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Impact of treated wastewater on soil hydraulic properties and vegetable crop under irrigation with treated wastewater, field study and statistical analysis

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Abstract

Due to aridity, scarcity and unsustainably of natural water resources many developing countries tend to utilize wastewater for crop production. The use of treated wastewater in irrigation has many advantages and disadvantages to soil, crop and environment. The objective of the study was to investigate the effect of irrigation with wastewater on soil physical and hydraulic properties of soil, as well as the effect on yield, yield components and irrigation water use efficiency (IWUE) of vegetable crop grown under surface and subsurface drip irrigation systems. Field experiments were carried out over two consecutive seasons (2011 and 2012) at an agricultural field site in Saudi Arabia. A strip plot design (split block) was constructed to maintain six wastewater qualities. Crop water requirement was calculated by Penman Monteith equation for dry land condition. Physical and hydraulic properties of soil were analyzed at pre-season and post-season to quantify the impact of wastewater treatment. Results were statistically analyzed by analysis of variance and mean separation by LSD test. Post-season analysis indicates that the second layer of soil profile was affected. The saturated hydraulic conductivity decreased by 43%, α value increased by 6%, and n value decreased by 2%. Accordingly simulation results a reduction of cumulative flow through soil profile was observed. On the other hand, the response of vegetable crop to wastewater qualities, irrigation systems and growing seasons was different. The fruit yield and IWUE under subsurface irrigation system were significant as compared to surface irrigation system using two seasons. However, the local groundwater (LGW) practice produced highest yield and maximum IWUE; followed by qualities containing less percentage of wastewater. The statistical approach was successful in the analysis of designed experiment.

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Introduction

Scarcity and shortage of fresh water in arid and semi-arid regions like Saudi Arabia have increased the demand for using wastewater effluent in agriculture. The use of wastewater in agriculture is gaining great popularity because of its wide range of benefits including agronomic, economic and environmental aspects. These benefits include water conservation, provision of sustainable water supply and protection of natural water resources from contamination with municipal and industrial wastewater flows. Generally, both treated and untreated wastewater is extensively used in agriculture because of their rich source of nutrients and moisture necessary for crop growth. Most crops give higher potential yields with wastewater irrigation; reduce the need for chemical fertilizers, resulting in net cost savings to farmers (Hussain *et al.,*, 2002). Water reuse is considered as the only solution to close the loop between water supply and wastewater disposal whereby wastewater that was termed as waste can now be considered as a valuable source after appropriate treatments (Urkiaga *et al.,* 2008).

Previous studies reported some economical, agronomical and environmental benefits of treated sewage water use in agriculture (Pereira *et al.,* 2011). The basic objective of all wastewater reuse projects is to maximize total benefits (difference between income and production costs), which in turn determines whether or not the project is feasible. Hernández *et al.,* (2006) showed a methodology to assess the feasibility of water reuse project taking into account not just the internal impact, but also the external impact such as environmental, social and cost effectiveness of the project. However, quantity and quality of crop production are of great concern. Use of wastewater in crop production sometimes decrease the quantity and quality of the yield, however, it is possible to achieve high yield without deterioration of quality by using treated wastewater under controlled conditions (Balkhair *et al.,* 2014, Esmailiyan *et al.,* 2008, Mohammad and Ayadi, 2005). Khan *et al.* (2011) and Ahmad *et al.* (2011) reported that increasing doses of municipal wastewater application reduces the overall yield of some vegetable crops such as radish and spinach.

The use of drip irrigation for vegetable production has increased rapidly worldwide and proved beneficial than the traditional methods of irrigation (Gadissa and Chemeda, 2009; Kumar and Palanisami, 2010). There are number of factors driving this conversion to drip irrigation. Most important among them are increased crop yield, water conservation and more efficient nutrient management. For implementation of these benefits careful management of both water and fertilizer inputs are required. Khalil *et al.* (1996) and Amer (2011) found that the total yield of squash was significantly higher for the drip irrigation method as compared to the furrow irrigation method. A number of researchers have examined the effects of irrigation quantities on yield, yield components and water use efficiency. Onder *et al.* (2005) investigated the effect of two drip irrigation methods and four different water stress levels on potato yield. Their results indicated that irrigation levels and water stress had significant difference on yield parameters of early potato production. Karam *et al.* (2011) studied the response to water stress timing and intensity of drip-irrigated eggplants in semiarid climate. They found that deficit irrigation prior to flowering resulted in water saving of the same magnitude of the treatment irrigated at 80% of field capacity, with least yield reduction. Cirelli *et al.* (2012) reported the result of two years of research on irrigating eggplant and tomato crops with municipal wastewater coming from a tertiary-constructed wet-land treatment. They interpreted the effect of irrigation with TWW on technological system management and effect on crops and soil as compared to test system irrigated by conventional fresh water.

