Effect of treated wastewater on soil chemical and physical properties in an arid region

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ABSTRACT

This study was carried out to investigate the effect of treated wastewater on soil chemical and physical properties. Field experiment was conducted in Borkhar region in Isfahan province in central Iran with two water treatments of wastewater and groundwater under sprinkler and surface irrigation systems for three crops of sugar beet, corn and sunflower. Soil samples were collected to 120 cm depth to determine concentration of lead (Pb), manganese (Mn), iron (Fe), cadmium (Cd), nickel (Ni), cobalt (Co), copper (Cu) and zinc (Zn). Irrigation systems had no significant effect on extractable heavy metals in soil. The accumulation of Pb, Mn, Ni and Co in the soil increased significantly in the wastewater treatment as compared to the groundwater treatment. The accumulation of Pb, Mn, Ni, Co, Cu and Zn decreases with the soil depth. Treated wastewater showed no effect on the increase of Fe, Cd, Ni, Cu and Zn during growing season. The irrigation system had a significant effect on infiltration rate, bulk density and total porosity. Under sprinkler irrigation system the infiltration rate increased significantly.

Keywords: treated wastewater; heavy metals; sprinkler irrigation; surface irrigation; infiltration

In arid and semi-arid regions, wastewater reclamation and reuse has become an important element in water resources planning (Abedi-Koupai and Bakhtiarifar 2003). This has occurred as a result of increasing fresh water scarcity, the high cost of chemical fertilizers, high nutrients in wastewater, the high cost of advanced treatment required for other applications and the availability of wastewater near agricultural lands. Wastewater possesses different biological, physical and chemical effects on the environment. In order to apply the wastewater for irrigation it should obtain the certain criteria of qualification after treatment, for parameters such as electrical conductivity (EC), total dissolved solids (TDS), and sodium adsorption ratio (SAR). Suspended materials and organic matters are also other parameters, which might be considered before application of wastewater to agricultural lands. The principal processes which affect the physical properties of the soil by using the wastewater are the salt contents and the suspended solids.

Streck and Richter (1997) reported that movement of heavy metals in soils irrigated with wastewater is very slow and more than 90% of Cd, Ni, and Pb accumulated in the 10–15 cm soil depth. Silver and Sommers (1977) showed that the application of wastewater with low pH causes a faster movement of the Cd and Pb to lower depths. The results also showed that the concentrations of Pb and Cd in the soil irrigated with wastewater effluent and groundwater were almost similar. Juwarkar and Subrehmanyam (1987) studied the effect of wastewater on the soil properties. They stated that wastewater could be applied for coarse texture soil because high ESP had no effect on the soil hydraulic properties. Xantholagis and Wallender (1991) reported that the final infiltration rate decreased when using wastewater from a tomato paste factory in a furrow irrigation system. Vandevivere and Baveye (1992) applied the wastewater on a sand column and reported that aerobic bacteria decreased the saturated hydraulic conductivity more than 4-times, particularly in the upper zone near the soil surface. Vinten et al. (1983) studied the influence of wastewater suspended materials on hydraulic conductivity and

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reported that the hydraulic conductivity in silty loam was reduced in comparison with sand and sandy loam soils. This is due to the accumulation of suspended materials in the soil surface. They also stated that wastewater irrigation would increase ESP and clogging of the soil porosity. Vinten et al. (1983) also reported that the decrease in hydraulic conductivity was due to the physical and chemical processes. They observed that the dissolved organic matter in wastewater even with low ESP had negative effect on hydraulic conductivity. The reduction in hydraulic conductivity is due to the retaining of the organic matters during infiltration and the change of pore size distribution as a result of expansion and dispersion of soil particles. Tarenitzky et al. (1999) showed that one of the important effects of adding organic matters to soil is the increase of moisture retention capacity which is due to reduction of the soil bulk density, increase of soil porosity and the specific surface area of soil particles.

The agricultural lands around the Wastewater Treatment Plant are irrigated using wastewater. However, limited information is available on effects of irrigation systems using treated wastewater on soil physical and chemical properties. Therefore, the objective of this study was to determine the suitability of treated wastewater for irrigation in order to have better irrigation systems management for higher crop production.

