Depth and Duration of Flooding Affect Growth, Yield, and Mineral Nutrition of Subirrigated Bell Pepper

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Additional index words. closed irrigation systems, drip fertigation, vegetable crops, greenhouse crops, sustainable production

Abstract. In containerized crop production, subirrigation is an attractive solution to reduce excessive water runoff and nutrient loss. However, this irrigation method is mainly used for the cultivation of containerized ornamental plants, with limited research on the cultivation of vegetable species. In the present study, we assessed the feasibility of using a subirrigation system on growth, yield, and nutrient status of bell pepper plants (*Capsicum annuum* L.) grown in 30-cm-tall (13-L) containers by measuring the effects of flooding depth (10 and 15 cm) and duration (20 and 30 minutes) and compared with drip-fertigated plants. Subirrigated bell pepper plants exhibited a fruit number and yield comparable to those of drip-fertigated plants when the solution depth was held at 15 cm for 30 minutes. There was a substantial increase in the electrical conductivity (EC) in the medium top layers for all subirrigated plants, but this was up to 50% lower when plants were irrigated/fertigated to a 15-cm depth for 30 minutes. The higher yield of subirrigated plants flooded to a depth of 15 cm for 30 minutes was associated with a decrease in Ca concentration in the plant tissue (–16%), probably due to a dilution effect associated with the higher biomass produced by these plants. The higher nutrient use efficiency (NUE) attributed to subirrigation systems is not only due to nutrient accumulation in the growing medium, but also to a higher uptake by the plants, as compared with drip-fertigated plants, as subirrigated plants with flooding depth and duration of 15 minutes and 30 cm contained 47% higher N, 44% P, 44% K, 17% Ca, 60% Mg, and 76% S. Subirrigation of bell pepper plants is a reliable and feasible irrigation system provided flooding depth and duration are considered.

Water quantity and quality are major issues for food production. About three billion people are predicted to live in water-stressed or water-scarce environments by 2025 (Hanjra and Qureshi, 2010). Agricultural crop production systems are one of the largest consumers of water (Frijia et al., 2009), accounting for nearly 80% of total global water use (Molden et al., 2007). The imperative need to provide food for a growing global population has resulted in increased interest in production systems that maximize water use and plant yield and quality. In

protected agriculture, greenhouse-grown, soil-cultivated plants may produce high quality and yields; however, due to current irrigation practices, and subsequent runoff and infiltration, the water use efficiency (WUE) may be low (Putra and Yuliando, 2015), which may pose a threat to the environment. Greenhouse production systems have been suggested to be highly correlated with WUE (Frijia et al., 2009), as similar yields have been achieved using 50% to 100% less water when plants are cultivated using soilless media systems, when compared with “conventional” soil-grown plants (Putra and Yuliando, 2015).

Closed irrigation systems are of particular interest when compared with conventional open irrigation systems as they have been demonstrated to reduce nutrient loss and

increase WUE and NUE in greenhouse crop production systems (Ahmed et al., 2000; Putra and Yuliando, 2015; Rouphael and Colla, 2005; Rouphael et al., 2004; Siddiqi et al., 1998; van Os, 1999). Among closed irrigation systems, subirrigation with nutrient and water recirculation is an excellent method to enhance plant production, quality, yield, and potentially the profitability of important cultivated plants (Cardarelli et al., 2010; Fascella and Rouphael, 2015; Rouphael et al., 2006; Santamaria et al., 2003; Uva et al., 2001).

Nonetheless, subirrigation of greenhouse crops is mainly used for the cultivation of containerized ornamental plants. It has been demonstrated that subirrigated ornamental plants have increased growth, and decreased water (van Os, 1999) and nutrient use (Blessington-Haley and Reed, 2004; Zheng et al., 2004). However, there is limited information available on using subirrigation systems for the production of vegetable species (Santamaria et al., 2003).

