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Assessing Reliability of Recycled Water in Wicking Beds for Sustainable Urban Agriculture

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Abstract: Urban agriculture requires sustainable solutions to secure its water resources. A wicking bed (WB) is a simple system that could provide high yield and water use efficiency. This single trial glasshouse study compares the performance of a WB and surface irrigation (SI) system for growing tomatoes (*Solanum lycopersicum* L.) using fresh (FW) and recycled water (RW). The performance of both treatments was compared when irrigating 2 days per week and for two environmental conditions (indoor and outdoor). In addition, the reliability of using FW and RW at a 7-day irrigation interval was studied for WBs alone. Results showed that the irrigation water use efficiency (kg/m³) and the yield (kg/plant) are significantly different only between WB (FW) and SI (RW) considering all conditions. The accumulation of salts and the sodium absorption ratio (SAR) were high in the surface layer of WBs compared to SI. This indicates that the use of RW affects the level of salinity and sodicity in soil, which in turn may decrease the yield. However, WBs perform similar to, if not better than, SI with FW. The WBs show the advantage of reducing the leachate of nutrients into groundwater, compared to SI systems. Further research into irrigation and nutrient management in WBs to reduce the effect of salinity at the surface is recommended to increase the efficiency of the system.

Keywords: irrigation; salinity; urban agriculture; wicking bed; water use efficiency; yield; water quality; sustainable



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1. Introduction

Countries must implement efficient irrigation systems to promote environmental sustainability and food security. Community, rooftop, and home gardens are widely accepted and are becoming increasingly popular, even in many developed cities, as they provide environmental, economic, and social benefits such as self-satisfaction, financial support, and healthy and safe foods.

Even though urban agriculture has great potential benefits [1], it also faces numerous challenges. These include availability of water, salinity in the soil, and soil contamination. One study showed that some inner-city vacant lands are too contaminated due to past uses and are not usable to grow crops safely without incurring prohibitively high remediation costs [2]. Another drawback in urban agriculture is the space availability [3]. People who live in densely populated cities or in apartments and high rise buildings often do not have the space and sunlight to grow edible plants. The space availability is further restricted due to infrastructure and urban development projects. Accordingly, open residential yards (front or back) offer potential plots to grow crops in most cities.

Despite space limitations, researchers have shown that urban agriculture has great potential to provide food production, contributing to self-sufficiency of city dwellers [1,4] by increasing the intensity of local food supply through future planning, policy-making, and proper management techniques [5,6]. Alternative farming methods such as community

gardens, greenhouses, vertical farms, roof gardens, or plant factories have been proposed as potential solutions for the land limitation issues [4,7]. Recent studies and experiments have taken place to develop hydroponic techniques to grow food vertically, which is known as vertical farming or sky farming [8].

Season changes and extreme weather patterns may restrict plant growth throughout the year, limiting the availability of fresh produce during the winter season. One of the main restrictions to urban agriculture in dry climates is water availability. Potable water is the main source of water used in many cities for irrigating the crops. Recycled water is a supplement to municipal water, but it is not readily available in most cities or countries. Accordingly, it is crucial to develop best practice technologies and approaches to conserve water resources and to upkeep the environmental sustainability.

Capillary irrigation systems have been investigated for some years as a method to deliver water to plants in container gardens. The wicking bed (WB) is not a new technology, but uses a new approach to deliver water to plants using capillary action. Although the concept is similar, the hydroponic and WB systems are different. The WB is comprised of a saturated media-filled reservoir beneath the unsaturated soil (root zone). Water is delivered by capillary action to the root zone in response to the rate of water uptake by the plant. Under this system, in theory, each plant should get precisely the right amount of water to meet its evapotranspiration (ET) needs over time. WBs are gaining popularity among the gardening community because they are relatively simple and scalable. WBs could also be installed in varied urban settings, even in places where space or soil quality is a restriction.

Despite increasing enthusiasm and claims about the performance of WBs, there is no comprehensive study to investigate their efficiency in terms of water use, environmental impact and labour. Sullivan et al. [9] showed that capillary-based subirrigation systems may have a higher yield and lower maintenance than other container gardening systems. Accordingly, Semananda et al. [10,11], in their research, for the first time, showed that WBs could provide high yield and water use efficiency (WUE). Further, an extensive literature review in this context was conducted [12] but was unable to find any published research supporting the design or recommendations for WB systems. Accordingly, a substantial knowledge gap exists relating to the WBs, specifically the engineering design, irrigation water use efficiency (iWUE), and related environmental benefits.

The present paper addresses the knowledge gap by assessing, for the first time, soil–water–plant relations in the WB system with the use of recycled water. Specifically, in this study, we assess the effect of water quality (fresh vs. recycled) and different irrigation treatments (SI vs. WB) on the soil health including accumulation of salt, as well as plant growth, iWUE, and crop yield. The WB's performance is evaluated relative to corresponding surface irrigated (SI) treatments, in order to investigate the potential for WBs to improve urban agriculture's contribution to environmental sustainability and food security.

2. Materials and Methods

2.1. Experimental Conditions

The experiment was conducted under both glasshouse and open environment conditions at the University of South Australia's Mawson Lakes campus located in Adelaide, South Australia (34.81° S, 138.61° E). In the glasshouse, air temperature (± 1 °C) and relative humidity ($\pm 3\%$) were recorded using a USB temperature/humidity data logger (LCD—QP6014, Jaycar Electronics, Adelaide, Australia). Outdoors, rainfall data were logged using a tipping bucket rain gauge (RIM8020) fixed at the university premises. The accuracy of the rain gauge was $\pm 2\%$ up to 200 mm/hr. Outdoor temperature and relative humidity (RH) were collected (daily data) from the nearest Australian Bureau of Meteorology weather station, Parafield Airport (Gauge 023013), located about 1 km from the study site.

2.2. Experimental Design and Treatments

The experiment was set up to compare the soil–water–plant relations between WBs and SI pots using two water qualities (freshwater (FW), recycled water (RW)), two soil areas (30 cm and 56 cm diameter), two irrigation water scenarios (2 days per week (2D) and 7-day intervals (7D)), and two environmental settings (indoor and outdoor). There were 11 irrigation setups, and each treatment was replicated four times, requiring a total of 44 pots. A randomized block design was followed when arranging the pots in each location. The experiment was started on 26 September 2015 and continued for 120 days. The plants were grown using plastic containers with diameters of 30 and 56 cm. WBs were fabricated as the typical arrangement shown in Figure 1. A previous study by the authors using different soil bed depths and reservoir depths showed that a 150-mm reservoir depth (using 10 mm aggregate) and a 300 mm soil bed depth is most suitable for achieving an optimal WUE of medium-rooted plants [10]. Accordingly, the same soil and reservoir depths were used in this experiment. The WB reservoir was filled using 10 mm quartzite aggregate, and a geotextile material was laid as a separation material between the soil and the reservoir. Coarse material was chosen because it has a considerable void content with high permeability, and it is less resistant to water being pulled out from the layers above. Geotextile fabric is used as the separation material because it allows water to penetrate but prevents fine particles from entering the reservoir. For conventional SI treatments, the same size and type of containers were used, but with holes drilled in the base for drainage.

