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ORIGINAL PAPER

Potential Use of Biochar as an Amendment to Improve Soil Fertility and Tomato and Bell Pepper Growth Performance Under Arid Conditions

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Abstract

The aim of this study was to assess the potential use of biochar derived from olive pruning to enhance soil properties and tomato and bell pepper plant growth and yield performance in arid environments. Biochar was prepared from olive tree–pruning residues. The biochar was applied to field experiments of tomato and bell pepper plants at five application rates (0, 8, 16, 30, and 40 t ha^{-1}). Relative water content (RWC), leaf chlorophyll, and leaf nutrient (nitrogen (N), phosphorus (P), and potassium (K)) contents were measured. The total yield was determined for each treatment. Fruit nutrient contents were determined in selected fruit samples. Soil samples were collected from each treatment at the middle and end of the experiment for physical and chemical analysis. All experiments were conducted in triplicate. The application of biochar at rates of 8 and 16 t ha^{-1} enhanced tomato and bell pepper growth; however, application of 30 and 40 t ha^{-1} adversely affected tomato and bell pepper growth. Nutrient analysis showed that N, P, and K concentrations in leaves and fruits were higher in plants treated with 8 and 16 t ha^{-1} of biochar than in biochar treatments of 30 and 40 t ha^{-1}. Higher biochar application rates increased soil pH and EC by 1.4% and 12.3% (8 t ha^{-1}) to 7.3% and 107.8% (40 t ha^{-1}), respectively. A biochar application rate of 8 t ha^{-1} is recommended as an optimal rate to enhance soil fertility for tomato and bell pepper production systems in arid environments.

Keywords Biochar · Arid region · Yield · Soil quality · Nutrient availability

1 Introduction

Globally, food production is threatened by different biotic and abiotic stresses. Poor soil fertility, low water holding capacity, and declining organic matter are critical issues affecting agricultural land production (Mohawesh 2014). To overcome poor soil fertility, farmers usually apply large amounts of chemical fertilizers to enhance crop growth and productivity (Mohawesh and Durner 2019). Biochar application can be beneficial to the arable land as it improves soil quality and, therefore, can enhance plant growth and yield (Lehmann et al. 2003). Biochar can persist in soils and sediments because it is resistant to degradation (Lehmann and Joseph 2009). Therefore, the application of biochar as a soil amendment can enhance plant growth and production for an extended period of crop growth and production (Singh et al. 2019). Soil application of biochar has numerous advantages, such as increasing water and nutrient retention capacity, decreasing nutrient loss, and supplying nutrients to

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the plants (Laird 2008; Lehmann et al. 2006). Furthermore, biochar has been shown to increase the cation exchange capacity of the soil (Albalasmeh et al. 2020), pH (Lehmann et al. 2006), and enhance the nutrient sorption capacity of soils (Verheijen et al. 2010). Consequently, plant shoot and root growth are improved, which can then lead to better soil structure and aggregation (Oni et al. 2019). Biochar application to soils can maintain organic matter (OM) levels and soil aggregation stability (Lehmann et al. 2006) because biochar is characterized by recalcitrant C from microbial degradation and by a charged surface with organic functional groups. Reducing soil erosion potential, maintaining OM, and improving soil aggregative stability are vital to maintaining healthy agricultural soils. Biochar also can promote rhizosphere microorganisms and mycorrhizal fungi, which will enhance plant growth (Głuszek et al. 2017).

It is well established that biochar can affect plant growth and stress responses (Singh et al. 2019). However, the results are often variable depending on the source materials, application rates, and other chemical and physical properties related to biochar composition (Semida et al. 2019). For example, biochar application was reported to have a positive impact on tomato, pepper, and radish growth and yield (Elad et al. 2012; Chan et al. 2008; Yilangai et al. 2014). On the other hand, insignificant effects on the annual yield of winter wheat and summer maize were observed by Liang et al. (2014), while Steiner et al. (2007) found no effects on nutrient contents of rice or sorghum. Furthermore, several studies reported negative plant responses following biochar application; for example, decreased plant nitrogen in cowpea (Lehmann et al. 2003) and decreased biomass and nitrogen uptake in beans (Rondon et al. 2007). The discrepancies in the effect of biochar on plant performance may be attributed to factors such as climate, soil characteristics, plants, the feedstock used to produce the biochar, and pyrolysis conditions; hence, illustrating the need for extensive research to optimize biochar applications in crop production.

Among the regions that could benefit from the positive qualities which biochar can contribute to soil are arid regions, such as Jordan. Arid soils in Jordan contain very low organic matter ($<1\%$) and nutrients with poor water and nutrient retention capacity (Mohawesh 2014). The soils are neutral to slightly alkaline, with $\text{pH}>7$, and contain large amounts of calcium carbonate (e.g., $>30\%$ in most soils) (Mohawesh 2014). Therefore, there is a need to improve the soil quality, nutrients, and water holding capacities of the soil. Biochar applications are among the most feasible solutions due to their availability and low cost. The use of biochar from locally abundant feedstock, such as olive pruning residues, can be a possible means to improve the productivity limitations of low fertility soils. More than 20 M olive trees in Jordan occupy 13×10^4 ha. Therefore, pruning residue can be a viable source for biochar production (Al Hiary et al. 2019). Moreover, other feedstock materials such as vegetable residues can be used, which are often collected and burned or wasted by the farmers at the end of the growing season (Mohawesh et al. 2018).

