*Bulgarian Journal of Agricultural Science, 24 (No 6) 2018, 1012–1019*

# Greenhouse evaluation of biochar to enhance soil properties and plant growth performance under arid environment

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## Abstract

Mohawesh, O., Coolong, T., Aliedeh, M., & Qaraleh, S. (2018). Greenhouse evaluation of biochar to enhance soil properties and plant growth performance under arid environment. *Bulgarian Journal of Agricultural Science*, *24*(6), 1012–1019

Agriculture production in arid and semi-arid regions face several problems such as soil degradation, water shortage, and chemical toxicity. Soil amendments to improve soil water and nutrient holding capacity have become an important tool to enhance soil properties. Biochar is being suggested as a soil amendment for improving the quality of the agricultural soils. Therefore, pot experiments were conducted under greenhouse conditions using five levels of biochar (0 - control, 0.5, 1.0, 2.5 and 5.0% wt/wt) produced from broccoli residue applied to an alkaline, sandy loam soil to evaluate the effects of biochar on plant growth and performance as well as on soil physical and chemical properties. The results indicated that the growth of tomato (*Solanum lycopersicum*) and bell pepper (Capsicum annuum) plants were adversely affected by biochar additions at high levels (2.5 and 5.0%). Bell pepper and tomato biomass were not significantly different compared to the control treatment at 0.5 and 1.0% biochar. Biochar applications significantly affected leaf nutrient concentrations in both plants. Proline concentrations increased significantly in bell pepper and tomato with increasing biochar levels. Soil pH and EC values increased significantly with biochar applications. The biochar application to the soil increased soil EC and pH by 35.8 to 192.4% and by 1.6 to 5.5%, respectively, compared to the control treatment. For most measured parameters, the highest level of biochar application (5% wt/wt) adversely affected plant growth and nutrient uptake. Based on the results, biochar may have benefit when used as soil amendments at application levels of less than 2.5% (wt/wt); however, additional studies are necessary to determine the impact of biochar feedstock, pyrolysis conditions, soil type, and growing conditions to better understand the effects of biochar under arid and semi-arid soil conditions.

*Keywords:* biochar; soil fertility; water availability; pyrolysis; sustainable waste recycling

## Introduction

Soil degradation can cause a significant damage in land productivity and negatively impact peoples' life quality and their food security around the world. Appropriate strategies are crucial to promote improved soil management policies to satisfy the food needs of the growing population in the world (Mohawesh and Durner, 2017). The use of naturally-derived soil amendments to increase soil water and nutrient holding capacity have become a significant tool to improve soil management, particularly in regions of limited water availability and fragile soil ecosystems, such as much of the Middle East region (Mohawesh, 2016). Biochar is a soil amendment that has been tested and is recommended to boost carbon sequestration in soils and to improve soil chemical and physical properties (Laird, 2008; Radin et al., 2017). Biochar is prepared by pyrolysis of organic waste material (Novak et al., 2014). Biochar is a carbon-rich material produced by heating a wide range of organic biomass (feedstocks) at low levels or in the absence of oxygen (pyrolysis or charring). The pyrolysis temperature as well as feedstock can result in yields of varying characterstics (Baldock and Smernik, 2002; Das et al., 2008; Novak et al., 2009b; Sohi, 2012). Biochar can persist in soils for years, it is highly resistant to microbial decomposition, and can enhance sequestration of carbon for a long period when applied to soil (Schmidt and Novak, 2000; Lehmann et al., 2006; Downie et al., 2011). These properties suggested that biochar may enhance agronomic production of the soil when applied as a soil amendment (Lehmann and Rondon, 2006).

Soil amendment with biochar have been recommended to combat desertification as a sustainable land management policy (United Nations Convention to Combat Desertification, 2009) around the world, as it has been stated to significantly enhance land productivity (Laird, 2008; Biederman and Harpole, 2013). These enhancements have been attributed to biochar›s impact on soil properties (Glaser et al., 2002; Liang et al., 2006; Verheijen et al., 2010). Biochar has been shown to decrease soil nutrients leaching such as nitrogen (N), phosphorous (P), and potassium (K) (Laird et al., 2010; Sarkhot et al., 2012).

