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Plant biomass and fruit quality response of greenhouse tomato under varying irrigation level and water quality

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Abstract

The impact of water quality with varying deficit irrigation level on the plant biomass and fruit quality parameters of greenhouse tomato (Lycopersicon esculentum L. cv *Izmir*) was investigated. A pot-based experiment was carried out over two growing seasons (2017-2018 and 2018-2019). Three water qualities: groundwater, recycled wastewater and an equal mix of both were applied in four irrigation scenarios which aimed to maintain soil moisture levels at 60%, 70%, 80% and 100% of field capacity. A surface drip irrigation system was designed maintaining irrigation frequency of two days. Results showed that both water quality and deficit irrigation significantly affected plant biomass. The fresh fruit weight was rather uniform, ranged from 53.2 to 85.4 gram and found highest in full irrigation. Most of the fruit quality parameters were not significantly affected by water quality.The significantly higher values of total soluble solid (7.87 degree brix), fruit firmness (9.28 kg/cm^2), fruit pH (4.24) and vitamin C content (68.33 mg/kg) were measured in treatments maintaining soil moisture content at 60% of field capacity (most water-stressed conditions). Based on these findings, it recommended that by adopting deficit irrigation and maintaining soil moisture at 60% of field capacity, fruit quality parameters can be significantly improved. In contrast, fresh fruit weight and plant biomass were reduced.

Keywords: Greenhouse tomato; irrigation deficiency; soil moisture content; tomato quality; recycled wastewater reuse.

Introduction

The need to adopt suitable techniques for saving agricultural water without significant compromising on sustainable yield and crop quality has been challenging for planners and scientists. Possible ways to overcome this challenge are using alternative sources of water and applying efficient irrigation management strategies (Hassanli et al., 2010) which is one of the fundamental objectives of this research. According to Djurovic et al., (2016), modern agriculture must accomplish two tasks: (1) to produce enough food for a growing global population, and (2) to ensure satisfactory crop quality while using water resources efficiently. To minimize water shortage, irrigators have begun to reduce dependence on surface and groundwater supplies using recycled wastewater as an irrigation source (Misra, 2014). In addition to novel water sources, various changes to irrigation practices have also been adopted in irrigated agriculture worldwide (Patane & Cosentino, 2010; Wei et al., 2018, Chand et al., 2020). Deficit irrigation is one such practice which has been applied in areas where access to fresh water is difficult or expensive (Hao et al., 2019; Khapte et al., 2019; Mattar et al., 2020). Deficit irrigation is defined as the irrigation management strategy through which water consumption is deliberately made lower than crop water requirements to improve water productivity (English & Raja, 1996).

Tomato (*Lycopersicon esculentum* L.) is herbaceous perennial and belongs to the Solanaceae family, with around 2800 species identified all with different fruit size, color, shape and quality (Jones, 2007; Klunklin and Savage, 2017; Maham et al., 2020). Tomato production is popular worldwide because of its high nutritional value, providing a source of antioxidants, fiber, vitamins, potassium, phenolic compounds, lycopene and β-carotene (Dumas et al., 2003; Favati et al., 2009; Maham et al., 2020). The global market is demanding horticultural commodities with superior quality as consumer demand is now shifting towards nutritionally rich fruit and vegetables rather than quantity (Chen et al., 2013; Bogale et al., 2016; Zhang et al., 2017). At present, the demand and preference of consumers for fruits and vegetables are becoming more diverse, for example, consumers are looking sweet tomatoes on the market (Sato et al., 2006; Prazeres et al., 2016; Garnet et al., 2013; Rameshwaran et al., 2016).

Tomatoes can be grown in a wide range of climates in open field as well as greenhouses. Greenhouse cultivation is attracting growers all over the world due to year-round production possibility (Harmanto et al., 2005; Yang et al., 2017; Liang et al., 2019). Weather uncertainties like heavy rain, high temperature and heat wave increases the probability of blossom-end-rot, fruit cracking and ultimately poor fruit quality in tomatoes which can be however, minimized by using greenhouse technology (William, 2009; Shao et al., 2015; Cui et al., 2020). Greenhouse tomato has many popular cultivars throughout the world. Cultivar selection plays an important role in planning of any deficit irrigation strategies (Chand et al., 2020). This study represents the first to consider combined effects of varying source water quality and deficit irrigation level on one of the most popular greenhouse tomato varieties, *Izmir*. Specific objectives of this research were: 1) to investigate and analyse the effect of three water quality with four irrigation scenarios on plant biomass content and fruit quality parameters; 2) to determine the optimum deficit irrigation level for a given source water quality.

Results and discussion

Plant biomass content and fresh fruit weight

Results in Table 1 showed that the highest value of plant biomass content was 20.24% (RWI, average of 2017-2018 and 2018-2019) followed by GWI (20.15%) and MWI (20.04%). The lowest plant biomass content was measured in MWI_3 (18.68%), slightly lower than RWI_3 (18.72%) and GWI_3 (18.74%). The plant biomass content values for all deficit irrigation treatments were significantly different compared to control at 5% level of significance. Also, plant biomass content of this research illustrated a positive linear trend with the volume of water applied because biomass got decreased with increasing water shortage in the root-zone (Cantore et al., 2016). This study found 8% plant biomass content loss in deficit irrigation treatments maintaining soil moisture at 60% field capacity compared to control. In Serbia, similar finding in the case of tomato was presented by Savic et al., (2008), who stated that deficit irrigation designed at 50% field capacity reduced plant biomass by 32%.

