Irrig Sci (2010) 28:513–523
DOI 10.1007/s00271-010-0211-y

ORIGINAL PAPER

Yield and quality of two tomato (*Solanum lycopersicum* L.) cultivars as influenced by drip and furrow irrigation using waters having high residual sodium carbonate

O. P. Choudhary · B. S. Ghuman · M. S. Dhaliwal · Neena Chawla

Received: 2 September 2009 / Accepted: 9 February 2010 / Published online: 27 February 2010
© Springer-Verlag 2010

Abstract Performance of tomato when irrigated with sodic waters particularly under drip irrigation is not well known. A field experiment was conducted for 3 years to study the response of tomato crop to sodic water irrigation on a sandy loam soil. Irrigation waters having 0, 5 and 10 $mmol_c\ L^{-1}$ residual sodium carbonate (RSC) were applied through drip and furrow irrigation to two tomato cultivars, *Edkawi* (a salt tolerant cultivar) and *Punjab Chhuhara* (*PC*). High RSC of irrigation water significantly increased soil pH, ECe and exchangeable sodium percentage progressively; the increases were higher in furrow compared to drip irrigation. Effect of high RSC on increasing bulk density and decreasing infiltration rate of soil was also pronounced in furrow-irrigated plots. Higher soil moisture and lower salinity near the plant was maintained under drip irrigation than under furrow irrigation. Performance of the two cultivars was significantly different; pooled over 2002–03 and 2003–04 seasons, *PC* yielded 38.8 and 30.0 Mg ha^{-1} and *Edkawi* yielded 31.8 and 22.9 Mg ha^{-1} under drip and furrow irrigation, respectively. At RSC10, cultivar *PC* produced 38 and 46% higher fruit yield than cultivar *Edkawi* under drip and furrow irrigation, respectively. Reduction in fruit yield at higher RSC was due to lower fruit weight under drip irrigation and due to reduced fruit number as well as fruit weight under furrow irrigation. Decrease in fruit weight was more pronounced in cultivar *Edkawi* than in cultivar *PC*. Increase in RSC lowered quality of the fruits except the ascorbic acid content. High RSC under drip irrigation, in general, had lesser deteriorating effect on the fruit quality particularly for cultivar *PC* than under furrow irrigation. For obtaining high tomato yield and better-quality fruits using high RSC sodic waters, drip irrigation should be preferred over furrow irrigation. Better performance of local cultivar *PC* compared to *Edkawi* at medium and high RSC suggests that cultivars categorized as tolerant to salinity should be evaluated in the sodic environment particularly when irrigated with high RSC sodic waters.

Communicated by J. Ayars.

O. P. Choudhary (✉) · B. S. Ghuman
Soil Salinity Laboratory, Department of Soils,
Punjab Agricultural University, Ludhiana 141004, India
e-mail: opc_2k@yahoo.com

M. S. Dhaliwal · N. Chawla
Department of Vegetable Crops,
Punjab Agricultural University,
Ludhiana 141004, India

Present Address:
M. S. Dhaliwal
AVRDC- The World Vegetable Center, Regional Breeding Unit,
PO Box 2008, Messa, Yaounde, Cameroon

Introduction

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop that requires sufficient irrigation for optimum production. Due to insufficient surface water supplies, supplemental irrigation with ground water is required in northwestern India where majority of ground waters (41–84%) contain high residual alkalinity with variable levels of salinity (Minhas and Gupta 1992; Minhas and Bajwa 2001). Tomato is moderately sensitive to soil salinity (Maas 1986). It can tolerate an ECe (EC of the saturation extract) of about 2.5 dS m^{-1} but its response to irrigation with waters having high residual sodium carbonate (RSC) is not well documented. Irrigation with high RSC sodic water would result in deterioration of soil properties

(Minhas and Gupta 1992; Choudhary et al. 2001, 2004), impact nutrient relations (Grattan and Grieve 1999) and thus may adversely affect yield and quality of crops.

Drip irrigation is typically more efficient than flood and furrow irrigation methods. Irrigation with drippers can maintain constantly higher matric potential in the rhizosphere by modifying salt distribution pattern (Meiri and Plaut 1985; Malash et al. 2008), controlling salinity and increasing yields (Michelakis et al. 1993; Hanson and May 2004). Wang et al. (2007) observed that saline water with EC ranging from 2.2 to 4.9 dS m^{-1} can be applied to irrigate tomato through drip irrigation without any yield loss. Others have reported that reduction in fruit yields due to salinity was compensated with enhanced quality of tomato fruits (De Pascale et al. 2001; Maggio et al. 2004; Mori et al. 2008). High proportion of Na than Ca present in saline water was observed to be detrimental to tomato yield and quality (Campos et al. 2006). Response of tomato to irrigation with sodic water rich in bicarbonates may be similar or different compared to irrigation with saline water rich in chlorides and sulfates. This information on fruit yield and quality of tomato irrigated with water high in bicarbonates is not adequately available. The objective of the work reported here is to compare drip irrigation with furrow irrigation using high RSC sodic waters to evaluate the performance of two tomato cultivars.

Materials and methods

Experimental site

A field experiment was conducted from 2001–02 to 2003–04 at the experimental farm of the Department of Soils, Punjab Agricultural University (PAU), Ludhiana (30° 56′N latitude, 75° 52′E longitude, 247 m above msl), India. The soil was classified as sandy loam, hypothermic, Typic *Ustochrept* having an initial ECe 0.40 dS m^{-1}; pH (1:2 soil water by weight) 8.02; organic carbon 2.8 g kg^{-1} soil; calcium carbonate <1%; clay content 185 g kg^{-1} soil; CEC 9.7 cmol (+) kg^{-1} soil and exchangeable sodium percentage (ESP) 4.8–5.2 in the 0–0.30 m soil layer. The field was well drained having water table deeper than 10 m during the study period.