Vegetable producers in arid and semi-arid regions such as Jordan face several challenges, including poor soil fertility, low water holding capacity, and low organic matter content (Al-Karaki and Al-Omoush, 2002; Ouda and Mahadeen, 2008). To overcome low soil fertility, farmers usually apply high quantities of inorganic fertilizers to sustain crop productivity (Al-Karaki and Al-Omoush, 2002). Glaser et al. (2002) and Lehmann et al. (2003) showed that biochar could be beneficial as a soil amendment for improving the quality of the agricultural soils. Hammond (2009) reported that the biochar feedstock and production conditions could influence its interaction with soil type, climate, and crop grown. Much of the research about the valuable effects of the biochar has been performed in temperate and the tropical regions such as North America, East Asia, and Europe. Where soils were generally acidic and when biochar was applied, it had a liming effect on soil pH (Dume et al., 2015). However, relatively little is known concerning the impact of biochar on crop growth and performance in arid and semi-arid conditions where the soils are alkaline. Therefore, this study was conducted to assess the effects of biochar as a soil amendment on soil properties and plant growth performance and to evaluate the usefulness of biochar for production systems under arid and semi-arid environment with alkaline soils.

## Material and Methods

***Biochar production and characterization***

The biochar used in this study was obtained from slow pyrolysis at 300-350°C of broccoli crop residue (shoots and leaves). Collected feedstock were placed inside a greenhouse at ambient conditions and allowed to air-dry prior to pyrolysis. After pyrolysis, the biochar was ground to a uniform particle size (2-3 mm) prior to experimental use. The pH and EC of the biochar were determined in a 1:10 (biochar: distilled water) ratio (Cheng and Lehmann, 2009). Scanning electron microscope (SEM) with energy dispersive spectroscopy (EDS) were used to determine the chemical composition and micrographs of the biochar. The specific surface area was determined using the Brunauer-Emmett-Teller method (Zhang et al., 2012).

***Pot experiment***

The experiment was conducted at the Faculty of Agriculture, Mutah University, Karak governate, Jordan (Elevation 920 m a.s.l, Longitude 35°45`E and Latitude 31°16` N), inside a greenhouse during the period from June to November, 2015. The experiment was repeated twice. Each experiment was terminated after 75 days after transplanting. Four-week-old seedlings of tomato and bell pepper were transplanted into 20 cm diameter plastic pots, containing about 5 kg of sandy loam soil (clay 14%, silt 18%, sand 68%, EC 0.48 dS $m^{-1}$, pH 7.3, organic matter 1.09%, total nitrogen 980 ppm, 47% $CaCO_3$, available K 42 ppm, available P 30 ppm) with five treatments of biochar applied on a dry weight basis (0.0, 0.5, 1.0, 2.5 and 5.0% wt/wt) in triplicates. Each pot received 65 mg N $kg^{-1}$, 31 mg P $kg^{-1}$ and 25 mg K $kg^{-1}$ soil applied as urea, di-ammonium phosphate and potassium sulfate prior to planting. The soil in each pot was thoroughly mixed after applications of biochar and fertilizer. The pots received an equal amount of irrigation. The irrigation was initiated when 50% of available water was depleted from the available water (readily available water, RAW = 50% of available water, AW). Soil samples were collected from each pot at the midpoint and the end of the experiment for pH and EC measurements. Soil samples were dried, crushed and sieved through a 2 mm screen and pH and EC were measured using a 1:1 ratio of soil: distilled water. Soil texture was determined using the hydrometer analysis (Klute, 1986). Soil chemical properties were analyzed according to the standard procedures of the United States Salinity Laboratory Staff.

***Plant measurements and analysis***

Leaf samples were collected from each pot at the end of the experiment to determine chloroplast pigments, proline content, leaf N, P, and K content. Leaf samples were kept in plastic bags with wet tissue paper at 4°C. Measurements were made within 1-2 h of leaf sampling to measure leaf chlorophyll content (Vemmos, 1994). Leaf proline content was measured using Bates method (Bates et al., 1973). The leaf samples were dried at 75°C, ground, and then used for N, P, and K measurements. Available P was measured using UV spectrophotometer (UV-1601PC, Shimadzu, Japan) according to the vanadate-molybdate method (Olsen et al., 1954). Available K was measured using atomic absorption spectrometer (Perkin Elmer Analyst 300, USA) (Knudsen et al., 1982). Total N was determined by the Kjeldahl method (Chapman and Pratt, 1962). Soil cation exchange capacity (CEC) was determined using the ammonium acetate method (Chapman, 1985). At the end of the experiments, plants were removed from the pots; roots were washed carefully to remove soil particles. Plant shoot and root fresh and dry weights (SFW, RFW, SDW, and RDW, respectively) were measured. Plant shoots and roots were dried at 75°C for 4 days.