Subirrigation systems may enhance vegetable crop production; however, vegetable crops may have a longer cultivation time, higher growth rate, and higher nutrient and water demands, when compared with containerized ornamental plants (Rouphael and Colla, 2005; Santamaria et al., 2003). Successful subirrigation of vegetable crops may need the use of containers of larger volume due to the higher biomass and longer cultivation period associated with these crops when compared with ornamental species. Therefore, irrigation solution depth and duration of flooding have to be determined to achieve optimum wetting of the substrate and nutrient distribution as they depend on the medium and container size used. The objective of the present study was to assess the feasibility of using a subirrigation system in the production of containerized bell pepper plants by measuring the effects of flooding depth and duration on growth, yield, and mineral composition.

Materials and Methods

Cultural conditions and plant material.

The study was conducted in a greenhouse in Saltillo, Coahuila, México (25°23′42″ N lat., 100°59′57″ W long., 1743 m above sea level). The mean maximum and minimum temperature for the study was 30 and 11 °C, respectively (average 18 °C). Mean maximum and minimum relative humidity were 95% and 40%, respectively (average 77%), and mean photosynthetically active radiation measured at solar noon was 306 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Bell pepper plants cv. Top 141 were planted on 12 Aug. 2014 into 13-L black polyethylene containers filled with a mixture of sphagnum moss, coconut fiber, and perlite (40%, 40%, 20% v/v) to a height of 30 cm. Initial medium pH and EC were 6.4 and 1.1 $\text{dS}\cdot\text{m}^{-1}$, respectively.

Nutrient solution. Nutrient solution for both subirrigated and drip-fertigated plants

Received for publication 23 Sept. 2016. Accepted for publication 9 Nov. 2016.

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was formulated according to Steiner's (1961) formulation, including macronutrients (meq·L⁻¹): 12 NO₃⁻, 1 H₂PO₄⁻, 7 K, 4 Mg, and 2 SO₄²⁻ and micronutrients (mg·L⁻¹): 5.3 Fe, 0.4 Zn, 2.6 Mn, 0.5 Cu, 0.2 B, and 0.2 Mo.

Subirrigation system and treatments. There were four subirrigation treatments, consisting of two flooding depths (10 or 15 cm) and two flooding durations (20 or 30 min) in which the containers remained standing in the nutrient solution. Subirrigation started when the growing medium registered a moisture tension of 1 kPa. In subirrigated treatments, two one-plant containers were placed in rigid plastic trays/troughs (69 × 39 × 16 cm; length, width, and height). The control treatment consisted of plants irrigated through a drip fertigation system on which each container had four emitters dispensing a total of 4 L of nutrient solution per hour; plants were irrigated as needed with enough solution to achieve a 25% leaching fraction. The nutrient solution, in both, subirrigated and drip-fertigated plants, was checked and adjusted as required for pH and EC before the next fertigation event. The nutrient solution pH was adjusted to 6.0 ± 0.1 with H₂SO₄ (0.1 N) and EC was maintained at 2.3 dS·m⁻¹ for experiment duration by replacing the evapotranspired water. In subirrigated plants, the unabsorbed solution was drained back into a 200-L storage tank and renewed every 15 d.

Plant growth and mineral composition. The experiment was ended 165 d after transplanting. Fruits were harvested throughout the experiment, starting 120 d after transplanting. Fruit was considered ready for harvest when 80% of the pericarp had obtained a red color. At experiment termination, total fruit number and yield were determined, and plants were harvested and washed twice in distilled water, separated into roots, stems and leaves, along with all the harvested fruits, and dried in an oven at 70 °C for 72 h for dry weight calculation.

Dry plant tissues [root, shoot (stem and leaves), and all the harvested fruits] were ground in a Wiley mill to pass a 20-mesh sieve (Thomas-Wiley Mill Co., Philadelphia, PA) and a tissue mineral analysis was conducted, including total N concentration with Kjeldhal's procedure (Bremner, 1996), while P, K, Ca, Mg, and S were determined with inductively coupled plasma emission spectrometer (ICP-AES, model Liberty; VARIAN, Santa Clara, CA) in ground tissues digested in a 2:1 mixture of H₂SO₄:HClO₄ and 2 mL of 30% H₂O₂ for P, K, Ca, and Mg, whereas S was determined in ground tissues digested in a mixture of HNO₃:HClO₄ (Soltanpour et al., 1996). Macronutrients accumulated in the root, shoot, fruit, and in the entire plant were calculated considering their concentration and the dry weight of each plant part.

