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Evaluation of Deficit Irrigation and Water Quality on Production and Water Productivity of Tomato in Greenhouse

Jeet Chand *, Guna Hewa, Ali Hassanli and Baden Myers

UniSA STEM, University of South Australia, Mawson Lakes, SA 5095, Australia;
guna.hewa@unisa.edu.au (G.H.); ali.hassanli@unisa.edu.au (A.H.); baden.myers@unisa.edu.au (B.M.)
* Correspondence: jeet.chand@mymail.unisa.edu.au; Tel.: +61-41-470-6324

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Abstract: This study deals with the evaluation of the effects of deficit irrigation (DI) and water quality (WQ) on the vegetative and productive response of greenhouse-grown tomatoes (*Lycopersicon esculentum* Mill. cv. *Izmir*). A pot-based experiment was carried out over two growing seasons. Three WQ: (groundwater, recycled wastewater and a mix of both) were applied in four irrigation scenarios which targeted soil moisture content (SMC) maintaining at 60%, 70%, 80% and 100% of field capacity (FC). Results showed that both DI and WQ had significant effects on crop development, yield and water productivity. The highest values of plant height (186.0 ± 0.58 cm) and stem diameter (23.40 ± 0.02 mm) were found at 100% FC (control). Total yield ranged from 2.33 ± 0.03 kg/plant (60% FC) to 4.05 ± 0.06 kg/plant (control). However, mild water stress (SMC maintaining at 80% FC) showed a positive effect on irrigation water use efficiency (IWUE) without significant yield reduction compared to control. IWUE was at its maximum (31.77 ± 0.47 kg/m^3) at 80% FC. A DI regime based on 80% FC could be an efficient irrigation strategy particularly in water-limiting condition. Recycled wastewater was superior among the three WQ for achieving a better crop growth, yield and water productivity at same DI level.

Keywords: greenhouse tomato; irrigation deficiency; water productivity; water quality; recycled water reuse

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1. Introduction

Water is a scarce resource; therefore, its future management must be carefully considered in a holistic approach that can successfully coordinate water, food and environmental needs [1]. Chenoweith and Bird [2] explained some important approaches for agricultural water management including technological advancement, identification of new water sources and modernization of management techniques. There is a need to enhance irrigation water use efficiency (IWUE) to make agriculture more productive, profitable and sustainable [3,4]. Arid, semi-arid and all regions where water resources are scarce; designing and managing an efficient irrigation system to achieve the highest possible IWUE is a pertinent issue [5,6]. Improved IWUE not only helps to achieve sustainability in water use but also contributes to increase the competitiveness of agricultural production [7]. Using alternative sources of water and employing efficient irrigation management strategies are the two immediate remedies for sustainable agricultural development where water supply is limited [8].

Tomatoes (*Lycopersicon esculentum*) are a horticultural crop that contain many nutrients beneficial for human health including fiber, vitamins, potassium, phosphorus and phenolic compounds [9–12]. Due to high commercial demand, tomato cultivation is popular around the world and covers over 4.5 million ha [13,14]. Tomatoes are cultivated both in open fields and greenhouse environments. However, the current trend of tomato farming as a profitable agribusiness is shifting toward greenhouse-based system for many reasons including the potential for off-season production and the impact of climate change [9,15–17]. Tomato production in a greenhouse system depends on many factors including local climate (particularly temperature and light intensity), facilities available in greenhouses and technical expertise [18]. Depending on the geographical factors and technologies applied, the productivity of greenhouse tomato production has been found to vary. For example, in Canada and The Netherlands, productivity has been reported to be up to 60 kg/m^2, while it is noted to be below 28 kg/m^2 in Spain [19]. Due to technological advancement and high-yielding varieties, the productivity of greenhouse-grown tomatoes in southwest America was 100 kg/m^2 [19]. Greenhouses equipped with heating and carbon dioxide enrichment yielded 55 kg/m^2 tomato in Italy [20]. However, severe outbreaks of diseases in the soil–plant system through insects and pests has been a significant challenge to increase the productivity of greenhouse tomato globally [21].

Several irrigation management strategies are currently practiced in greenhouse tomato cultivation. Among them, deficit irrigation (DI) has been generally applied in areas where access to freshwater is difficult or expensive [22–24]. The concept of DI in tomato horticulture was introduced in 1990's and investigations are ongoing to explore its potentials under different agronomic conditions including greenhouse-based production system [25–27]. Under DI, a certain degree of water stress is applied to a plant either throughout the cropping period or in a certain time frame of crop growth stages. The principal objective behind DI strategy is to maximize water productivity [22,24,28,29]. Crop yield may be decreased with the application of DI, but when applied appropriately, any yield reduction is mitigated by increased irrigation water productivity [30].

Banjaw et al. [31] published a review article explaining the effect of water quality (particularly untreated wastewater) and DI on tomatoes in Ethiopian conditions. However, in addition to the geographical limitation, the authors did not define the physical, biological and chemical characteristics of the wastewater which they indicated to have caused negative impacts on yield and quality of irrigated tomatoes. Mounzer et al. [32] recommended that the practice of DI should be avoided where saline or reclaimed wastewater is used for irrigation because it poses a higher risk on the sustainability of the soil. The use of treated wastewater for DI requires appropriate fertigation management strategies as wastewater typically contains higher nutrient concentrations and numerous toxic elements [33]. In their review specific to tomatoes, Banjaw et al. [31] concluded that low-quality wastewater irrigation increases the chance of salinity build-up in the root zone of a crop, which is one of the leading causes of yield reduction.

Water-saving irrigation techniques like DI also have the potential to reduce nutrient and fertilizer leaching below the root-zone and may also inhibit crop disease and enhance soil aeration [26]. IWUE significantly increased by 45% under DI conditions, particularly where the supplied irrigation volume was designed to meet 75% of crop evapotranspiration [34]. However, the impacts of DI are complex and, in many cases, site-specific. For example, the effect of DI on tomatoes depends on local climate, soil–water properties and crop cultivars [35]. Bogale et al. [36] reported that the yield reduction of the greenhouse tomato cultivar *Cochoro* was 35% under a DI regime (50% of full irrigation) and resulted in a 19% improvement in water use efficiency (WUE), whereas yield reduction was 25% for cultivar *Matina* resulted in 35% improvement in WUE. These results verify that same crop with different cultivar, responses different yield and WUE even if the DI strategy is same. Hence, crop cultivar has important role while designing DI strategy. Scientific literature has not been found available comparing the effects of varying water quality and DI level on different vegetative and productive aspects of tomato (cultivar *Izmir*) production in a greenhouse environment. The work presented in this paper focuses on production of this *Izmir* cultivar and the specific objectives are: (1) to investigate and analyze the effects of different DI level and WQ on crop development parameters, potential yield and water productivity (IWUE and marginal productivity of water); (2) to determine the optimum DI level for a given source WQ for sustainable production.

2. Materials and Methods

2.1. Experimental Site

This study simulated tomato growing conditions in Northern Adelaide Plains (NAP) using a pot-based experiment conducted in a greenhouse located at Mawson Lakes Campus, (–34.92900 S, 138.60100 E, 10.86 m), University of South Australia. The NAP often described as "Veggie Bowl" of South Australia, produces 198,000 tons of premium quality vegetables including tomatoes and is the largest greenhouse zone of Australia [37]. The experimental study was executed in two consecutive years (2017–2018 and 2018–2019) during the most popular growing season (September to March) for greenhouse tomatoes in NAP region. The utilized greenhouse was equipped with an automatic temperature control system (Power Plant OMNIGROW, Horticultural Technology, Hallam, VIC, Australia).