***Experimental design and statistical analysis***

The experimental design was randomized complete block design (RCBD) in triplicates. SPSS version 16 was used for statistical analyzes of the data (SPSS, Inc., Chicago, IL, USA). Means separation were done using the least significant difference (LSD) test and t-test at 0.05 level of significance.

## Results and Discussion

***Biochar characterization***

The chemical and physical properties of the biochar used in our experiments are shown in Table 1. As there was no significant difference between the two experiments, the data were pooled for analysis. The biochar gave high values of EC, N, K and P contents. The biochar is alkaline with a pH value of 9.5. The CEC of the biochar was 29.6 cmol kg$^{-1}$, which is lower than the humified organic matter (200-300 cmol kg$^{-1}$). Zhao et al. (2013) showed that the CEC is diverse significantly between biochar produced from different feedstocks and production conditions. This can be attributed to the fact that CEC is related to biochar minerals content, which differs with used feedstock (e.g., K and Ca).

A Scanning Electron Microscope (SEM) micrograph of the broccoli-based biochar is shown in Fig. 1. The biochar microscopic physical structure is a key property associated with its impact on soil properties (Zhang et al., 2012). The surface area of the biochar feedstock can be increased several hundreds folds during pyrolysis, which will significantly enhance its water holding capacity (Table 1). The physical structure of biochar (pore volume, pore size and distribution) are usually correlated to its nutrient retention and water holding capacity which can be related to its influence on soil structure, minerals mobility, and microbial activity (Zhao et al., 2013; Mohawesh and Durner, 2017). Several researchers considered that the properties of the produced biochar are mainly related to the feedstock type (Novak et al., 2009a;

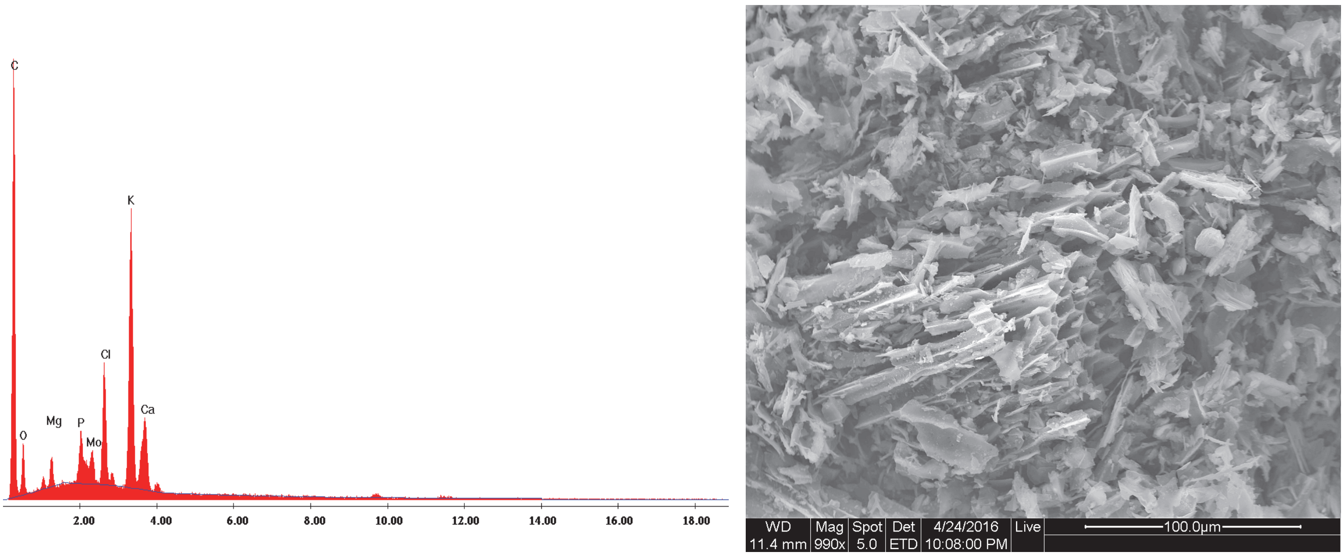


**Fig. 1. Scanning electron microscope and energy dispersive spectroscopy (EDS) of biochar prepared by charring broccoli crop residues**