Table 1 indicated that there was an inversely proportional relationship between fresh fruit weight and amount of water stress (deficit applied). Larger fruit size (indicated by higher weight) were measured under the control treatment while the fruit size reduced considerably under deficit irrigation scenarios. The GWI treatment produced the significantly higher fresh fruit weight (81.95-gram, average of 2017-2018 and 2018-2019) followed by RWI (81.2-gram,) and MWI (80.5-gram). However, there was not significant difference among these highest fresh fruit weight values. The average loss in fresh fruit weight due to irrigation deficiency in treatments GWI_3, RWI_3 and MWI_3 were 40%, 34% and 32% respectively, all significantly lower than the control. These results were consistent with Ripoll et al., (2016) where fresh fruit weight was decreased by 32% when applying deficit irrigation at 60% of full irrigation for cultivar *Virosa*. The results were, however, different from Chen et al., (2013) who found the decrease in fresh fruit weight at 60% deficit irrigation level was 13% using cultivar *Jinzuan-3*. This suggested that tomato variety is an important factor in the extent of fresh fruit weight impact. The crop development process gets negatively affected in deficit irrigation due to decreased photosynthesis rate at reduced evapotranspiration and carbon availability, resulting in smaller fruit size and reduced plant biomass (Li et al., 2010; Zheng et al., 2013). Tomatoes are a highly water-dependent crop and are unfavourably affected by any kind of water shortage which hampers process of photosynthesis, plant growth and fruit production (Marjanovic et al., 2012; Klunklin and Savage 2017).

The interactive effects of varying water quality and deficit irrigation level on fresh fruit weight and plant biomass content was evaluated using a two-way ANOVA, and the findings are presented in Supplementary Table 1. The results showed that water quality and deficit irrigation levels both had significant effects on plant biomass content at $P < 0.05$.

Total soluble solid content

Table 2 indicated the assessment of total soluble solid to various combinations of water quality and deficit irrigation in the two growth seasons (2017-2018 and 2018-2019). The result showed that the value of total soluble solid increased with an increase in amount of water stress provided. There was not significant difference in the top three values of total soluble solid; reflecting that water quality had no significant effects on total soluble solid when maintained soil moisture at 60% field capacity. However, total soluble solid values of all deficit irrigation treatments were significantly different with that of the control. The results for total soluble solid in this study were consistent with Savic et al., (2011) for cultivar *Cadrico* and Chen et al. (2014) for cultivar *Taikong-1* and Lahoz et al., (2016) for cultivar *H-9036*. In our research, the average increase in total soluble solid in GWI_3, MWI_3 and RWI_3 compared to control were 10.2%, 8.1% and 10.0% respectively. These findings are confirmed by Cui et al., (2020) who reported that 9% increase in total soluble solid at 70% field capacity for cultivar *Asian Fenwang*. This indicated that there was an increased potential for sweetness to occur for tomato fruits with lower deficit irrigation levels. Tomato flavor is generally related to the relative concentrations of sugars and acids in the fruit and the most flavorsome combination in fruit is a high total soluble solid and high acid content (Korob, 2019).

Figure 1 indicated the mean variation of total soluble solids among 12 selected treatments of this study. The total soluble solids values considered in Figure 1 are the average of two experimental years. Results showed that irrigating the tomato crop by maintaining the soil moisture at 60% field capacity produced significantly higher total soluble solid. The highest total soluble solid was observed for GWI_3 (7.81-degree brix), followed by MWI_3 (7.73-degree brix) and RWI_3 (7.66-degree brix). The total soluble solids content increases when deficit irrigation is applied in fruit flowering and development stage (Chen et al. 2013) but decreases in over-irrigated condition (Sensoy et al. 2007). The total soluble solids content of tomato has significant implication for industrial proposes of paste or concentrated juice making process because the tomato with high TSS consumes less energy for water evaporation from fruit (Favati et al. 2009). In their study, Kumar et al., (2015) found that water stress applied throughout the crop growth season resulted increment in dry matter and soluble solids compared to full irrigation.

The interactive effect of varying water quality and deficit irrigation level on total soluble solid was analyzed using a two-way ANOVA, and the results are presented in Supplementary Table 2 which showed that deficit irrigation levels had significant effects on total soluble solid, but the effect of water quality was not significant.

Fruit firmness

The results in Table 3 indicated that fruit firmness produced proportional relationship with water stress (deficit) applied. The average increase in fruit firmness in treatments GWI_3, RWI_3 and MWI_3 compared to the control were 9.4%, 8.2% and 8.6% respectively which indicates that there is an increased potential for storage to occur for tomato fruit produced from higher water stress levels. Previous studies have shown a stronger relationship between fruit firmness and degree of water deficit provided. For example, Wang et al. (2011) demonstrated that the fruit firmness value

Table 1. Effects of water quality and deficit irrigation on fresh fruit weight and plant biomass content.

Years	Treatment	FFW (gm)	PBC (%)
2017-2018	GWI	78.50 ±0.493ab	20.03±0.040a
	GWI1	74.13 ±0.491cd	19.57±0.075bc
	GWI2	59.17 ±0.433f	18.93±0.090d
	GWI3	53.23 ±0.467h	18.70±0.053ef
	RWI	79.20 ±0.289a	20.16±0.049a
	RWI1	72.37 ±0.433d	19.60±0.031b
	RWI2	64.23 ±0.353e	18.90±0.091de
	RWI3	58.93 ±0.318f	18.74±0.059def
	MWI	77.67 ±0.384b	20.00±0.053a
	MWI1	74.93 ±0.463c	19.33±0.120c
	MWI2	64.10 ±0.289e	18.91±0.118de
	MWI3	56.57 ±0.463g	18.63±0.064f
2018-2019	GWI	85.40 ±0.265a	20.27±0.044ab
	GWI1	80.43 ±0.549d	19.78±0.041c
	GWI2	74.33 ±0.348e	19.08±0.065e
	GWI3	63.47 ±0.593h	18.78±0.042f
	RWI	83.33 ±0.176b	20.33±0.058a
	RWI1	82.00 ±0.436c	19.81±0.038c
	RWI2	74.47 ±0.067e	19.07±0.088e
	RWI3	62.20 ±0.321i	18.71±0.037f
	MWI	83.27 ±0.219b	20.08±0.044b
	MWI1	80.23 ±0.176d	19.59±0.128d
	MWI2	69.83 ±0.176f	19.07±0.078e
	MWI3	64.70 ±0.361g	18.73±0.074f

Note: FFW= Fresh fruit weight; PBC= Plant biomass content, Values are given means ± standard error of mean. The same letter following the values within the same column indicates non-significant differences between the treatments, whereas different letters show significant difference ($P < 0.05$).