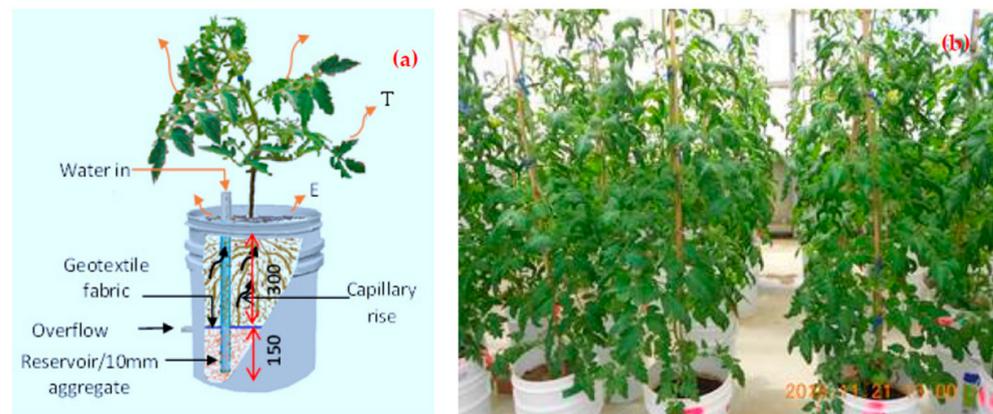


Figure 1. (a) Schematic arrangement of the wicking bed, (b) photograph of plants growing inside glasshouse during the experiment.

Mulching is a soil water management technique to reduce the soil water evaporation, and some studies have shown that scoria can be highly effective as a landscaping material [13,14]. To evaluate the effectiveness of mulch on WBs, treatments were included with and without mulch, where the mulch used was 10 mm scoria gravel (50 mm thick). All outdoor pots (WB and SI) were mulched. In addition, large size WBs (56 cm diameter containers) were arranged to compare the effect of different soil volume on the iWUE and plant growth.

The experimental soil, a commercial mix especially developed for gardening purposes, was purchased from a local supplier. The soil was a poorly graded sandy soil, according to the unified soil classification system (90% sand and <5% fines). It had a field capacity of 30%, porosity of 48%, and dry bulk density of 1.33 g/cm³. One 4-week-old tomato seedling (*Solanum lycopersicum* L., var. 'Mighty red') was transplanted into each bed at the end of the initial growth stage, in accordance with the Food and Agriculture Organization (FAO 56) [15], on 26 September 2015. The tomato plants were irrigated with two different water qualities—FW and RW. The RW at this site was a mixture of recycled wastewater and stormwater delivered by the local RW supplier. The recycled wastewater was sourced from Bolivar wastewater treatment plant and stormwater was harvested and treated through

wetlands to produce this high quality RW. Table 1 outlines chemical parameters of soil and each irrigated water type at the beginning of the experiment.

Table 1. Initial chemical and physical characteristics of the experimental soil and waters.

Soil Properties		Water Properties		
Soil texture	90/5	Element	FW	RW
pH (H ₂ O)	7.57	pH	7.55	7.67
EC _{1:5} (dS/m)	1.75	EC (dS/m)	0.38	1.42
Nitrate NO ₃ (mg/kg)	6.20	Cl (mg/L)	68.75	330.00
Ammonium NO ₃ (mg/kg)	1.23	Total N (TKN + NO _x)	0.15	2.45
Ca (mg/kg)	4659.53	TC (mg/L)	9.50	30.00
Mg (mg/kg)	188.53	Ca (mg/L)	14.50	31.50
K (mg/kg)	376.48	Mg (mg/L)	7.25	24.25
P (mg/kg)	29.00	K (mg/L)	2.50	31.75
Na (mg/kg)	143.08	TP (mg/L)	0.02	0.05
Ca:Mg	15.00	Na (mg/L)	49.25	232.5
		SAR	2.62	7.56

Note: Soil texture is expressed in percentage of sand/fines. FW = fresh tap water, RW = recycled water (a mixture of recycled and storm water).

The irrigation water was directly applied to the subsoil reservoir via the vertical pipe to the WBs at a twice-weekly interval (denoted 2D in treatment codes) (Sunday and Wednesday) or at a weekly interval (denoted 7D) (Sunday only). The SI pots were hand irrigated with the same amount of water applied to the corresponding WB treatments. No SI pots were set up for the 7D interval. A water-soluble fertiliser (22.1N-6.2P-11.7K) was applied with irrigation water, at 5 g/L in 14 d intervals. Irrigation for the large-volume beds was based on the drop in moisture content and the water level in the reservoir. A portable moisture-measuring probe, Diviner 2000[®] [16], was used to measure the soil moisture content during the crop-growing period. The Diviner was calibrated gravimetrically for the experimental soil during the progress of the experiment. The amount of water applied to each irrigation type was recorded manually. The experiment was started by applying an equal amount of FW to the surface to all pots. Ten days after transplanting, watering from the surface was stopped for WBs, and different irrigation scenarios were started. These are listed in Table 2.

Table 2. Different irrigation treatments and irrigation scenarios.

Item No.	Treatment Label	Description
1	T1WF2D	Wicking bed with fresh water, 2-day irrigation interval
2	T2WFM2D	Wicking bed with fresh water, 2-day irrigation interval, surface mulched
3	T3WR2D	Wicking bed with recycled water, 2-day irrigation interval
4	T4SF2D	Surface irrigation treatment with fresh water, same amount in treatment T1, 2-day irrigation interval
5	T5SF1.22D	Surface irrigation treatment with fresh water, 20% extra of treatment T1, 2-day irrigation interval
6	T6SR2D	Surface irrigation treatment with fresh water, same amount in treatment T3, 2-day irrigation interval
7	T7WF7D	Wicking bed with fresh water, 7-day irrigation interval
8	T8WR7D	Wicking bed with recycled water, 7-day irrigation interval
9	T9WFO2D	Surface irrigation treatment with fresh water, outdoor, 2-day irrigation interval
10	T10SFO2D	Surface irrigation treatment with fresh water, same amount in T9, outdoor, 2-day irrigation interval
11	T11WFB	Wicking bed with fresh water in large container

Note: T1–T11—treatments.

2.3. Soil, Water and Plant Tissue Analysis

Water samples were collected from the two types of source water (FW and RW) for analysis at three different stages of the experiment: the beginning, middle, and in the final week. Three soil samples were taken while filling the pots—at the beginning, middle, and end of filling—and were analyzed separately and the results averaged. Soil samples were collected from six treatment types (T1, T3, T4, T6, T7, and T8) and from four depths of each (0–75, 75–150, 150–225, and 225–300 mm) after harvesting to compare the soil salinity, sodicity, and residual nutrients in the soil at the end of the experiment. The most recently matured leaves were collected from each treatment for plant tissue analysis on 20 January 2016, taking three replicates from each treatment (total of 33 samples). Leaf samples were cleaned with deionized water and then dried in an air forced oven at 55 °C. Water quality analysis was conducted according to the guidelines of the American Public Health Association (APHA) standards [17], which also comply with National Environment Protection Measure of National Environment Protection Council, Australia [18]. Soil and plant tissue analysis was carried out according to Australian soil and plant analysis council codes.

