepper fruit nutrients content were 53.55, 30.49, 44.63, 69.54, and 69.57%, for N, P, K, Ca, and Mg, respectively as compared to 0% biochar application rate as control (Table 11).

The interaction effect for irrigation regimes and biochar rates was highly significant and the best treatment was attained at 100% of ET0 and 2% of biochar rate, except for N and K which the maximum values were attained at 80% of ET0 and 2% of biochar rate.

Table (10). Pepper fruit nutrient contents as affected by irrigation, biochar, and their interaction

Irrigation regimes, % of ET_0	Biochar application, %	N	P	K	Ca	Mg
				%		
40	0	0.79	0.29	2.56	0.57	0.29
	0.25	0.87	0.32	3.60	0.70	0.45
	0.5	0.99	0.53	3.78	0.73	0.51
	1	1.03	0.32	4.81	1.60	0.54
	2	2.12	0.40	5.16	2.09	1.17
60	0	0.61	0.31	3.27	0.64	0.43
	0.25	0.98	0.34	3.60	0.93	0.55
	0.5	1.00	0.38	4.62	1.32	0.63
	1	1.90	0.41	4.67	1.84	0.68
	2	2.02	0.45	5.00	2.31	0.77
80	0	0.89	0.35	2.33	0.93	0.34
	0.25	1.23	0.37	3.97	1.00	0.53
	0.5	1.38	0.40	4.57	1.22	0.60
	1	1.53	0.46	4.69	2.19	0.74
	2	1.88	0.51	6.14	2.93	1.22
100	0	1.23	0.43	3.51	0.80	0.29
	0.25	1.32	0.47	4.03	1.48	0.48
	0.5	1.40	0.52	4.70	1.73	0.77
	1	1.57	0.58	4.75	2.22	1.23
	2	1.58	0.63	4.79	2.33	1.31

Table (11). Main effects of irrigation, biochar, and their interaction on pepper fruit nutrient contents

Irrigation regimes, % of ET_0 / Biochar application, %	N	P	K	Ca	Mg
			%		
The main effect of irrigation					
40	1.16	0.34	3.98	1.13	0.59
60	1.30	0.38	4.23	1.41	0.61
80	1.38	0.42	4.34	1.66	0.68
100	1.42	0.53	4.36	1.71	0.82
LSD 0.05	0.03**	0.03**	0.12**	0.07**	0.03**
The main effect of Biochar					
0	0.88	0.35	2.92	0.74	0.34
0.25	1.10	0.37	3.80	1.03	0.50
0.5	1.19	0.41	4.42	1.25	0.63
1	1.51	0.44	4.73	1.96	0.80
2	1.90	0.50	5.27	2.42	1.12
LSD 0.05	0.05**	0.02**	0.10**	0.08**	0.04**
Irrigation X Biochar interaction					
LSD 0.05	0.09**	0.05**	0.22**	0.16**	0.07**

The study's findings highlight how crucial effective irrigation techniques are to achieving the best possible nutrient availability and uptake in irrigated systems. It highlights how important it is for farmers to think about irrigation techniques that reduce nitrogen loss and increase nutrient retention in the root zone. Plant growth and productivity can therefore be enhanced by effective irrigation management, which can also improve nutrient availability and uptake.

The type of biochar and its application rate has an impact on pepper's nutrient levels, based on the search findings. According to one study, poultry manure had enough nutrients for the plant's growth and development, whereas corncob biochar's nutrient content was insufficient for the best possible pepper growth (Jaaf et al., 2022). A different study discovered that while biochar made only from corncobs was not enough to provide sufficient nutrients for ideal plant growth, adding biochar to poultry litter enhanced the soil's macro- and micronutrient concentrations and enhanced the majority of red pepper growth parameters. According to a third study, biochar considerably improved sweet pepper's ability to absorb N, P, and K (Lévesque et al., 2020). Also, the type of biochar, how much of it is applied, and the particular growing conditions are only a few of the variables that affect how pepper's nutrient contents are affected by biochar.