Table 2. Effects of water quality and deficit irrigation on total soluble solid content.

Treatment	Total soluble solid (° brix)	
	2017-2018	2018-2019
GWI	7.20±0.06de	7.16±0.02d
GWI1	7.24±0.02d	7.20±0.03cd
GWI2	7.60±0.12ab	7.53±0.02b
GWI3	7.75±0.03a	7.87±0.04a
RWI	7.03±0.09ef	7.05±0.06ef
RWI1	7.20±0.06de	7.28±0.06d
RWI2	7.50±0.06bc	7.45±0.03c
RWI3	7.67±0.12ab	7.65±0.03b
MWI	6.83±0.09f	7.08±0.03g
MWI1	7.37±0.07cd	7.32±0.02e
MWI2	7.67±0.07ab	7.53±0.04cd
MWI3	7.73±0.02a	7.73±0.05ab

Values are given means ± standard error of mean. The same letter following the values within the same column indicates non- significant differences between the treatments, whereas different letters show significant difference ($P < 0.05$).

Table 3. Effects of varying water quality and deficit irrigation on fruit firmness.

Treatment	Fruit firmness (kg/cm^2)	
	2017-2018	2018-2019
GWI	8.53±0.02e	7.47±0.04ef
GWI1	8.72±0.02d	7.57±0.04def
GWI2	8.87±0.02c	7.83±0.03c
GWI3	9.28±0.03a	8.17±0.04a
RWI	8.50±0.03e	7.43±0.04f
RWI1	8.73±0.03d	7.63±0.06d
RWI2	8.90±0.03c	7.80±0.08c
RWI3	9.20±0.03b	9.00±0.03b
MWI	8.52±0.02e	7.45±0.05ef
MWI1	8.75±0.03d	7.58±0.04de
MWI2	8.78±0.02d	7.87±0.04bcd
MWI3	9.25±0.03ab	8.90±0.03bc

Values are given means ± standard error of mean. The same letter following the values within the same column indicates non-significant differences between the treatments, whereas different letters show significant difference ($P < 0.05$).

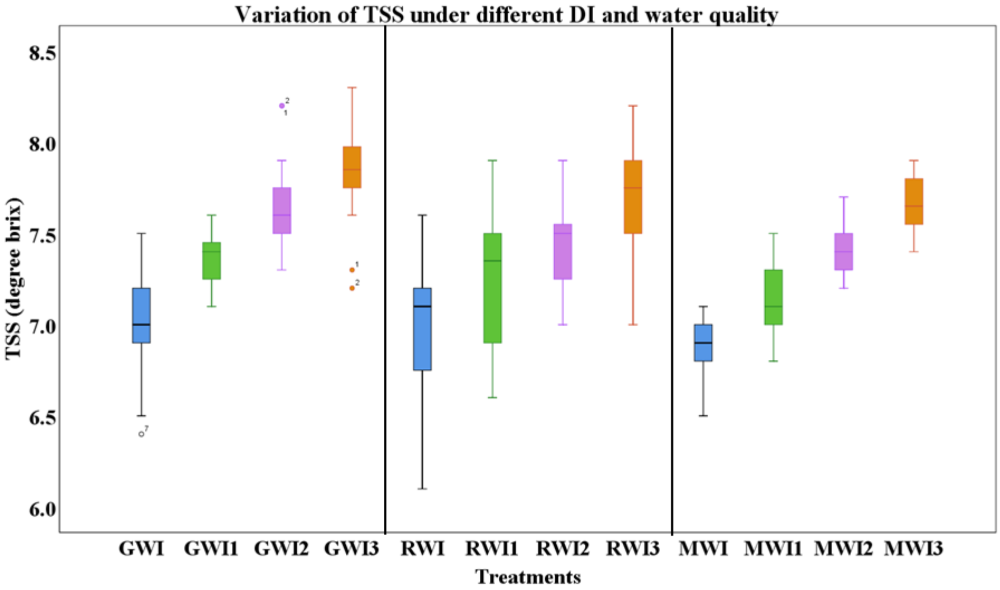

Fig 1. Variation of mean total soluble solid (TSS) across 12 selected treatments.

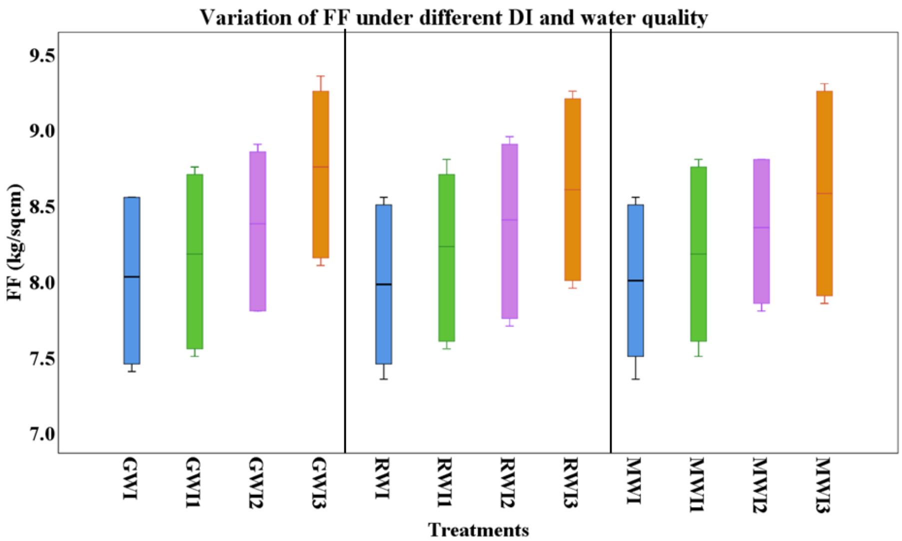

Fig 2. Variation of mean fruit firmness (FF) across 12 selected treatments.