The physical structure of biochar is affected by the properties of the parent biomass. Biochar feedstock can result in products that range from powdery to brittle due to the microstructure of the source materials. Woody feedstocks show a prevalently xylemic structure that is coarse, solid, and strong (Ding et al. 2016). There is considerable evidence that this structure plays a role in the way biochar influences soil properties (Lehmann et al. 2011). Based on the findings of previous studies (Hafeez et al. 2017; Lehmann et al. 2011; Novak et al. 2009), the outcomes of biochar application may be variable and may limit our ability to predict agronomic impacts in different situations. Therefore, biochar produced from various materials should be investigated under different climates, soil, and plant conditions (Novak et al. 2009). Therefore, this research aims to examine the potential use of olive pruning residue biochar to enhance soil physicochemical properties and tomato and bell pepper plant growth performance in the arid climate of Jordan. Although Jordan is used as a case study to demonstrate the viability of using biochar derived from olive pruning to enhance soil fertility, the results can be of use for many countries across the Middle East and North Africa where climatic and soil conditions are similar.

2 Material and Methods

2.1 Biochar Production and Characterization

Olive tree–pruning residues were obtained from local farmers and were allowed to air-dry in the shade before pyrolysis. Biochar was produced via slow pyrolysis at 300–350 °C for 2 h. Slow pyrolysis at low temperatures was used because it produces a higher biochar yield (25–35%) (Mohawesh et al. 2018). A simple low-cost pyrolysis reactor was constructed using two steel barrels. The outer barrel acted as a heated container and had a volume of 200 L while the inside barrel (reaction chamber) was made of a 120-L barrel with a relatively tightly sealed door to load and unload the feedstock/biochar. Thermocouple probes were used at the top and bottom to monitor the temperature. The inner barrel was filled with dry, cut, and split olive pruning residues. The space between the outer and inner barrel was filled with olive pruning which was used as the heating source. The resulting biochar was ground to uniform particle size (2–3 mm). Biochar pH and EC were measured using a 1:10 ratio of biochar to distilled water (Ippolito et al. 2020). Chemical composition and micrographs of biochar were determined using a scanning electron microscope and energy dispersive spectroscopy (Quanta 450 FEG, FEI, USA). The Brunauer–Emmett–Teller method was used to measure the biochar's specific surface area (SSA) (Brunauer et al. 1938).

2.2 Field Experimental Design and Setup

Field experiments were conducted at the National Agricultural Research Centre (NARC) Research Station, Ghor Al-Safi, Jordan Valley (elevation—387 m below mean sea level, longitude 35° 29′ 29″ E and latitude 31° 03′ 28″ N) from September 2016 to February 2017. The Ghor Al-Safi site has a subtropical climate with a long-term mean annual temperature and rainfall of 24 °C and 50 mm, respectively. Figure 1 shows meteorological data during the experimental period where the average temperature was 23 °C, and the average relative humidity was 44%. Each plot consisted of 3 beds of 3 m × 1 m × 0.2 m covered by plastic mulch with a 1.0-m buffer zone between beds. Each bed was irrigated by a single drip line running in the center of the bed (0.3 m drippers intervals). The average electrical conductivity (EC_w) of the irrigation water was 1.9 dS m^{-1}. The treatment beds were prepared manually after disking and leveling the experimental sites. Each block contained five treatments with a 1.0-m buffer zone between plots (block area of 120 m^2). Five biochar treatment rates (0, 8, 16, 30, and 40 t ha^{-1}) were applied to soil in each of the experimental fields. These biochar application rates were equivalent to 0, 0.8, 1.6, 3, and 4 kg m^{-2}, respectively. Applied studies using biochar as soil amendments are limited in Jordan; application rates were selected based on recommended rates found in the literature (Al Hiary et al. 2019; Mohawesh et al. 2018); economic and practical feasibility as well as to represent a wide range to allow for proper evaluation of the potential impacts. Moreover, as the soil OM and nutrient contents are usually low in arid and semiarid regions, high application rates were chosen (30 and 40 t ha^{-1}). Application rates of 0, 8, 16, 30, and 40 t ha^{-1} will hereafter be referred to as B0, B8, B16, B30, and B40, respectively. A randomized complete block design (RCBD) was used to arrange each crop's experimental treatments with triplicate. In total, we had 30 plots (15 plots for each crop) (2 crops × 5 biochar treatments × 3 replicates). Each treatment consisted of 10 plants.