The main properties that control flow of water and contaminants in porous medium are soil structure, dry bulk density, porosity, cation exchange capacity, soil texture, soil solution chemistry, and microbial activity. Some of these properties may change significantly as a result of WW application to soil. Many researchers have reported that irrigation with treated wastewater (TWW) affects the physical and hydraulic properties of soil (Mathan, 1994, Viviani and Iovino, 2004). Increasing amount of organic matter and soil nutrients under the effects of wastewater application increases plant growth with a positive influence on the soil's physical, chemical and biological properties (Mohammad and Ayadi, 2005, Mousavi *et al.,* 2013). Magesan *et al.* (1999) observed a decrease in the infiltration rate and hydraulic conductivity due to blocking of soil pores by suspended solids. Soluble calcium and magnesium that are bounded by organic ligands increase the effective sodium adsorption ratio (SAR) of WW and decrease the soil hydraulic conductivity at the application site (Nelson *et al.,* 1999).

Many researchers have used ANOVA for various analysis in agricultural experiments (Hurtado *et al.,* 2013, Khan *et al.,* 2011). Gatta *et al.* (2015) have carried out a comparative study to evaluate the effects of two water irrigation sources on the quality and microbiological safety of tomato plants and fruits including microbiological soil properties using irrigation with groundwater and with treated agro-industrial wastewater. The measured data from each of the continuum variables relating to the qualitative/ quantitative traits of tomato fruit were processed by ANOVA. Aiello *et al.* (2007) investigated the effects of reclaimed urban wastewater for irrigation on tomato fruit quality and hydrological soil behavior using different drip and sub-drip laterals and filtering technologies. Their analyses of variance identified the main effects of treatments and their interactions on crop production. Tukey's significant difference test was used for mean separation. Gaveh *et al.* (2011) on the other hand used ANOVA under a completely randomized design and mean separation by LSD for all parameters to investigate the physiological growth and development of different transplants of the African eggplant (*Solanum macrocarpon.*) to varying irrigation water management regimes during rainy and dry seasons.

In spite of the benefits of using wastewater in crop production, the production is faced by some risks from heavy metal accumulation and microbial pollution. Depending on the source of wastewater it might contain chemical pollutants and heavy metals that can accumulate in soil and crops thereby posing a threat to human health. These risks can be reduced by treating the wastewater before using it or by applying some precautions while using it (Balkhair *et al.*, 2014). The objective of the present study was to investigate the effect of irrigation with wastewater on soil physical and hydraulic properties as well as the effect on yield, yield components and irrigation water use efficiency (IWUE) of a vegetable crop grown under the surface and subsurface drip irrigation systems.

Materials and Methods

Experimental design : Eggplant cultivation experiments were carried out in two consecutive seasons (2011 and 2012) at the Agricultural Research Station of King Abdulaziz University (KAU), located at Hada Al-Sham village; 110 km north east of Jeddah city, Saudi Arabia. The soil at the experimental site was classified as loamy sand. Prepared and pre-recommended doses of phosphorus and potassium fertilization were added @ 200 kg P_2O_5/ha and 200 kg K_2O during soil harrowing before plantation. The eggplant crop was cultivated in strip plot design (Split block) with 4 replications; each of 2x3 m in size. The main plot treatments consisted of two irrigation systems, surface and subsurface, while the sub plot treatments designed and arranged in strips containing six irrigation water supplies.

Irrigation water source : Bani-Malik wastewater treatment plant which is located in Jeddah city was the main source of irrigation. The raw effluent of WWTP was diluted with local groundwater at pre-defined ratios. Six wastewater qualities were prepared viz.: 0%, 20%, 40%, 60%, 80% and 100%. The percentage indicated the wastewater portion. For example, 20% means 80% of water was mixed with 20% raw effluent. Accordingly, 0% and 100% corresponded to local groundwater and undiluted wastewater (raw effluent), respectively.