2.2. Selection of Experimental Pot, Soil, Plant, Water and Irrigation System

A polyvinyl chloride (PVC) pot of 75 cm depth and 52 cm diameter was selected for this experiment. Figure 1 shows the layout and details of an individual plant in a pot and the location of drippers and drip line, soil moisture monitoring probe and a water tank.

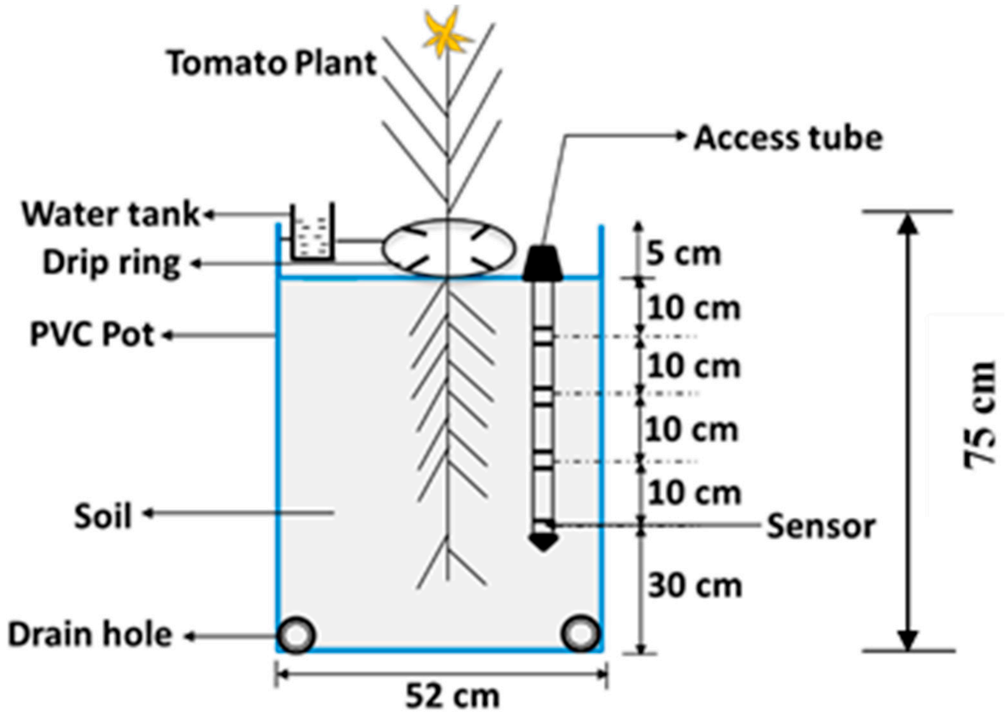


Figure 1. Layout of an experimental pot and details.

The selected soil for this experiment was loamy sand and the pots were manually filled in 20 cm layers. Each layer was compacted using a wooden hammer and leveler. After filling pots with soil and allowing 15 days for settling time, the dry bulk density was determined using a core sampler method as described by [38]. The average bulk density within the soil profile at 95% confidence interval was 1.57 ± 0.07 g/cm^3 ($n = 6$). The soil field capacity (FC) was determined as described by [38]. The average value of FC at 95% confidence interval was 17.3 ± 0.05% (volumetric base, $n = 6$). All pots were watered to reach FC level 24 h prior to transplanting the tomato plants using the same approach as [39].

One of the most popular greenhouse tomato varieties, *Izmir* in the NAP region was selected for this study. *Izmir* is an indeterminate and heat tolerant greenhouse tomato cultivar with fruit color uniform deep red and fruit size approximately 150–180 g [40]. To begin the experiment, 28-day-old seedlings prepared in soil media were sourced from a local nursery. These seedlings were transplanted into pots at the 4th leaf stage in accordance with the procedures explained in [26,33].

Three major WQ used in the NAP region as irrigation source were selected. These were: groundwater (GW, directly extracted from the T2 aquifer from a bore hole in Virginia, SA, Australia); recycled wastewater (RW, Class A) from Bolivar Wastewater Treatment Plant at Bolivar, SA, Australia; and mixed water (MW, consisting of 50% GW and 50% RW by volume), which is typical of local farmers who routinely use both RW and GW in the blend [41].

As most greenhouse tomato growers in the NAP region use drip irrigation, this study also adopted the same method. Distribution uniformity of the selected drip system was measured prior to the experiment and was equal to 92%. As shown in Figure 1, a one-liter water tank made from 90 mm PVC pipe was installed on each experimental pot to feed the drip line.

The initial physical and chemical parameters of the experimental soil and irrigation waters were analyzed prior to starting the experiment with the results shown in Table 1. The data shows mean results from the analysis of three replicate samples of each source WQ and three soil samples.

Table 1. Initial chemical and physical characteristics of experimental water and soil.

	Characteristics	**GW**	**RW**	**MW**	**Soil**
Chemical composition	Ca (mg/L)	41	70	58	3030
	Mg (mg/L)	44	41	43	1070
	Na (mg/L)	229	325	280	80
	K (mg/L)	9	38	24	2020
	B (mg/L)	0.24	0.47	0.37	3.1
	TN (mg/L)	0.07	5.7	2.7	1550
	P (mg/L)	0.02	0.02	0.01	1720
	TC (mg/L)	61	41	46	0.23
	pH	7.14	7.34	7.21	7.35
	EC (dS/m)	1.85	2.1	1.93	1.05
Physical	Texture				80/9/11 (Loamy Sand)

Note: TN = Total nitrogen, TC = Total carbon, EC = Electrical conductivity.

2.3. *Experimental Design and Treatments*

A "3 × 4 factorial randomized design" was applied to this study. The first factor represented WQ (three levels: GW, RW and MW) and the second factor represented irrigation scenarios (four levels: 100% FC, 80% FC, 70% FC and 60% FC) listed in Table 2.

Table 2. Details of the experimental design treatments.

No.	**Treatments**	**Water Source**	**Supply Level**	**Scenario**
1	GWI	Ground water	100% FC	Control
2	GWI_1	Ground water	80% FC	Test
3	GWI_2	Ground water	70% FC	Test
4	GWI_3	Ground water	60% FC	Test
5	RWI	Recycled wastewater	100% FC	Control
6	RWI_1	Recycled wastewater	80% FC	Test
7	RWI_2	Recycled wastewater	70% FC	Test
8	RWI_3	Recycled wastewater	60% FC	Test
9	MWI	Mixed water	100% FC	Control
10	MWI_1	Mixed water	80% FC	Test
11	MWI_2	Mixed water	70% FC	Test
12	MWI_3	Mixed water	60% FC	Test

In this study, 12 treatments each with four replications were examined. Similar research on pot-based experiments in greenhouses with three replications by [30] and four replications by [36,42] have been reported. A 7.6 m (length) by 6.2 m (width) space of greenhouse was utilized to place pots in 12 rows by maintaining row to row distance 75 cm and plant to plant distance 50 cm, which is common practice of growers in the NAP region.

The principle of randomization was followed as is required in similar scientific experiments. The design matrix with treatments and replications is presented in Table 3.

Table 3. Design matrix and randomized configuration of pots representing the corresponding treatments and replications.