The biochar was applied on September 5, 2016, 10 days before seedlings were transplanted. The biochar was mixed with soil manually using a hoe. Tomato and bell pepper plant seedlings were transplanted on September 15, 2016, with a spacing of 30 cm between plants. The growing season lasted for six months (September to February). Application of fertilizer was based on local farming practices, which consisted of ammonium sulfate (100 kg ha^{-1} per growing season) and NPK (20:20:20) (320 kg ha^{-1} per growing season) applied by fertigation 5 times (required fertilizer amount was divided into five doses) during the growing season. At the plant maximum growth stage (mid-December), relative water content (RWC) was measured using the Weatherley method (Weatherley 1950), and leaf chlorophyll content was measured according to Inskeep and Bloom (1984). Leaf samples were collected from randomly chosen plants in each treatment, dried at 75 °C for 4 days, ground, and stored in paper bags for further chemical determination (nitrogen (N), phosphorus (P), and potassium (K). N, P, and K in leaf samples, hereinafter referred to as NL, PL, and KL, respectively. PL was determined using a spectrophotometer according to the Olsen method (Olsen et al., 1954), and atomic absorption was used to determine KL (Knudsen et al. 1982). Total NL was determined by the Kjeldahl method (Chapman and Pratt 1962). Soil cation exchange capacity (CEC) was determined using the ammonium acetate method (Chapman 1985). The average results obtained from the three replicates of each measured parameter were reported and used in the data analysis.

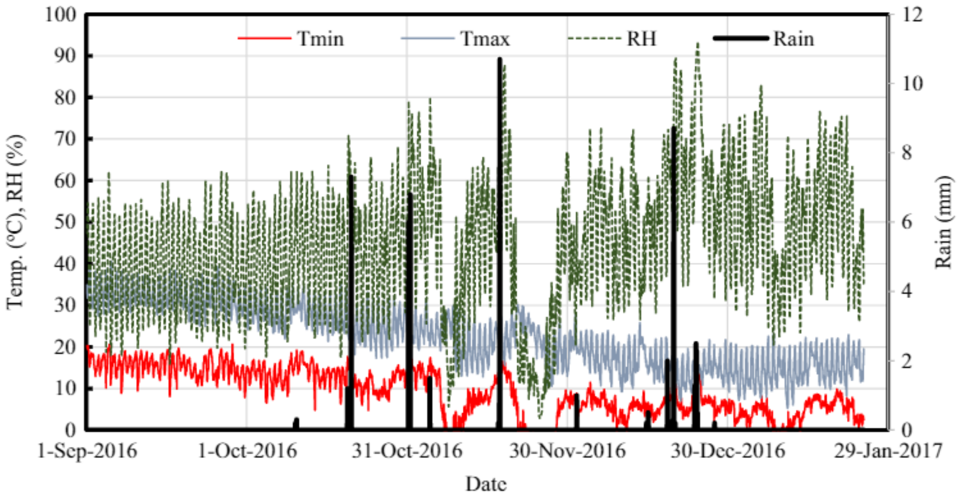

Fig. 1 Meteorological data during the field experiment period. T_{min}, minimum temperature; T_{max}, maximum temperature; RH, relative humidity; Rain, daily rain

Tomato and bell pepper fruits were harvested regularly throughout the growing season. The total yield for each treatment was determined by the accumulation of the harvested yield from each fruit treatment. For fruit N, P, and K determination, select fruit samples were chosen from each treatment, dried at 75 °C for 1 week, and ground for mineral analysis. N, P, and K in fruit samples, hereinafter referred to as NF, PF, and KF, respectively. At the end of the season, three plants were uprooted, cut at their bases, and roots were carefully washed using tap water and blotted to minimize root damage and loss. Plants shoot and root fresh weight was recorded. After that, shoots and roots dry weight were determined after drying at 75 °C for 1 week. Soil samples were collected from the treatment plot twice (at the middle and end of the experiment). Soil samples were prepared (i.e., air-dried, crushed, and sieved through a 2-mm screen) for pH, EC, CEC, N, P, K, and soil texture measurements. Standard procedures were followed to analyze soil samples according to the US Salinity Laboratory (1954) (Table 1).

2.3 Statistical Analysis

All measurements were conducted in triplicates and average values are reported in this work. SPSS version 16 was used for statistical data analyses (SPSS, Inc., Chicago, IL, USA). For mean separation, the least significant difference and *t*-test ($p \leq 0.05$) were applied. Mean values of soil alkalinity at the middle of the growing season (pH_m), soil alkalinity at the end of the growing season (pH_e), soil electrical conductivity at the middle of the growing season (EC_m), soil electrical conductivity at the end of the growing season (EC_e), shoot fresh weight (SFW), shoot dry weight (SDW), root fresh weight (RFW), root dry weight (RDW), leaf chlorophyll content, RWC, NL, PL, KL, NF, PF, and KF were compared at five biochar application rates (0, 8, 16, 30, and 40 t ha^{-1}).