MATERIAL AND METHODS

This research was conducted in Borkhar (Longitude 51°31'–51°40'E and Latitude 32°44'–32°52'N) region located in Isfahan province, in central Iran. The experimental site has an arid climate and is 1630 m above sea level. The average annual rainfall and temperature at the site are 140 mm and 14.5°C, respectively. The experiments included two types of water (wastewater and groundwater), two irrigation systems (sprinkler and surface) and three crops sugar beet (*Beta vulgaris*), corn (*Zea mays*) and sunflower (*Helianthus annus*). The municipal wastewater used in this experiment was from the wastewater treatment plant of Shahinshahr located near city of Isfahan. The plant is designed to provide both primary and secondary treatment for the municipal wastewater. In this experiment the secondary treated wastewater was used.

For each irrigation system, two experimental plots were used. Each experimental plot was divided into two sections, one section was irrigated using sprinkler irrigation (semi portable sprinkler with lateral move) and another section was irrigated using surface irrigation (small diked basin with furrows inside). The experiment was conducted at three replications. Crop water requirements were computed based on water use efficiency, the root depths of plants and the moisture deficiency of soil for different stages of growth and irrigation were applied to meet each crop water requirement. To determine the physical and chemical properties of irrigation water treatments, groundwater and wastewater was sampled and analyzed during growth season.

Based on the USDA method of soils classification the soils for both experimental fields (wastewater and groundwater fields) were classified as Aridisols. The soil related to groundwater experiment subgrouped as Calcic Argigypsic and the soil related to wastewater experiment subgrouped as Calci Argids. The soils had weak and unstable structures.

Sugar beet was planted on May, 26 irrigations were applied and 7 months after planting it was harvested. Corn was planted on May, 15 irrigations were applied and 5 months after planting it was harvested. Sunflower was planted on June, 13 irrigations were applied and it was harvested 4.5 months after planting.

The soil samples were air-dried and ground to pass a 2 mm sieve size, and then extracted using a solution of DTPA (0.05 mol/l) contains $CaCl_2$ (0.01 mol/l) in pH of 7.3 (Lindsay and Norvell 1978). The extractable DTPA-Pb, Mn, Fe, Cd, Ni, Co, Cu, and Zn were determined by atomic absorption method (Perkin-Elmer model 3030).

Infiltration rate, bulk density and total porosity were also measured at the beginning and end of growing season. In order to measure infiltration rate double ring infiltrometer was used. The inner and outer rings were 30 and 50 cm in diameter, respectively, and the height was 35 cm. The Infiltration test data were analyzed and the related Kostiakov equation for infiltration rate and cumulative infiltration were determined as follows:

$$I = at^b \quad (1)$$

where: I = infiltration rate (cm/h), t = time (min), a, b = coefficient and exponent, respectively

$$F = mt^n \quad (2)$$

where: F = cumulative infiltration (cm), m, n = coefficient and exponent, respectively

Table 1. The average concentration of heavy metals in irrigation water treatments

Elements	Wastewater (mg/l)	Groundwater (mg/l)	FAO acceptable level (Pescod 1992) (mg/l)
Fe	0.07	0.01	5
Cu	0.01	0.01	0.2
Mn	0.11	0.08	0.2
Zn	0.054	0.01	2
Ni	0.01	0.01	0.2
Cd	0.01	0.01	0.01
Co	0.055	0.08	0.05
Pb	0.016	0.02	5
Cr	0.01	0.01	0.1
pH	7.8	7.5	6.5–8.4
EC	1.81 (dS/m)	4.78 (dS/m)	< 3

Data were analyzed statistically the statistical software called SPSS (Kinnear and Gray 2000). The basic infiltration rate for both experimental soils was determined to be about 2 cm per hour.