GWI-R1	MWI_1-R1	RWI_2-R1	MWI_3-R1
RWI-R1	GWI_1-R1	MWI_2-R1	GWI_3-R1
MWI-R1	RWI_1-R1	GWI_2-R1	RWI_3-R1
MWI_1-R2	RWI_2-R2	MWI_3-R2	GWI-R2
RWI_1-R2	GWI_2-R2	RWI_3-R2	RWI-R2
GWI_1-R2	MWI_2-R2	GWI_3-R2	MWI-R2
.RWI_2-R3	MWI_3-R3	GWI-R3	MWI_1-R3
MWI_2-R3	GWI_3-R3	RWI-R3	GWI_1-R3
GWI_2-R3	RWI_3-R3	MWI-R3	RWI_1-R3
MWI_3-R4	GWI-R4	RWI_1-R4	GWI_2-R4
GWI_3-R4	RWI-R4	MWI_1-R4	RWI_2-R4
RWI_3-R4	MWI-R4	GWI_1-R4	RWI_2-R4

R1 = first replication; R2 = second replication; R3 = third replication and R4 = fourth replication.

2.4. Soil Moisture Measurement

A PR2/4 Profile Probe (Delta-T Devices Ltd, Cambridge, UK) was used for measuring soil moisture content (SMC) using the procedures outlined by [43]. The PR2/4 Profile Probe measures soil moisture at different depths within the soil profile on volumetric basis. SMC was measured before each irrigation event. For this, access tubes were installed in the effective root zone area of pots (Figure 1). The tubes were fixed at 11 cm from the center of each pot to ensure that measurements were accurate, in accordance with [44].

2.5. Application of Irrigation

Irrigation frequency was scheduled for two days and each irrigation event occurred at 8 am throughout the crop growth period. The irrigation volume was determined based on the SMC measured for each treatment. During the first 10 days after transplanting (DAT), all plants were in the crop establishment period as suggested by previous DI studies including [30,45,46]. Full irrigation was applied during the crop establishment period for all treatments. Following the crop establishment period, the irrigation program based on DI scenarios was applied accordingly.

To illustrate the process, irrigation volume for control treatment as full irrigation (100% FC) on day i was calculated using Equation (1).

$$I_{vol,i} = V \times [\theta_{FC} - \theta_i] \tag{1}$$

where,

$I_{vol,i}$ = Irrigation water to meet soil FC at day i (liter)
V = Volume of soil in the effective root-zone area (liter)
θ_{FC} = Volumetric soil moisture content (%) at FC
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 DI treatments were calculated accordingly. For example, in GWI_1, 80% of $I_{vol,i}$ was supplied using groundwater.

2.6. Crop Development Monitoring

The style of modern tomato growing practices in NAP greenhouses was adapted through several site visits and discussions with the growers before the experiment was commenced. During the growing seasons, 2.4 L liquid concentrated chemical fertilizer (PowerFeed, Seasol International Pty Ltd, Victoria, Australia, water-soluble nutrient, *w/v*: N = 14%; P = 1.4%, K = 8%) was applied as fertigation. Fertilizers were applied four times during the growing season. The fertilizer solution was prepared by diluting water-soluble chemical fertilizer (PowerFeed) with water. The recommended dilution dose provided by the fertilizer manufacturer was 50 mL of PowerFeed in 9 L of water. The prepared solution was applied according to designed water supply principle in each treatment as fertigation. In the first fertilizer application time (30 DAT), the control treatment received 1.95 mL fertilizer per plant, whereas treatments maintaining SMC at 80%, 70% and 60% FC received 1.66 mL, 1.46 mL and 1.28 mL per plant, respectively. All side shoots were pruned to maintain the plant in one stem, which is a standard practice [47,48].

Crop development parameters, particularly stem diameter (SD) and plant height (PH) were measured at 14-day intervals using a Vernier caliper and a measuring tape, respectively. SD was measured 5 cm above the soil surface as per [34]. The PH was recorded from the soil surface to the apex of the plant.

2.7. Tomato Harvesting

Harvesting was conducted following commercial greenhouse tomato farmer practices in the NAP region. Nearly ripened fruits (90% ripe based on visual assessment) were picked manually and weighed on a precision balance with an accuracy of ±0.01 g. For each measurement, fruit with no defects such as blossom end-rot were selected for further analysis. Fruits with defects were classified as “culls” (unmarketable fruits) and their mass was recorded separately but were not used for quality assessment.

2.8. Irrigation Water Use Efficiency (IWUE)

IWUE (kg/m^3) of each treatment was calculated as described by [34,49] using Equation (2).

$$IWUE = \frac{Y}{I} \tag{2}$$

where,

Y = Total marketable tomato fruit yield (kg)

I = Total irrigation water applied (m^3)

2.9. Marginal Productivity (MP) of Irrigation Water

Marginal productivity (MP) of irrigation water was estimated as per [50,51] using Equation (3).

$$MP = \Delta Y / \Delta W \tag{3}$$

where,

ΔY = variation of gross output in yield (maximum yield − yield in chosen treatment)

ΔW = variation in supply volume of water (maximum water used − water used in the chosen treatment)

To estimate the MP for different irrigation scenarios, the control treatment was considered for the highest yield and the maximum water use.

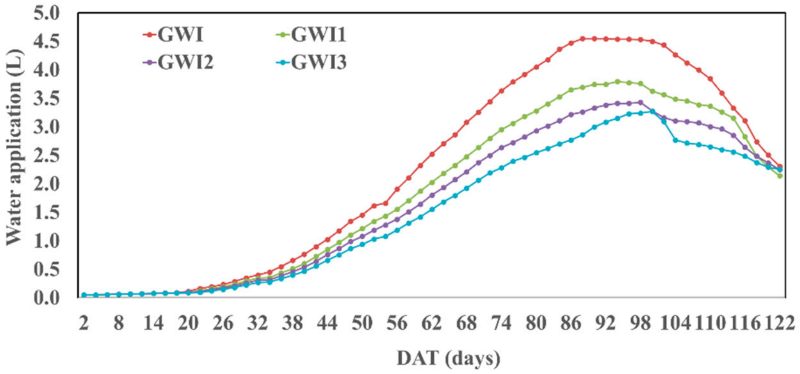
2.10. Statistical Analysis

To examine the experiment performance; WQ and DI levels were taken as independent variables whereas IWUE, crop yield, MP, PH and SD were the dependent variables. Differences between means were evaluated for significance using the Least Significance Differences (LSD) test at 95% confidence ($p < 0.05$). Duncan's Multiple Range Test for significance comparison of two individual treatments were applied. A two-way ANOVA was conducted to compare the mean difference between groups (water qualities and DI levels) and the interaction between the groups.