Table 1 Soil physical and chemical properties

pH (–)	7.7 ± 0.08*
EC (dS m^{-1})	0.65 ± 0.04
CEC (m_{eq}/100 g)	22.7 ± 3.5
N (ppm)	980 ± 230
P (ppm)	10 ± 1.6
K (ppm)	23 ± 2.7
Sand (%)	64 ± 2.5
Silt (%)	14 ± 1.4
Clay (%)	22 ± 2.6

*Standard deviation

pH, alkalinity; *EC*, electrical conductivity; *CEC*, cation exchange capacity; *N*, nitrogen content; *P*, phosphorous content; *K*, potassium content

3 Results

3.1 Biochar Characterization

The produced biochar was characterized by high EC, N, K, and P contents (Table 2). In addition, the biochar exhibited an alkaline pH value of 9.5 and a relatively low CEC value of 33.9 meq 100 g^{-1}, which is much lower than the CEC of organic matter (Albalasmeh et al. 2020). To further analyze the characteristics of this biochar, a scanning electron microscope micrograph was taken (Figs. 2 and 3). The scanning electron microscope micrograph shows a well-developed porous structure with an average pore diameter of between 20 and 30 µm (Fig. 2). According to the energy dispersive spectroscopic analysis (Fig. 3), the biochar contained carbon (C), oxygen (O), calcium (Ca), and silicon (Si) which were the most abundant elements; it also contained potassium (K), sulfur (S), and magnesium (Mg) which are important nutrients for plants.

3.2 Soil pH and EC Measurements

A significant increase in pH was seen with biochar application at both sampling dates (Table 3). The soil pH_e values increased between 2.6% (B8) and 7.3% (B40) compared to B0. In addition, there was a significant increase in EC with increasing biochar rates, with the highest EC observed in the treatments with the largest amounts of biochar applied (Table 3). The soil EC_e values increased between 12.3% (B8) and 107.3% (B40) compared to B0.

Table 2 Biochar characteristics produced from olive pruning residues at low pyrolysis temperature (300–350 °C)

pH (1:10) (–)	9.5 ± 0.35*
EC (1:10) (dS m^{-1})	6.5 ± 0.64
CEC (m_{eq}/100 g)	33.9 ± 2.8
N (%)	1.4 ± 0.13
P (%)	0.69 ± 0.03
K (%)	2.55 ± 0.15
C (%)	76.43 ± 5.73
O (%)	10.08 ± 1.68
Ca (%)	9.94 ± 1.36
SSA (m^2 g^{-1})	2.1 ± 0.17

*Standard deviation

pH, alkalinity; *EC*, electrical conductivity; *N*, nitrogen content; *P*, phosphorous content; *K*, potassium content; *C*, carbon content; *O*, oxygen content; *Ca*, calcium content; *SSA*, surface specific area

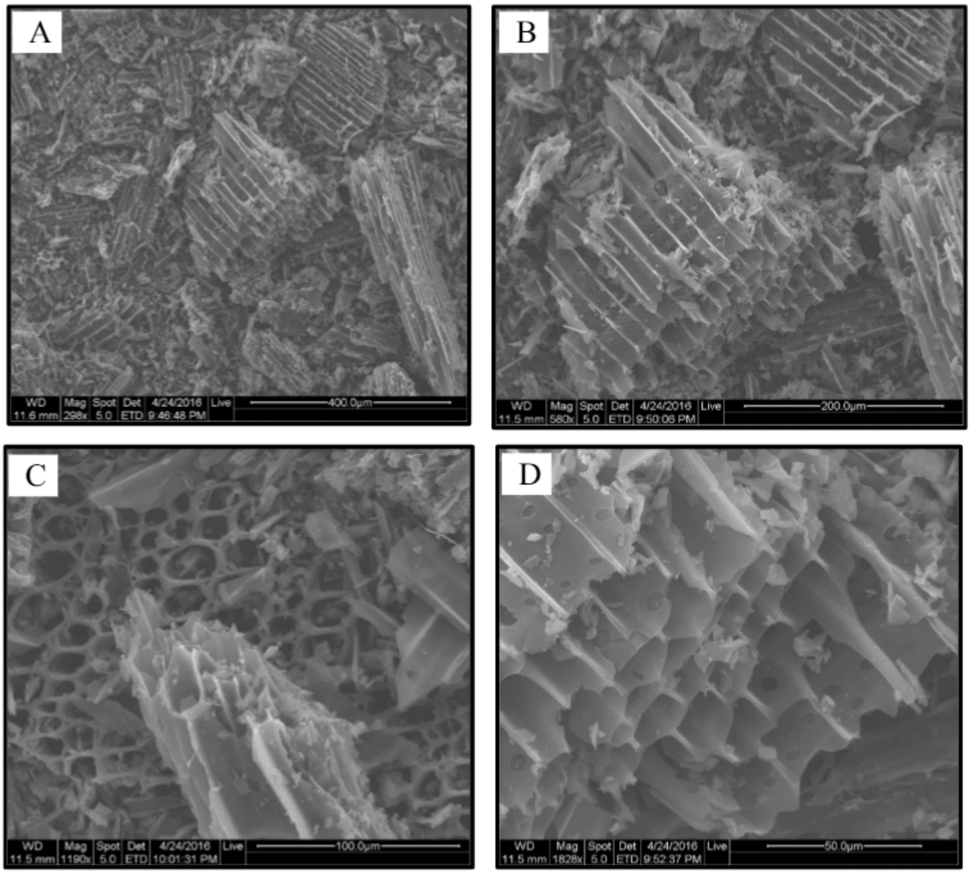

Fig. 2 Scanning electron microscope of biochar prepared by charring olive pruning residues (**A** 298×, **B** 580×, **C** 1190×, **D** 1828×)