At harvest, the root ball was carefully separated into four layers; from bottom to

the top, the layers were 0–7, 7–14, 14–21, and 21–28 cm. Samples of the growing medium from each layer were collected and thoroughly mixed with distilled water in a 1:2 proportion (30 mL of growing medium: 60 mL of water) allowed to sit for 60 min and then filtered. The filtrate pH (LAQUA twin B-712; Horiba Ltd., Kyoto, Japan), EC (LAQUA twin B-771; Horiba Ltd., Kyoto, Japan), NO₃⁻ (LAQUA twin B-741; Horiba Ltd., Kyoto, Japan), K (LAQUA twin B-731; Horiba Ltd., Kyoto, Japan), and Ca (LAQUA twin B-751; Horiba Ltd., Kyoto, Japan) concentrations were determined.

Statistical design. The experimental unit consisted of two plants (20 cm apart), each in an individual container. Four replicates of each experimental unit were distributed in a completely randomized block design. Data were analyzed with analysis of variance and Duncan's multiple mean comparison test ($P \leq 0.05$) using SAS v. 9.2; the data for the chemical properties of the growing medium layers were analyzed as a factorial on which fertigation treatments and medium layers were the factors with four levels each.

Results and Discussion

Bell pepper plants grown in flooded trays/troughs to a depth of 15 cm for 30 min produced a number and yield of fruits similar to those of drip-fertigated plants (Table 1). In addition, these subirrigated plants exhibited increased biomass production as they had a higher root, stem, leaf, and total dry weight when compared with drip-fertigated plants (Table 2). All the other flooding depths and durations assessed resulted in a lower number of fruits and yield, as well as decreased

dry weight. The results observed in the present study suggest that subirrigation is a feasible irrigation method for vegetable species as long as important aspects such as flooding depth and duration are considered. In contrast to our results, Santamaria et al. (2003) and Bouchaaba et al. (2015) indicate that, when compared with drip-fertigated plants, the yield of subirrigated cherry tomato (*Lycopersicon esculentum* var. *cerasiforme* Alef.) and green beans (*Phaseolus vulgaris* L.) decreased by 20% and 33%, respectively, whereas Scholberg and Locascio (1999) reported a decrease in the size and number of fruits in tomato (*Lycopersicon esculentum* Mill.).

The decrease in yield, growth, and biomass that has been reported for subirrigated plants has been ascribed to the increase in the EC of the top layer of the growing medium and to an uneven distribution of moisture throughout the medium profile (Bouchaaba et al., 2015; Cox, 2001; Montesano et al., 2010; Nemali and van Iersel, 2004). In the present study, subirrigation also resulted in higher EC in the growing medium when compared with that of drip-fertigated plants (Table 3). However, the effect on EC was more pronounced in the 21–28 cm top layer of the growing medium as in subirrigated plants it ranged from 5.0 to 7.5 dS·m⁻¹, whereas in the drip-fertigated plants, it was ≈2.0 dS·m⁻¹ (Fig. 1A). The higher EC in the top layers that is typically observed in subirrigated containerized plants is due to the upward migration of salts along with the capillary movement of water (Cox, 2001; Incrocci et al., 2006; Matysiak and Bielenin, 2005; Montesano et al., 2010; Rouphael et al., 2008; Whitcher et al., 2005; Zheng et al., 2004). The concentration, root uptake rate, and mass flow of

Table 1. Effect of the flooding depth and duration on fruit number and yield of subirrigated and drip-fertigated greenhouse bell pepper in containers.