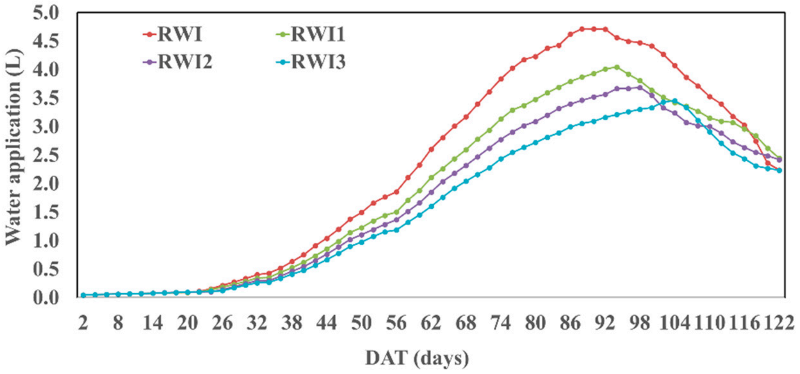
3. Results and Discussions

3.1. Water Application

Figure 2a–c shows the variation of water application with days after transplantation (DAT) in different treatments of GW, RW and MW, respectively. A very similar trend was observed for all treatments regardless of WQ. Figure 2 indicated that water consumption by the plant was maximum between 45 to 90 DAT. In the early stage of the crop (from day 1 to 24 days), crop–water demand was low with little increment. After 24 DAT, the crop–water requirement increased with a steep slope until 98 DAT. Water demand then started to decrease until the end of the harvesting period. RWI had the highest cumulative volume of water applied (139 L) followed by GWI (137 L) and MWI (135.5 L) throughout the season. The lowest irrigation volume was monitored in GWI$_3$ (99 L), just lower than MWI$_3$ (101.5 L) and RWI$_3$ (102 L). When irrigation events were individually examined, the highest value of applied water was recorded 4.96 L (MWI, 90 DAT), followed by GWI (4.87 L, 94 DAT) and RWI (4.86 L, 90 DAT).

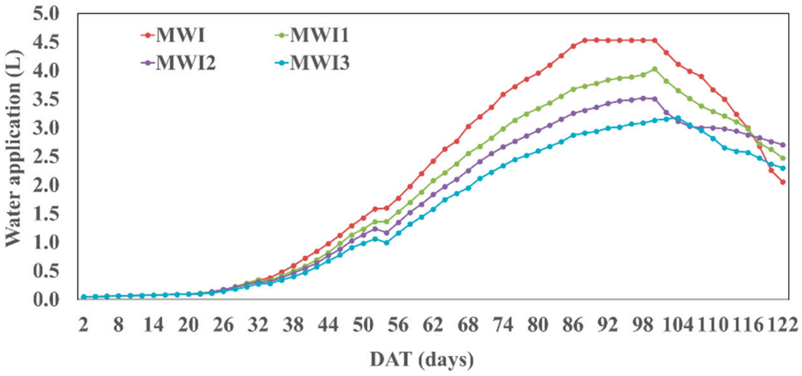


(**a**)



(**b**)

Figure 2. *Cont.*

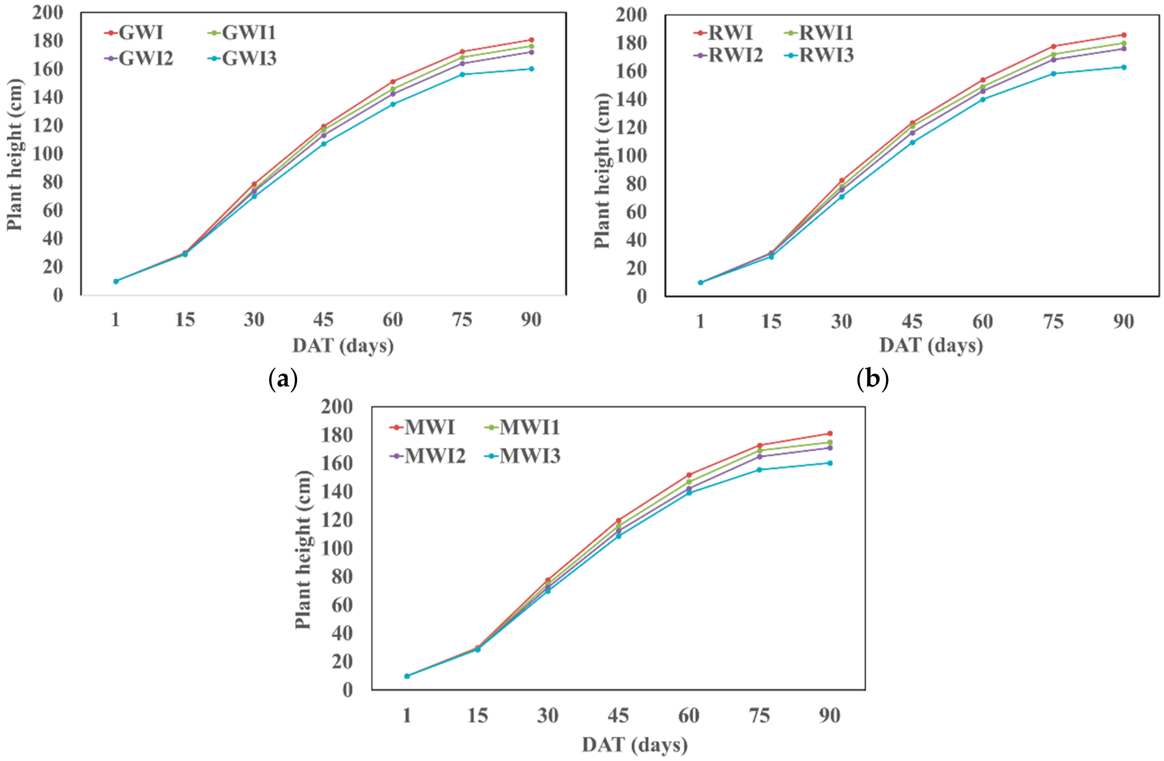


(**c**)

Figure 2. Applied GW (**a**), RW (**b**) and MW (**c**) throughout the growing season for different DI level in experimental year 2017–2018.

3.2. Crop Growth and Development

Figure 3a–c shows how PH varied across different treatments with time when choosing GW, RW and MW as WQ. A similar trend was observed in all treatment despite of the WQ in both experimental years. The general observation from Figure 3 showed that the extent of applied DI impacted PH; i.e., a higher DI level (more water stress) resulted in lower PH and vice-versa. After 90 DAT, PH reached a maximum and remained nearly constant.