**Table 1. Characterization of biochar produced from broccoli residues**

| Parameter | Values |
|---|---|
| Yield (%) | 34.70 ± 1.5 |
| Surface area ($m^2$ $g^{-1}$) | 12.9 ± 0.48 |
| pH | 9.50 ± 0.27 |
| EC (dS $m^{-1}$) | 8.8 ± 0.71 |
| CEC (cmol $kg^{-1}$) | 29.60 ± 2.37 |
| N (%) | 3.50 ± 0.24 |
| P (%) | 1.90 ± 0.09 |
| K (%) | 17.01 ± 1.52 |
| C (%) | 59.85 ± 1.14 |
| O (%) | 6.76 ± 0.07 |
| Ca (%) | 4.82 ± 0.31 |

Zhao et al., 2013; Novak et al., 2014). Hamer et al. (2004) showed that biochar from corn was fine, friable, and easily broken down, which was similar to the produced biochar from broccoli residue used in this study.

***Plant and soil measurements and analysis***

Biochar applications at higher levels (2.5 and 5%) adversely affected tomato and bell pepper plant growth (Table 2). Some pots showed inhibited growth but with no clear signs of salt damage or nutrient insufficiencies. Initially, limited plant growth compared to the control was observed in pots receiving the 2.5 and 5% treatments, but plants began to recover one month after transplanting. The tomato plant biomass at the lower levels of biochar (0.5 and 1%) was similar to the control. Lower levels biochar applications resulted in significantly greater biomass production than the higher biochar levels (2.5 and 5%) (Table 2). This decrease in biomass production at the higher levels of biochar addition was likely the result of a high soil pH and EC in the 2.5 and 5% biochar treatments. Adding biochar to the soil increased soil EC and pH by 35.8 to 192.4% and by 1.6 to 5.5%, respectively, compared to the control treatment. The increases in soil pH were expected due to high pH value of the biochar. Kishimoto and Sugiura (1985) and Mikan and Abrams (1995) showed an overall decrease of the plant growth at high levels of the biochar applications, due to nutrient deficiency caused by the increasing of soil pH and EC. Direct toxicity effects may also provide a justification, even though these were not explicitly examined. The increase in soil pH due to biochar application can be temporary owing to the buffering capacity of the soil, as the microbial activity and atmospheric $CO_2$ will react with alkaline biochar salts to produce bicarbonate that will control the soil pH (Steiner et al., 2007; Artiola et al., 2012). At the lower biochar levels (0.5 and 1%), there was no significant positive effect on tomato and bell pepper plant growth (Table 2). Even though our results showed an insignificant effect of low biochar levels on plant growth, some previous studies reported an increase in plant growth performance with biochar application (Chan et al., 2007; Saxena et al., 2013; Naeem et al., 2016, 2017). Tomato growth performance increased with application of biochar (Yilangai et al., 2014). In a study conducted on the response of dry matter production of radish using green wastes, it was reported that a yield increases were only found at biochar application rates greater than 50 tons $ha^{-1}$ (Chan and Xu, 2009). Improvements in plant growth due to biochar amendments have been stated to combine effects of biochar on soil water holding capacity (Lehmann and Joseph, 2009), increasing nutrient retentivity (Yanai et al. 2007), and enhanced soil structure (Lehmann and Joseph, 2015). Increased nutrient availability following biochar amendments was reported in Rondon et al. (2007).

**Table 2. Effect of biochar levels on shoot and root fresh weight of tomato and bell pepper**

| Biochar (%) | SFW (g) | SDW (g) | RFW (g) | RDW (g) |
|---|---|---|---|---|
| Tomato | | | | |
| 0 | 137.83 a | 14.99 a | 12.41 a | 3.63 a |
| 0.5 | 141.11 a | 14.33 ab | 10.43 a | 3.56 a |
| 1 | 140.83 a | 14.98 a | 10.68 a | 3.44 a |
| 2.5 | 119.17 b | 13.10 ab | 11.58 a | 2.97 ab |
| 5 | 115.83 b | 12.64 b | 9.35 a | 2.10 b |
| Bell pepper | | | | |
| 0 | 34.06 a | 6.54 a | 10.18 ab | 3.97 b |
| 0.5 | 38.69 a | 9.32 a | 12.41 a | 5.74 ab |
| 1 | 38.36 a | 8.75 a | 11.91 a | 5.95 a |
| 2.5 | 29.58 d | 7.76 a | 9.36 b | 4.66 ab |
| 5 | 16.21 c | 3.87 c | 7.13 c | 1.52 c |