Experimental design and treatments

Field plots measuring 2×2 m^2 were lined all around with polythene sheets down to 1 m depth to minimize lateral movement of water between plots. *Edkawi*, an established salt-tolerant cultivar (Chetelat and Rick 2000), and *Punjab Chhuhara* (*PC*), a popular local cultivar of tomato, were transplanted in mid-November with seedlings of 0.15–0.20 m height on 0.75 m beds and 0.25 m wide furrows. Spacing between plants in a row was 0.30 m. Both the cultivars have determinate growth habit, *PC* has thick foliage, while *Edkawi* has moderate foliage cover. Before transplanting seedlings, 25 Mg ha^{-1} of farmyard manure (FYM) was applied on fresh weight basis (40–50% moisture). During 3 years of study, total nitrogen, phosphorus and potassium contents of FYM ranged between 1–1.2, 0.5–0.7 and 1–1.4%, respectively. Salt contribution of applied FYM toward soil salinity was, however, negligible. Fertilizers were applied at rates of 55 kg N, 25 kg P and 25 kg K ha^{-1} as recommended for cultivation of tomatoes in the region (Anonymous 2001). Nitrogen fertilizer was applied in two splits; the first split of 20 kg N ha^{-1} was applied along with P and K in November before transplanting, and the second split of 35 kg N ha^{-1} was applied in mid-February. Irrigation water treatments consisted of three sodic waters having RSC of 0, 5 and 10 $mmol_c$ L^{-1} (Table 1). Corresponding EC values of these waters were 0.5, 2.0 and 3.5 dS m^{-1}. Irrigation water having RSC of 10 $mmol_c$ L^{-1} was synthesized by dissolving 0.84 g $NaHCO_3$ per litre in good-quality canal water (EC < 0.5 dS m^{-1}, RSC—nil, SAR—1.2). The targeted EC_{iw} was obtained by dissolving appropriate quantities of NaCl in water e.g. 0.5 g NaCl in one litre of water to make EC of 1 dS m^{-1}. Irrigation treatments were imposed from the beginning of the experiment. Irrigation applied by drip and furrow methods was based on irrigation water/pan-evaporation (IW/PAN-E) ratio of 1.0. Each treatment was replicated three times. In order to study the cumulative effect of sodicity of irrigation water, the experimental plots were kept unchanged during the 3 years. The plots were kept fallow during June–October each year coinciding with the monsoon season.

Each irrigation event consisted of 50 mm water that was applied in furrows when cumulative pan-evaporation (CPE) equaled 50 mm. The irrigation water was delivered to each

Table 1 Composition of irrigation waters

Characteristics	RSC0	RSC5	RSC10
pH	7.80	8.23	8.35
EC	0.48	1.96	3.54
Soluble ions ($mmol_c$ L^{-1})			
$Ca^{2+} + Mg^{2+}$	3.0	3.8	4.2
Na^+	1.5	10.7	21.8
$CO_3^{2-} + HCO_3^-$	2.2	8.7	14.3
Cl^-	2.8	6.8	11.6
RSC[a]	−0.8	4.9	10.1
SAR[b]	1.2	7.8	15.0

[a] RSC = $(CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$ (all cations and anions in $mmol_c$ L^{-1})

[b] SAR = $Na^+/\sqrt{(Ca^{2+} + Mg^{2+})/2}$ (all cations in $mmol_c$ L^{-1})

furrow through a 5-cm-diameter hosepipe about once in 1–3 weeks. Drip irrigation was applied when CPE equaled 10 mm 2–3 times weekly for the length of time required to deliver the calculated quantity of water. In-line drippers spaced at 0.30 m apart supplied water @ 4 L h^{-1} directly placed in plant row under an operational pressure of 0.2 MPa. The total quantity of irrigation water applied at different RSC and for drip and furrow irrigation was kept same. It was 750, 500 and 600 mm in 2001–02, 2002–03 and 2003–04, respectively. An adjustment was made in the amount of irrigation water applied to account for rain. Monthly rainfall received during the 3 years is recorded in Table 2.

Measurements

Gravimetric soil water content and EC (1:2, soil water) was measured at 48 h following an irrigation event at three locations; 0.025, 0.185 and 0.375 m on both sides across the plant row in different treatments. It was averaged over five such events coinciding with irrigation to drip- and furrow-irrigated plots simultaneously in the year 2003–04. At each site, soil samples were collected for moisture determination with an auger from 0 to 0.60 m depth at an interval of 0.15 m. Each year after the crop was harvested, soil samples were taken from 0 to 0.30 m under the plant row to measure physical and chemical properties of soil. The pH and EC (1:2 soil water by weight), ECe, exchangeable sodium percentage (ESP) and CEC of the soil were measured using standard methods (Richards 1954). Bulk density of the soil was measured by core method (Blake and Hartage 1986). Infiltration rate was measured in situ using double ring infiltrometer (Bouwer 1986) in the plant row in 2003–04.

Table 2 Rainfall received during growing and fallow period in different years

Month	2001–2002	2002–2003	2003–2004
Rainfall (mm) during tomato crop			
November	0	0	4.4
December	0	6.9	8.4
January	0	38.1	62.8
February	14	134.8	0
March	9.4	21.3	0
April	15.4	5.8	9
Total	38.8	206.9	84.6
Rainfall (mm) during fallow period			
May	61.8	12.7	72.6
June	36.7	49.6	55.4
July	36.8	179.6	30.9
August	23	297.7	226.6
September	193	52.8	2.6
October	0	0	33
Total	351.3	592.4	421.1
Grand total	390.1	799.3	505.7

Tomato fruits were harvested at weekly intervals in the month of April. Total soluble solids (TSS) were measured on tomato juice samples with a refractometer and expressed as °Brix. Other quality parameters viz. lycopene, carotenoids, ascorbic acid (vitamin C) concentrations and acidity were determined by methods described by Ranganna (1994), Stevens et al. (1979) and Umiel and Gabelman (1971). The data for individual fruit weight, average number of fruits and quality parameters were recorded for 2 years, 2002–03 and 2003–04. Individual fruit weight was determined by taking average of five representative fruits each from second and third pickings, whereas actual fruits from these two pickings were counted to determine average fruit number for each treatment. Five ripened fruits from second picking were used for quality analysis. TSS was determined by extracting fruit juice from the blossom end.

The field experiment was carried out in a randomized block factorial design (Gomez and Gomez 1990). The data were statistically analyzed through analysis of variance (ANOVA) using software 'CPCS 1' (Cheema and Singh 1990).

Results and discussion

Effect on soil properties

Chemical properties

Soil pH, ECe and exchangeable sodium percentage (ESP) of the top 0.30 m soil layer increased significantly with increasing RSC during the 3 years (Table 3). For all the 3 years, the values of these properties remained lower under drip irrigation than under furrow irrigation. Maximum values for pH, ECe and ESP were recorded after the third year (2003–04) due to progressive salt and Na buildup in RSC5 and RSC10 treatments. Compared to drip irrigation, soil pH was higher in furrow-irrigated plots by 0.11 and 0.20 units in RSC5 and RSC10 treatments, respectively. Corresponding increase in ESP under furrow irrigation was 4.8 and 9.4. An increase in pH and ESP of soil irrigated with higher RSC water was caused by the formation of sodium carbonate that led to excessive adsorption of Na^{+} on colloidal complex replacing Ca^{++} and Mg^{++} ions (Minhas and Bajwa 2001; Choudhary et al. 2004).