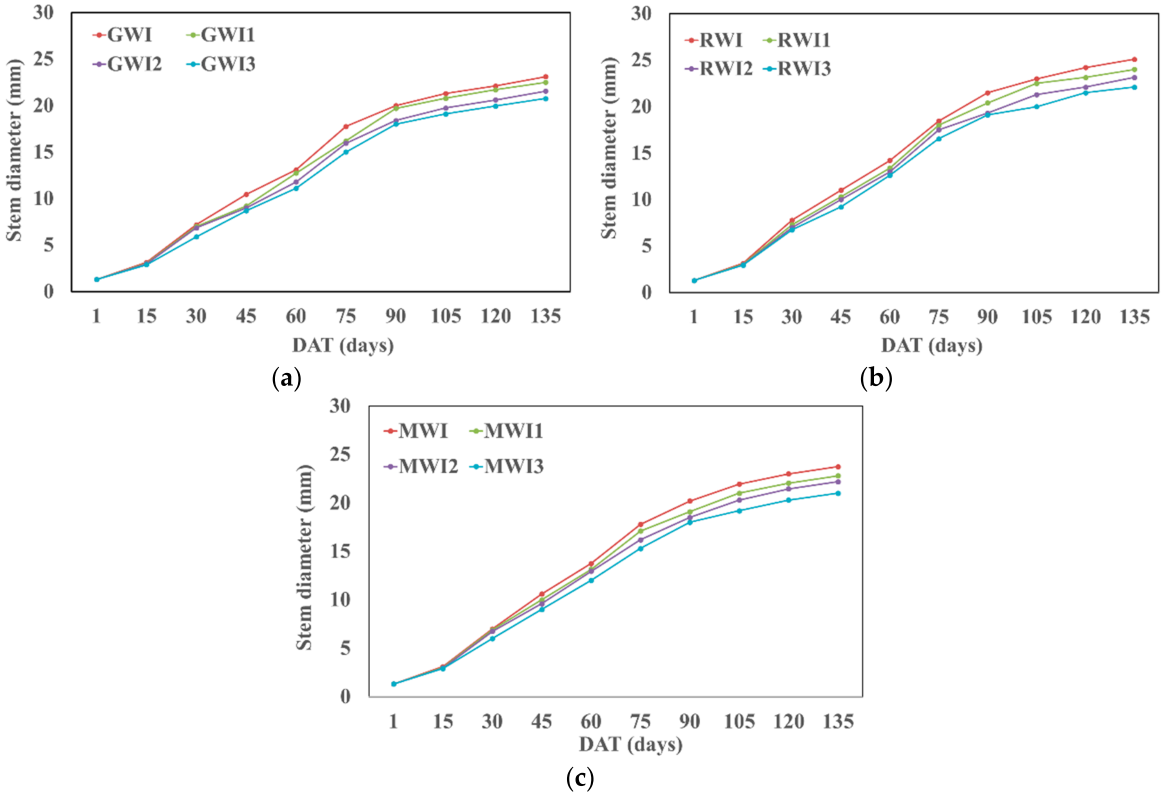


(**a**) (**b**)

(**c**)

Figure 3. Plant height variation under different DI levels of GW (**a**), RW (**b**) and MW (**c**) in experimental year 2017–2018.

The variation of SD across different treatments throughout the cropping season is presented in Figure 4a–c. The general observation from Figure 4 is that DI affected SD: higher DI levels resulted in a smaller SD indicating that like PH, SD is adversely impacted by water stress. Similarly, after 90 DAT, SD, like PH, reached a maximum and remained nearly constant until the end of the harvesting period.



(**a**)

(**b**)

(**c**)

Figure 4. Stem diameter variation under different treatments of GW (**a**), RW (**b**) and MW (**c**) in experimental year 2017–2018.

Significance tests were conducted for PH and SD at 30 days, 60 days and 90 days of DAT. It is found that WQ and DI level both had significant effects (at 5% level) on PH in each experimental year. The variation of PH in same treatment in 2017–2018 was not significantly different from that in 2018–2019. Table 4 indicates that PH under RWI was the highest (at 90 DAT) in both experimental years and was significantly greater than GW and MW. The highest value was 184.6 cm followed by MWI (180.1 cm) and GWI (180 cm). The lowest PH was recorded in MWI_3 (161.3 cm), just smaller than GWI_3 (163.2 cm) and RWI_3 (164.4 cm). Plant height of GWI and MWI were not significantly different indicating that when water is supplied to satisfy full FC level, greenhouse tomatoes grow equally well with both GW and MW. At 80% FC level, the values of average PH measured at 90 DAT were 174.3 cm, 180.5 cm and 173.9 cm for GW, RW and MW, respectively. These values for GW and MW were statistically similar but different to RW. In terms of WQ, plants were taller at RW treatments compared to GW and MW at same DI level.

Table 4. Plant height and stem diameter at 30, 60 and 90 DAT for 12 experimental treatments.

Year	T	PH (cm)			SD (mm)		
		30 Days	**60 Days**	**90 Days**	**30 Days**	**60 Days**	**90 Days**
2017–2018	GWI	78.80 ± 0.46b	151.2 ± 0.66b	180.73 ± 0.61b	7.20 ± 0.06bc	13.1 ± 0.23d	20.0 ± 0.12c
	GWI_1	75.0 ± 0.58cd	146.0 ± 0.58d	176.2 ± 0.55c	7.00 ± 0.06cd	12.8 ± 0.06ef	19.7 ± 0.12d
	GWI_2	73.53 ± 0.58de	142.5 ± 0.52e	172.0 ± 0.58d	6.85 ± 0.06de	11.8 ± 0.03g	18.4 ± 0.23f
	GWI_3	70.23 ± 0.85f	135.2 ± 0.52g	162.2 ± 0.52f	5.90 ± 0.12f	11.1 ± 0.06h	18.0 ± 0.12g
	RWI	82.50 ± 0.64a	154.3 ± 0.88a	186.0 ± 0.58a	7.80 ± 0.06a	14.2 ± 0.12a	21.5 ± 0.12a
	RWI_1	78.30 ± 0.52b	149.2 ± 0.52c	181.0 ± 0.58b	7.30 ± 0.12b	13.5 ± 0.06c	20.4±0.06b
	RWI_2	75.87 ± 0.58c	146.0 ± 0.58d	176.1 ± 0.52c	7.00 ± 0.12cd	13.0 ± 0.06d	19.3 ± 0.12e
	RWI_3	71.00 ± 0.58f	140.1± 0.58f	163.0 ± 0.58e	6.75 ± 0.02e	12.6 ± 0.03f	19.1 ± 0.06e
	MWI	77.90 ± 0.64b	152.0 ± 0.58b	181.3 ± 0.64b	7.00 ± 0.03cd	13.8 ± 0.02b	20.2 ± 0.06bc
	MWI_1	75.00 ± 0.58cd	147.1 ± 0.52d	175.0 ± 0.58c	6.90 ± 0.00de	13.2 ± 0.03d	19.1 ± 0.12e
	MWI_2	72.60 ± 0.35e	142.3 ± 0.52e	171.13 ± 0.55d	6.75 ± 0.03e	13.0 ± 0.03de	18.5 ± 0.17f
	MWI_3	70.10 ± 0.35f	139.2 ± 0.52f	160.4 ± 0.52f	6.00 ± 0.12f	12.0 ± 0.09g	18.0 ± 0.12g
2018–2019	GWI	81.20 ± 0.64b	151.4 ± 0.89a	179.3 ± 0.58b	8.0 ± 0.03b	14.95 ± 0.01a	22.35 ± 0.02b
	GWI_1	77.3 ± 0.52de	147.0 ± 0.58c	172.4 ± 0.58c	7.15 ± 0.02d	13.21 ± 0.01e	20.30 ± 0.17f
	GWI_2	75.2 ± 0.58f	142.5 ± 0.61de	168.9 ± 0.55d	7.00 ± 0.01e	12.78 ± 0.01g	18.95 ± 0.01i
	GWI_3	72.50 ± 0.29g	135.2 ± 0.61f	164.3 ± 0.55f	6.75 ± 0.1h	11.89 ± 0.01i	18.34 ± 0.01j
	RWI	83.2 ± 0.12a	152.3 ± 0.55a	183.2 ± 0.52a	8.05 ± 0.01a	14.98 ± 0.01a	23.40 ± 0.02a
	RWI_1	80.1 ± 0.55c	148.3 ± 0.52bc	180.0 ± 0.55b	7.22 ± 0.01c	13.25 ± 0.02e	20.99 ± 0.02d
	RWI_2	76.40 ± 0.46ef	143.2 ± 0.55d	172.33 ± 0.52c	6.95 ± 0.02f	12.87 ± 0.01f	20.18 ± 0.02f
	RWI_3	73.13 ± 0.61g	141.5 ± 0.55e	165.8 ± 0.61ef	6.81 ± 0.01g	12.05 ± 0.01h	19.67 ± 0.01g
	MWI	82.0 ± 0.58ab	151.5 ± 0.58a	179.0 ± 0.61b	7.99 ± 0.01b	14.29 ± 0.02b	22.40 ± 0.02b
	MWI_1	78.2 ± 0.52d	149.0 ± 0.58b	172.8 ± 0.91c	6.98 ± 0.01ef	14.12 ± 0.02c	21.54 ± 0.02c
	MWI_2	75.23 ± 0.58f	144.2 ± 0.61d	166.97 ± 0.52e	6.82 ± 0.01g	13.76 ± 0.02d	20.51 ± 0.01e
	MWI_3	73.03 ± 0.58g	141.4 ± 0.64e	162.2 ± 0.49g	6.43 ± 0.01i	12.86 ± 0.2f	19.20 ± 0.12h

Note: Values are given means ± standard error of the mean. The same letter following the values within the same column indicates nonsignificant differences between the treatments, whereas different letters show significant difference (95% confidence).