Irrigation systems : Each water quality treatment and its corresponding irrigation system consisted of storage tank with a capacity of 5000 litre, disk filter, pump, controller, drip lines and solenoid to control flow time and irrigation interval. In sub-surface drip irrigation systems, the field was leveled and the dripper lines were installed at 10 cm deep on 40 cm between two adjacent dripper lines. The distance between drippers was 45 cm with a discharge of 0.9 G/h (*RAIN BIRD LD- 06- 12-1000 Landscape drip 0.9 G/h @18"*). The downstream end of each dripper line was connected to a manifold for convenient flushing. Inlet pressure on each tape was about 1.5 bars. The system used 125 μ disk filter to prevent blockage. The layout of the surface drip irrigation was same as in subsurface drip, except for the position of dripper lines. They were installed on soil surface.

Irrigation water requirements and IWUE : The required irrigation water was calculated based on crop water requirement (Evapotranspiration) and total available soil moisture. Evapotranspiration for each plant was calculated from reference evapotranspiration and crop coefficient as follows:

$$ET_c = K_c \times ET_o$$

Where, Et_c is crop evapotranspiration (mm day^{-1}); ET_o is Reference evapotranspiration (mm day^{-1}) and K_c is Crop Coefficient.

Reference evapotranspiration was calculated using Penman-Monteith equation as described by Allen *et al.,* (1998) and crop coefficient values were obtained (Allen *et al.,* 1998) for vegetable crops. The IWUE was calculated by dividing the total yield in kg ha^{-1} by total water supply in mm/ha.

Soil physical and hydraulic analysis : Six soil samples were collected at 20 cm depth along the soil profile of 120 cm. The particle size distribution of soil samples was carried out according to International Pipette method (Klute, 1986). Saturated hydraulic conductivity was determined in laboratory by permeameter method following the principles of Darcy's law. Soil moisture content was determined by gravimetric method (Klute, 1986).

Soil characteristic curves : Soil water characteristic curves were determined by the pressure plate apparatus (Klute, 1986). Collected soil samples were initially saturated for 24 hrs. The saturated samples were then subjected to incremental pressures in the range of 0.1–2500 kPa. After achieving equilibrium at each applied pressure, the retained moisture was weighed for each sample and the collected experimental data were used to construct a plot between applied pressure and water content (soil water characteristic curve [SWCC]). Soil water retention parameters were determined by fitting the experimental data to SWCC according to the empirical equation of Van Genuchten (1980):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \quad (1)$$

Where, θ is the water content ($cm^3\ cm^{-3}$); θ_r is the residual water content; θ_s is the saturated water content; h is the matric potential (kPa or cm of water); α is an empirical parameter often assumed to be related to air-entry suction (L^{-1} or kPa^{-1}); and n and m ($m = 1 - 1/n$) are empirical parameters related to pore-size distribution.

RETC is a computer code used to analyze soil water retention (Van Genuchten *et al.,* 1991). This code draws upon the parametric models of Van Genuchten to represent the soil water retention curve. Unknown parameters in Eq. (1), mainly α, n, θ_r, and m, were estimated by nonlinear least-squares parameter optimization method that was built in RETC.

HYDRUS-1D (Simunek *et al.,* 2005), a software package for simulating water, heat, and solute movement in one-dimensional variably saturated media, was used to simulate the flow of water through the soil profile of the study area in the pre- and post-season conditions. The aim was to investigate the impact of various physical and hydraulic parameters of soil on the flow properties under given boundary conditions.

2.5 Crop data collection and analysis : Before harvesting, ten random guarded plants per plot were labeled and different traits were measured for each eggplant (*Abelmoschus esculentus*). The traits collected and measured for two seasons 2011-2012. The traits are plant height in (cm), number of fruits per plant, fruit weight per plant, and fruit yield (ton ha^{-1}). The collected data in each experiment was statistically analyzed for analysis of variance (ANOVA) and Least Significant Difference (LSD) by SPSS. The analysis was carried out based on the used experimental design, and after applying the assumptions of the statistical analysis according to El-Nakhlawy (2011).