Higher ECe was observed in RSC10 treatment under furrow irrigation (3.29 in 2002–03 and 4.43 dS m^{-1} in 2003–04) than under drip irrigation (2.31 and 2.77 dS m^{-1}). High ECe values indicate little leaching of the salts from ridges because irrigation was applied in furrows (Rajak et al.

2006). In furrow-irrigated plots, higher ECe values than the threshold limit of 2.5 dS m^{-1} for tomatoes (Maas 1986) might have also adversely affected fruit yield in addition to increased sodicity.

Salt and water distribution

Soil water distribution in the rhizosphere 48 h after an irrigation event is shown in Table 4. Water content was higher near the plant base (0.025 m) under drip than under furrow. Soil moisture decreased from 16.0 to 13.7% with increase in soil depth from 0 to 0.60 m under the plant row in drip irrigation. Under furrow irrigation, the soil water content increased from 12.8 to 14.6% with depth. It is interesting to note that lateral movement of moisture in a given soil layer was more under furrow irrigation compared to that under drip irrigation. Soil moisture content increased from 12.8 to about 15% as distance from plant increased horizontally in the 0–0.15 m layer under furrow irrigation. But under drip irrigation, soil moisture decreased from 16.0 to about 13% with distance in the same layer. Similar trend of moisture distribution was observed in deeper soil layers. Less horizontal and downward movement of applied water ensured more moisture under the dripper available for uptake by plant than under furrow irrigation. This typical moisture distribution happened due to the fact that water was localized directly under the drippers. Water moved under unsaturated flow away from the dripper with soil water content decreasing with distance. Under furrow irrigation, most of the soil in furrow was saturated, and the ridge soil was moistened with unsaturated flow from furrow resulting in low moisture content near the plant. These findings are similar to those of Kahlon et al. (2004) who found higher moisture content near the plant row under drip compared to furrow irrigation.

Salt distribution measured in terms of EC (1:2 soil water by weight) 48 h after an irrigation event was 0.62 dS m^{-1} near the emitter (at 0.025 m) and it increased to 0.88 dS m^{-1} at 0.185 m from the emitter in the 0–0.15 m soil layer (Table 4). However, under furrow irrigation, maximum salt concentration (1.20 dS m^{-1}) was observed at the base of the plant (0.025 m) and minimum (0.93 dS m^{-1}) at 0.185 m away from the plant. In sub-soil layers also, drip irrigation maintained lower values of EC near the emitter compared to furrow irrigation. Higher soil moisture near the emitter under drip irrigation can help in keeping the salts and Na concentration lower in the vicinity of the plant roots (Kumar and Sivanappan 1980). Thus, drip irrigation can support optimum plant growth.

Physical properties

Steady state infiltration rate (IR) decreased with increase in RSC. In the year 2003–04, steady state IR under good-quality water irrigation (RSC0) was similar (3.5 cm h^{-1}) in the two irrigation systems. When irrigated with RSC10 water, it decreased to 2.6 cm h^{-1} under drip irrigation and to 1.4 cm h^{-1} under furrow irrigation (Fig. 1). The bulk density of the soil increased with increase in RSC of irrigation water; the increase was higher for furrow irrigation than for drip irrigation (Fig. 1).

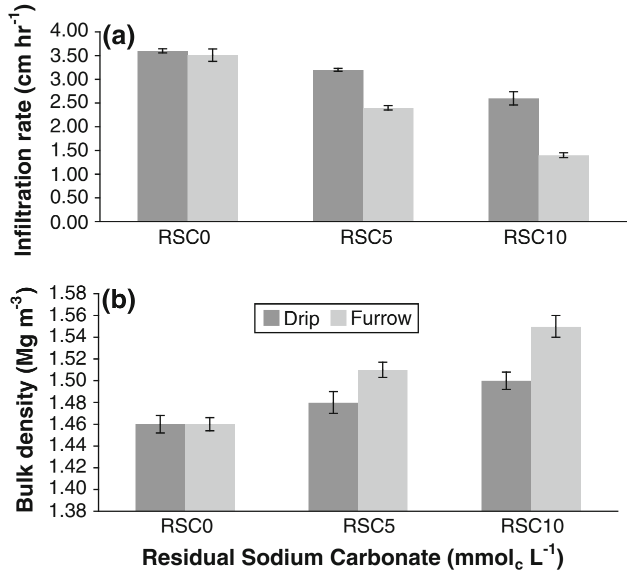

Fig. 1 Effect of RSC of irrigation water and irrigation methods on **a** infiltration rate and **b** bulk density in 2003–04

Greater decline in steady state IR and increase in bulk density under furrow irrigation may be attributed to the compaction of soil due to flooding of water and crust formation particularly in plots irrigated with high RSC waters (Malik et al. 1994). Josan et al. (1998) and Grattan and Oster (2003) also observed that increase in RSC of irrigation water promoted dispersion of clays, reduction in pore size and blocking of pores.

Effect on yield and quality

Fruit yield

Irrigation methods and RSC of irrigation water affected the fruit yield of both the cultivars; significant effects were observed during 2nd and 3rd year of the study, although trends were visible in the 1st year. In 2002–03 and 2003–04 seasons, mean fruit yields for drip-irrigated tomatoes were 40.6 and 29.7 Mg ha^{-1} compared to 34.6 and 18.3 Mg ha^{-1} for furrow-irrigated ones (Fig. 2). Increase in RSC significantly decreased fruit yield. In 2002–03, compared to the RSC0 treatment, yields were reduced to 90 and 75% under RSC5 and RSC10 treatments, respectively. Corresponding values for 2003–04 were 84 and 79%, respectively.