Also, results showed that both WQ and DI levels individually had significant effects (at 5% level) on SD. The value of SD in same treatment in 2017–2018 was not significantly different from that in 2018–2019 which indicates the accuracy of experiment conducted. Table 4 confers that like PH, the SD under RWI was significantly higher at 90 DAT with that of GW and MW. The highest value was 22.5 mm (average of 2017–2018 and 2018–2019) followed by MWI (21.3 mm, average of 2017–2018 and 2018–2019) and GWI (21.20 mm, average of 2017–2018 and 2018–2019). The lowest value was monitored for GWI_3 (18.0 mm, 2017–2018), just lower than MWI_3 (18.05 mm, 2017–2018) and RWI_3 (19.1 mm, 2017–2018). Further, and again like PH, it was found that SD of GWI and MWI were not significantly different indicating that when water was supplied to satisfy FC, greenhouse tomatoes grow equally well with both GW and MW. However, consistently, plants irrigated by RW had a larger SD than the plants irrigated with GW or MW at the same water deficit level.

This study indicated that morphological characteristics (particularly PH and SD) of greenhouse-grown tomatoes were adversely affected in water-stressed scenarios. DI hampers crop growth because of reduction in photosynthesis process [52]. Abayomi et al. [53] and Ahmed et al. [54] reported that water supply restriction reduces leaf growth mechanism which ultimately affects plant photosynthesis and crop development. Also, [55] showed that carbon fixation, leaf area and chlorophyll content get reduced in DI conditions, which play major role in photosynthesis and plant morphology.

3.3. *Yield*

Harvesting of fruits started at 77 DAT in the year 2017–2018 and 79 DAT in 2018–2019. In first experimental year, total harvesting period was 55 days with 20 picking events, while it was 57 days with 21 total harvesting number in second experimental year. In both years, the control treatments (GWI, RWI and MWI) were ready to be harvested before the other treatments. DI treatments maintaining SMC at 80% and 70% FC were not ready for harvesting for another two days while treatments with 60% FC were delayed by five days. This suggests that watering with full irrigation results in earlier harvesting than when DI is applied although the delay was only a few days.

The result showed that WQ and DI levels both had significant effects on the crop yield per plant at 5% level of significance (indicated by * symbol in table), however, their interactive effect was nonsignificant (Table 5).

Table 5. Output of the two-way ANOVA for yield per plant under four irrigation scenarios (DI), three water qualities (WQ) and their interactions (WQ × DI).

Component	Year	Source	Df	SS	MS	F	P	Remarks
Yield	2017–2018	WQ	2	0.277	0.139	22.583	0.000	*
		DI	3	7.436	2.479	403.586	0.000	*
		WQ × DI	6	0.090	0.015	2.437	0.055	
	2018–2019	WQ	2	0.262	0.131	15.689	0.000	*
		DI	3	5.303	1.768	211.822	0.000	*
		WQ ×DI	6	0.124	0.021	2.470	0.053	

Note: * = Significantly different at 5% level of significance, Df = Degree of freedom, SS = Sum of square, MS = Mean square, F = F-value, P = P-value

Table 6 designated that the mean value of yield resulting from same treatment in 2017–2018 was not significantly different from that in 2018–2019, which proves the accuracy of experiment conducted. The total yields were recorded in the range of 2.63 kg/plant (GWI_3, average of 2017–2018 and 2018–2019) to 3.88 kg/plant (RWI, average of 2017–2018 and 2018–2019). The results indicated that irrigating greenhouse tomato crops with RW and maintaining soil moisture at 100% FC could produce the highest yield (3.88 kg/plant, average of 2017–2018 and 2018–2019) followed by GWI (3.79 kg/plant, average of 2017–2018 and 2018–2019) and MWI (3.68 kg/plant, 2017–2018 and 2018–2019) respectively. The lowest production was resulted from GWI_3 (2.63 kg/plant, average of 2017–2018 and 2018–2019) just lower than MWI_3 (2.68 kg/plant, average of 2017–2018 and 2018–2019) and RWI_3 (2.81 kg/plant, average of 2017–2018 and 2018–2019). The average production loss due to irrigation deficiency in treatments GWI_1, GWI_2 and GWI_3 was 7.7%, 25% and 45% respectively compared to the control treatment. These values for RW were 6.4%, 18.5%, 38.5%, while for MW they were 3.9%, 20.8% and 37.9%. The result of this study about production loss is consistent with [45] for cultivar *Zhongyang-9999*; [56] for cultivar *Virosa* and [57] for cultivar *F1 Fantastic*. RW was found to be a better option than GW and MW for achieving higher yield at the same water deficit level. One of the main reasons behind this result could be that the RW taken in this experiment contained higher levels of nutrients than the GW and MW (Table 1).

Table 6. Descriptive statistics of yield per plant across three water qualities and four irrigation scenarios in experimental year 2017–2018 and 2018–2019.

Treatment	Yield Per Plant (kg)	
	2017–2018	2018–2019
GWI	3.60 ± 0.05ab	3.98 ± 0.06ab
GWI_1	3.26 ± 0.05c	3.79 ± 0.05c
GWI_2	2.60 ± 0.03e	3.54 ± 0.05d
GWI_3	2.33 ± 0.03f	2.93 ± 0.06f
RWI	3.71 ± 0.05a	4.05 ± 0.06a
RWI_1	3.38 ± 0.05c	3.94 ± 0.06ab
RWI_2	2.90 ± 0.05d	3.72 ± 0.05c
RWI_3	2.62 ± 0.05e	3.00 ± 0.06f
MWI	3.52 ± 0.06b	3.84 ± 0.06bc
MWI_1	3.32 ± 0.06c	3.77 ± 0.04c
MWI_2	2.80 ± 0.02d	3.31 ± 0.05e
MWI_3	2.41 ± 0.03f	2.96 ± 0.03f

Note: Values are given means ± standard error of the mean. The same letter following the values within the same column indicates nonsignificant differences between the treatments, whereas different letters show significant difference (95% confidence).

While comparing yield of same treatments in two years, it was found small difference (nonsignificant) in most of the treatments. However, some treatments (GWI2, RWI2 and MWI2) had a large difference in yield. The main reason was due to attack of blight disease and leaf sucking insects (which was solved after a week with the help of senior agricultural officer) to some plants at initial stage, the yield was little bit reduced in first experimental year. However, due to experience gained and more precautions provided, the problem did not occur in the second year. This was the major reason for the increased yield in second year as compared to first year in above three treatments.