SFW: shoot fresh weight (g), SDW: shoot dry weight (g), RFW: root fresh weight, RDW: root dry weight

Foliar nutrient concentrations in tomato and bell pepper were affected by biochar applications. The different soil-biochar mixtures had no significant effect on the leaf tissue N content in tomato or bell pepper (Table 3). Similarly, Zeelie (2012) indicated that different soil-biochar mixtures had no significant effect on the leaf N content. However, in the present study, it is likely that the reduced growth was not due to a deficiency of N uptake as leaf N content were within acceptable ranges for tomato and bell pepper. Biochar applications at 0.5% increased the concentration of P in tomato compared to the control. This increase was due to the high concentrations of available P and exchangeable K found in the biochar. Salim (2016) reported increases in leaf concentrations of N, P, and K in response to biochar. For tomato K and P, the maximum concentrations were found at 0.5% of biochar,

**Table 3. Effect of biochar levels on N, P, K, Ca, and Na concentrations in tomato and bell pepper plants shoot**

| Biochar (%) | N | P | K | Ca | Na | N | P | K | Ca | Na |
|---|---|---|---|---|---|---|---|---|---|---|
| | (%) | | | | | | | | | |
| | Tomato | | | | | Bell pepper | | | | |
| 0 | 2.69a | 0.30b | 1.39ab | 0.99ab | 0.09a | 3.7ab | 0.26abc | 1.17b | 1.55ab | 0.09bc |
| 0.5 | 2.79a | 0.46a | 1.66a | 0.84ab | 0.10a | 3.7ab | 0.24abc | 1.53ab | 1.29ab | 0.10bc |
| 1 | 2.65a | 0.42ac | 1.53ab | 1.18a | 0.12a | 3.9 a | 0.21bc | 1.49ab | 1.00b | 0.08c |
| 2.5 | 2.88a | 0.35bc | 1.40ab | 0.97ab | 0.11a | 3.8 a | 0.29a | 1.69a | 1.81a | 0.13ab |
| 5 | 2.74a | 0.36bc | 1.27b | 0.73b | 0.10a | 3.5 b | 0.27ac | 1.43ab | 1.27ab | 0.15a |

N: Nitrogen content, P: Phosphorus content, K: Potassium content, Ca: Calcium content, Na: Sodium content

while Ca and Na, though not significantly different from the control treatment, exhibited the highest values at 1% of biochar. In bell pepper, the 2.5% biochar treatment increased K levels compared to the control. This increase could be attributed to the high concentrations of available P and exchangeable K found in the biochar. The control showed the lowest foliar K concentrations. It has been reported that the addition of biochar to soils increased plant K tissue concentration, compared to control (Taiz and Zeiger, 2002; Chan and Xu, 2009). In addition, the 5.0% biochar treatment increased Na levels in bell pepper compared to the control. In a study conducted on the response of dry matter production of radish using green wastes, biochar application increased the plant P and K concentrations (Chan et al., 2007; Biederman and Harpole, 2013). The increased pH due to the biochar applications was probably associated with less availability of some nutrients responsible for optimum growth and development at high biochar levels.

Leaf proline content significantly increased with increasing biochar levels (Table 4). In both tomato and bell pepper, the lowest leaf proline content was observed at control (15 and 24.36 μmol/g FW, respectively). Biochar increased proline and reduced availability of some nutrients (Ca), which suggests that biochar amendment may cause stress for plants, mainly, just after biochar application. Total chlorophyll contents were significantly decreased at high biochar levels (5.0%) in tomato and bell pepper. Asai et al. (2009) reported that there was a decrease in leaf chlorophyll content in response to biochar amendments and leaf chlorophyll contents were the lowest with the highest biochar applications. The decreased chlorophyll contents due to biochar application were attributed to the high C/N ratio caused by biochar application to which led to immobilization of N (Zeelie, 2012; Zemanová et al., 2017). However, in our study, the N uptake and leaf content weren't affected by biochar application levels. This low chlorophyll content at high biochar levels could be attributed to high EC of the soil-biochar mixtures, which may have resulted in a salinity stress on plants. Biochar did positively affect chlorophyll content in bell pepper plant at 0.5 and 1.0% biochar levels. Chlorophyll increases because of biochar application to soil were also reported in Zea mays (Brennan et al., 2014) and in wheat (Alburquerque et al., 2013). Increased chlorophyll content in plant leaves is a sign of increased plant photosynthesis and hence improvement of plant growth (Alburquerque et al., 2013).