The accumulation of salt in the soil was measured in terms of electrical conductivity ($EC_{1:5}$). The water, soil, and plant tissue analysis was carried out at the APAL Agricultural laboratory, South Australia [19]. The presence of a high proportion of sodium (Na^+) ions relative to other cations in soil or water is termed as sodicity and is measured in two forms: sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP). The SAR is the ratio of the concentration of Na^+ (meq/L) to the concentration of Ca^{2+} (meq/L) and Mg^{2+} (meq/L) ions. It is calculated using Equation (1) [20].

$$SAR = Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{1/2} \quad (1)$$

The ESP is usually calculated using Equation (2) [14], p. 36.

$$ESP = (Na^+) \times 100/CEC \quad (2)$$

where, Na^+ is the ionic concentration of Na^+ (meq/L), and CEC is the cation exchange capacity of the soil (meq/L).

2.4. Yield, Fruit Quality, Plant Growth and Water Use Efficiency

Tomato plants were trained to produce one stem and trimmed at the top after six fruiting trusses were formed in each tree. Tomato fruit quality was evaluated using two parameters: fruit weight and diameter. Fruits were handpicked and graded into different marketable and non-marketable grades: small (40 to 55 mm), large (55 to 75 mm), and extra-large (>75 mm) [21]. Fruits that did not fit into the marketable grades above, as well as infected fruits (e.g., blossom end rot), were graded as unmarketable. The total fruit produced by each plant was weighed using a digital balance with an accuracy of ± 0.01 g, and individual fruit height and crosswise diameters were recorded using a Vernier caliper. Plant growth and performance were evaluated fortnightly in terms of plant height, plant stem diameter, and number of leaves. Plant height was recorded from the soil surface. Stem diameter measured 5 cm above the soil.

The iWUE represents the ratio of total yield to the amount of water applied through irrigation. It was calculated using Equation (3) [22]:

$$iWUE = Y/I \quad (3)$$

where, iWUE is the irrigation water use efficiency in kg/m^3 , Y is the yield (kg), and I is the irrigation water (m^3).

2.5. Statistical Analysis

The effects of the different water quality; irrigation method; and irrigation scenarios on yield, iWUE, soil salinity, and sodicity were statistically analyzed using SPSS software Version 22. Levene's test was used to examine the data for normality and homogeneity of variance. The mean differences between the groups were compared using one-way and two-way analysis of variance (ANOVA) to examine the level of effect of water quality; irrigation method; and irrigation scenarios on marketable fruit yield, plant growth, iWUE, soil salinity, and sodicity. When the F-value was statistically significant, a post hoc multiple comparison was performed using Tukey's honest significant difference test at a p -value of 0.05 to evaluate the statistical significance of apparent differences between the groups.

3. Results

3.1. Yield, Plant Growth and Water Use Efficiency

The results were compared between the two main treatment types (SI and WB), between identical indoor and outdoor pots, between different soil volumes, and between different water quality treatments. There was no significant difference in plant height or number of leaves between different treatments within the indoor setting. A significant difference ($p < 0.05$) was observed in plant height and number of leaves between indoor and outdoor settings, for a given irrigation treatment (i.e., WB or SI). However, no significant difference in plant girth was found between the different irrigation settings or treatments. Table 3 compares the estimated marketable yield. There was a significant difference in yield between treatments depending on a variety of parameters. A relatively high marketable yield was obtained in the large soil volume WB, followed by the outdoor, then mulch, no mulch 2D, no mulch 7D, recycled 2D, and recycled 7D.

Table 3. Comparison of yield, total water, and iWUE between irrigation treatments.

Treatment	Marketable Yield (kg/plant)	Total Water (L/plant)	Crop Water Use (L/kg)	iWUE (g/L)
T1 WF2D	1.43 bcd	68.32 d	48.0 b	20.90 ab
T2 WFM2D	1.54 abc	72.52 cd	47.5 b	21.20 a
T3 WR2D	1.04 de	58.38 e	56.5 ab	17.80 abc
T4 SF2D	1.16 cde	68.32 d	59.6 ab	17.00 bc
T5 SF1.22D	1.42 bcd	81.98 b	58.0 ab	17.40 abc
T6 SR2D	0.92 e	58.58 e	66.2 a	15.60 c
T7 WF7D	1.05 de	53.70 e	51.7 ab	19.50 abc
T8 WR7D	0.78 e	43.34 f	63.9 ab	18.10 abc
T9 WFO2D	1.77 ab	86.22 b	48.8 b	20.50 ab
T10 SFO2D	1.63 ab	86.26 b	53.0 ab	19.00 abc
T11 WFB	1.96 a	103.36 a	54.4 ab	19.00 abc

Note: Means within columns followed by different lower case letters are significantly different for irrigation treatments ($p \leq 0.05$). See Table 2 for treatment descriptions.

Figure 2 compares the yield and number of fruits in each size group (defined in Section 2.4) for different treatments. Extra-large fruits were found only in large soil volume WBs. The number of marketable fruits was higher in the small range, except for the large soil volume WB (Figure 2b). The number and weight of fruits in the small fruit grade were higher for RW irrigated treatment. The water uptake by plants with the RW treatment was lower than for the FW treatment and appears approximately correlated to the overall fruit yield.