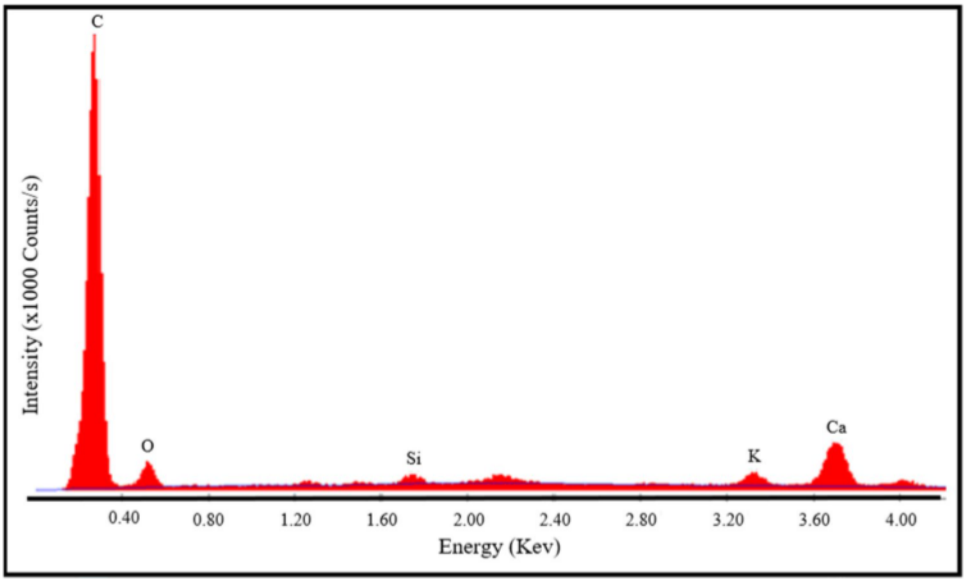

Fig. 3 Energy dispersive spectroscopy of biochar prepared by charring olive pruning residues. C, carbon content; O, oxygen content; Si, silicon content; K, potassium; Ca, calcium content

3.3 Plant Biomass Measurements

In tomatoes and bell peppers, shoot and root fresh and dry weights were significantly higher for B8 and B16 than the B30, and B40 treatments (Table 4). The lowest biomass measurements were seen in the two highest biochar application rates (B30 and B40), indicating that the threshold of beneficial effects of biochar application is under 30 t ha^{-1}. Table 4 suggests that no significant influence of biochar application was seen on tomato or bell pepper relative water content (RWC) which is consistent with the findings of Hafeez et al. (2017), who showed an insignificant

Table 3 Effect of biochar application on soil alkalinity (pH) and electrical conductivity (EC) at the middle and the end of the growing season

Biochar (t ha^{-1})	pH$_m$ (–)	pH$_e$ (–)	EC$_m$ (dS m^{-1})	EC$_e$ (dS m^{-1})
Tomato				
B0	7.69±0.05[*] c	7.68±0.10 c	0.57±0.02 b	0.61±0.03 c
B8	7.88±0.03 c	7.96±0.09 b	0.64±0.01 b	0.84±0.05 b
B16	7.97±0.07 b	8.02±0.07 b	0.74±0.05 ab	0.96± 0.10 a
B30	8.06± 0.03 b	8.09±0.1 b	0.72±0.07 ab	0.98±0.06 a
B40	8.15± 0.04 a	8.24±0.08 a	0.90±0.7 a	1.09±0.07 a
Bell pepper				
B0	7.78±0.11 C	7.79±0.07 C	0.62±0.05 D	0.64±0.03 C
B8	7.89±0.08 B	8.03±0.07 B	0.74±0.02 C	0.78±0.07 B
B16	7.97±0.05 B	8.09±0.08 B	0.79±0.06 BC	0.89±0.06 B
B30	8.06±0.07 AB	8.14±0.11 AB	0.89±0.09 B	1.07±0.10 A
B40	8.17±0.05 A	8.28±0.09 A	1.01±0.07 A	1.11±0.09 A

[*] Standard deviation

Different uppercase/lowercase letters in the same column indicate significant difference by LSD at $p \leq 0.05$ for tomato and bell pepper, respectively. B0, B8, B16, B30, and B40 are biochar application rates at 0 (control), 8, 16, 30, and 40 t ha^{-1}. pH_m, soil alkalinity at the middle of the growing season; pH_e, soil alkalinity at the end of the growing season; EC_m, soil electrical conductivity at the middle of the growing season; EC_e, soil electrical conductivity at the end of the growing season

effect of biochar on RWC in soybean. The effect of biochar application on chlorophyll in tomatoes and bell peppers was different. In tomatoes, the difference in chlorophyll content was not significant in all treatments compared to the control except B16 which had higher chlorophyll concentrations, while in bell peppers, all treatments including control were significantly higher than B40. In this work, the highest chlorophylls were seen in the B16 treatment of tomatoes, combined with increased biomass in this treatment, which provides evidence that biochar at rates of up to 16 t ha^{-1} can improve the overall health of tomato plants.