Results and Discussion

Analysis of variance : Mean squares of all studied traits are shown in Table 1. The statistical analysis shows that plant height, number of fruits/plant, fruit weight/plant in the first season, and IIWUE in the second season were not affected by the irrigation systems. Conversely, fruit weight/plant in the second season and fruit yield ha^{-1} during two seasons were significantly affected by the irrigation systems. On the other hand, all the agronomic traits were significantly affected by the wastewater treatments ($p \leq 0.01$) during two seasons, except for fruit weight per plant. Moreover, no significant effects observed on any of the traits under interaction between irrigation system and wastewater treatments during the two seasons.

Analysis of means : Mean values of eggplant fruit yield (ton/ha) under the effect of surface and subsurface irrigation systems are presented in Table 2. The mean values of each treatment were designated by letters (a, b, c) which represented the significance degree of the difference between the means. Means represented by two letters in common indicated that the difference was not significant or weakly significant. Results of both seasons indicated that the fruit yield under the subsurface irrigation system was higher than that of surface irrigation system. The yield under subsurface irrigation in 2011 and 2012 seasons were 40.7 and 38.8 ton ha^{-1}, and were 37.6 and 36.7 ton ha^{-1} under the surface irrigation system, respectively. Although the rate of increase

Table 1 : Analysis of variance of the studied agronomic traits under the effects of irrigation systems, wastewater qualities during 2011 and 2012 seasons.

	df	MS									
		Plant height (cm)		No. of fruits/ plant		Fruit wt/ plant (g)		Fruit yield (ton/ha)		IIWUE (kg/mm/ha)	
		2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Source of variation	1	215.5 NS	216.8 NS	1.33 NS	1.33 NS	8721 NS	1987140*	112.9*	190.8*	193.8	244.4 NS
Waste-water (%)	5	184.1**	183.1**	2.28**	2.28**	357760 NS	357754 NS	422.6**	407.8**	461.3**	5439**
IS x WW	5	69.3 NS	68.7 NS	0.52 NS	0.53 NS	287121 NS	287122 NS	17.47 NS	21.13 NS	23.67 NS	282.3 NS

NS: not significant at $p \leq 0.05$; *, ** Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively.

Table 2 : Means of the studied agronomic traits and irrigation water use efficiency of eggplant crop under the effects of irrigation systems and wastewater qualities during 2011 and 2012 seasons.

Treatment	Agronomic traits									
	Plant height (cm)		No. of fruits/Plant		Fruit weight (g/plant)		Fruit yield (ton/ha)		IWUE (kg/mm/ha)	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Irrigation system										
Surface	47.4	47.5	3.03	3.0	482	484 a	37.6 b	36.7 b	40.4 b	62.1 b
Subsurface	51.6	51.8	2.63	2.61	508	365 b	40.7 a	38.8 a	43.2 a	66.6 a
Wastewater quality effect										
0%	54.8 a	57.7 a	3.9 a	3.9 a	674	679.6	53.1 a	42.6 a	56.3 a	86.6 a
20%	46.5 b	43.5 c	2.6 b	2.7 b	433	407.5	37.7 b	37.4 b	42.2 b	64.9 bc
40%	48.4 b	48.4 bc	2.6 b	2.7 b	361	367.5	37.5 b	37.4 b	39.7 b	61.8 b
60%	50.0 b	50.0 bc	2.5 b	2. 6 b	423	429.6	37.4 b	37.3 ab	39.8 b	61.0 b
80%	46.8 b	46.8 bc	2.6 b	2.7 b	359	360.3	34.2 b	34.6 ab	38.8 bc	59.6 bc
100%	50.6 b	50.7 b	2.5 b	2.5 b	304	305.7	34.3 b	35.8 ab	34.1 c	52.2 c

*, Means followed by the same letter(s) are not significantly different according to LSD test at $p \leq 05$.

Table 3 : Means of agronomic traits and irrigation water use efficiency under the effects of the interaction between irrigation systems and wastewater qualities during 2011 and 2012 seasons.