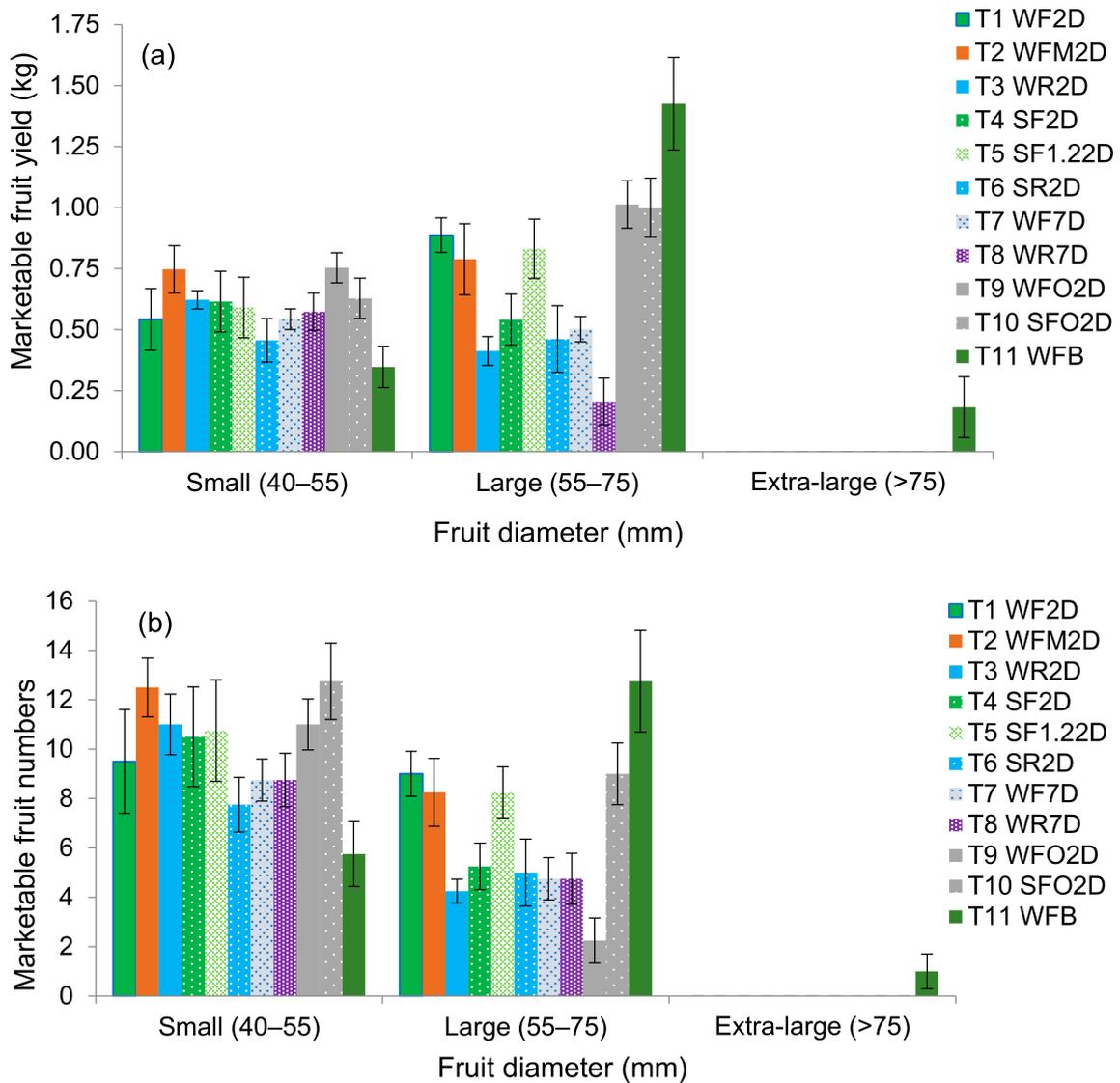


Figure 2. Comparison of (a) marketable yield and (b) number of fruits in each fruit grade. Error bars indicate standard error. See Table 2 for treatment descriptions.

The amount of water applied was kept constant between WB and SI treatments; for example, the amount of water irrigated at each time was based on the water uptake by the plant in the corresponding WB treatment. The amount of rainfall during the growing period was about 3 L per pot and was counted towards the outdoor irrigation treatments. The daily record of temperature and RH at 1500 h for the period of fruiting and harvesting was shown in Figure 3.

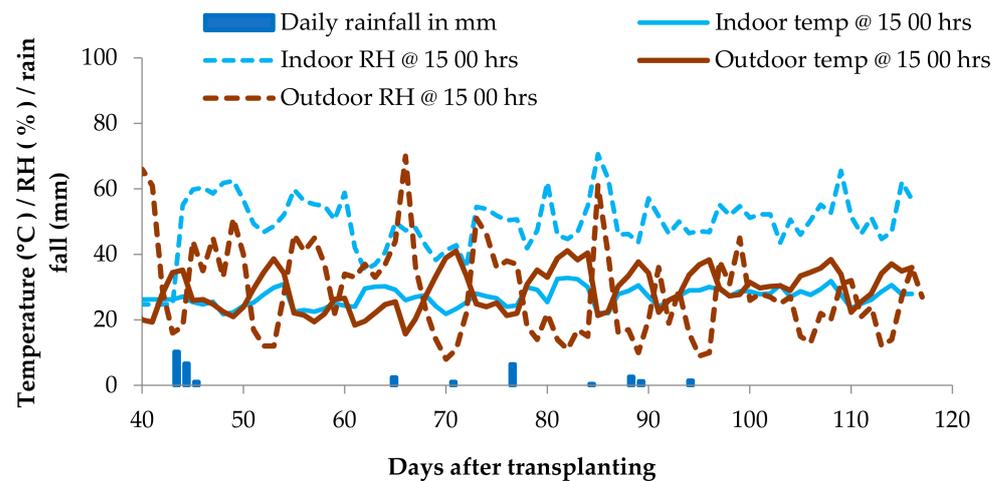


Figure 3. Daily indoor and outdoor air temperature (°C), relative humidity (RH) (%), and rainfall (mm). See Table 2 for treatment descriptions.

Although the iWUE was always higher in wicking treatments than surface treatments, it was mostly not found to be significantly different when comparing relevant pairs of treatments. The only relevant statistically significant difference in iWUE was between a mulched WB (T2 WFM2D) relative to an unmulched surface treatment (T4 SF2D) in glasshouse conditions, where the difference was approximately 25%. In other cases, when comparing relevant treatments, the differences observed were not statistically significant. However, a general pattern has emerged that tends to support higher iWUE in wicking treatments. For instance, in the outdoor treatments (both mulched), the average iWUE was 8% higher in wicking (T9 WFO2D) compared to surface (T10 SFO2D). Using recycled water, wicking (T3 WR2D) treatments gave iWUE on average 14% higher than SI treatments (T6 SR2D). When using RW in WBs (T3 WR2D), the iWUE was 5% higher compared to FW irrigated SI treatments (T4 SF2D). Although the yield was highest in the large soil volume WB (1.96 kg), the iWUE was not significantly different between other FW irrigated WB treatments (Table 3).

The percentage of unmarketable yield in each treatment was calculated as a percentage of the total yield produced (Figure 4). The percentage of rejected fruits was higher in RW and surface irrigated treatments than in wicking treatments. A significantly lower percentage of rejected fruits was produced by large soil volume WBs.

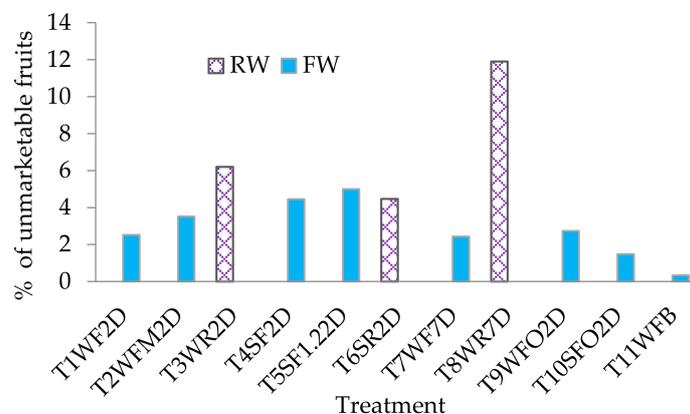


Figure 4. Percentage of unmarketable fruits within each irrigation treatment. RW = recycled water, FW = fresh water. See Table 2 for treatment descriptions.

