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Effects of deficit irrigation and biochar addition on the growth, yield, and quality of tomato

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ABSTRACT

Biochar soil amendments have the potential to improve the soil water and nutrient status, and could enhance crop productivity. A greenhouse experiment was conducted over two consecutive growing seasons to investigate the effects of biochar amendment (BA) in combination with deficit irrigation (DI) on tomato growth, physiology, yield, fruit quality, and irrigation water use efficiency (IWUE). Plants were grown in a ridge and furrow system. A randomized complete block design was used that comprised three irrigation regimes (W1 = 50%, W2 = 75% and W3 = 100% of the reference evapotranspiration) as blocks; each block had nine plots with BA applied at three rates (T1 = 0, T2 = 25, and T3 = 50 t ha^{-1}) in three replications. The BA treatments (T2 and T3) improved soil water storage in both DI treatments (W1 and W2), which consequently enhanced growth, physiology and yield of tomato compared with the control (T1). There was no significant difference ($P < 0.05$) in yield between the W1-T2 and the W3-T1 treatments, i.e., BA (T2) could reduce water use by 50% without affecting yield. Furthermore, BA significantly increased soil organic matter (SOM) and total nitrogen (TN), while soil nitrate nitrogen and ammonium nitrogen levels were decreased significantly ($P < 0.05$). DI significantly increased the fruit quality and IWUE compared to the full irrigation regime (W3). The integration of BA along with DI can be considered as a viable approach that improves crop productivity and promotes irrigation water use efficiency (IWUE).

1. Introduction

The intensity of water resource limitations and the frequency of droughts will probably increase in the context of global climate change (Garcia Galiano et al., 2015). Consequently, this is expected to adversely affect crop production (Zhou et al., 2012). To address this problem, water use efficiency (WUE) must improve. This will help to sustain the water resources that are available for agriculture. In order to achieve this, different innovative irrigation strategies have been developed and assessed. One such technique is deficit irrigation (DI), which is an optimization approach that improves soil water exploitation by plant roots (Ćosić et al., 2015). The effects of DI on the yield and quality of crops are dependent on a number of factors including good land management and agronomic practices (Rao et al., 2016). The appropriate use of DI has the potential to deliver promising crop yields without compromising quality (Ćosić et al., 2015).

Tomato is considered to be one of the more popular vegetables or fruits, with an extensive worldwide distribution and massive economic value (Bilton et al., 2001; Savić et al., 2008). The production of tomatoes in greenhouses has been rapidly increasing, and plays an important role in supplying the fresh tomato industry (Bao and Li, 2010). However, tomato is one of the highest water demanding crops (Patanè et al., 2011). Under drought stress, plant photosynthesis can significantly decrease, consequently reducing the amount and energy of metabolites (Kulkarni and Phalke, 2009) required for the proper development of both the above- and below-ground biomass (Dias et al., 2007; Dorji et al., 2005). However, Hanson et al. (2006) and Favati et al. (2009) have shown that tomato can grow under deficit irrigation without a significant reduction in yield. Moreover, the characteristics that determine the quality of the fruit, such as the content of sugar and antioxidant moieties can also be improved. These finding seem contradictory, but suggest that using the proper regiment

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of deficit irrigation can save considerable amounts of water, while sustaining tomato production and quality. Notably, the appropriate amount of deficit irrigation water may greatly differ, depending on the various characteristics of the soils, growing conditions, and tomato cultivar.

Biochar is biomass that has been pyrolyzed in a low oxygen environment, and has the potential ability to improve soil fertility and enhance crop productivity (Smith et al., 2010). Many studies have been carried out around the world, with the objective of investigating the effects that biochar applications to soils would have on crops yields. The majority of the studies reported that biochar amendment (BA) has improved soil quality, structure, and nutrient availability, as well as plant productivity (Chan et al., 2008; Glaser et al., 2002; Streubel et al., 2011; Wardle et al., 1998). Furthermore, research has found that BA improves crop productivity and mitigates drought, salinity, acidity, and toxic metal stresses that are commonly associated with plant stress (Fiaz et al., 2014; Thomas et al., 2013). In addition, Streubel et al. (2011) reported that BA has the potential ability to improve soil water holding capacity. Thus, it can be deduced that crop productivity can be enhanced under soil amended with biochar by better retaining rainwater in the soil in arid regions, which will lead to a decrease in the frequency and amount of irrigation required. It is worth noting that the effects of BA were typically tested in poor soils (Van Zwieten et al., 2010) or in soils with sub-optimal fertilization management (Chan et al., 2008; Hanson et al., 2006; Van Zwieten et al., 2010). However, the agronomic benefits of biochar are affected by many factors such as soil type, soil chemistry and climate conditions. Nevertheless, the biomass source, or feedstock, and the pyrolysis conditions are considered to be the main agents that determine the physical and chemical properties of the biochar that will affect the plant responses (Keshavarz Afshar et al., 2016). Although there have been a number of studies conducted on BA, plant responses and the underlying mechanisms that are affected by BA remain poorly understood.