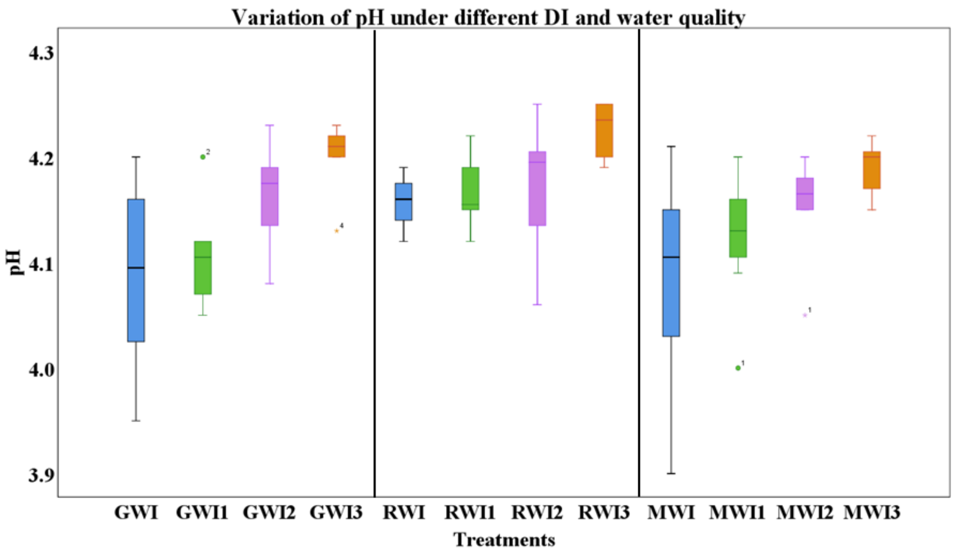

Fig 3. Variation of mean fruit pH across 12 selected treatments.

Table 4. Effects of varying water quality and deficit irrigation on fruit pH.

Treatment	Fruit pH	
	2017-2018	2018-2019
GWI	4.07 ± 0.006f	4.10 ± 0.009f
GWI1	4.08 ± 0.012ef	4.12 ± 0.003ef
GWI2	4.14 ± 0.003cd	4.17 ± 0.009c
GWI3	4.20 ± 0.007a	4.22 ± 0.003ab
RWI	4.16 ± 0.012bc	4.13 ± 0.009de
RWI1	4.17 ± 0.003b	4.15 ± 0.003cd
RWI2	4.17 ± 0.003b	4.19 ± 0.003b
RWI3	4.22 ± 0.003a	4.24 ± 0.006a
MWI	4.07 ± 0.003f	4.11 ± 0.003f
MWI1	4.10 ± 0.006ef	4.14 ± 0.009de
MWI2	4.13 ± 0.003d	4.17 ± 0.009c
MWI3	4.18 ± 0.003b	4.20 ± 0.009b

Note: Values are given means ± standard error of mean. The same letter following the values within the same column indicates non-significant differences between the treatments, whereas different letters show significant difference (P < 0.05).

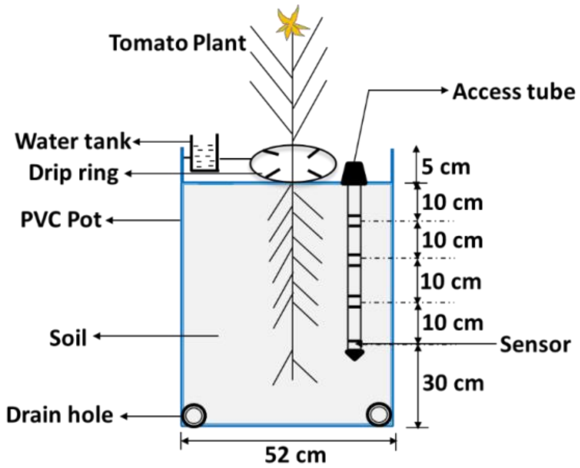

Fig 4. Layout of an experimental pot and details

Table 5. Effects of water quality and deficit irrigation on vitamin C content.

Years	Treatment	Vitamin C (mg/kg)
2017-2018	GWI	62.33 ± 0.333g
	GWI1	65.33 ± 0.333ef
	GWI2	66.33 ± 0.333cde
	GWI3	67.33 ± 0.333abc
	RWI	62.67 ± 0.333g
	RWI1	66.00 ± 0.000de
	RWI2	67.67 ± 0.333ab
	RWI3	68.33 ± 0.333a
	MWI	62.00 ± 0.577g
	MWI1	64.67 ± 0.66f
	MWI2	66.67 ± 0.333bcd
	MWI3	67.67 ± 0.333ab

Note: Values are given means ± standard error of mean. The same letter following the values within the same column indicates non-significant differences between the treatments, whereas different letters show significant difference (P < 0.05).

Table 6. Initial chemical and physical characteristics of the experimental soil.

EC	pH	TN	P	K	Ca	Mg	Na	B	TC
dS/m		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
1.05	7.35	1550	1720	2020	3030	1070	80	3.1	2.95

Table 7. Initial chemical and physical characteristics of the experimental waters.

Water	EC	pH	TN	P	K	Ca	Mg	Na	B	TC
Quality	dS/m		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
GW	1.9	7.1	2.1	0.1	9	41	41	229	0.2	61
RW	2.1	7.3	5.7	0.3	38	70	44	325	0.5	43
MW	1.9	7.2	2.7	0.2	24	58	43	280	0.4	46

Note: GW= Groundwater; RW= Recycled wastewater; MW= Mixed water.

increased by 18% under deficit irrigation compared to full irrigation for cultivar *Caihong-1*. A similar increase of 15% in fruit firmness was reported by Chen et al., (2013) also noting that a higher fruit firmness can reduce mechanical damage during transport and storage. While the actual reasons behind having increased fruit firmness in deficit irrigation are complicated, Guichard et al., (2001) reported that irrigation deficiency could lead to a lower pressure on the cell walls of tomatoes which results in a higher epidermal elasticity and improved fruit firmness.