Although indoor 7D irrigated wicking treatments were irrigated at 7-day intervals during the initial and development stage, it was necessary to top up water to the reservoir

one extra time per week, repeating over a number of weeks during the fruiting stage because the reservoir was observed to be empty. Irrigation scheduling to larger soil volume WBs was based on the drop in moisture content in the soil bed and the water level in the reservoir. Accordingly, the number of irrigation events was significantly lower in WBs using large soil volume (12 events) compared to those using small soil volumes or a smaller reservoir (32 for 2D irrigation and 20 for 7D irrigation). Therefore, this study suggests that WBs with large soil volume are more practical than smaller volumes for growing tomatoes because they can hold a large amount of water, which helps to reduce irrigation frequency (particularly important for manually irrigated WB systems).

Several other physical differences were observed during the experiment. Indoor plants grew faster and taller than outdoor plants, but outdoor plants appeared to be stronger. The distance between consecutive fruit trusses was also larger in indoor plants than outdoor plants, so while they were smaller, the outdoor plants still fruited quite well. Moreover, compared to outdoor plants, the fruit trusses on indoor plants were more prone to breaking under the weight of the fruits. Not surprisingly (given the generally higher maximum temperature and lower RH), outdoor pots used more water than indoor treatments, and reservoirs were mostly found to be nearly empty between 2-day intervals, especially during the harvesting period.

3.2. Salt Accumulation in Soil Layer

Figure 5 shows the EC values in different soil layers of WB and SI treatments at the end of the harvest, taken as an indicator of salt accumulation. The difference in soil EC among the treatments was noticeable in the surface layer (0–75 mm), ranging from a minimum of 0.64 ± 0.16 in FW surface irrigation to a maximum of 2.63 ± 0.12 dS/m in the 2D RW wicking treatments, respectively. The trend changed with an increase in soil depth, as observed by the decreasing difference in soil salinity between the treatments. The difference in EC values in the bottom layer of FW irrigated treatments ranged from 1.4 ± 0.17 to 2.17 ± 0.06 dS/m. FW irrigated SI irrigation pots had significantly lower EC levels in the surface layer; however, they gradually increased and exceeded the salinity of the WBs in the bottom layers. The EC values were always higher at the surface level of the WBs, with a tendency towards higher values when RW was applied. The same change was observed between SI irrigated pots where FW and RW was applied. Although there was a small difference in the EC value at the surface layer between 2D and 7D irrigated wicking treatments, the value was almost the same in the bottom layer for corresponding water qualities.

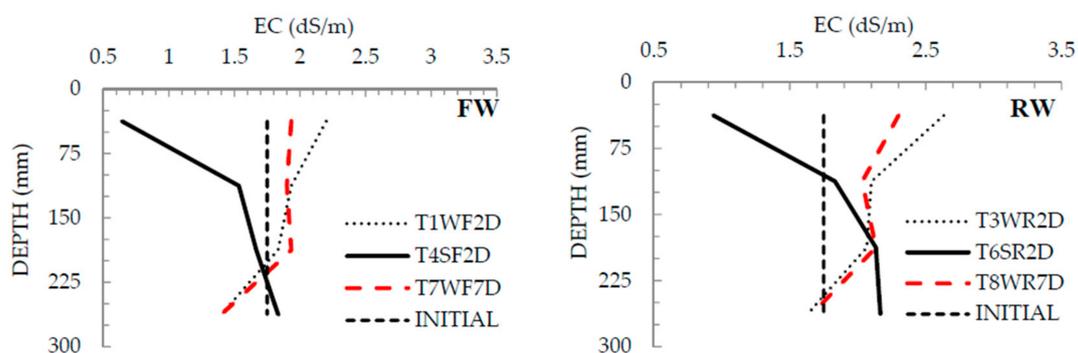


Figure 5. Soil salinity (EC) at different soil depths for fresh water (FW) treatments (left) and recycled water (RW) treatments (right). See Table 2 for treatment descriptions.

The frequent addition of water (2D irrigation) to the reservoir increased the salinity level at the soil surface in both FW and RW cases. Two-way ANOVA showed a significant difference between the main irrigation methods. Tukey's post hoc test showed that the effect of water source on soil EC was highly significant ($p < 0.05$) and EC was always higher in RW irrigated treatments (Table 4). The difference between the main irrigation treatments

decreased up to some distance and reversed at the bottom layer. Thus, the EC level of soil in the surface layer increased in WBs from the initial value by around 26% and doubled in the RW irrigated treatment (50%). The percentage decrease in surface irrigated treatments was 63% and 46% in FW and RW, respectively. Table 5 shows the descriptive statistics for each treatment method. The variation of EC in the mulched soil was not analyzed in this study. However, based on previous studies, we would expect mulch to have the effect of preserving water and reducing salinity and sodicity in the soil when compared to unmulched soils [23,24].

Table 4. Descriptive statistics of soil salinity (EC) between two different water qualities, six irrigation methods, and two irrigation scenarios (each value being a mean of three replicates \pm standard deviation).

Treatment	Water Quality	Mean	Depth (mm)			
			0–75	75–150	150–225	225–300
T1WF2D	FW	1.84 \pm 0.33 a	2.20 \pm 0.10	1.93 \pm 0.06	1.83 \pm 0.21	1.40 \pm 0.20
T3WR2D	RW	2.11 \pm 0.36 b	2.63 \pm 0.12	2.10 \pm 0.00	2.07 \pm 0.06	1.63 \pm 0.06
T4SF2D	FW	1.42 \pm 0.50 c	0.64 \pm 0.16	1.53 \pm 0.25	1.67 \pm 0.15	1.83 \pm 0.06
T6SR2D	RW	1.77 \pm 0.53 a	0.94 \pm 0.16	1.83 \pm 0.06	2.13 \pm 0.12	2.17 \pm 0.06
T7WF7D	FW	1.79 \pm 0.26 a	1.93 \pm 0.12	1.90 \pm 0.10	1.93 \pm 0.06	1.40 \pm 0.17
T8WR7D	RW	2.03 \pm 0.28 b	2.30 \pm 0.30	2.03 \pm 0.06	2.13 \pm 0.06	1.67 \pm 0.15

Note: FW = fresh water, RW = recycled water. Means within columns followed by different lower case letters are significantly different for irrigation treatments ($p \leq 0.05$). See Table 2 for treatment description.

Table 5. Descriptive statistics of soil sodicity (SAR) between two water qualities, six irrigation methods, and two irrigation scenarios (each value being a mean of three replicates \pm standard deviation).