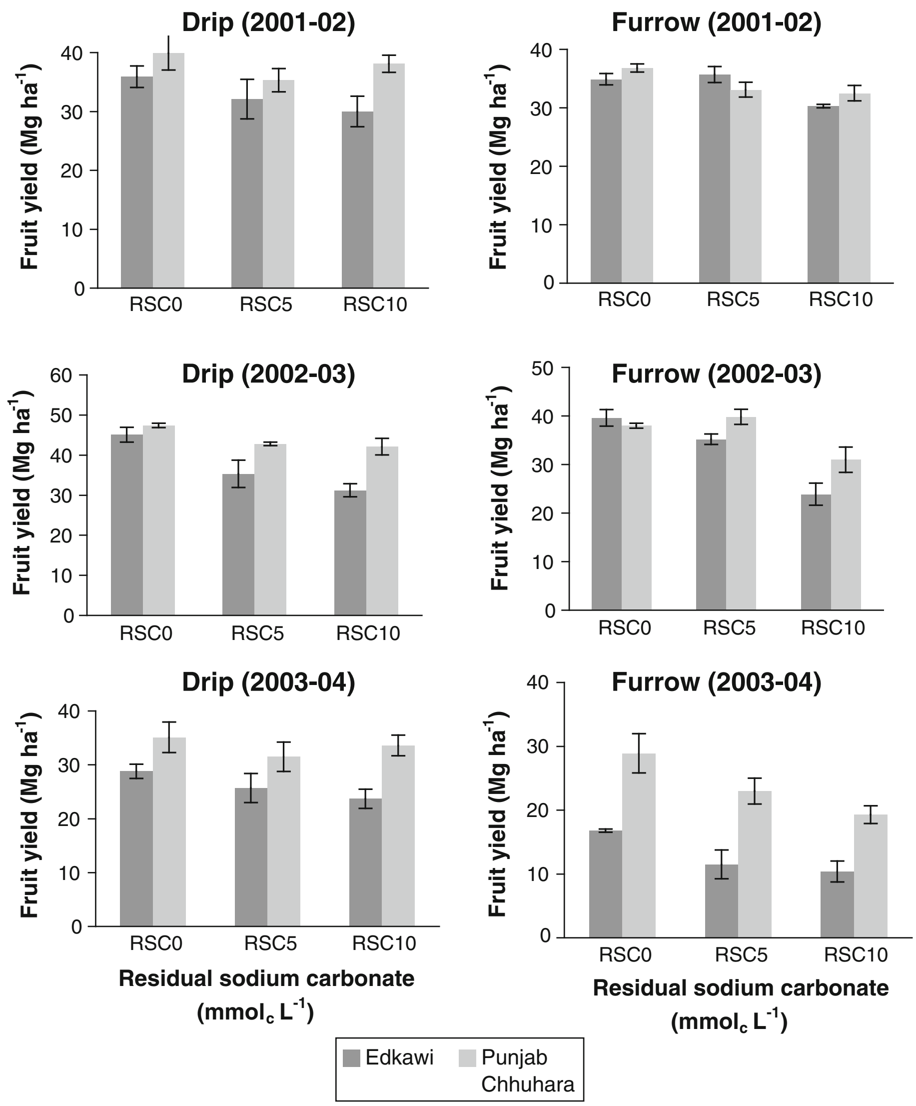

Fig. 2 Tomato fruit yields (Mg ha^{-1}) as influenced by RSC of irrigation water under drip and furrow irrigation

Decrease in tomato yield resulting from irrigation with high RSC waters may be attributed to higher pH and ESP and associated poor aeration and permeability problems in the soil. Several workers (Minhas and Gupta 1992; Bajwa et al. 1998; Choudhary et al. 2006) found similar effect of high RSC on crop yields. Deteriorating effect of high pH on other soil properties as well as nutritional imbalances such as Ca deficit in the soil solution (Pearson 1960; Minhas and Gupta 1992) should also have resulted in yield decline (Bajwa et al. 1992; Choudhary et al. 1996, 2001). Higher fruit yields using higher RSC waters in drip-irrigated plots can be attributed to relatively higher soil moisture and lower values for soil pH, ECe and ESP of the soil compared to in the furrow-irrigated ones (Tables 3, 4). Hanson and May (2004) observed that drip irrigation provides better environment for plant growth by favorably modifying the salt and water distribution in the rhizosphere. When both drip and furrow systems were compared under saline water irrigation, tomato crop under drip outperformed the one irrigated in furrows (Maggio et al. 2004; Malash et al. 2008).

Irrespective of RSC and irrigation method, cultivar *PC* outyielded salt-tolerant cultivar *Edkawi* by 15 and 47% in 2nd and 3rd year, respectively. Pooled over 2002–03 and 2003–04 seasons, relative fruit yields (compared to RSC0) for RSC5 and RSC10 treatments were 92 and 84% for cultivar *PC* and 83 and 68% for cultivar *Edkawi,* respectively. Both cultivars produced higher fruit yields (24–30%) under drip compared to furrow irrigation in non-sodic soil conditions (ESP 5). The difference between the two irrigation methods widened (50–68%) at higher levels of ESP (Fig. 3), because under furrow irrigation, magnitude of reduction in yield increased with increase in ESP of the 0.30 m soil layer. In contrast, in drip-irrigated plots, fruit yield decreased linearly at 0.2 Mg ha^{-1} for cultivar *PC* and at 0.5 Mg ha^{-1} for cultivar *Edkawi* per unit increase

Table 3 Effect of irrigation methods (IM) and water quality (RSC) on pH, ECe and ESP of the upper 0.3 m soil layer (in the plant row) for 3 years

Soil property	Irrigation method	RSC0	RSC5	RSC10	Mean
2001–02					
pH (1:2 soil water)	Drip	8.00	8.35	8.61	8.32
	Furrow	8.05	8.54	8.86	8.48
	Mean	8.03	8.45	8.74	8.40
	LSD (0.05): IM = 0.05; RSC = 0.06; Interaction = 0.09				
ECe (dS m^{-1})	Drip	0.42	1.34	2.17	1.31
	Furrow	0.43	2.04	2.76	1.74
	Mean	0.43	1.69	2.47	1.53
	LSD (0.05): IM = 0.11; RSC = 0.14; Interaction = 0.20				
ESP	Drip	5.17	10.7	16.6	10.8
	Furrow	5.30	14.5	22.5	14.1
	Mean	5.24	12.6	19.6	12.5
	LSD (0.05): IM = 0.70; RSC = 0.85; Interaction = 1.20				
2002–03					
pH (1:2 soil water)	Drip	8.03	8.43	8.73	8.40
	Furrow	8.04	8.65	8.96	8.55
	Mean	8.04	8.54	8.85	8.48
	LSD (0.05): IM = 0.07; RSC = 0.08; Interaction = 0.12				
ECe (dS m^{-1})	Drip	0.51	1.51	2.31	1.44
	Furrow	0.53	2.43	3.29	2.08
	Mean	0.52	1.97	2.80	1.76
	LSD (0.05): IM = 0.13; WQ = 0.1.5; Interaction = 0.22				
ESP	Drip	5.28	14.4	22.0	13.9
	Furrow	5.35	18.9	29.0	17.8
	Mean	5.32	16.7	25.5	15.9
	LSD (0.05): IM = 1.0; RSC = 1.22; Interaction = 1.70				
2003–04					
pH (1:2 soil water)	Drip	8.06	8.65	8.95	8.55
	Furrow	8.08	8.76	9.33	8.72
	Mean	8.07	8.71	9.14	8.64
	LSD (0.05): IM = 0.09; RSC = 0.12; Interaction = 0.17				
ECe (dS m^{-1})	Drip	0.54	1.81	2.77	1.71
	Furrow	0.58	2.76	4.43	2.59
	Mean	0.56	2.29	3.60	2.15
	LSD (0.05): IM = 0.10; RSC = 0..12; Interaction = 0.17				
ESP	Drip	5.57	20.1	26.2	17.3
	Furrow	5.80	24.9	35.6	22.1
	Mean	5.69	22.5	30.9	19.7
	LSD (0.05): IM = 1.07; RSC = 1.31; Interaction = 1.86				