It has been demonstrated that biochar increases nutrient availability and soil qualities, which benefits plant growth. According to Hamzah and Shuhaimi (2018), Rawat et al. (2019), Biederman and Harpole (2013), and other studies, biochar can improve soil fertility, water holding capacity, cation exchange capacity, and nutrient retention capacity. This will improve plant availability of nutrients. Depending on variables like soil type, climate, pyrolysis temperature, and biochar feedstock, the effects of biochar on plant growth can differ (Helliwell, 2015). Additionally, biochar can increase plant yield and productivity by modifying the pH of the soil and enhancing physical conditions (Biederman and Harpole, 2013).

Nevertheless, the kind of plant and the quantity of biochar used can also affect how biochar affects plant growth (Hamzah and Shuhaimi, 2018; Simiele, et al., 2022; Biederman and Harpole, 2013). All things considered, biochar has the potential to be a useful soil supplement for enhancing plant growth, but more research and evaluation of its effects in various situations are required (Hamzah and Shuhaimi, 2018; Rawat et al., 2019; Simiele et al., 2022).

Plant growth is enhanced by the addition of biochar to the soil. It improves crop yields in regions with depleted soils, low organic resources, inadequate water supplies, and/or access to agrochemical fertilizers, increasing food production and sustainability. It typically takes up to a year to see results from biochar, and not all soils respond to it in the same way. biochar can increase crop yields on low-carbon soils by up to four times. Applying biochar to soil to promote plant development can be done in the following ways:

Activate the biochar: To prevent raw biochar from initially absorbing soil nutrients, mix it with organic material, such as compost. One way to initiate this process of activation is to apply the activated biochar directly to the base of the plant and let it seep into the soil as you water it.

Integrate it with the Root Zone: Apply the biochar directly to the plant root zone by using a subsurface liquid injector or vertical mulching, or mix it into the soil with a spade. When utilizing a liquid injector, the recommended ratio is one part biochar to 40 parts water.

Add it to the Potting Mix: You can apply a mixture of one part raw biochar and one part compost with two parts soil to plant plots and flower beds. When planting a new tree, add one pound of biochar amendment to the soil where the roots of the tree would eventually cover. Allow the biochar to combine with the soil for a week before planting the tree.

Before application, make sure the biochar has had enough time to cure and is clean. It is important to consider the kind of soil, the desired result, and the needs of the particular crop when determining the right rate of application. If the desired effects are not obtained, gradually increase the amount and think about pre-soaking biochar before applying it to enhance water retention.

Applying biochar to soil for plant growth regularly is dependent upon various aspects, including soil type, fertility, and crop requirements. In general, adding biochar to soil can have positive long-term impacts on soil health. However, depending on the situation, biochar's usefulness may vary, and some research has shown that crops may react negatively to it as reported by Bonanomi et al.(2017).

When plants are under water stress, using biochar has been shown to have several benefits on plant growth, yield, and root spread. Through the enhancement of soil organic matter, soil structure, water and nutrient holding capacity, and the activity of beneficial bacteria and fungi, biochar enhances soil health and increases crop output under stress conditions. Additionally, it raises resistance to harmful abiotic stressors such as drought (Wu et al., 2023). Moreover, applying biochar improves photosynthetic, water use efficiency, antioxidant activity, membrane stability, and osmolyte accumulation, all of which contribute to a notable increase in drought tolerance (Wu et al., 2023). Moreover, biochar enhances plant development under water stress conditions, especially pepper, and mitigates the adverse effects of water stress (Hou et al., 2023; Obadi, et al., 2023). In general, the use of biochar can be a valuable strategy to enhance the growth, yield, and root distribution of pepper plants under water stress conditions, where the highest values of plant growth, root fresh weight, and root distribution were attained with 100% of ET0 and 2% of biochar application rate.