Treatment	Water Quality	Mean	Depth (mm)			
			0–75	75–150	150–225	225–300
T1W 2D	FW	0.70 \pm 0.18 a	0.95 \pm 0.16	0.66 \pm 0.04	0.62 \pm 0.10	0.58 \pm 0.06
T3W 2D	RW	1.52 \pm 0.24 b	1.58 \pm 0.13	1.24 \pm 0.19	1.54 \pm 0.16	1.73 \pm 0.20
T4S 2D	FW	0.47 \pm 0.13 c	0.37 \pm 0.17	0.39 \pm 0.08	0.53 \pm 0.06	0.60 \pm 0.07
T6S 2D	RW	1.46 \pm 0.14 b	1.40 \pm 0.03	1.35 \pm 0.15	1.54 \pm 0.14	1.53 \pm 0.14
T7W 7D	FW	0.63 \pm 0.13 a	0.73 \pm 0.23	0.64 \pm 0.04	0.60 \pm 0.05	0.57 \pm 0.10
T8W 7D	RW	1.20 \pm 0.23 d	1.11 \pm 0.13	0.96 \pm 0.12	1.28 \pm 0.13	1.47 \pm 0.18

Note: FW = fresh water, RW = recycled water. Means within columns followed by different lower case letters are significantly different for irrigation treatments ($p \leq 0.05$). See Table 2 for treatment descriptions.

3.3. Soil Sodicity

The SARs were significantly different between RW and FW irrigation treatments (Figure 6). SAR was significantly higher when irrigated with WBs compared to corresponding SI treatments. The SARs were similar between 2D and 7D irrigated WB treatments. There was no significant difference between FW irrigated WBs for 2D and 7D irrigation scenarios; however, the mean difference was significant for RW application.

The results showed that the irrigation increased the SAR at the soil surface, and the difference was higher with RW application (Figure 7). The SAR difference between the treatments decreased when the depth of the soil increased. Table 5 shows the post hoc comparison of SARs between the treatments and soil depths.

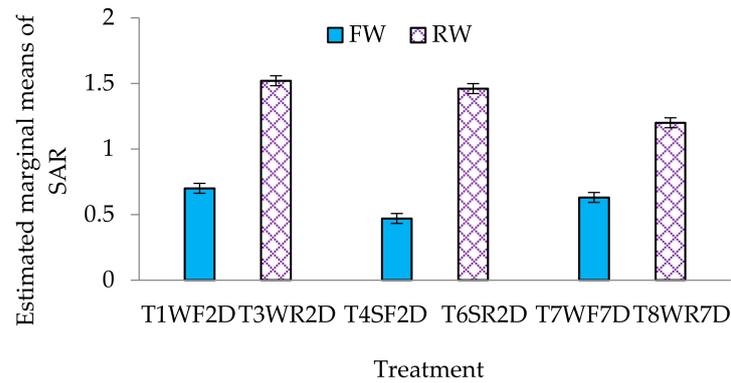


Figure 6. Estimated marginal means of sodium absorption ratio (SAR). FW = fresh water, and RW = recycled water. Error bars indicate standard error. See Table 2 for treatment descriptions.

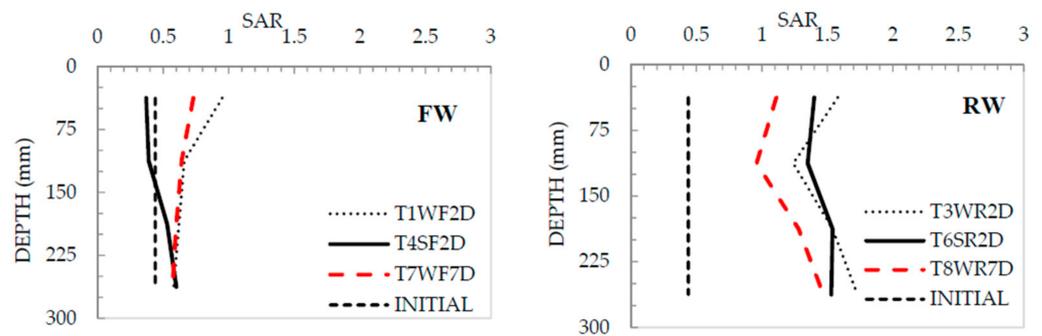


Figure 7. Soil sodium absorption ratio (SAR) at different soil depths for fresh water (FW) (left) and recycled water (RW) treatments (right). See Table 2 for treatment descriptions.

3.4. Total Nitrogen and Other Nutrients

Figure 8 shows the average residual total nitrogen (TN) content per cm depth of each pot after harvesting. The TN was always higher in WB treatments compared to SI treatments. These results also suggest that frequent use of RW may increase the TN level in WBs. Moreover, compared with FW, the use of RW significantly increased the soil TN by 70%, 34%, and 19%, respectively, under the wicking 2D, surface 2D, and wicking 7D treatments.

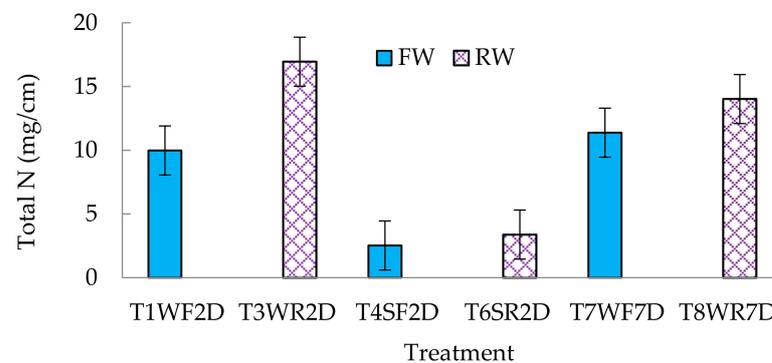


Figure 8. Total nitrogen (TN) in soil under six treatments and two different water qualities. Error bars indicate standard error. FW = fresh water, RW = recycled water. See Table 2 for treatment descriptions.

Retention of nitrogen was then investigated in each layer, and it was found that TN was comparatively high at the surface layer (Figure 9). 2D irrigation interval WBs had the highest TN at the surface layer, followed by the 7D irrigated WB and SI pots. TN distribution was fairly uniform throughout the bed for SI pots, while by comparison there

was a significant difference between the top and bottom layers of the WBs. The distribution of residual nutrient concentration between and within each layer of each treatment was evaluated for other major nutrients such as phosphorous (P) and potassium (K). The results showed that there was no significant difference between the corresponding treatments and within each layer of the same treatment for the P concentration. However, a similar pattern as with TN was observed for the potassium levels among treatments—specifically a higher K at the surface of WB compared to SI pots.