in ESP (Fig. 3). Similarly decline in fruit yields was also related to soil pH and ECe; the extent of decrease was pronounced in furrow-irrigated plots (Fig. 3). These results suggest that when using high RSC waters, drip irrigation should be preferred over furrow irrigation. Though categorized as salt-tolerant cultivar (Chetelat and Rick 2000), the cultivar *Edkawi* rather than *PC* was adversely affected to a greater extent by high RSC–induced sodic environment.

Individual fruit weight and fruit number

The fruits of *Edkawi* were about three times heavier (98–101 g) than that of *PC* (29–31 g) in both the irrigation methods (Table 5). Larger fruit size of cultivar *Edkawi* is its genetic character. Individual fruit weight decreased with increase in RSC, the extent of decrease was more in cultivar *Edkawi*. Decrease in individual fruit weight of cultivar *PC* upon irrigation with RSC10 relative to RSC0 in

Table 4 Soil moisture content and salt distribution (EC) across the plant row with drip and furrow irrigation method 48 h after irrigation for RSC10 treatments in third year (2003–04)

Soil depth (m)	Distance from plant row on ridge (m)				
	Left side		← →	Right side	
	0.375	0.185	0.025 (Plant row)	0.185	0.375
Soil moisture (%)					
Drip irrigation					
0–0.15	12.8	14.1	16.0	14.0	12.5
0.15–0.30	12.0	13.5	15.4	13.2	11.6
0.30–0.45	10.2	12.7	14.6	12.4	10.8
0.45–0.60	9.8	11.3	13.7	11.7	9.6
Furrow irrigation					
0–0.15	14.9	14.2	12.8	14.7	15.1
0.15–0.30	15.5	15.0	13.4	15.3	15.8
0.30–0.45	16.2	16.0	13.9	16.2	16.4
0.45–0.60	17.1	16.6	14.6	16.8	17.3
EC (dS m^{-1})					
Drip irrigation					
0–0.15	0.72	0.88	0.62	0.86	0.74
0.15–0.30	0.67	0.81	0.58	0.80	0.68
0.30–0.45	0.61	0.72	0.52	0.70	0.61
0.45–0.60	0.52	0.60	0.48	0.58	0.52
Furrow irrigation					
0–0.15	1.16	0.93	1.20	0.95	1.18
0.15–0.30	1.02	0.86	0.90	0.82	1.04
0.30–0.45	0.86	0.70	0.78	0.73	0.92
0.45–0.60	0.68	0.62	0.73	0.66	0.78

drip-irrigated plots was 10% compared to 25% observed in *Edkawi*. In furrow-irrigated plots, reduction in fruit weight with increase in RSC to 10 $mmol_c\ L^{-1}$ was similar (13–15%) for both the cultivars.

Pooled over 2002–03 and 2003–04, reductions in fruit yield at RSC10 treatment compared to RSC0 for cultivars *Edkawi* and *PC* were 26 and 8% in drip and 39 and 25% in furrow-irrigated plots, respectively. It suggests that under drip irrigation, decrease in tomato yield with increase in RSC of irrigation water for both cultivars corresponds to the decrease in fruit weight. On the other hand, under furrow irrigation, lower reduction in fruit weight observed at high RSC compared to the corresponding decrease in fruit yields suggests that fruit number, the second most important component of fruit yield, was also reduced at RSC10 treatment. For cultivar *Edkawi*, the reduction in fruit number (33%) was more pronounced than the reduction in fruit weight (13%). In case of cultivar *PC*, 10% reduction in fruit number was lower than 15% observed in fruit weight under furrow irrigation (Table 5). Ritchie (1991) argued that differentiating (quantitative increase in size due to cell expansion) growth is more sensitive than development (fruit setting, number of organs) to abiotic stresses other than light and temperature. In the present study, moderate salinity (ECe 3.86 dS m^{-1}) coupled with high sodicity (pH 9.15, ESP 32) in the soil at RSC10 treatment in furrow-irrigated plots pooled over 2002–03 and 2003–04 seasons affected development as well as differentiation in growth, whereas in drip-irrigated plots (ECe 2.54 dS m^{-1}, pH 8.84, ESP 24), mainly differentiation in growth of tomato fruits was affected. Several studies have reported that increase in salinity decreased fruit size due to reduced water uptake (Cuartero and Munoz 1999; Campos et al. 2006) but not the fruit number in tomatoes up to ECiw of 5 dS m^{-1} (Campos et al. 2006). Cruz et al. (1990) reported that at high salinity, fruit set could be decreased resulting in reduced fruit number.

Fruit quality

Tomato fruit quality was assessed based on six parameters; total soluble solids (TSS), lycopene, carotenoids, ascorbic acid, acidity and pH of the juice (Table 6). TSS was significantly reduced at RSC10 treatment compared to good-quality water treatment (RSC0) in both the cultivars; it was not affected at medium RSC (RSC 5). It is contrary to results from several studies using saline water showing decrease in fruit yield and increase in fruit TSS (De Pascale et al. 2001; Campos et al. 2006; Mori et al. 2008). Increase in soluble solids with increasing water salinity was caused by the reduction in import of water by the fruit (Sakamoto et al. 1999) and an accumulation of solutes, mainly ions and organic molecules produced in salt-stressed plants (Munns 2002). Reduction in TSS due to irrigation with high RSC water having higher content of HCO_3^- than Cl^- ions should have inhibited the accumulation of solutes, although this aspect was not investigated in the present study. Campos et al. (2006) reported that TSS values below 4.5 for tomatoes are considered low for industrial purposes. TSS values in the present study were appropriate for processing.