Figure 2 showed the mean variation of fruit firmness among 12 treatments. Overall GWI_3 produced the highest fruit firmness (8.72 kg/cm^2) followed by RWI_3 (8.60 kg/cm^2) and MWI_3 (8.57 kg/cm^2) as presented in Figure 2. Fruit firmness describes the force offered by fruit against mechanical pressure and hence is a vital storage quality parameter (Patane & Cosentino 2010). Consumers prefer tomato having higher FF value because, higher the FF, the longer will be the storage life and vice-versa (Yang et al. 2017).

The interactive effect of varying water quality and deficit irrigation level on fruit firmness was analyzed using a two-way ANOVA, and the results are presented in Supplementary Table 5 which showed that deficit irrigation had significant effects on fruit firmness at the 5% level of significance, but water quality effect was not significant.

Fruit acidity (pH)

In both experimental year of this research, the result showed that fruit acidity (pH) increased with increase in water deficit applied (Table 4). The fruit pH was found significantly higher in 60% field capacity regardless of water quality. An optimum pH range in commercial tomatoes is 4 to 4.5 and the lower the pH, the tarter or sour the fruit (Korob, 2019). In this study, pH values of all treatment remained in the normal range (4.0 – 4.5).

The findings of this study showed that the largest value of fruit pH was observed in RWI_3 (4.23, average of 2017-2018 and 2018-2019), just larger than GWI_3 (4.21) and MWI_3 (4.19) which has been presented in Figure 3. In contrast, the lowest pH was measured in GWI (4.08), just lower than MWI (4.09) and RWI (4.14). The interactive effect of varying water quality and deficit irrigation level on fruit pH are presented in Supplementary Table 3 and 4 which showed that water quality, deficit irrigation levels and their interactions all had significant effects on the fruit acidity at $P < 0.05$.

Vitamin C content

The results in Table 5 revealed that vitamin C content of tomato fruit was found to be improved by adopting deficit irrigation. The highest value of vitamin C was found in treatment RWI_3 (68.33 mg/kg), while the lowest value was measured in MWI (62.00 mg/kg). These results showed that providing irrigation by maintaining soil moisture at 60% field capacity produced a significantly higher vitamin C content in tomato fruits compared to other treatments. An average increase in vitamin C due to water deficiency in treatments GWI_3, RWI_3 and MWI_3 were found to be 8%, 9% and 9.2% respectively compared to control which gives an added benefit for human health. The results of this study are consistent with Bogale et al. (2016) who found vitamin C was increased by 30% when applying deficit irrigation at 50% of full irrigation for cultivar *Cochoro* and Agbna et al. (2017) where vitamin C was increased by 28% when applying deficit irrigation at 50% of full irrigation for cultivar *Yazhoufenwang*.. It is generally assumed that the reduced leaf area index, increased light intensity and higher sugar accumulation in fruits due to lower water supply promotes more vitamin C synthesis in deficit irrigation treatments (Dumas et al., 2003; Wang et al., 2011).

Discussion

Overall, the results of this study suggested that suitably applied deficit irrigation techniques, which consider appropriate timing and degree of water stress can significantly improve quality parameters of greenhouse-grown tomato fruits. For example, total soluble solid, fruit firmness, pH and vitamin C were significantly improved by increasing the degree of water stress which are in consistent with the findings of Liu et al., (2019). Nangare et al., (2016) and Zegbe et al., (2006) reported that a water deficit condition is favourable to accumulate photo-assimilates in tomato fruits which is primarily responsible for improving total soluble solid and fruit firmness. The reduced fresh fruit weight and low dilution due to decreased water levels in fruits have potentially resulted in higher accumulation of the photo-assimilates, thereby the improved quality parameters (Nangare et al., 2016). As a result of greater water supply in full irrigation, antioxidant activities reduce in fruit and hence reduction of certain quality parameters in tomato occurs (Pek et al., 2014; Buttaro et al., 2015). Wide canopy growth with higher plant biomass occurs in tomato plants which receive full irrigation, might result more shading to fruits during ripening which reduces vitamin C content (Gautier et al., 2008).

Similar findings were described by Cahn et al. (2001), who recommended deficit irrigation up to 70 – 85% of the crop evapotranspiration as a sound compromise between tomato yield and quality, while Patane et al., (2011) proposed deficit irrigation at 50% of evapotranspiration during the entire growing season, as a trade-off between water saving and fruit quality of tomato. However, one aspect that is still unclear from this research is the ultimate degree of water stress in deficit irrigation beyond which fruit quality starts to deteriorate. Further research on this aspect is necessary to optimize the quality of the tomato fruit under a selected deficit irrigation strategy.

Materials and methods

Experimental site

The study aimed to simulate tomato growing conditions in the Northern Adelaide Plain of South Australia using pot-based experiment conducted in a laboratory greenhouse located at the University of South Australia, Mawson Lakes Campus (-34.9290^{0}S, 138.6010^{0}E, 10.86m), Mawson Lakes. The Northern Adelaide Plain represents 90% tomato production in South Australia and contains the largest area of greenhouse coverage in whole Australia (Phogat et al., 2020). This research was executed in 2017-2018 and 2018-2019.

Plant material

A polyvinyl chloride pot of 75 cm depth and 52 cm diameter was selected for this study. Figure 4 shows the layout and details of an experimental pot with necessary arrangements.