3.4 Plant Yield and Nutrients Content

Table 5 presents the yield and nutrient concentrations in leaves and fruits. Tomato yields increased with biochar application, reaching a maximum at B16, after which the yields declined but remained numerically higher than the control. On the other hand, bell pepper yields increased up to B16 reaching a maximum at B8. However, bell pepper yield fell to levels below the control when application rates were greater than 16 t ha^{-1}, as shown in Table 5 and Fig. 4. Figure 4 shows the regression analysis between the biochar application rates and tomato and bell pepper yields. The nature of the third degree polynomial means that there will be another peak. However, the regression equation is valid only within the tested range.

It can be seen from Table 5 that N in leaves and fruit, P in leaves, and K in fruits were greater in the B16 treatments than in others. B8 treatment's yield was not statistically significantly different from B16 treatment's yield. Bell pepper mineral analysis showed that N and K concentrations were greater in the leaves and fruits and P in leaves of the plants treated with 16 t ha^{-1} of biochar; although not significantly higher than B8. However, the biochar application rates B30 and B40 showed a significantly negative effect on bell pepper plants' nutrient content.

4 Discussion

Biochar characteristics depend mainly on feedstock, pyrolysis temperature, and time. The chemical characteristics of the produced biochar in this study are consistent with other studies that examined the chemical properties of biochar as shown in Table 2 (Trupiano et al. 2017). Biochar properties such as pore volume, pore size, and distribution are typically related to its nutrient and water holding capacity, influencing soil structure, minerals mobility, and microbial activity (Ippolito et al. 2020). Therefore, the produced biochar used in this study is characterized by homogeneous pore composition and abundant nutrient elements that might affect soil properties and enhance plant growth.

The produced biochar was characterized by high EC and pH. Therefore, biochar application as soil amendments might increase soil EC and pH which might affect plant shoot and root growth. A significant increase of soil pH and EC with increased biochar application was noticed at both sampling dates (Table 3). Increases in soil pH and EC with the addition of biochar were observed with both low- and high-rate applications, illustrating the impact of biochar on soil chemistry (Chan et al. 2008; Novak et al. 2009). The

Table 4 Effect of biochar application on tomato and bell pepper shoot, root fresh, and dry weight at the end of the growing season

Biochar (t ha^{-1})	SFW (g)	SDW (g)	RFW (g)	RDW (g)	Chlorophyll (mg L^{-1})	RWC (%)
Tomato						
B0	492.2 ± 13.2* c	90.8 ± 2.9 b	69.3 ± 2.6 b	25.0 ± 1.3 b	14.8 ± 0.4 b	78.6 ± 2.4 a
B8	592.9 ± 16.4 a	94.6 ± 4.2 a	81.4 ± 2.9 a	38.6 ± 2.7 a	14.6 ± 0.7 b	79.7 ± 3.4 a
B16	548.9 ± 8.3 b	92.5 ± 5.4 b	79.4 ± 4.5 a	37.9 ± 3.1 a	17.8 ± 1.3 a	82.5 ± 5.1 a
B30	462.3 ± 10.4 d	78.2 ± 4.8 c	68.7 ± 3.1 c	25.7 ± 4.1 b	14.9 ± 3.1b	80.4 ± 4.7 a
B40	458.3 ± 17.4 d	80.2 ± 7.5 c	66.8 ± 5.2 c	24.3 ± 1.2b	14.6 ± 1.5 b	78.3 ± 2.9 a
Bell pepper						
B0	168.6 ± 5.4 A	47.4 ± 2.7 A	27.4 ± 0.9 B	8.5 ± 0.8 B	26.9 ± 1.9 A	79.1 ± 3.1 A
B8	173.7 ± 2.1 A	51.3 ± 3.7 A	29.0 ± 1.6 A	10.4 ± 0.7 A	26.8 ± 2.1 A	80.4 ± 5.4 A
B16	170.9 ± 3.5 A	54.2 ± 2.3 A	31.1 ± 2.9 A	9.7 ± 1.3 A	28.4 ± 1.5 A	80.8 ± 2.7 A
B30	162.7 ± 5.7B	42.6 ± 1.9 C	25.5 ± 1.7 B	8.6 ± 1.9 B	26.5 ± 0.9 A	80.1 ± 1.9 A
B40	138.5 ± 6.4 C	37.6 ± 2.9 C	19.9 ± 3.1 C	6.9 ± 0.7 C	23.3 ± 1.3 B	77.4 ± 3.7 A

*Standard deviation

Different uppercase/lowercase letters in the same column indicate significant difference by LSD at $p \leq 0.05$ for tomato and bell pepper, respectively. B0, B8, B16, B30, and B40 are biochar application rates at 0 (control), 8, 16, 30, and 40 t ha^{-1}. *SFW*, shoot fresh weight; *SDW*, shoot dry weight; *RFW*, root fresh weight; *RDW*, root dry weight; *Chlorophyll*, leaf chlorophyll content; *RWC*, relative water content

Table 5 Effect of biochar application on tomato and bell pepper yield, fruit weight, leaves, and fruits minerals content