**Table 4. Effect of biochar levels on proline and total chlorophyll of tomato and bell pepper**

| Biochar (%) | Proline (μmol/g FW) | Total chlorophyll (mg/100 g FW) |
|---|---|---|
| Tomato | | |
| 0 | 15.07e | 37.69a |
| 0.5 | 16.92d | 34.13b |
| 1 | 24.94c | 37.38a |
| 2.5 | 33.93b | 38.30a |
| 5 | 36.00a | 35.46b |
| Bell pepper | | |
| 0 | 24.42d | 41.05b |
| 0.5 | 24.80c | 44.49a |
| 1 | 26.54b | 45.92a |
| 2.5 | 34.88a | 41.55b |
| 5 | 37.30a | 37.51c |

It is clear that the addition of biochar led to a significant increase of pH values at the mid (1.9 to 5.5%) and at the end (1.6 to 5.4%) of the experiments. The 5% biochar level gave a significant increase compared to control (Table 5). This can be explained by the potential effect of biochar pH to modify soil pH, as biochar is a highly alkaline product due to the existence of organic ions and inorganic carbonates. Novak et al. (2009b) explained through their study that pH increased from 4.8 to 6.3 with the addition of 2% biochar. Van Zwieten et al. (2010) tested two biochars produced from slow pyrolysis of paper mill waste for two agricultural soils; they found that they differed slightly in their liming values by 33% and 29%, respectively. In addition, there was an increase of soil EC with increasing the biochar levels. At the end of the experiment, the EC was increased significantly at 2.5 and 5% biochar levels compared to the control. The soil-biochar mixtures EC values in the 5% biochar treatment were increased by 192.4 and by 146.7% at the mid and at the end of the experiment, respectively. Chan et al. (2008a) found significantly higher EC at higher rates (> 50 tons $ha^{-1}$) of green waste biochar in alfisol soils. Similar results were observed also, when poultry litter biochar was tested (Chan et al., 2008b).

**Table 5. Effect of biochar levels on soil pH and EC at the middle and the end of the experiment**

| Biochar (%) | $pH_{mid}$ | $pH_{end}$ | $EC_{mid}$ (dS $m^{-1}$) | $EC_{end}$ (dS $m^{-1}$) |
|---|---|---|---|---|
| 0 | 7.25e | 7.37e | 0.53c | 0.60c |
| 0.5 | 7.39d | 7.49d | 0.72bc | 0.96c |
| 1 | 7.46c | 7.56c | 0.61c | 0.87c |
| 2.5 | 7.55b | 7.61b | 0.90b | 1.27b |
| 5 | 7.65a | 7.77a | 1.55a | 1.48a |

$pH_{mid}$: Soil alkalinity at the middle of the experiment; $pH_{end}$: Soil alkalinity at the end of the experiment; $EC_{mid}$: Soil electrical conductivity at the middle of the experiment; $EC_{end}$: Soil electrical conductivity at the end of the experiment

## Conclusions

The addition of high levels of biochar adversely affected plant growth and there were no significant positive effects on growth at low levels of biochar. The concentration of some leaf nutrients of tomato and bell pepper plants increased with biochar applications. The soil pH and EC values increased significantly with biochar application. Proline content increased significantly with increasing biochar level, suggesting that the high levels of biochar application introduced abiotic stress, which might adversely influence on plant growth and development. To our knowledge, the research on the application of biochar as a soil amendment has not been investigated under similar conditions to those in Jordan. Thus, this present study suggests that biochar can be used as a soil amendment at application levels of less than 2.5% (wt/wt); however, still several studies are needed to investigate the effect of biochar feedstock, pyrolysis conditions on different soil, climate, and plants for longer-term field studies to better understand the effects of biochar on arid and semi-arid soil.

***Acknowledgement***

The authors would like to thank the assistance of the EU funded project (SRTDII) managed by the Higher Council for Science & Technology and Norman E. Borlaug International Agricultural Science and Technology Fellowship Program, The United States Department of Agriculture's (USDA) Foreign Agricultural Service (FAS) for their finical support.

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*Received*: August 17, 2018; *Accepted*: October 23, 2018; *Published*: December 31, 2018