Lycopene content varied between 0.20 and 2.32 mg 100 g^{-1} juice in cultivar *Edkawi* and between 0.54 and 1.46 mg 100 g^{-1} juice in cultivar *PC* (Table 6). With increase in RSC of irrigation water, decrease in lycopene content was observed. Under both the irrigation methods, lycopene content in cultivar *Edkawi* was significantly higher than in *PC* when irrigated with good-quality water (RSC0) or medium RSC (RSC5), but at high RSC (RSC10), lycopene content in cultivar *PC* compared to *Edkawi* was 2.5 times higher in drip-irrigated and 4 times higher in furrow-irrigated plots. A decrease in carotenoids concentration was observed in both cultivars in RSC5 and RSC10 treatments when compared to RSC0 treatment (Table 6). For cultivar *PC*, significantly higher contents of

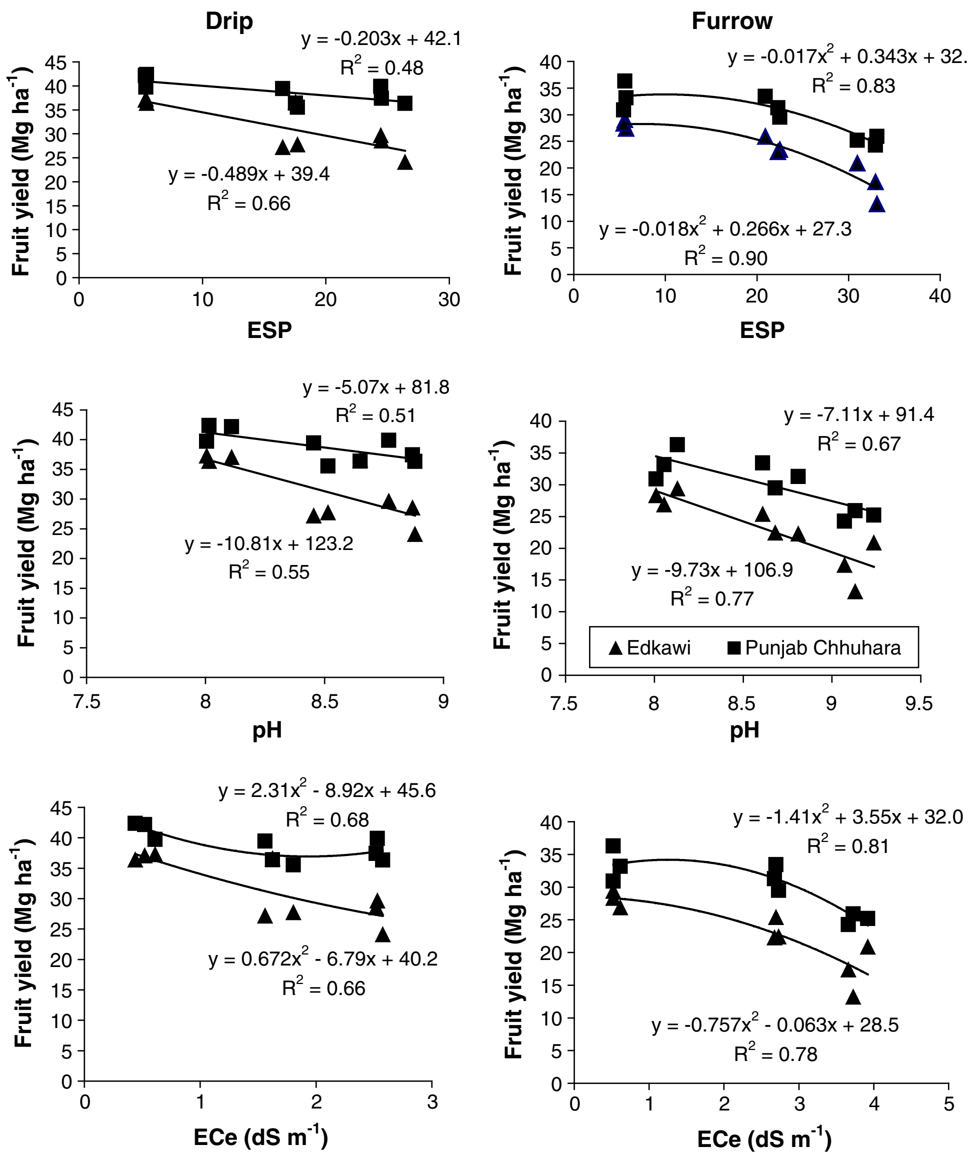

Fig. 3 Tomato fruit yield of two cultivars as influenced by soil ESP, pH and ECe (0–0.3 m) under drip and furrow irrigation pooled over 2002–03 and 2003–04

carotenoids were recorded in drip- than in furrow-irrigated plots at each level of RSC. On the other hand, cultivar *Edkawi* had similar content of carotenoids under both irrigation methods.

Ascorbic acid was not adversely affected by RSC under drip irrigation. Rather, an increase in ascorbic acid in cultivar *Edkawi* was observed with increase in RSC from 0 to 5 $mmol_c\ L^{-1}$. At RSC10, it decreased compared to RSC5 but remained higher than RSC0 treatment. Higher ascorbic acid content was recorded under furrow irrigation than under drip irrigation at RSC0 for both cultivars. However, a progressive decrease in ascorbic acid content was observed in cultivar *PC* with increase in RSC in furrow-irrigated plots; in case of cultivar *Edkawi,* decrease was observed at RSC10. Low titratable acidity was observed in furrow ($0.56\ g\ 100\ g^{-1}$) compared to drip-irrigated plots ($0.77\ g\ 100\ g^{-1}$). Higher pH and alkalinity in furrow-irrigated plots than in drip-irrigated ones might have accounted for overall lower acidity under furrow irrigation. However, with in furrow-irrigated plots, relatively higher values for acidity observed at RSC5 and RSC10 compared to RSC0 treatment could be attributed to increased NaCl stress due to higher ECe values at higher RSC. The increased fruits acidity under salt stress has been reported for tomatoes by Maggio et al. (2004). De Pascale et al. (2001) also reported increase in acidity of tomato fruit with increase in salinity. The values observed in the present study were above $0.35\ g\ 100\ g^{-1}$, the minimum value for processing of tomatoes. Campos et al. (2006) opined that fruit with titratable acidity below

Table 5 Effect of irrigation method (IM) and water quality (RSC) on individual fruit weight and number of fruits of tomato (pooled for 2 years, 2002–03 and 2003–04)