Soil selected for this study was loamy sand. The bulk density and field capacity of experimental soil was determined as described by Michael, (2003). One of the most popular greenhouse tomato varieties, *Izmir* was selected as a crop cultivar. 28-day old seedlings at the 4^{th} leaf stage was sourced from a local nursery and were transplanted into pots in accordance with Wang et al., (2015) and Alrajhi et al., (2017). The major water sources: groundwater, recycled wastewater and mixed water (consisting of 50% groundwater and 50% recycled wastewater by volume) used for tomato production in the Northern Adelaide Plain were selected in this study as varying water quality.

Experimental design and irrigation treatments

A "3 × 4 factorial randomized design" was applied to this study. The first factor represented water quality (three levels: groundwater, recycled wastewater and mixed water) and the second factor represented irrigation scenarios (four levels: 100%, 80%, 70% and 60% of field capacity) which are presented in Supplementary Table 5. The physico-chemical parameters of the experimental soil and irrigation waters were analysed prior to starting the experiment with the results shown in Table 6 and 7. The data shows mean results from the analysis of three replicate samples of each source water type and three soil samples. In total, 12 treatments each with four replications were examined. The principle of randomization was followed as is required in similar scientific experiments.

Soil moisture content monitoring and estimation

A PR2/4 Profile Probe (Delta-T Devices Ltd, Cambridge, UK) was used for measuring soil moisture content followed by Savic et al., (2011). The access tubes were fixed at 11 cm from the centre of each pot to ensure accuracy of soil moisture measurement in accordance with Soulis et al., (2015).

Application of irrigation

Drip irrigation system was used for the study. Irrigation frequency was scheduled for two days. The irrigation volume was determined based on the soil moisture content measured for each treatment. To illustrate the process, irrigation volume for control treatment as full irrigation (100% field capacity) on day i was calculated using Equation 1 (Chand et al. 2020).

$$I_{vol,i} = V \times [\theta_{FC} - \theta_i]$$

Where,

$I_{vol,i}$= Irrigation water to meet soil field capacity at day i (litre)

V= Volume of soil in the effective root zone area (litre)

θ_{FC} = Volumetric soil moisture content (%) at field capacity

θ_i = Volumetric soil moisture content (%) at day i (just prior to irrigation)

Based on the $I_{vol,i}$ value, the volume of water to be applied for deficit irrigation treatments were calculated accordingly. For example, in GWI_1, 80% of $I_{vol,i}$ was supplied using groundwater.

Tomato harvesting

Plant biomass content

Plant biomass content was evaluated by adopting the procedures outlined by Zhang et al., (2017), Semananda et al., (2016) and Zotarelli et al., (2009). Soon after harvesting all the tomato fruits, leaves and stems were cut from the base of the plant and made into small uniform pieces. Moist plant weight was recorded and then the samples were placed into a drying oven for 48 hours with a constant temperature of 70°C.

Fruit quality parameters

Total soluble solid content of tomato fruits was determined following standard procedures (AOAC Methods, 1980; Nuruddin et al., 2003; Savic et al., 2011). Fruit firmness was determined using following standard procedures recommended by AOAC Methods, (1980); OECD, (2009) and Chen et al., (2014). Fruit acidity/ pH was determined following procedures as described by AOAC, (1980); OECD, (2009) and Ripoll et al., (2016). Vitamin C content was determined in accordance with standard procedures outlined in AOAC, (1980); Chen et al., (2013) and Agbna et al., (2017).

Statistical analysis

To examine the experimental data; water qualities and deficit irrigation levels were taken as independent variables and fruit quality parameters and plant biomass were the dependent variables. Differences between means were evaluated for significance using the Least Significance Differences test at 95% confidence ($P < 0.05$). Duncan's Multiple Range Test for significance comparison of two individual treatments were applied. The SPSS Statistics 21 software package (Version 25.0; IBM SPSS, Armonk, New York, USA) was used for analysis of variance (ANOVA) and boxplots.

Conclusions

The major objective of this study was to evaluate the effects of varying water quality and deficit irrigation level on plant biomass content and fruit quality parameters of greenhouse tomatoes and for establishing an optimum deficit level for sustainable production. Both deficit irrigation scenarios and water quality had significant impacts on plant biomass content. The results revealed that the fruit qualities of greenhouse-grown tomatoes were proportional to increasing irrigation deficiency level. Fruit quality parameters were found significantly higher in the most water stressed deficit irrigation conditions examined (maintaining soil moisture at 60% field capacity). The main reason could be that with deficit irrigation, as less water is ultimately delivered (to) tomato fruit, the soluble solid content and dry matter content were increased resulting higher total soluble solid, fruit firmness, pH and vitamin C. The results concluded that the application of a deficit irrigation strategy could be an effective approach for improving fruit quality for greenhouse tomatoes when appropriately applied with defined levels of irrigation deficiency, i.e. by adopting deficit irrigation at 60% field capacity level, fruit quality parameter can be significantly improved. This is important in water-limiting conditions, particularly arid and semi-arid regions where water scarcity is an increasing concern and water costs are continuously rising.

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References

Agbna GH, Dongli S, Zhipeng L, Elshaikh NA, Guangcheng S, Timm LC (2017) Effects of deficit irrigation and biochar addition on the growth, yield, and quality of tomato. Sci Hortic. 222: 90-101.

Alrajhi A, Beecham S, Hassanli A (2017) Effects of partial root-zone drying irrigation and water quality on soil physical and chemical properties. Agr Water Manage. 182: 117-125.

AOAC (1990) Official methods of analysis, 15th ed. Association of Official Analytical Chemistry, Washington DC, USA.

Bogale A, Nagle M, Latif S, Aguila M, Müller J (2016) Regulated deficit irrigation and partial root-zone drying irrigation impact bioactive compounds and antioxidant activity in two select tomato cultivars. Sci Hortic. 213.

Buttaro D, Santamaria A, Signore A, Cantore V, Boari F, Montesano FF Parente A (2015) Irrigation management of greenhouse tomato and cucumber using tensiometer effects on yield quality and water use. Agr Sci Procedia. 4: 440-444.