Irrigation method	Flooding		No. of fruits	Fruit yield (g/plant)
	Depth (cm)	Duration (min)		
Subirrigation	10	20	4.15 b	550 c
		30	3.33 b	540 c
	15	20	5.00 a	712 b
		30	5.25 a	857 a
Drip fertigation			5.38 a	790 ab
		<i>P</i> value	≤0.001	≤0.001

Treatments with different letters were significantly different according to Duncan's multiple comparison test ($P \leq 0.05$).

Table 2. Effect of the flooding depth and duration on root, stem, leaf, and total dry mass of subirrigated and drip-fertigated greenhouse bell pepper in containers.

Irrigation method	Flooding		Roots	Stems	Leaves	Total
	Depth (cm)	Duration (min)				
Subirrigation	10	20	17.5 b	17.2 c	13.4 e	48.2 e
		30	14.8 c	22.7 b	17.8 d	55.3 d
	15	20	23.2 a	31.3 a	26.7 b	81.2 b
		30	23.8 a	34.8 a	29.7 a	88.3 a
Drip fertigation			19.6 b	25.0 b	20.6 c	65.1 c
		<i>P</i> value	≤0.001	≤0.001	≤0.001	≤0.001

Treatments with different letters were significantly different according to Duncan's multiple comparison test ($P \leq 0.05$).

Table 3. Effect of flooding depth and flooding duration and growing medium layer (from bottom to top) in subirrigated and drip-fertigated greenhouse bell pepper in containers on pH, electrical conductivity (EC), and calcium (Ca), potassium (K), and nitrate (NO_3^-) concentrations in the growing medium at experiment termination.

Irrigation method	Flooding depth (cm)	Flooding duration (min)	pH	EC ($\text{dS}\cdot\text{m}^{-1}$)	Ca (ppm)	K (ppm)	NO_3^- (ppm)
Subirrigation	10	20	4.71	2.51 a	39.5 b	306 c	78.7 b
		30	4.88	2.49 a	28.5 c	280 cd	74.1 b
	15	20	4.72	2.12 b	30.8 c	404 a	80.4 b
		30	4.72	1.96 c	29.1 c	362 b	77.4 b
Drip fertigation	Growing medium layer (cm)	0–7	4.87	1.14 d	91.9 a	253 d	97.1 a
		7–14	6.16 a	0.73 d	39.3 b	208 d	145 a
		14–21	5.69 b	0.84 c	40.1 b	256 c	97 b
		21–28	4.49 c	1.23 b	43.4 b	308 b	52 c
<i>P</i> value	Irrigation method	21–28	2.77 d	5.37 a	53.0 a	511 a	32 d
		Interaction	NS	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001
		Medium layer	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001
<i>P</i> value	Medium layer	Interaction	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001
		Interaction	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001
		Interaction	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001

Treatments with different letters were significantly different according to Duncan's multiple comparison test ($P \leq 0.05$).

Fig. 1. Electrical conductivity (EC), pH, and concentration of potassium (K), nitrate (NO_3^-), and calcium (Ca) at experiment termination in four medium layers as affected by flooding depth (cm) and duration (min).

nutrients in the medium, as well as the evapotranspiration rate, are other factors that cause a higher EC in the top layer (Incrocci et al., 2006; Kang and van Iersel, 2001; Reed, 1996; Rouphael and Colla,

2005; Rouphael et al., 2008). In spite of the substantial increase in the EC in the top layers of the medium for all the subirrigated plants observed in our study, it was 50% lower when plants were irrigated to a depth

of 15 cm for 30 min, suggesting that flooding depth and duration are critical issues to avoid excessive salinization of the medium. This lower media EC when plants were irrigated to a depth of 15 cm for 30 min may be due to a more even distribution of nutrient solution throughout the media, which in turn may enhance root growth in the top layers.