Savic et al. [43] argued that DI would be profitable only in the areas where irrigation water is relatively expensive and limited. Based on reduced overall performance following the application of DI at 50% of leaf water potential, [56] recommended not to introduce water stress during the flowering and fruit setting stages of greenhouse tomatoes. They found 45% less yield under DI compared to full irrigation and commented that the DI as a water management alternative was only effective in water-limiting conditions. Chen et al. [13] demonstrated that tomato yield in greenhouse facilities was not significantly reduced when regulated deficit irrigation at 66% of full irrigation was applied at the seedling stage. In their study, 6–7% yield loss was reported in DI for cultivars *Jinzuan-3* and *Taikung-1*, respectively, in the sandy loam soil. Though IWUE can be increased when DI is applied; the crop development process can be negatively affected due to decreased photosynthesis rate at reduced evapotranspiration and carbon availability, resulting in reduced yield [25,26,47]. However, for producing crops in water scarce regions, it is more profitable to improve IWUE than just focusing on better yield [58].

Figure 5 demonstrates that greenhouse tomato yield was greater for lower levels or no DI application. This study confirmed the findings of [13] who reported that water applied had a linear relationship to yield in tomato production. Also, Patanè and Cosentino [29] found that fruit yield was inversely proportional to the amount of water stress (deficit) applied, establishing that the crop yield of greenhouse tomatoes will decrease as the water deficit increases. From Figure 5, it can be postulated that greenhouse the tomato is a highly water-dependent horticultural crop.

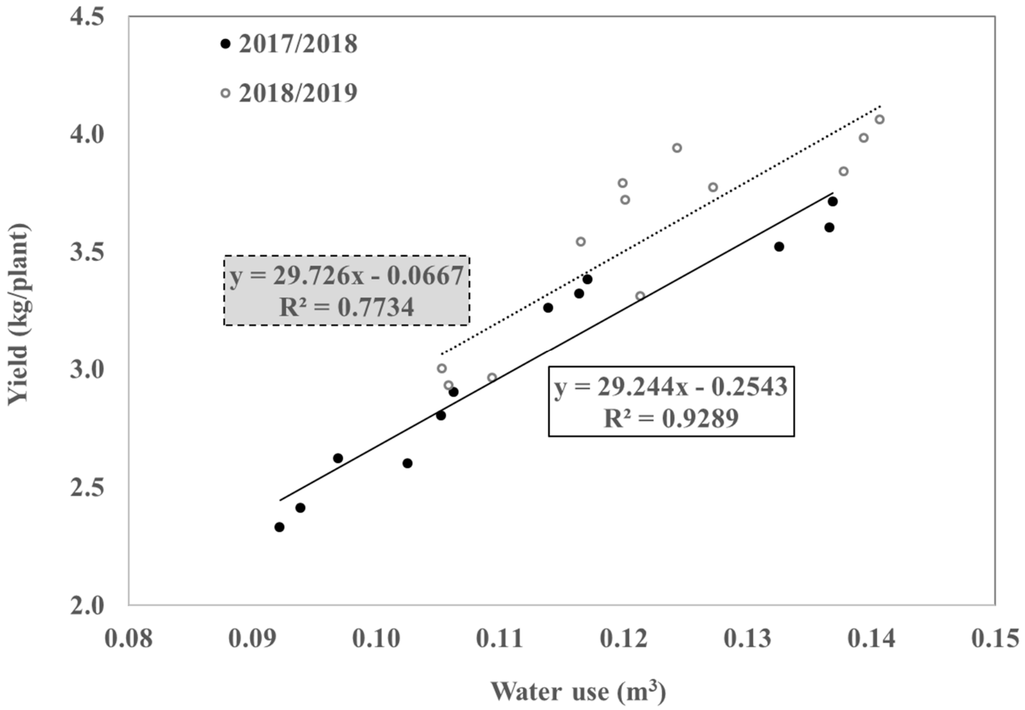


Figure 5. The correlation between applied water and yields in 2017–2018 and 2018–2019.

3.4. Irrigation Water Use Efficiency and Marginal Productivity

A two-way ANOVA (Table 7) showed that both WQ and DI had significant effects on IWUE and MP of greenhouse tomatoes at the 5% level of significance (indicated by * symbol in table); however, their interactive effect was nonsignificant.

Table 7. Output of the two-way ANOVA for IWUE and MP under three water qualities (WQ), four irrigation scenarios (DI), and their interactions (WQ × DI).

Component	Year	Source	Df	SS	MS	F	P	Remarks
IWUE	2017–2018	WQ	2	9.960	4.980	10.631	0.000	*
		DI	3	38.869	12.956	27.656	0.000	*
		WQ × DI	6	4.160	0.693	1.480	0.227	
	2018–2019	WQ	2	26.592	13.296	25.995	0.000	*
		DI	3	53.552	17.851	34.899	0.000	*
		WQ × DI	6	8.623	1.437	2.810	0.057	
MP	2017–2018	WQ	2	146.853	73.427	10.669	0.000	*
		DI	3	4425.955	1475.318	214.372	0.000	*
		WQ × DI	6	102.940	17.157	2.493	0.051	
	2018–2019	WQ	2	93.913	46.957	4.220	0.027	*
		DI	3	5068.074	1689.358	151.808	0.000	*
		WQ × DI	6	233.583	38.930	3.498	0.125	

Note: * = Significantly different at 5% level of significance.

Table 8 indicated that IWUE was highest for RWI_1 (30.33 kg/m^3; average of 2017–2018 and 2018–2019) and lowest for GWI_3 (26.37 kg/m^3; average of 2017–2018 and 2018–2019) and both values were statistically significant with each other at 5% level of significance. With regards to water quality, RW showed a higher IWUE compared to GW and MW at same DI level. This is because more yield was produced under RW treatment while consuming nearly equal amount of water in comparison with GW and MW. In both experimental years, the trend showed that IWUE reached highest at 80% FC level, then started to decrease. For 80% FC treatment, the average increase in IWUE was 9.5% compared to control for GW; 8.7% for RW and 7.0% for MW. Similar result was observed for [34] for cultivar *Yazhoufenwang* (maintaining DI level at 75% of full irrigation). Bogale et al. [36] reported that the yield reduction of the tomato cultivar *Cochoro* was 35% under a DI regime (supplying 50% water of full irrigation) and resulted in a 19% improvement in IWUE. Savic et al. [43] examined regulated deficit irrigation on two cultivars named *Cedrico* and *Abellus F1* and found that 47% of water was saved for *Cedrico* whereas this value was 41% for *Abellus F1* compared to full irrigation. It reflects that different cultivars of greenhouse tomato respond differently to DI and hence, cultivar selection can play an important role in the application of such a strategy. DI can save up to 50% of water requirements with a yield reduction of nine to 46% depending on the magnitude of water stress level [26,57]. Also, the analyzed result of this study inferred that by applying irrigation maintaining SMC at 80% FC, 18% water can be saved in GWI_1; 14.6% water can be saved in RWI_1 and 8.6% in water savings occur in MWI_1 with respect to control treatments, which shows the importance of DI in water scarce regions.

Table 8. Descriptive statistics of IWUE and MP across three water qualities and four irrigation scenarios in experimental year 2017–2018 and 2018–2019.