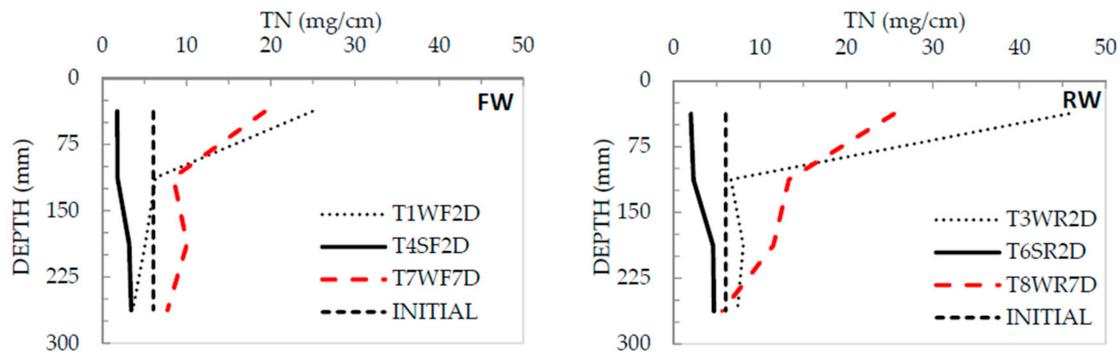


Figure 9. Total nitrogen (TN) level at different soil depths for fresh water (FW) treatments (left) and recycled water (RW) treatments (right). See Table 2 for treatment descriptions.

3.5. Tomato Plant Tissue

The amount of major (N, P, and K) and minor nutrients (Ca, Mg, Na, S, B, Cu, Zn, Mn, Fe, Al, Co, and Mo) accumulated in the plant biomass was analyzed at the end of the harvest. The results showed that the percentage of Na was significantly higher in the RW applied treatments. Further, accumulated B was significantly higher in SI-treated plants, while Mn was relatively higher in the WBs. It should be noted that Boron is typically higher in RW than other irrigation waters [25]. The concentration of major elements and some minor elements in different treatments are shown in Figure 10. The major elements—N, P, and K—were always higher in RW irrigated treatments than FW irrigated treatments, but these differences were not statistically significant.

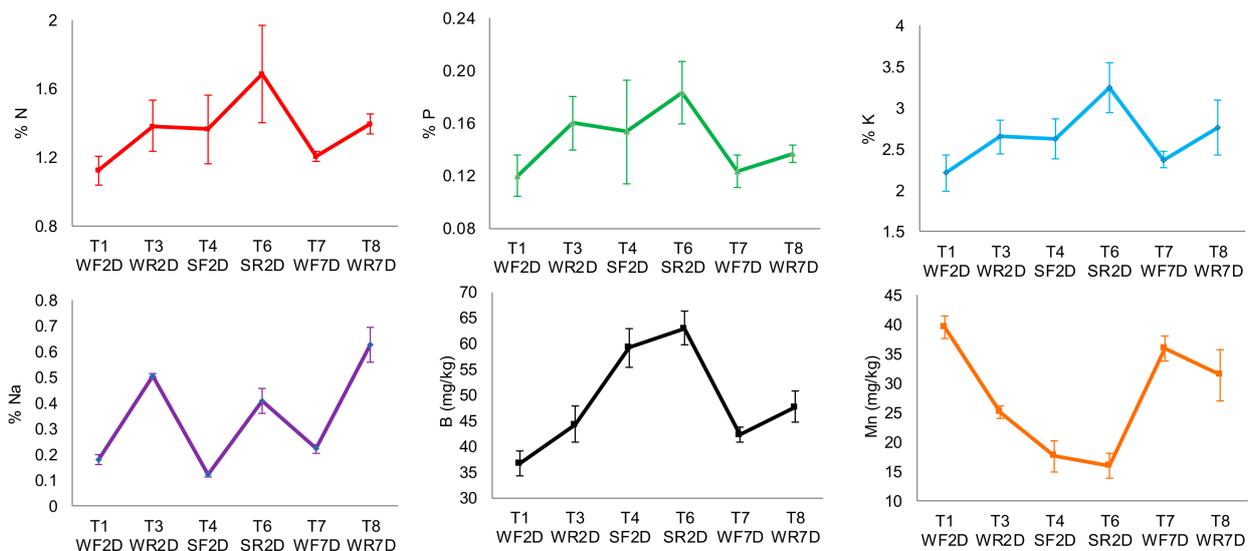


Figure 10. Accumulated elements in plant tissues for different irrigation treatments. See Table 2 for treatment descriptions.

4. Discussion

An excessive accumulation of soluble salts in soil or high soil salinity may suppress a plant's growth and yield if it exceeds the tolerable limit [26]. High salt levels in soil may also affect the nutrient balance of a plant. As a result, plants have to use more energy to extract water due to the osmotic pressure effect in the soil, detracting from energy available for growth or fruiting. Irrigation water contains different amounts of salts and is one of the major sources of increased salt in soil. In this study, the EC level of RW was about four times higher than that of FW (Table 1), suggesting that RW irrigated plots should be expected to underperform. Other factors that result in the accumulation of salt in the root zone are evaporation from the soil surface, application of fertilizers, water uptake by plants, and levels of low leaching. The amount of water uptake by plants in RW irrigated treatments was lower than for FW irrigated plants; hence, a lower yield was produced. Thus, the combined effect of leaching, moisture, evaporation, and water quality may have led to higher levels of salt and a lower yield in RW irrigated pots. Generally, soil salinity tends to increase with an increase in water salinity or soil depth [27,28], and the present study observed a similar pattern (Figure 5). Soil salinity increased with the use of RW irrigation irrespective of the irrigation method, and the difference was significant at the top layer (0–75 mm). Salt accumulation was higher in WBs with more frequent irrigation (2D compared to a 7D irrigation); however, the overall mean was not significantly different (Table 4). The regular addition of water to the reservoir may have facilitated more capillary rise and hence greater evaporation from the soil surface. Accordingly, capillary rise, high evaporation, shallow soil bed depth, and water uptake by the roots may have combined to cause the observed high concentration of salts in the top layers. However, although the percentage of rejected fruits was higher in the 7D treatment, the marketable yield and iWUE were not significantly different from the 2D treatment.

Most interestingly, in contrast to the SI method (which exhibited increasing salinity with depth), soil salinity decreased with soil depth in WBs. This is likely due to the direction of vertical water movement; generally, the high infiltration rate of sandy soil and frequent irrigation in this study may have led to more salt percolating into the lower layers in SI-treated pots. The mean EC was higher in WB treatments than in SI treatments and was significantly different (Table 4). A WB is a type of subsurface irrigation; however, no previous studies have compared the level of salinity that develops in the soil bed. The results of this study agree with previous studies stating that the salinity of soil is higher in the surface layers under subirrigation systems [29–31].