Recently, there has been an increase in the use of integrated approaches to soil management in order to improve crop production by confronting the problems of drought conditions, nutrient-poor soils, salinization, and other forms of soil degradation (Akhtar et al., 2014; Ismail and Iberahim, 2003; Zahir et al., 2012). Using reduced irrigation techniques such as deficit irrigation along with BA is considered to have the potential to substantially reduce the amount of irrigation water required, and to enhance crop productivity. To date, there have been relatively few studies that investigated the effects of BA under water stress for plant production. Keshavarz Afshar et al. (2016) found that the application of biochar under DI conditions improved soil water holding capacity but did not influence milk thistle plant performance in a sandy loam soil, possibly because greater amounts of biochar were needed in order to do so. Akhtar et al. (2014) reported that the yields and quality of tomatoes grown in pots were enhanced by a combination of biochar and reduced irrigation (DI or partial root-zone drying) in a sandy loam soil. However, it appears that using such techniques has not yet been documented for tomatoes grown in depleted loam soils. Therefore, the objectives of this study were to investigate the effects of BA along with DI, on the production of tomato, including its physiology, yield, IWUE, and fruit quality in a depleted loam soil. Furthermore, this study considers tomato plants growing in a ridge and furrow system similar to those used in practice.

2. Materials and methods

2.1. Experimental site

The study was carried out in a greenhouse at the Water-Saving Park of Hohai University, Nanjing, Jiangsu Province, China. The study site is located at latitude 31°57′N and longitude 118°50′E, and is 144 m above mean sea level. The study was conducted over two growing seasons: 14 April to 24 August in 2014; and 19 April to 18 August in 2015. The area is dominated by a humid subtropical climate, and is under the influence of the East Asia Monsoon. The temperature inside the greenhouse during the cropping seasons (April to August) was adjusted to be 28 °C, while it was range from 18.5 to 41.0 °C during the same period outside the greenhouse. The mean pan evaporation is 900 mm and the mean annual precipitation is 1073 mm. The upper soil layer (0–30 cm) at the study site is loam, which overlies a layer of clay loam (30–60 cm). Basic soil physical and chemical properties of the 0–30 cm and 30–60 cm soil layers are presented in Table 1.

Table 1
Basic physical and chemical properties of biochar and the soil in the study area.

Soil Properties	Units	Depth		Biochar properties
		0–30 cm	30–60 cm	
pH		7.7	8	9.9
Electrical Conductivity	dS m^{-1}	1.42	0.42	1.0
Organic matter (O.M)	g kg^{-1}	2.24	–	–
Organic carbon (O.C)	g kg^{-1}	1.3	–	467.2
Ca	g kg^{-11}	0.16	0.04	0.0016
Mg	g kg^{-1}	0.07	0.02	–
Cl	g kg^{-1}	0.11	0.02	1.44
HCO_3	g kg^{-1}	0.20	0.05	0.85
$CaCO_3$	g kg^{-1}	0	2.8	–
total N	g kg^{-1}	0.18	–	5.9
total P	g kg^{-1}	–	–	14.43
total K	g kg^{-1}	–	–	11.5
CEC	cmol kg^{-1}	–	–	21.7
Bulk density	g cm^{-3}	1.35	–	0.40
Field capacity	%	25.8	–	–
Silt	%	30	23	–
Sand	%	50	42	–
Clay	%	20	35	–
Texture		Loam	Clay loam	–

2.2. Experiment design

The study was carried out in a greenhouse that was constructed with glass over the soil *in situ.* A randomized complete block design was used, comprising three blocks, each receiving a different level of irrigation. Within each of the blocks, there were plots that received an allocated BA treatment. The blocks each received one of the three irrigation regimes: 50% (W1), 75% (W2), and 100% (W3) of the reference evapotranspiration (ET_0). The BA treatments for the plots in each block were applied at three rates: 0 t ha^{-1} (T1, control), 25 t ha^{-1} (T2), and 50 t ha^{-1} (T3); these rates were comparable with those used by Liu et al. (2014) and Jones et al. (2012) and were considered appropriate for the soil which was structurally poor and relatively deficient in nutrients and organic carbon. Each treatment combination was replicated three times and distributed randomly in order to minimize any effects from the differences between plots. Thus, each block consisted of nine plots (3 m × 0.9 m) and the experiment had a total of 27 plots (Fig. 1). The same treatment scheme was used for both growing seasons. Irrigation water (tap water) was delivered to the blocks via a gravity drip system. At the upper end of each block, a tank (61483 cm^3) was installed at a height of 1 m in which to store irrigation water. Each treatment plot had a separate drip line placed at the center of the plot; the emitters had a 0.5-m spacing. The drip line network and plant locations are shown in Fig. 1a and b. The ridge and furrow system in the soil was prepared manually.

2.3. Biochar characterization

The commercial biochar that was used in this study was produced from wheat straw, pyrolyzed at 350–550 °C in a vertical kiln, manufactured by Sanli New Energy Company, Henan Province, China. Using this technique, about 30% of the dry wheat straw matter would be