Years	Treatment	Water Applied (m^3/Plant)	IWUE (kg/m^3)	MP (kg/m^3)
2017–2018	GWI	0.137	26.28 ± 0.38bcd	Control
	GWI_1	0.114	28.60 ± 0.41a	15.45 ± 2.1c
	GWI_2	0.103	25.24 ± 0.28de	29.41 ± 0.85a
	GWI_3	0.092	25.11 ± 0.38e	29.45 ± 0.40a
	RWI	0.137	27.08 ± 0.38b	Control
	RWI_1	0.117	28.89 ± 0.39a	16.00 ± 2.31c
	RWI_2	0.106	27.36 ± 0.49b	25.81 ± 1.68ab
	RWI_3	0.097	27.01 ± 0.48b	27.00 ± 1.15a
	MWI	0.133	26.47 ± 0.43bc	Control
	MWI_1	0.116	28.45 ± 0.50a	7.06 ± 3.40d
	MWI_2	0.105	26.67 ± 0.22bc	22.14 ± 0.82b
	MWI_3	0.094	25.64 ± 0.31cde	25.90 ± 0.74a
2018–2019	GWI	0.139	28.73 ± 0.34de	Control
	GWI_1	0.120	31.58 ± 0.43a	10.00 ± 2.73c
	GWI_2	0.117	30.26 ± 0.35bc	20.00 ± 1.84b
	GWI_3	0.106	27.64 ± 0.54ef	31.82 ± 1.75a
	RWI	0.141	28.75 ± 0.41de	Control
	RWI_1	0.124	31.77 ± 0.47a	7.06 ± 3.40c
	RWI_2	0.120	31.00 ± 0.38ab	16.19 ± 2.20b
	RWI_3	0.105	28.57 ± 0.55de	29.44 ± 1.60a
	MWI	0.138	27.87 ± 0.29ef	Control
	MWI_1	0.127	29.69 ± 0.32cd	7.88 ± 2.48d
	MWI_2	0.121	27.33 ± 0.45f	30.00 ± 2.12a
	MWI_3	0.109	27.16 ± 0.32f	30.57 ± 1.00a

Note: Values are given as means ± standard error. The same letter following the values within the same column, separately to each growth season indicates a nonsignificant value between the treatments, whereas different letters show significant difference at 95% confidence level.

Figure 6 shows that the IWUE of greenhouse tomatoes examined and the volume of applied water in this study indicate a quadratic function relationship which is also consistent with the findings of [35] who did experiment on DI with tomato cultivar *Tunhe No. 2*. As shown in Figure 6, more applied water at the early stages leads to higher IWUE. The rising trend continued up to 0.115 m^3/plant in the year 2017–2018 and up to 0.125 m^3/plant in the year 2018–2019. However, further applied water led to reduction of IWUE from the peak. This shows to achieve a higher IWUE does not necessarily mean more irrigation water should be applied but optimum level of applied water leads to an optimum level of yield (not necessarily the maximum yield). Davies et al. [59] and Obreza et al. [60] reported that DI strategies decrease transpiration rate in plant; causing reduction in leaf area and stomatal openings which ultimately improve IWUE. In water-limiting conditions, farmers should distill their efforts to maximize net income per unit of water used rather than per unit of land by selecting water-saving irrigation methods, like the DI, which generally increases IWUE [61].

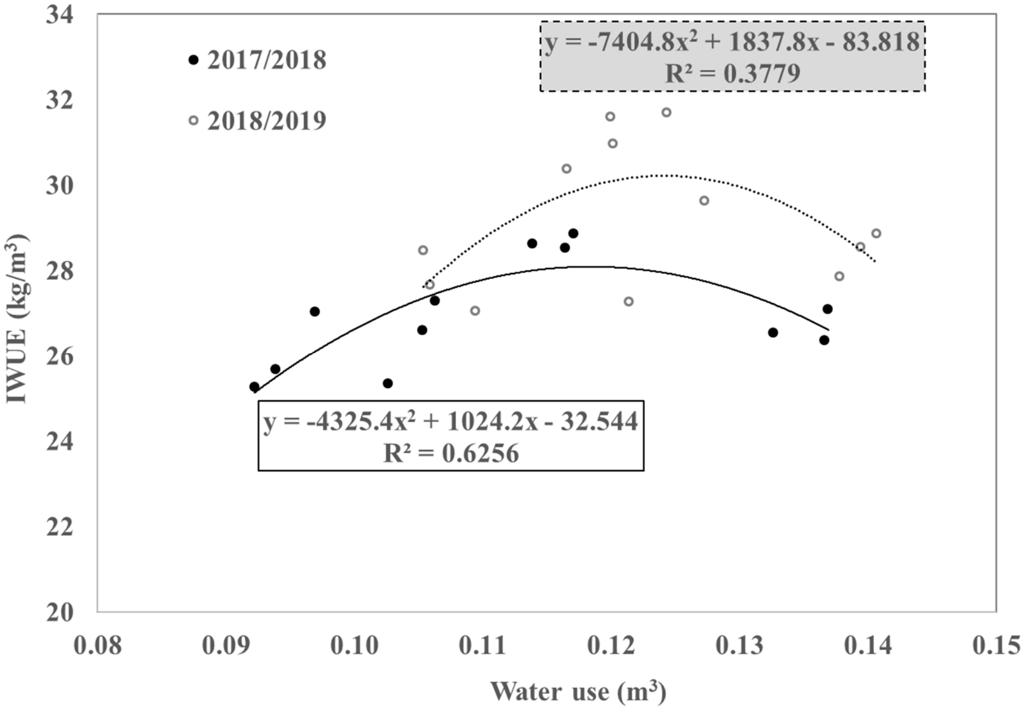


Figure 6. The effect of applied water on IWUE of greenhouse tomato in 2017–2018 and 2018–2019.

The results in Table 8 indicated the highest value of MP was monitored in GWI_3 (30.63 kg/m^3, average of 2017–2018 and 2018–2019), followed by RWI_3 and MWI_3 (28.23 kg/m3, average of 2017–2018 and 2018–2019). However, these values were statistically similar indicating that MP resulted by maintaining SMC at 60% FC level was not significantly different, irrespective of water quality. The lowest strength of MP was measured in MWI_1 (7.50 kg/m^3, average of 2017–2018 and 2018–2019), just lower than RWI_1 (11.53 kg/m^3, average of 2017–2018 and 2018–2019) and GWI_1 (12.72 kg/m^3, average of 2017–2018 and 2018–2019). These lowest values for MW was statistically different to GW and RW (Table 8). In both experimental years, the trend showed that MP follows an increasing trend with increasing level of DI or more deficit strategy. It showed that MP and DI have a proportional relationship.

4. Conclusions

The overall aim of this study was to evaluate the effects of varying irrigation deficiency levels and water quality for greenhouse-grown tomatoes and to establish an optimum deficit level. Plant height, stem diameter, yield and water productivity (particularly IWUE and MP) were measured for this purpose. The study demonstrated that the pattern of effects attributed to DI level and water quality in both experimental years was almost identical in terms of plant growth characteristics, yield and water productivity. A vital element of this paper is to establish the credibility in the eyes of growers and farm managers who use nonconventional sources of water in agriculture and where water has been a scarce resource. The paper's "novel contribution" is its finding that by using recycled wastewater as an irrigation source, crop yield and irrigation water use efficiency can be increased compared to mixed water and conventional groundwater. In this study, recycled wastewater showed superior performance (plant height, stem diameter, yield and irrigation water use efficiency) to groundwater and mixed water for tomato production at same DI level. The major reason could be that the recycled wastewater contains more nutrients than other water sources, which is a crucial factor for crop production. Also, applying DI maintained the soil moisture content at 80% FC, thus was found to be the most water-efficient irrigation application (highest IWUE) among the various 12 treatments, despite the water quality. Thus, by applying this particular deficit irrigation strategy (soil moisture content maintaining 80%

FC) with recycled wastewater, growers can save a considerable amount of water without a significant yield reduction.

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