Irrigation System	Waste water (%)	Agronomic traits									
		Plant Height (cm)		No. of Fruits/ Plant		Fruit weight (g)/Plant		Fruit Yield (ton/ha)		IIWUE (kg/mm/ha)	
		2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Surface	**0.0**	56.3	60.3	4.50	4.50	867.8	868.9	49.0	49.1	52.05	80.00
	20	46.5	42.5	2.53	2.55	465. 8	469.7	32.3	33.3	39.55	60.80
	40	44.8	44.7	2.75	2.77	443.8	446	36.3	37.9	32.40	49.77
	60	46.8	46.7	2.54	2.57	385.5	388.5	37.4	37.3	39.57	60.82
	80	45.5	45.5	2.77	2.79	406.2	409.5	36. 0	38.7	40.33	62.02
	100	44.5	44.5	2.76	2.78	321.5	327.6	33.0	36.2	38.48	59.17
Sub-surface	**0.0**	53.3	55.3	3.25	3.20	490.3	490.3	57.0	36. 9	60.52	93.10
	20	46.5	44.5	2.73	2.72	200.0	345.2	35.8	35.8	37.97	58.37
	40	52.0	52.0	2.49	2.46	292.0	289.1	38.8	33.6	35.59	54.70
	60	53.2	53.2	2.50	2.52	471.7	476.0 8	37.5	37.4	39.83	61.22
	80	48.0	48.0	2.53	2.51	312.5	310.5	39.5	41.8	44.07	67.77
	100	56.8	56.7	2.26	2.27	285.7	283.7	35.5	38.6	41.16	64.50
LSD	**(0.05)**	NS	NS	NS	NS	NS	NS	NS	NS	NS	5.04

LSD : Least Significant Difference; NS: Not Significant

Table 4 : Physical and hydraulic properties of soil layers along with RETC fitted soil water characteristic curves parameters

Layer	Depth (cm)	Sand %	Silt %	Clay %	Texture	Ks (cm/hr)	θr	θs	α	n
L1	0-20	82	12	6	LS	17.6	0.043	0.36	0.41	1.539
L2	20-40	77	13	10	SL	5.6	0.08	0.41	0.235	1.476
L2*	20-40	78	12	10	SL	3.2	0.076	0.407	0.249	1.299
L3	40-60	84	9	7	LS	14.3	0.042	0.36	0.462	1.527
L4	60-80	81	13	6	LS	12.4	0.040	0.38	0.692	1.493
L5	80-100	84	11	5	LS	12.8	0.042	0.37	0.522	1.516
L6	100-120	82	13	5	LS	12.8	0.045	0.37	0.402	1.541

LS: Loamy sand, SL: Sandy loam, *: post-season

during the both seasons was less than 5%, statistically significant difference between the two irrigation systems was noted but not between the two seasons. Similar results were obtained for IWUE as far as irrigation systems are concerned. The subsurface irrigation system resulted in higher IWUE than the surface irrigation system. In addition, there was a large difference in the values of IWUE between the two seasons; the second season produced approximately 35% higher than the first season. On the other hand, plant height and number of fruits per plant were not affected by the irrigation systems in the two seasons, but the fruit weight per plant was significantly affected by the irrigation systems in the second season only. The higher production was under the surface irrigation systems with a weight of 484 (g per plant) as compared to 365 (g per plant) in the case of subsurface irrigation.

The impact of wastewater qualities on the yield of eggplant (ton ha^{-1}) is also shown in Table 2. Local groundwater produced the highest fruit yield ha^{-1} during the two seasons with in significant differences between the other five wastewater qualities (20%, 40%, 60%, and 100% wastewater). Fruit yield ranged from 53.1 – 34.3 ton ha^{-1} in 2011 and from 42.6 – 35.8 ton ha^{-1} in 2012. On the other hand, water use efficiency responded similar to the fruit yield i.e., the highest IWUE was produced due to local groundwater in the two seasons. Values of IWUE in 2011 ranged from 56.3 – 34.0 kg mm^{-1} ha^{-1} and in 2012 season ranged from 86.6 – 52.2 kg mm^{-1} ha^{-1}. However, variation in the values of IWUE was much higher than that of fruit yield, especially during second season. The other agronomic traits responded quite similar to fruit yield per hectare and IWUE. For example, plant height, number of fruits per plant, and fruit weight per plant were significantly affected by local groundwater treatment as compared to other treatments. The highest values were obtained under local groundwater in these traits, while no significant differences were found between all other treatments.