Cahn MD, Herrero EV, Snyder RL, Hanson BR (2001) Water management strategies for improving fruit quality of drip irrigated processing tomatoes. Acta Hortic. 542: 111-117.

Cantore V, Lechkar O, Karabulut E, Sellami MH, Albrizio R, Boari F, Stellaci AM, Todorovic, M (2016) Combined effect of deficit irrigation and strobilurin application onyield, fruit quality and water use efficiency of “cherry” tomato (Solanum lycopersicum L.). Agr Water Manage. 167: 53-61.

Chand J, Hewa G, Hassanli A, Myers B (2020) Evaluation of deficit irrigation and water quality on production and water productivity of tomato in greenhouse. Agriculture. 10: 1-18.

Chen J, Kang S, Du T, Guo P, Qiu R, Chen R, Gu F (2014) Modelling relations of tomato yield and fruit quality with water deficit at different growth stages under greenhouse condition. Agr Water Manage. 146: 131-148.

Chen J, Kang S, Du T, Qiu R, Guo P, Chen R (2013) Quantitative response of greenhouse tomato yield and quality to water deficit at different growth stages. Agr Water Manage. 129: 152-162.

Cui J, Shao G, Lu J, Keabetswe L, Hoogenboom G (2020) Yield, quality and drought sensitivity of tomato to water deficit during different growth stages. Sci Agr. 77: 1-9.

Djurovi´c N, Cosi´c M, Striˇcevi´c R, Savi´c S, Domazetc M (2016) Effect of irrigation regime and application of kaolin on yield, quality and water use efficiency of tomato. Sci Hortic. 201: 271-278.

Dumas Y, Dadomo M, Di Lucca G, Grolier P (2003) Effects of environmental factors and agricultural techniques on antioxidant content of tomatoes. J. Sci. Food Agric. 83: 369–382.

English M, Raja SN (1996) Perspectives on deficit irrigation. Agr Water Manage. 32: 1-14.

Favati F, Lovelli S, Galgano F, Miccolis V, Tommaso TD, Candido V (2009) Processing tomato quality as affected by irrigation scheduling. Sci Hortic. 122: 562-571.

Garnet T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Doaln L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HC (2013) Sustainable intensification in agriculture: premises and policies. Science. 341: 33-34.

Gautier H, Diakou-Verdin V, Benard C, Reich M, Buret M, Bourgaud F, Poessel JL, Caris-Veyrat C, Genar M (2008) How does tomato quality (sugar, acid and nutritional quality) vary with ripening stage, temperature and irradiance. J Agr Food Chem. 56: 1241-1250.

Guichard S, Bertin N, Leonardi C, Gary C (2001) Tomato fruit quality in relation to water and carbon fluxes. Agronomie. 21: 385-392.

Hao S, Cao H, Wang H, Pan X (2019) The physiological responses of tomato to water stress and re-water in different growth periods. Sci Hortic. 249: 143-154.

Harmanto, Salokhe VM, Babel MS, Tantau HJ (2005) Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. Agr Water Manage. 71: 225-242.

Hassanli AM, Ahmadirad S, Beecham S (2010) Evaluation of the influence of irrigation methods and water quality on sugar beet yield and water use efficiency. Agr Water Manage. 97: 357-362.

Jones JB (2007) Tomato Plant Culture in the Field, Greenhouse and Home Garden CRC Press, New York, USA.

Khapte PS, Kumar P, Burman U, Kumar P (2019) Deficit irrigation in tomato: Agronomical and physio-biochemical implications. Sci Hortic. 248: 256-264.

Michael AM (2003) Irrigation Theory and Practice. Vikas Publishing House Pvt Limited, New Delhi. 546-548.

Klunklin W, Savage G (2017) Effect on Quality Characteristics of Tomatoes Grown Under Well-Watered and Drought Stress Conditions. Foods. 6: 1-10.

Korob S (2019) ‘*Managing tomato taste’*, Yara North America, viewed on 13 April 2020, available at: https://www.yara.us/crop-nutrition/tomato/managing-tomato-taste/.

Kumar, PS, Singh, Y, Nangare, DD, Bhagat, K, Kumar, M, Taware, PB, Kumari, A, Minhas PS (2015) Influence of growth stage specific water stress on the yield, physico-chemical quality and functional characteristics of tomato grown in shallow basaltic soils. Sci Hortic. 197: 261-271.

Lahoz, I, Perez-de-Castro, A, Valcarcel, M, Macua, JI, Beltran, J, Rosello, S, Cebolla-Cornejo, J (2016) Effect of water deficit on the agronomical performance and quality of processing tomato. Sci Hortic. 200: 55-65.

Li X, Liu F, Li G, Lin Q, Jensen CR (2010) Soil microbial response, water and nitrogen use by tomato under different irrigation regimes. Agr Water Manage. 98: 414-418.

Liang L, Ridoutt BG, Lal R, Wang D, Wu W, Peng P, Hang S, Wang L, Zhao G (2019) Nitrogen footprint and nitrogen use efficiency of greenhouse tomato production in North China. J Clean Prod. 208: 285-296.

Liu, H, Li, H, Ning, H, Zhang, X, Li, S, Pang, J, Wang, G, Sun J (2019) Optimizing irrigation frequency and amount to balance yield, fruit quality and water use efficiency of greenhouse tomato. Agr Water Manage. 226: 1-11.

Maham SG, Rahimi A, Subramanian S, Smith DL (2020) The environmental impacts of organic greenhouse tomato production based on the nitrogen-fixing plant (*Azolla*). J Clean Prod. 245, pp. 1-9.

Marjanovic M, Radmila S, Biljana VR, Sladjana S, Zorica J, Nadia B, Mireille F (2012) Growth and proteomic analysis of tomato fruit under partial root-zone drying. OMICS: J Integr Biol. 16: 343-356.