Cultivar	Drip irrigation				Furrow irrigation			
	RSC0	RSC5	RSC10	Mean	RSC0	RSC5	RSC10	Mean
Individual fruit weight (g per fruit)								
Edkawi	114	104	85	101.0	104	100	91	98.3
Punjab Chhuhara	31	29	28	29.3	33	32	28	31.0
Mean	72.5	66.5	56.5	65.2	68.5	66.0	59.5	64.7
LSD (0.05): IM = 1.47; RSC = 1.80; Cult = 1.47; IM × RSC × Cult = 3.63								
Number of fruits (plant^{-1})								
Edkawi	10.8	10.0	9.6	10.1	9.0	7.8	6.1	7.9
Punjab Chhuhara	44.4	43.0	44.5	44.0	33.8	32.7	30.4	32.3
Mean	27.6	26.5	27.1	27.1	21.4	20.3	18.3	20.1
LSD (0.05): IM = 0.76; RSC = 0.93; Cult = 0.76; IM × Cult = 1.07								

Table 6 Effect of irrigation method (IM) and water quality (RSC) on fruit quality of tomato (pooled data for 2 years, 2002–03 and 2003–04)

Quality parameter	Cultivar	Drip irrigation				Furrow irrigation			
		RSC0	RSC5	RSC10	Mean	RSC0	RSC5	RSC10	Mean
TSS (°Brix)	*Edkawi*	5.17	4.90	4.80	4.95	4.90	5.07	4.70	4.89
	PC	5.23	5.07	4.97	5.09	5.03	5.03	4.80	4.95
	Mean	5.20	4.98	4.88	5.02	4.96	5.05	4.75	4.92
	LSD (0.05): IM = NS; RSC = 0.16; Cult = NS								
Lycopene (mg 100 g^{-1})	*Edkawi*	2.19	2.06	0.20	1.48	2.14	2.32	0.20	1.55
	PC	1.46	0.64	0.54	0.88	1.03	0.85	0.83	0.90
	Mean	1.82	1.35	0.37	1.18	1.58	1.58	0.51	1.25
	LSD (0.05): IM = NS; RSC = 0.07; Cult = 0.06; IM × RSC[a] = 0.10; RSC × Cult = 0.10; IM × RSC × Cult = 0.15								
Carotenoids (mg 100 g^{-1})	*Edkawi*	1.37	1.04	1.04	1.15	1.29	1.16	1.16	1.20
	PC	1.86	1.36	1.36	1.53	1.30	0.75	0.75	0.93
	Mean	1.61	1.20	1.20	1.34	1.29	0.95	0.95	1.07
	LSD (0.05): IM = 0.06; RSC = 0.07; Cult = NS; RSC × Cult = 0.10; IM × Cult = 0.09								
Ascorbic acid (mg 100 g^{-1})	*Edkawi*	39.5	48.1	45.3	44.3	46.8	46.3	40.7	44.6
	PC	37.7	35.4	36.3	36.5	53.1	45.0	42.9	47.0
	Mean	38.6	41.7	40.8	40.4	49.9	45.6	41.8	45.8
	LSD (0.05): IM = 0.76; RSC = NS; Cult = 0.76; IM × RSC = 1.32; RSC × Cult = 1.32; IM × Cult = 1.08; IM × RSC × Cult = 1.90								
Acidity (mg 100 g^{-1})	*Edkawi*	0.75	0.77	0.72	0.75	0.40	0.65	0.64	0.56
	PC	0.82	0.82	0.75	0.80	0.46	0.54	0.64	0.55
	Mean	0.79	0.76	0.74	0.77	0.43	0.60	0.64	0.56
	LSD (0.05): IM = 0.03; RSC = 0.04; Cult = NS								
pH	*Edkawi*	4.65	4.67	4.70	4.67	4.37	4.41	4.30	4.36
	PC	4.35	4.32	4.32	4.33	4.41	4.33	4.37	4.37
	Mean	4.50	4.49	4.51	4.50	4.39	4.37	4.33	4.37
	LSD (0.05): IM = 0.05; RSC = NS; Cult = 0.05; IM × Cult = 0.07; IM × RSC × Cult = 0.13								

PC Punjab Chhuhara, *Cult* cultivar

[a] Only significant interactions given

0.35 g 100 g^{-1} requires extra time and higher temperature for processing.

Juice pH varied between 4.24 and 4.70 and was not affected by RSC of irrigation water. Significantly higher juice pH (4.64) was recorded for cultivar *Edkawi* in drip-irrigated plots. The pH below 4.5 is desirable to prevent proliferation of microorganisms in the processed product (Giordano et al. 2000). For cultivar *PC*, juice pH was ideal

(4.33–4.37) for processing under both the irrigation methods.

Conclusions

Irrigation with sodic waters high in bicarbonates can be deleterious to soil physical and chemical properties; effects can be severe in furrow than in drip irrigation. Better soil moisture conditions and lesser deterioration in soil properties when irrigated with medium and high RSC water under drip irrigation can lead to higher tomato yields than under furrow irrigation. Decrease in fruit yield at higher RSC is mainly due to reduction in fruit weight under drip irrigation. Reduction in both fruit weight and fruit number lead to decrease in fruit yield under furrow irrigation. When irrigated with higher RSC waters, cultivar *Punjab Chhuhara* can perform better than salt-tolerant cultivar *Edkawi* under both the irrigation methods. Higher soil and water sodicity in general leads to reduced fruit quality. Nevertheless, better fruit quality can be maintained at higher RSC in drip-irrigated tomatoes. With sodic waters high in bicarbonates, drip irrigation should be preferred over furrow irrigation to obtain higher tomato production with good-quality fruits. Cultivars categorized as tolerant to salinity should be evaluated in the sodic environment because these may not perform as well as these do in a saline environment, particularly when irrigated with high RSC sodic waters.

Acknowledgments The authors are grateful to Dr Bijay Singh, ICAR National Professor, Department of Soils, PAU, Ludhiana, for editing the manuscript.