Potassium in the growing medium tended to increase in the top layers of the root ball profile regardless of the irrigation system (Table 3; Fig. 1B); however, the increase was greatest in the 21–28 cm layer of subirrigated plants. Medium NO_3^- concentration (Fig. 1C) and pH (Fig. 1D) exhibited a contrasting response as both tended to decrease in the top layers, regardless of the irrigation method. Calcium concentration was very consistent throughout the growing medium layers in subirrigated plants as it ranged from 20 to 60 ppm (Fig. 1E); however, it increased in the upper layers, from the 7–14 to the 21–28 cm layer, in drip-fertigated plants. Zheng et al. (2004) suggested that the higher EC in the top third of the medium of subirrigated plants was associated with a higher concentration of NO_3^- , HPO_4^{2-} , H_2PO_4^- , K, Mg, and Ca. However, in our study, the higher EC observed in the 21–28 cm layers was associated with an accumulation of K, which was 40% to 71% higher in the medium of subirrigated plants compared with that of the top layer of drip-fertigated plants. Blessington-Haley and Reed (2004) reported similar results as EC and K concentration in the medium exhibited the same tendency. The increase in Ca concentration in the top layers of the growing medium observed in drip-fertigated plants, which is in contrast to the negligible effect observed in subirrigated plants, may be due to a lower uptake rate of this nutrient as roots usually exhibit poor growth in the top layers of subirrigated plants (Kent and Reed, 1996).

Nitrate tended to accumulate in the bottom layers of the medium, regardless of the irrigation method. This is in contrast to reports by Zheng et al. (2004) and by Kent and Reed (1996), which indicate that the concentration of NO_3^- is reflective of

the higher EC in the medium profile. The contrasting results may be due to the different physical properties of the medium used between the respective studies and to the leaching fraction used for the drip-fertigated plants.

The higher yield of subirrigated plants flooded to a depth of 15 cm for 30 min was associated with a decrease in total plant Ca concentration, which occurred primarily in the shoot and roots, but not in the fruit (Table 4). This may be due to a dilution effect associated with the higher biomass produced by these plants, as suggested by the higher total content of Ca in subirrigated plants when compared with drip-fertigated plants. Phosphorus concentration was affected in the root and in the whole plant with no clear trend as to the effect of irrigation method or flooding depth or duration (Table 4).

Total plant N, P, Mg, and S contents were higher in subirrigated plants when flooded to 15-cm depth for 20 to 30 min (Table 4; Fig. 2). Potassium and Ca content were also higher when plants were flooded to 15-cm depth for 30 min (Fig. 2). However, Ca and K contents were lower in subirrigated plants flooded to 10-cm depth for 20 to 30 min (Fig. 2). In addition, this lower solution depth (10 cm) was also associated with a shift in nutrient allocation as Ca tended to accumulate in the roots, whereas K accumulated in the shoots. In general, flooding of plants in solutions of 15-cm depth for 30 min had limited effect on

nutrient allocation when compared with the drip-fertigated plants.

Subirrigated plants, regardless of flooding depth and duration, showed higher K concentration in the fruit tissues than drip-fertigated plants, which may be due to the higher K accumulated in the growing medium (Table 4). However, shoot Mg and S concentration in subirrigated plants increased due to a higher allocation to the shoots when flooded to 15-cm depth for 30 min (Table 4).

The present study showed that the higher NUE attributed to subirrigation systems in similar studies (Ahmed et al., 2000; Putra and Yuliando, 2015; Rouphael and Colla, 2005; Rouphael et al., 2004; Siddiqi et al., 1998; van Os, 1999) might not be only due to their “even/balanced” accumulation in the growing medium by capillary action, but also to a higher uptake by plants. This is demonstrated by the increased total content of all the macronutrients observed in subirrigated plants with flooding depths of 15 cm for 30 min when compared with drip-fertigated plants. These results are in contrast to reports by Rouphael and Colla (2005) in that subirrigated zucchini plants (*Cucurbita pepo* L.) had decreased total N, P, K, Ca, and Mg content. In our study, the higher accumulation of macronutrients was associated with flooding duration as this trend was also observed for the total content of N, P, Mg, and S in plants flooded to a 20-cm depth, suggesting that plants flooded with

10 cm were not able to take advantage of the higher availability of nutrients in the medium.