Mattar MA, El-Abedin TKZ, Alazba AA, Al-Ghobari HM (2020) Soil water status and growth of tomato with partial root-

zone drying and deficit drip irrigation techniques. Irrigation Sci. 38: 163-176.
Michael, AM 2003, *Irrigation Theory and Practice*, Vikas Publishing House Pvt Limited, New Delhi, India, 546-548.
Misra AK (2014) Climate change and challenges of water and food security. J Sustain Blt Environ. 3: 153-165.
Nangare D, Singh Y, Kumar PS, Minhas P (2016) Growth, fruit yield and quality of tomato (Lycopersicon esculentum Mill.) as affected by deficit irrigation regulated on phenological basis. Agr Water Manage. 171: 73-79.
Nuruddin MM, Madramootoo CA, Dodds GT (2003) Effects of water stress at different growth stages on greenhouse tomato yield and quality. HortScience. 38.
OECD (2009) Organization for Economic Cooperation and Development Fruit and Vegetable Schemes. Viewed on 15 June 2020, available at: https://www.oecd.org/agriculture/fruit-vegetables.
Patanè C, Cosentino S (2010) Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. Agr Water Manage. 97: 131-138.
Patanè C, Tringali S, Sortino O (2011) Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. Sci Hortic. 129: 590-596.
Pek Z, Szuvandzsiev P, Daood H, Nemenyi A, Hylyes L (2014) Effect of irrigation on yield parameters and antioxidant profiles of processing cherry tomato. Cent Eur J Biol. 9: 383-395.
Phogat V, Mallants D, Cox JW, Simunek J, Oliver DP, Awad J (2020) Management of soil salinity associated with irrigation of protected crops. Agr Water Manage. 227: 1-11.
Prazeres AR, Rivas J, Almeida MA, Patanita M, Dores J, Carvalho F (2016) Agricultural reuse of cheese whey wastewater treated by NaOH precipitation for tomato production under several saline conditions and sludge management. Agr Water Manage. 167: 62-74.
Rameshwarana P, Tepe A, Yazar A, Ragab R (2016) Effects of drip-irrigation regimes with saline water on pepper productivity and soil salinity under greenhouse conditions. Sci Hortic. 199: 114-123.
Ripoll J, Urban L, Brunel B, Bertin N (2016) Water deficit effects on tomato quality depend on fruit developmental stage and genotype. J Plant Physiol. 190: 26-35.
Sato S, Sakaguchi S, Furukawa H, Ikeda, H 2006, 'Effects of NaCl application to hydroponic nutrient solution on fruit characteristics of tomato (Lycopersiconesculentum Mill.). Sci Hortic. 109: 248–253.
Savic S, Stikic R, Vucelic Radovic B, Bogicevic B, Jovanovic Z, Hadzi-Taskovic Sukalovic V (2008) Comparative effects of regulated deficit irrigation (RDI)and partial root-zone drying (PRD) on growth and cell wall peroxidase activity in tomato fruits. Sci Hortic. 117: 15–20.
Savic S, Stikic R, Zaric V, Vucelic-Radovic B, Jovanovic Z, Marjanovic M, Djordjevic S, Petkovic D (2011) Deficit irrigation technique for reducing water use of tomato under polytunnel conditions. J Cent Euro Agr. 12**:** 597-607.
Semananda NPK, Ward JD, Myers BR (2016) Evaluating the efficiency of wicking bed irrigation systems for small-scale urban agriculture. Horticulturae. 2: 1-18.
Sensoy, S, Ertek, A, Gedik, I, Kucukyumuk C (2007) Irrigation frequency and amount affect yield and quality of field-grown melon (Cucumis melo L.). Agr Water Manage. 88: 269–274.
Shao GC, Deng S, Liu N, Wang MH, She DL (2015) Fruit quality and yield of tomato as influenced by rain shelters and deficit irrigation. J Agr Sci Technol. 17: 691-704.
Soulis KX, Elmaloglou S, Dercasn N (2015) Investigating the effects of soil moisture sensors positioning and accuracy on soil moisture-based drip irrigation scheduling systems. Agr Water Manage. 148: pp. 258-268.
Wang CX, Gu F, Chen JL, Yang H, Jiang JJ, Du TS, Zhang JH (2015) Assessing the response of yield and comprehensive fruit quality of tomato grown in greenhouse to deficit irrigation and nitrogen application strategies. Agr Water Manage. 161: 9–19.
Wang F, Kang S, Du T, Li F, Qiu R (2011) Determination of comprehensive quality index for tomato and its response to different irrigation treatments. Agr Water Manage. 98: 1228-1238.
Wei Z, Du T, Li X, Fang L, Liu F (2018) Interactive effects of CO_2 concentration elevation and nitrogen fertilization on water and nitrogen use efficiency of tomato grown under reduced irrigation regimes. Agr Water Manage. 202: 174-182.
William JL (2009) Overview of the use of high tunnels worldwide. HortTech. 19: 25-29.
Yang H, Du T, Qiu R, Chen J, Wang F, Li Y, Wang C, Gao L, Kang S (2017) Improved water use efficiency and fruit quality of greenhouse crops under regulated deficit irrigation in northwest China. Agr Water Manage. 179: 193-204.
Zegbe JA, Behboudian MH, Clothier BE (2006) Response of 'Petopride' processing tomato to partial root zone drying at different phenological stages. Irrigation Sci. 24: 203-210.
Zhang H, Xiong Y, Huang G, Xu X, Huang Q (2017) Effects of water stress on processing tomatoes yield, quality and water use efficiency with plastic mulched drip irrigation in sandy soil of the Hetao Irrigation District. Agr Water Manage. 179: 205-214.
Zheng J, Huang G, Jia D, Wang J, Mota M, Pereira LS, Huang Q, Xu X, Liu H (2013) Responses of drip irrigated tomato (Solanum lycopersicum L.) yield, quality and water productivity to various soil matric potential thresholds in an arid region of Northwest China. Agr Water Manage. 129: 181-193.
Zotarelli L, Scholberg JM, Dukes MD, Muñoz-Carpena R, Icerman J (2009) Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agr Water Manage. 96: 23-34.