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الملخص العربي

التأثيرات الإيجابية لإضافة البيوتشار على نمو الفلفل – المحصول وتوزيع الجذور تحت ظروف الاجهاد المائي

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تهدف الدراسة الحالية لتقييم تأثير إضافة البيوتشار الناتج من قوالح الذرة (والذي يُنتج محلياً عن طريق التحلل الحراري البطيء على 500 درجة مئوية)على النمو الخضري والمحصول وتوزيع الجذور للفلفل الأخضر. كانت التربة المستخدمة في هذه الدراسة هي رملية القوام تم جمعها من الطبقة السطحية (0 – 30 سم) تم خلط التربة مع البيوتشار الناتج من التحلل الحراري على درجة حرارة مرتفعة 500 درجة مئوية. وقد تم خلط التربة الرملية مع البيوتشار بمعدلات صفر و0.25 و0.5 و1 و2 في المائة (وزن/وزن). تم ترطيب مخلوط الرمل والبيوتشار عند السعة الحقلية وتم التحضين على درجة حرارة الغرفة (25±2 مئوية) لمدة شهر واحد مع إعادة الترطيب كل 7 أيام. وخضع خليط التربة والبيوتشار للتحليل الفيزيائي والكيميائي. وقد أجريت تجربة أصص في تصميم القطاعات العشوائية الكاملة مع ثلاث مكررات في صوبة مكشوفة. وتم دراسة عاملين وكان العامل الرئيسي هو نظام الري أربع معاملات هي 40، 60، 80، و 100% من البخر–نتح المرجعي (ET0) والعامل الفرعي هو معدلات إضافة البيوتشار وهى0.0 و0.25 و0.50 و1.0 و2 % (وزن/وزن). زرع الفلفل الأخضر صنف cv. 103 (2 شتلة لكل أصيص بعمر 4 أسابيع) في 15 سبتمبر 2020. وقد طُبقت الممارسات الزراعية على النحو الموصي به. أصهرت النتائج التي تم الحصول عليها عن أن جميع عناصر النمو الخضري للفلفل قد زادت زيادة كبيرة مع زيادة معدلات الري من 40 إلى 100% من معدل البخر–نتح المرجعي. كما أن معدلات اضافة البيوشار أدت الى زيادة لحد كبير في عناصر النمو الخضري للفلفل. وقد زادت جميع عناصر نمو جذور الفلفل زيادة كبيرة مع زيادة معدلات الري من 40 إلى 100% من البخر–نتح المرجعي. وفي الوقت نفسه، أدت زيادة معدلات إضافة البيوتشار الى زيادة معنوية عالية في عناصر نمو جذور الفلفل. أدت اضافة البيوشار بمعدل 2% الى زيادة بشكل كبير في عناصر نمو جذر الفلفل. وتأثر محصول وخصائص الثمار إلى حد كبير بمعدل الري ومعدل إضافة البيوتشار، حيث أعطى معدل 2% أعلى القيم. وتؤثر معدلات الري ومعدلات إضافة البيوتشار تأثيراً كبيراً جداً على محتوى العناصر الغذائية لثمار الفلفل، حيث تحققت أعلى القيم عند اضافة 2% من البيوتشار.

عندما تكون النباتات تحت ضغط الماء (اجهاد مائي) ، فان إضافة البيونشار يحقق عدة فوائد على نمو النباتات والمحصول وتوزيع الجذور من خلال تعزيز المادة العضوية للتربة، وبناء التربة، والقدرة على حفظ المياه والمغذيات، ونشاط البكتيريا والفطريات المفيدة، ويعزز البيوتشار صحة التربة ويزيد من إنتاج المحاصيل في ظروف الإجهاد. وبصفة عامة، يمكن أن يكون استخدام البيوتشار استراتيجية قيمة لتعزيز نمو نباتات الفلفل وإنتاجيتها وتوزيعها الجذري في ظروف إجهاد المياه، حيث تم تحقيق أعلى قيم نمو النبات، والوزن الجذري الطازج، وتوزيع الجذور مع 100% من البخر– نتح المرجعي و2% من معدل إضافة البيونشار