The tomato is a moderately sensitive plant, tolerating soil salinity up to 2.5 dS/m, and a yield reduction of about 9–11% has previously been observed for each 1 dS/m increase of water salinity above this level [32,33]. Shalhevet and Bernstein [34] reported that plants have some adaptive capacity, exhibiting higher water uptake from low salinity regions and lower uptake from high salinity regions, rather than relying on absolute salinity in the soil. Hence, the yield decrement will not always be significant [27]. The EC of the RW in this study was about 1.42 dS/m (Table 1). Although the highest salinity of 2.63 dS/m was reported in the surface layer of WBs with RW application, the average soil salinity in a pot was not greater than 2.11 dS/m in either of these cases (Table 4), and it was presumed that these pots were within the tolerance limit of salinity for tomatoes during the growing period. However, all RW applied treatments had the lowest marketable yield. The percentage yield decreases of 25%, 21%, and 17% were observed between FW and RW 2D irrigation WB pots, FW and RW surface irrigated pots, and FW and RW 7D irrigation WB treatments, respectively. The yield and iWUE between 2D FW irrigated SI and RW irrigated WB were not significantly different, and the yield decrease was about 9% in WB. However, the percentages of rejected fruits in both these treatments were about 4 and 2%, respectively (Figure 4). This implies that RW may be used in WBs safely with a minimal yield reduction, at least over one growing season. Moreover, the combined effect of other unforeseen factors may have led to an inconsistent yield; careful fertilizer application, use of mulch, and intermittent leaching may be some strategies to further improve results.

An increased soil volume may have led to an increase in root growth and water uptake. Studies have shown that container size and soil volume may have a significant effect on plant growth, fruit yield, and the number of fruits harvested, but an increase in container size has no effect on fruit size [35–38]. In contrast, in this study, fruit yield and fruit size were found to increase with an increase in the area of WB. The yield of the larger area WB was always higher than that of other types of WB arrangements, but it was not significantly different from WBs with mulch (both indoor and outdoor) (Table 3). However, it was found in separate experiments by the authors that an excessive increase of soil depth will decrease the WUE. The iWUE was significantly higher in mulched WBs than the conventional surface irrigation treatment and the improvement could probably be further increased by selecting a more effective mulch type than scoria gravel.

Interestingly, despite the harsh summer conditions, the yield was higher in outdoor WB and SI treatments than the corresponding indoor treatments. The influence of pollination on the yield of flowering plants has been studied by several researchers [39–41], who observed that there is a positive effect of wind and insect pollination to increase the fruit yield and the quality. Accordingly, natural or self-pollination in the glasshouse may have resulted in comparatively less fruit yield in indoor treatments [41]. A higher evapotranspiration in response to higher outdoor temperature (Figure 3) may have led to uptake of more water; however, this was compensated by a comparatively higher yield.

Overall, a significant difference in yield was observed between soil volume, location, and water quality. Accordingly, this study suggests that WBs in outdoor settings will not necessarily be outperformed by those in glasshouse conditions. It also highlighted that the frequency of irrigation in WBs depends on the area of the WB and environmental conditions. A small amount of intermittent rain was experienced during the growing period, but was not expected to have affected the leaching of excessive amounts of nutrients and did not lead to an observable yield decrease in the outdoor plants.

Several studies have established leaching requirement guidelines to reduce salinity buildup in the root zone [42–44]. Studies have shown that most of the horticultural and landscaping plants are moderately sensitive to soil salinity [45]. Accordingly, as soil salinity buildup was observed in even the FW irrigated plots, leaching is suggested as part of WB maintenance, at intermittent intervals of possibly a few days to a few weeks during the growing period, when salinity control is required. Careful leaching without overflowing the reservoir may actually help to re-mobilize (by percolation) the essential nutrients that are needed by plants, because they are not completely drained out from the WB. Similarly, applying mulch to the surface will help to reduce water evaporation and therefore should help to decrease the rate of salt buildup in the upper soil. This study shows that the iWUE and yield were high in the mulched WB compared to non-mulched WB and SI treatments. More detailed studies are required to determine optimal regimes for leaching and nutrient uptake in WBs.

Other investigators have observed a similar pattern of increase in soil sodicity with the use of a high level of sodium-contained irrigation water, namely RW and desalinated sea water [46–48]. However, compared to salinity, sodium has the opposite effect on soil; for example, elevated amounts of sodium in the soil resulted in the dispersion of soil particles, which in turn led to a reduced infiltration rate, reduced hydraulic conductivity, and led to surface crusting [49]. As a result, low yield and plant growth were prominent. Ganjgunte et al. [50] showed that the use of saline water in a drip irrigation system increased the EC and SAR at the surface layer. In the present study, the initial SAR of RW and soil were 232.5 mg/L and 143.08 mg/L, respectively. However, the mean SAR of the soil at the end of the harvest was a maximum of 1.52 in the RW irrigated 2D WB and was lower than the maximum tolerance level of 3.

It is difficult to study the effects of water stress on the uptake of nutrients and accumulation on a plant. However, several studies have shown that water stress levels decrease a plant's nitrogen uptake [51,52]. Nahar and Gretzmacher [51] showed that N uptake in tomato plants may decrease up to 34% with 40% of field capacity (FC) irrigation compared

with 100% FC. The moisture content of the surface layer of WBs usually dropped around 4%, which may have reduced the nutrient uptake by the plant and resulted in the accumulation of salt on the surface layer. In contrast, a reliably high moisture content in the surface treatments may have promoted nutrient uptake (Figure 9). Moreover, the results of this study exposed that the frequent use of RW may increase the soil TN level significantly. This result is consistent with previous observations of RW increasing soil TN such as Alrajhi et al. [53]. A comparatively high Na in RW may have resulted in the accumulation of a high Na percentage in RW irrigated treatments. Boron (B) is a vital micronutrient for plant growth, and its uptake was higher in surface treatments compared to WBs. The amount of Mn was always high in WBs; this may have been due to the presence of Mn in the quartzite, which was used as the reservoir material.

5. Conclusions

This study was conducted to investigate the soil–water–plant relations of a wicking bed (WB) using two water qualities (freshwater, recycled water), two soil areas (30 cm and 56 cm diameter), two irrigation water scenarios (2 days per week and 7-day intervals) and two environmental settings (indoor and outdoor). The results were compared with corresponding surface irrigated (SI) treatments. Irrigation water use efficiency (iWUE) was higher in WB treatments than SI treatments in both indoor and outdoor conditions. Less frequent irrigation was required in WBs, although it mainly depended on the area of the WB and the environmental conditions. WBs work in relation to the evapotranspiration rate of the plant, and accordingly, no water deficiency should occur in the system as long as the reservoir contains water. The yield was higher in WBs compared to SI pots, but the difference was most significant when WBs incorporated the use of mulch. The EC, SAR, and residual nutrient concentrations were higher in the surface layer of the WBs.

It is proposed that irrigation management including intermittent leaching may be undertaken to reduce salinity levels and re-mobilize beneficial nutrients, potentially increasing the yield of WBs further, which we recommend should be investigated in future studies. Another way to view the accumulation of salt on the soil surface in the WB system is that it is easy to remove (by excavation of the upper level), thus reducing leachate of nutrients and salt to groundwater. This is a potentially added advantage when compared to SI systems.

The structure of a WB is simple; hence, they can be rescaled to different sizes and installed in a variety of settings, including balconies, back gardens, parks, rooftop gardens or city landscaping. It may use as a simple glasshouse model by connecting multiple pots in series, and the reservoir can be filled manually or automatically. WBs show potential as a low-tech and high water- and labour-efficient irrigation technique for urban settings using fresh or recycled water. They also show potential for reducing pollution through leaching, supporting overall environmental sustainability.

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