Biochar (t ha^{-1})	Yield (t ha^{-1})	NL (%)	PL (%)	KL (%)	NF (%)	PF (%)	KF (%)
Tomato							
B0	24.1±1.3 * b	2.99±0.21 c	0.15±0.01 c	1.15±0.11 b	1.30±0.12 c	0.24±0.02b	3.19±0.12 c
B8	27.1±1.9 a	3.20±0.18 b	0.19±0.03 b	1.35±0.09 a	1.90±0.21 b	0.44±0.01 a	3.91±0.24 b
B16	28.5±1.4 a	3.78±0.27 a	0.30±0.01 a	1.08±0.05 b	2.42±0.14 a	0.24±0.03 b	5.43±0.27 a
B30	25. 3±0.9 b	2.84±0.19 c	0.19±0.03 b	1.16±0.10 b	1.27±0.11 c	0.24±0.02 b	3.09±0.31 c
B40	24.6±2.3 b	2.92±0.11 c	0.21±0.02 b	1.03±0.07 c	1.23±0.07 c	0.28±0.01b	3.24±0.17 c
Bell pepper							
B0	15.2±1.3 B	4.01±0.17 B	0.21±0.02 B	1.12±0.05 C	2.03±0.09 C	0.21±0.01 C	2.07±0.13 C
B8	18.3±0.9 A	3.82±0.23 B	0.26±0.03 A	1.30±0.07 B	2.24±0.07 B	0.37±0.03 A	2.74±0.09 B
B16	17.6±1.8 A	4.84±0.39 A	0.30±0.01 A	1.40±0.8 A	2.46±0.11 A	0.30±0.01 B	3.82±0.18 A
B30	14.6±1.1 B	3.01±0.13 C	0.21±0.01 B	1.08±0.03 C	1.91±0.05 C	0.23±0.01 C	2.22±0.07 C
B40	14.5±0.8 B	3.08±0.09C	0.25±0.02 B	1.07±0.09C	1.79±0.07 D	0.23±0.02 C	2.18±0.11 C

*Standard deviation

Different uppercase/lowercase letters in the same column in each plant trait indicate significant difference by LSD at $p \leq 0.05$ for tomato and bell pepper, respectively. B0, B8, B16, B30, and B40 are biochar application rates at 0 (control), 8, 16, 30, and 40 t ha^{-1}. *NL*, leaves nitrogen content; *PL*, leaves phosphorus content; *KL*, leaves potassium content; *NF*, fruit nitrogen content; *PF*, fruit phosphorus content; *KF*, fruit potassium content

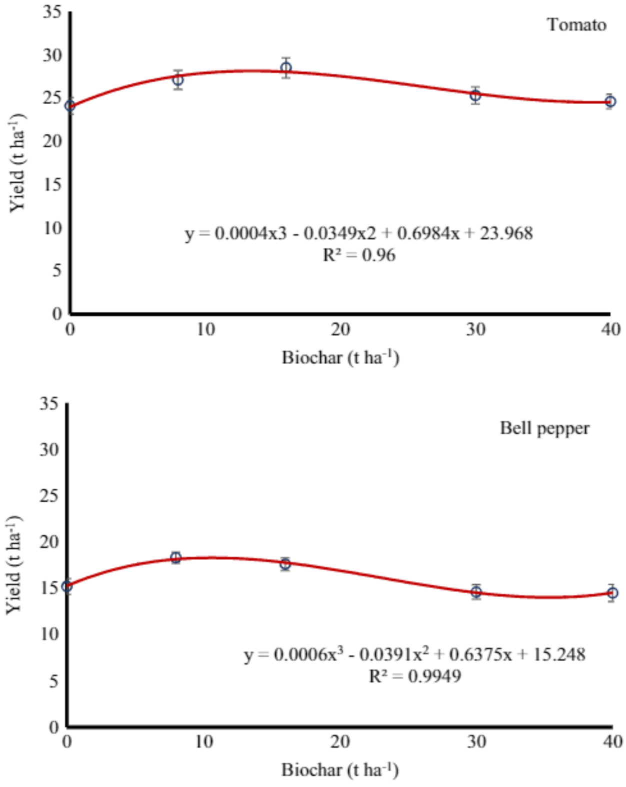

Fig. 4 Tomato and bell pepper's yield with biochar application rates: 0, 8, 16, 30, and 40 t ha^{-1} prepared by charring olives pruning residues