References

Anonymous (2001) Package of practices for cultivation of vegetables. Punjab Agric University, Ludhiana, p 115

Bajwa MS, Choudhary OP, Josan AS (1992) Effect of continuous irrigation with sodic and saline-sodic waters on soil properties and crop yields under cotton-wheat in north-western India. Agric Water Manag 22:345–356

Bajwa MS, Choudhary OP, Josan AS (1998) Sodic waters and their management. In: Tyagi NK, Minhas PS (eds) Agricultural salinity management in India. ICAR Pub, New Delhi, pp 431–450

Blake GR, Hartage KH (1986) Bulk density. In: Klute A (ed) Methods of soil analysis, part I: physical and mineralogical methods, 2nd edn. ASA-SSSA, Madison, pp 363–375

Bouwer H (1986) Intake rate: cylinder infiltrometer. In: Klute A (ed) Methods of soil analysis, part I: physical and mineralogical methods, 2nd edn. ASA-SSSA, Madison, pp 825–844

Campos CAB, Fernandes PD, Gheyi HR, Blanco FF, Goncalves CB, Campos SAF (2006) Yield and fruit quality of industrial tomato under saline irrigation. Sci Agric (Piracicaba, Brazil) 63:146–152

Cheema HS, Singh B (1990) A programme package for analysis of commonly used experimental designs. Punjab Agricultural University, Ludhiana

Chetelat RT, Rick CM (2000) TGRC stock list. Tomato Genetics Cooperative 50:49–78

Choudhary OP, Josan AS, Bajwa MS (1996) Tolerance of wheat and triticale to sodicity. Crop Improv 23(2):238–246

Choudhary OP, Josan AS, Bajwa MS (2001) Yield and fibre quality of cotton cultivars as affected by sustained sodic irrigations in semi-arid conditions. Agric Water Manag 49:1–9

Choudhary OP, Josan AS, Bajwa MS, Kapur ML (2004) Effect of sustained sodic and saline sodic irrigation and application of gypsum and farmyard manure on yield and quality of sugarcane under semi-arid conditions. Field Crops Res 87:103–116

Choudhary OP, Ghuman BS, Josan AS, Bajwa MS (2006) Effect of alternating irrigation with sodic and non-sodic waters on soil properties and sunflower yield. Agric Water Manag 85:151–156

Cruz V, Cuartero J, BolarõÂn MC, Romero M (1990) Evaluation of characters for ascertaining salt stress responses in Lycopersicon species. J Am Soc Horti Sci 115:1000–1003

Cuartero J, Munoz RF (1999) Tomato and salinity. Sci Hortic 78:83–125

De Pascale S, Maggio A, Fogliano V, Ambrosino P, Ritieni A (2001) Irrigation with saline water improves carotenoids content and antioxidant activity of tomato. J Hort Sci & Biotech 76:447–453

Giordano LB, Silva JBC, Barbosa V (2000) Escolha de cutivares e plantio. In: Silva JBC, Giordano LB (eds) Tomate para processamento industrial. EMBRAPA, CNPH, Brasilia, pp 36–59

Gomez AK, Gomez AA (1990) Statistical procedures for agricultural research, 2nd edn. Wiley, New York, p 657

Grattan SR, Grieve CM (1999) Salinity-mineral nutrient relations in horticultural crops. Sci Hortic 78:127–157

Grattan SR, Oster JD (2003) Use and reuse of saline-sodic waters for irrigation of crops. J Crop Prod 7:131–162

Hanson B, May D (2004) Effect of subsurface drip irrigation on processing tomato yield, water table depth, salinity and profitability. Agric Water Manag 68:1–17

Josan AS, Bajwa MS, Choudhary OP (1998) Effect of sustained sodic irrigations on physical properties and root growth in a Typic Ustochrept soil under two cropping systems. J Res (PAU, Ludhiana) 35:125–131

Kahlon MS, Choudhary OP, Josan AS (2004) Effect of sodic water applied through drip irrigation on soil properties. In: Extended summaries (Theme V), Intern Conf Sustainable Mgmt Sodic Lands, Indian Inst Sugarcane Res, Lucknow, India, pp 450–452

Kumar V, Sivanappan RK (1980) Salt distribution in drip irrigation. In: Proceedings of the 7th International Symposium on Salt Affected Soils, CSSRI, Karnal, India, pp 265–268

Maas EV (1986) Salt tolerance of plants. Appl Agri Res 1:12–26

Maggio A, De Pascale S, Angelino G, Ruggiero C, Barbieri G (2004) Physiological response of tomato to saline irrigation in long-term salinized soils. Eur J Agron 21:149–159

Malash NM, Flowers TJ, Ragab R (2008) Effect of irrigation methods, management and salinity of irrigation water on tomato yield, soil moisture and salinity distribution. Irrig Sci 26:313–323

Malik RS, Sharma IP, Bhandari AR (1994) Soil water relations and water application efficiency of trickle irrigation under fruit crops—Apricot. Ind J Agric Res 28:263–269

Meiri A, Plaut Z (1985) Crop production and management under saline conditions. Plant Soil 89:253–271

Michelakis N, Vougioucalou E, Clapaki G (1993) Water use, wetted soil volume, root distribution and yield of avocado under drip irrigation. Agric Water Manag 24:119–131

Minhas PS, Bajwa MS (2001) Use and management of poor quality waters for the rice–wheat based production system. J Crop Prod 4:273–305

Minhas PS, Gupta RK (1992) Quality of irrigation water: assessment and management. ICAR, New Delhi, pp 123–124

Mori M, Amato M, Di Mola I, Caputo R, Quaglietta Chiaranda F, Tommaso TDI (2008) Productive behaviour of “cherry”-type tomato irrigated with saline water in relation to nitrogen fertilization. Eur J Agron 29:135–143

Munns R (2002) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–250

Pearson GA (1960) Tolerance of crops to exchangeable sodium. USDA Inf Bull 216

Rajak D, Manjunatha MV, Rajkumar GR, Hebbara M, Minhas PS (2006) Comparative effects of drip and furrow irrigation on the yield an water productivity of cotton (*Gossypium hirustum* L.) in a saline and waterlogged vertisol. Agril Water Manag 83:30–36

Ranganna S (1994) Handbook of analysis and quality control for fruit and vegetable production, 2nd edn. Tata McGraw Hill Co. Ltd, New Delhi

Richards LA (1954) Diagnosis and improvement of saline and alkali soils. USDA Handbook 60, p 160

Ritchie JT (1991) Wheat phasic development. In: Hanks RJ, Rictchie JT (eds) Modeling plant and soil systems. Agron Monograph 31, ASA, CSSA, SSSA, Madison, WI, pp 31–54

Sakamoto Y, Watanabe S, Nakashima T, Okano K (1999) Effect of salinity at two ripening stages on the fruit quality of single-truss tomato grown in hydroponics. J Hort Sci & Biotech 74:690–693

Stevens MA, Kedr AA, Albright-Holton M (1979) Potential for increasing tomato flavor via increased sugar-acid content. J Amer Soc Hort Sci 104:40–42

Umiel N, Gabelman WH (1971) Analytical procedures for detecting carotenoids of carrots (*Uaucus Carotel*) roots and tomato (*Lycopersicon esculentum* Mill.) fruits. J Amer Soc Hort Sci 96:702–704

Wang S, Kang Y, Wang D, Liu SP, Feng LP (2007) Effect of drip irrigation with saline water on tomato (*Lycopersicon esculentum* Mill) yield and water use in semi-humid area. Agril Water Manag 90:63–74