The best practice was obtained when local groundwater was used. All other wastewater qualities significantly decreased the yield of eggplant. A decrease in the yield might be attributed to the adverse effect of wastewater on the crop due to the accumulation of micro and micro elements in stem and plant leaves which accordingly decreased the metabolic processes and total yield. The response mainly depends on the interaction between crop genetic makeup and wastewater concentration in irrigation water, in addition to the effect of environmental factors as reported by Ahmad *et al.* (2011) and Khan *et al.* (2011). For example, Ahmad *et al.* (2011) reported that application of increasing doses of municipal wastewater reduces the overall yield of some vegetable crops such as radish and spinach. Another view to variation in the yield could be positive response of crop yield to the irrigation with wastewater. The increase in the absorption of macro and microelements that exist in the wastewater lead to increase in the production (Al-Lahham *et al.,* 2003, Lopez *et al.,* 2006, Mandi and Abissy, 2000). These results may also be due to the increasing content of nutrients in soil irrigated with wastewater (M. Kiziloglu *et al.,* 2007); or to the increase in total chlorophyll and carotene that establishes good growth (Singh and Agrawal, 2009).

Unlike fruit yield per hectare and IWUE, plant height, number of fruit per plant and fruit weight per plant had no clear relation between the wastewater qualities and the values of yield component. This means, the fruit yield per hectare and IWUE slip decreased as the wastewater percentage in the irrigation water increased. This situation was not true in the case of other three traits. For example, 60% wastewater

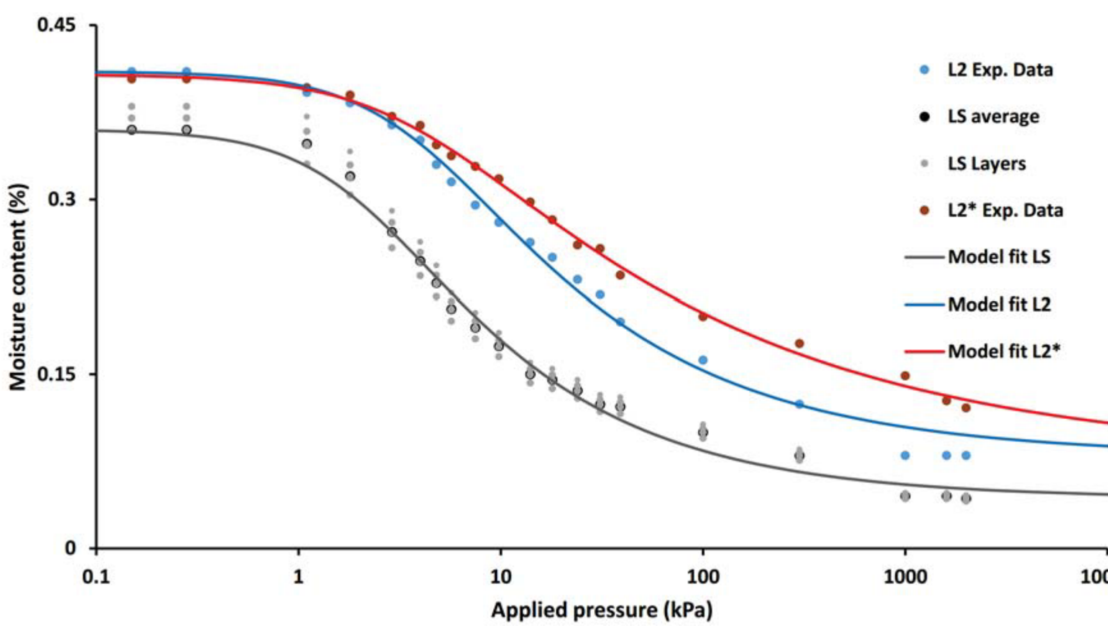

Fig. 1 : Experimental and model fit soil-water characteristic curves of the six soil layers. All are pre-season results (grey circles) except layer two where both pre (blue) and post (red) season plots are presented. Solid lines are model fit