The lower total content of macronutrients in plants flooded to depths of 10 cm may be due to the higher EC (7.0 to 7.6 dS·m⁻¹) observed in the 21–28 cm medium layer when compared with the EC (5 to 5.7 dS·m⁻¹) of plants flooded to depths of 15 cm. Subirrigation also affected the allocation of nutrients as, from the total content, higher K and P were diverted to the shoot and fruits; Mg and S allocation to the shoot in plants flooded to 15-cm depth for 30 min was at the expense of the roots.

In conclusion, subirrigation is an effective and feasible irrigation system for the production of bell pepper plants if flooding depth and duration are controlled. Fruit yield may be as high as that of drip-fertigated plants when the nutrient solution depth is 15 cm and it is maintained for 30 min. This response was associated with a higher nutrient accumulation, lower EC of the top layers of the growing medium, unaffected N and P plant tissue concentration, and increased Mg and S plant tissue concentration. Nonetheless, more research is required as to the effect of flooding depth and duration since the results observed were obtained in very specific growing conditions, and the physical properties of the growing medium used in the study directly impact capillary movement of water and water retention.

Table 4. Effect of flooding depth and flooding duration on nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) concentration in plant parts of subirrigated and drip-fertigated greenhouse bell pepper in containers at experiment termination.

Irrigation method	Flooding		N	P	K	Ca	Mg	S
	Depth (cm)	Duration (min)	(mmol·kg ⁻¹)					
			Fruit					
Subirrigation	10	20	2,117	101	109 ab	31.0 ab	76.9 a	54.0
		30	2,050	101	125 ab	28.0 b	72.7 ab	54.2
	15	20	2,000	101	134 a	31.5 a	69.0 b	53.6
		30	2,033	106	112 ab	29.6 ab	72.8 ab	56.4
		<i>P</i> value	2,000	101	89 b	30.2 ab	69.5 b	53.8
Drip fertigation	10	20	NS	NS	≤0.050	≤0.030	≤0.001	NS
		30						
	15	20	2,300	71.7 c	93.2 b	280 b	137	107 b
		30	2,533	103.6 a	108.1 b	320 a	126	116 a
		20	2,283	105.1 a	117.2 b	163 c	128	102 b
Subirrigation	10	20	2,483	94.0 b	116.0 b	188 c	121	104 b
		30	2,400	96.4 b	232.7 a	252 b	131	103 b
	15	20	NS	≤0.001	≤0.001	≤0.001	NS	≤0.001
		30						
		<i>P</i> value						
Drip fertigation	10	20	2,617	77.6	343 a	473 c	387 a	167 ab
		30	2,533	98.8	328 a	548 ab	389 a	179 ab
	15	20	2,567	91.5	144 b	480 c	360 ab	177 ab
		30	2,533	91.3	380 a	508 bc	371 ab	190 a
		<i>P</i> value	2,367	87.6	332 a	600 a	317 b	140 b
Subirrigation	10	20	NS	NS	≤0.001	≤0.001	≤0.010	≤0.030
		30						
	15	20	2,414	80.9 b	218 a	320 c	246 ab	125 ab
		30	2,445	100.2 a	242 a	401 a	273 a	142 a
		20	2,399	96.7 a	135 b	323 bc	250 ab	137 ab
Drip fertigation	10	20	2,428	94.6 a	271 a	347 b	260 a	146 a
		30	2,310	92.0 ab	265 a	415 a	228 b	116 b
	15	20	NS	≤0.003	≤0.001	≤0.001	≤0.004	≤0.006
		30						
		<i>P</i> value						

Treatments with different letters were significantly different according to Duncan's multiple comparison test ($P \leq 0.05$).

Fig. 2. Total tissue content (mg/plant) of nitrogen (N), calcium (Ca), phosphorus (P), magnesium (Mg), potassium (K), and sulfur (S) (figures at the top of each column) and allocation in organs of bell pepper plants as affected by flooding depth (cm) and duration (min). Means followed by different letters are significantly different according to Duncan's multiple comparison test ($P \leq 0.05$). DF = drip fertigation.

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