significantly negative effect of the B30 and B40 application rates on tomato and bell pepper biomass is most likely associated with the increase of soil pH and EC (Table 3). The soil EC and pH values increased with increasing biochar application rates: 12.3 % (B8) to 107.3% % (B40) and 2.6 (B8) to 7.3 % (B40), respectively, compared to B0. This significant increase ($p \leq 0.05$) in soil pH was associated with the increase of biochar application rates. The increase in soil pH might be harmful to plant growth at a higher biochar application rate due to its effect on nutrient availability (Liu and Zhang 2012). However, because the nutrient levels of the leaves and fruits at higher rates (B30 and B40) were not significantly different from the control, this could indicate that the effects may be due to other nutrients or micronutrients not measured in this study (Table 4). But when considering EC, the significant increase of soil EC with biochar application might also explain the negative results at higher application rates (Table 3). The EC was highest in the B30 and B40 treatments at 1.09 and 1.11 dS m^{-1} for tomato and bell pepper, respectively. This increase in EC may be related to the pyrolysis process, resulting in a large, concentrated amount of the mineral content that is then passed to the biochar from the feedstock (de Souza Souza et al. 2021). It should be noted that soil EC of 1 dS m^{-1} is not considered detrimental to the growth of tomato or bell pepper, whose threshold of yield declines are 2.5 dS m^{-1} and 2.4 dS m^{-1}, respectively (Semiz et al. 2014). Irrigation water quality plays a role in the tolerance to these thresholds, so this may have contributed to these observations (Mohawesh et al. 2018). Our results of tomato and bell pepper's shoot and root fresh and dry weights support these findings that plant growth decreased above 30 t ha^{-1} (Table 5). In the literature, biochar application rates of up to 30 t ha^{-1} have enhanced lettuce and potato growth, which declined when biochar application rates exceeded 30 t ha^{-1} (Upadhyay et al. 2014). These findings might reveal a harmful effect of biochar on plant roots by either organic or inorganic (high mineral content) compounds (Lehmann et al. 2011).

Biochar application affected plant growth and nutrient content and uptake. Tomato's chlorophyll content was not significantly different among the treatments while in bell peppers, all treatments were significantly higher than B40. Chlorophylls are dependent on the absorption and availability of many nutrients and can be negatively affected by stress conditions. Carpenter and Nair (2013) showed that the biochar application of up to 20 t acre^{-1} (~45 t ha^{-1}) did not significantly affect bell pepper's chlorophyll content, while Hua et al. (2012) described that the biochar-soil mixed with 40% (w/w) improved ryegrass' chlorophyll contents. The tomato and bell peppers exhibited significantly higher leaf and fruit nutrient content at B8 and B16. This increase could be related to the effect of biochar on soil chemical properties such as improvement of soil nutrient retention and enhancing soil nutrient content (Upadhyay et al. 2014). This increase in mineral concentrations can be justified by showing that biochar application could increase soil nutrient availability (Mohawesh et al. 2018). Still, the negative impact on plant growth may have not been due to the deficiency of NPK uptake as the leaf NPK minerals contents were within the acceptable range (Upadhyay et al. 2014). Based on previous research, the type of biochar and its composition is related to the threshold at which benefits occur (Oni et al. 2019). In this case, the olive biochar may impart toxic compounds or negative pH/EC traits that may overcome the soil's buffering capacity at rates greater than 16 t ha^{-1}. Based on our observations, this may not be due to a toxic effect, but the increase in soil pH and EC may have made plants more susceptible to abiotic stresses, like osmotic stress (Singh et al. 2019). These soil quality indicators were eventually affected by biochar application, which directly impacted plant roots and shoots (Prapagdee and Tawinteung 2017). It is well known that biochar applications affect soil physical and chemical properties; for example, biochar application reduces soil bulk density which could enhance plant root development and thus improve plant nutrient uptake (Omondi et al. 2016).

The biochar application rates up to 16 t ha^{-1} have a positive impact on yield for bell pepper and tomato plants

(Table 5). These results are consistent with the literature where lower rates have been reported to have positive effects; for example, Yilangai et al. (2014) reported that the application of 10 t ha^{-1} enhanced tomato production and growth in Northcentral Nigeria; and Prapagdee and Tawinteung (2017) reported that a 10% (w/w) application rate improved green bean yield in Thailand. However, from an economic perspective, the increased yield derived from the application of 16 t ha^{-1} compared to that derived from the 8 t ha^{-1} may not justify the extra cost (Table 5). Therefore, an application rate of 8 t ha^{-1} is likely to provide the optimal compromise between yield and cost. Furthermore, lower application rates may be more beneficial for long-term–repeated applications of the biochar as it reduces the risk of reaching the soil's tolerance threshold.

5 Conclusions

The biochar applications as organic amendments improved soil physical and chemical properties with some limitations. Tomato and bell pepper yields increased at 8 and 16 t ha^{-1} biochar application rates. However, at rates over 30 t ha^{-1}, plant growth and yields declined significantly. For both crops, biochar application rates up to 16 t ha^{-1} have a significant positive impact on tomato and bell pepper's yield, leaf, and fruit nutrient contents. The biochar application rates 30 and 40 t ha^{-1} also exhibited a significant negative effect on tomato and bell pepper plants' yield and nutrient content. Based on this study, the threshold of benefits of biochar application as a soil conditioner can be concluded to be between 16 and 30 t ha^{-1}, beyond which detrimental effects on plant growth and yield can occur. Still, an application rate of 8 t ha^{-1} is likely to provide the optimal compromise between yield increase and cost. Yet, further research is needed to investigate the effect of biochar for longer term field studies. In particular, the persistence of biochar benefits and periodic assessment of soil fertility and crop quality parameters to confirm effects under arid conditions and long-term application.

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Declarations

Conflict of Interest The authors declare no competing interests.

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