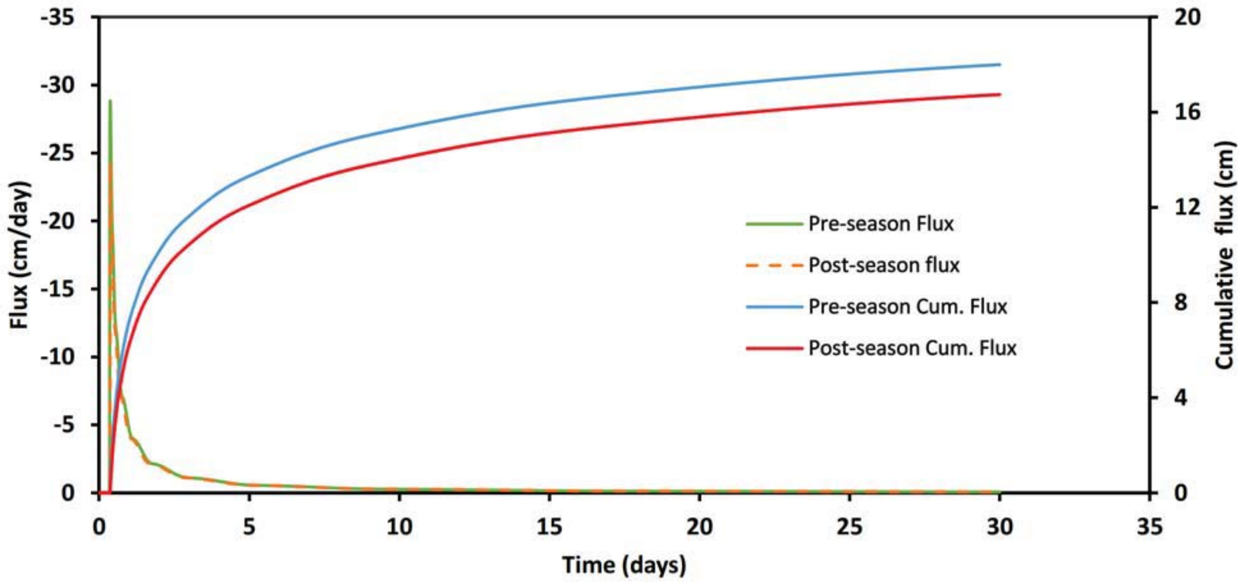

Fig. 2 : Fluxes at the soil outlet in the pre and post seasons obtained from HTDRUS 1D model

treatment produced higher plant height and fruit weight than 40% wastewater quality.

Analysis of interactions : Interaction between the irrigation systems and irrigation wastewater qualities were analyzed and presented in Table 3. Means have been compared by LSD test at 5% level of significance. The obtained results indicate that there were no significant difference between these two variables in all the studied agronomic traits. However, the IWUE during second season showed significant difference between the irrigation systems and wastewater treatments.

In the present study, IWUE was a good indicator of crop production. Since the amount of irrigation water supply was same for both irrigation systems, increase in IWUE under subsurface irrigation system might be due to the minimal water losses and/or no surface evaporation as compared to surface drip irrigation system (Ismail *et al.,* 2011, Phene *et al.,* 1992). In addition, soil moisture content is usually uniform in the case of subsurface drip irrigation. This suggests little or no potential for deep percolation losses. As a result, crop production increased, thereby leading to an increase in the IWUE (Senyigit *et al.,* 2013).

Impact on soil physical and hydraulic properties :

Hydraulic properties : Table 4 shows physical and hydraulic properties of six soil layers along with the optimized soil characteristic curve parameters obtained by RETC. All soil layers were classified as loamy sand (LS), with the exception of second layer (20 cm – 40 cm) which was classified as sandy loam (SL) due to its relatively high clay and silt percentages. The hydraulic conductivity of this layer was approximately three times lower than that of the loamy sand layers, a characteristic which indicates that the sandy loam soil is a moisture flow limiting layer along the entire soil profile. Moreover, the relatively high content of fine particles gave rise to its capacity to attract treated wastewater constituents through different mechanical processes including sorption-adsorption, attachment-detachment and cation exchange. On the other hand, the hydraulic conductivity of loamy sand soil layers ranged from 12.8 – 17.6 cm hr^{-1} with an average of 14 cm hr^{-1}. In addition, their soil particle size distributions were almost same, thereby indicating one type of soil material with properties that may be averaged and utilized in the calculation of soil water flow. The range of saturated moisture content and residual moisture content values of the loamy sand layers was narrow (Table 4); however, the average values were 0.37 and 0.042 for θ_r and θ_s, respectively.

Soil-water characteristic curves: The soil-water characteristic curves of six soil layers are presented in Fig. 1. The figure depicts eight experimental data plots as per Van Genuchten (1980) model fit plots. The data plots are comprised of five loamy sand soil layers (grey), pre-season second layer (blue), average over loamy sand layers (black), and post-season second layer (red). The model equation was fit to the representative average loamy sand, soil as well as to pre-season and post-season of the second layer. The post-season plot of loamy sand soil is presented here because it was found almost similar to the results obtained in the pre-season. Similar findings were reported by Al-Othman (2009). Model fit parameters - primarily α and n - are shown in Table 1 for all layers. As expected, the sandy loam soil parameters differed from all other layers, especially the value of α which was almost half of the values found in the other layers. The most interesting result was found in the hydraulic properties and model parameters for sandy loam soil in the post-season as compared to the pre-season. The saturated hydraulic conductivity in the post-season decreased by 43%, the α value increased by 6%, and the n value decreased by 2%. Reduction in hydraulic conductivity may reach up to 80% in loamy soil as reported by Viviani and Iovino (2004).

These parameters play a significant role in the soil water flow and storage. For example, the hydraulic conductivity measures the ability of soil to transmit water, where α and n indicate the resistance of soil to water movement due to any flow driving forces. The role of these parameters are shown in Fig. 1 for sandy loam soil (blue and red curves). Due to changes in these parameters as a result of wastewater application over two seasons, the pre-season curve or experimental data (blue) shifted to right to become a red color plot in the post-season. This shift indicates that the sandy loam soil layer had become more resistant to flow driving forces and soil moisture movement. Moreover, soil may contain more moisture as compared to its condition in the pre-season for a given applied pressure. For example, at 100 kPa, soil in the post-season contains 25% more soil moisture content (θ = 0.201) than its condition in the pre-season (θ = 0.154). It is to be noted that increase in moisture content between seasons occurs after an applied pressure of 3 kPa and the rate of increase decreases after 1 MPa.

Flow simulation : The pre-season and post-season soil profile (120 cm) was examined by Hydrus 1D model. The model was run for 30 days with an upper boundary condition of atmospheric surface layer and a lower boundary condition of free drainage. Water was applied at the top of the soil column @ 4.1 cm hr^{-1} for 6 hrs. The soil profile was initially dry and both loamy sand (five layers) and sandy loam (one layer). Soil materials with their corresponding parameters were adopted in the model. The model was run for both pre- and post-season cases. Fig. 2 shows the fluxes at soil bottom (outlet) in the pre- and post-seasons. The impact due to change in the hydraulic properties and model parameters in the second layer caused a clear difference in the cumulative fluxes between pre- and post-season results. The cumulative flux of post-season was less than that of the pre-season (red and blue plots); this result is a typical consequence of model parameter changes in the second layer as indicated in Table 4 and in the plots of Fig. 1. Although, the sandy loam soil depth constitutes only one-sixth of the entire soil profile, it creates a clear decrease in the flux of post-season. This result suggests that if the change of properties occurs in more than one soil layer, then the out fluxes may potentially drop. Fig. 1 also shows the plots of pre- and post-season fluxes. These appeared as identical spikes with a higher flux in the pre-season soil profile. These fluxes dropped suddenly and had low magnitudes as compared to upper boundary condition input flux. The low fluxes indicated that most of the moisture were stored in soil; however, the storage and drainage through soil profile are functions of applied flow rate and duration. If the flow rate is in excess of soil field capacity it drains immediately. This condition, which might occur during heavy rainfall and has not been tested here.

This study indicates that the response of the vegetable crop to wastewater qualities, irrigation systems, and seasons are different. The experimental design and the statistical analysis are good measures in the exploration of the effect of irrigation systems and irrigation water qualities on the yield components of the eggplant crop. The statistical analysis of the treatment indicates that the irrigation regimes significantly affect the eggplant yield, irrigation water use efficiency and water saving. In almost all studied agronomic traits, the subsurface irrigation system dominated the surface irrigation system in the production of the crop. The local groundwater (0% wastewater) quality produced the highest eggplant fruit yield/ha during the two seasons, while no significant differences observed between all other diluted wastewater treatments in both seasons. The effect of irrigation with different wastewater qualities is clearly reflected in the fruit yield per hectare and IWUE. These two traits decreased when the wastewater percentage in the irrigation water increased, while this conclusion is not true for the other traits.

There was a clear effect of wastewater on the soil's physical and hydraulic properties. The second layer (sandy loam) of the soil profile was affected significantly while the impact was negligible on the other layers. When the saturated hydraulic conductivity of the second layer decreased by 43%, the soil water characteristic parameter changed to values sufficient to consider the soil layer as flow resistance to driving forces. Hence, it becomes a layer controlling the flow along the entire soil profile. In addition, its storage capacity increased by 25%. As a consequence of these alterations, the cumulative outflow flux decreased moderately.

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