RESULTS AND DISCUSSION

Effect of treated wastewater on soil chemical properties

Some chemical properties of treated wastewater and groundwater are shown in Table 1. The pH and EC of both water treatments are in the acceptable range based on FAO standards (Pescod 1992). The concentrations of all the heavy metals except Co are also in the proposed FAO range. Table 2 shows the soil physical and chemical properties of both experimental fields. Clay can play an important role in some chemical and physical properties of soil such as adsorption of heavy metals and hydraulic conductivity, respectively.

Concentration of heavy metals in the soil profile. The concentration of heavy metals in the soil profile due to irrigation with wastewater for two irrigation treatments and three crops at the beginning and end of growing season is shown in Table 3. Statistical analysis for the changes of heavy metals due to irrigation with wastewater compared with the beginning of growth stage and groundwater treatment are shown in Table 4. It should be noted the amount of changes in heavy metals is average of different depths for two irrigation systems listed in Table 3. From comparison of Table 3 with Table 4, the following results can be concluded.

The average Pb concentration in the soil is 1.87 and 1.90 mg/l for the beginning and end of growing stage, respectively. The concentration of Pb decreases with soil depth. Application of treated wastewater having 0.016 mg/l Pb had no significant effect on the accumulation of soil Pb compared with the beginning stage. However, in the wastewater treatment, the accumulation of Pb increased significantly compared with the groundwater treatment (Table 4). The average Fe concentration in the soil is 7.32 and 7.40 mg/kg for the beginning and end of growing stage, respectively. The distribution of Fe is uniform in the soil profile. Application of treated wastewater had no significant effect on the amount of soil Fe compared with the beginning stage. The accumulation of Mn, decreases with increasing of soil depth. Application of wastewa-

Table 2. Selected soil physical and chemical properties at the experimental fields

Treatment	Soil depth (cm)	Sand (%)	Clay (%)	Silt (%)	Soil texture	Gypsum (meq/100 g)	Lime (%)
Wastewater	0–20	8.9	52	39.1	clay	0.8	30.8
	20–40	7.8	51	41.2	silty clay	1.0	31.5
	40–80	10.1	53	36.9	clay	5.2	31.0
	80–120	7.2	38.3	54.6	silty clay loam	11.4	29.0
Groundwater	0–20	13.1	43.5	43.4	silty clay	1.3	29.5
	20–40	12.1	42	45.9	silty clay	1.0	29.3
	40–80	5.8	42.9	51.3	silty clay	0.8	32.5
	80–120	6.2	45	48.8	silty clay	0.6	33.5

Table 3. Concentration of heavy metals (mg/kg) in the soil profile due to irrigation with wastewater at the beginning and end of growing season

Heavy metals	Soil depth (cm)	Beginning of growing season	Surface irrigation (end of growing season)			Sprinkler irrigation (end of growing season)		
			sugar beet	corn	sunflower	sugar beet	corn	sunflower
Zn	0–20	0.858	0.489	0.714	1.336	0.772	0.610	0.337
	20–40	0.721	0.648	1.02	0.504	0.969	0.856	1.25
	40–80	0.678	0.728	0.846	0.777	0.838	0.756	0.746
	80–120	0.610	0.697	0.537	0.634	0.576	0.633	0.581
Cu	0–20	0.675	0.380	0.503	0.726	0.583	0.486	0.386
	20–40	0.700	0.469	0.710	0.470	0.683	0.500	0.716
	40–80	0.589	0.658	0.508	0.666	0.616	0.576	0.686
	80–120	0.623	0.653	0.625	0.624	0.591	0.616	0.625
Ni	0–20	0.940	0.900	0.900	1.030	0.975	1.058	0.975
	20–40	0.645	0.775	0.733	0.625	0.591	0.758	0.809
	40–80	0.550	0.516	0.466	0.591	0.466	0.591	0.683
	80–120	0.530	0.575	0.508	0.510	0.566	0.416	0.416
Fe	0–20	7.675	7.790	7.510	8.590	7.770	7.250	7.390
	20–40	7.400	7.260	7.410	8.450	5.800	5.870	8.120
	40–80	7.220	7.230	7.350	7.530	7.520	8.260	7.470
	80–120	0.675	0.380	0.503	0.726	0.583	0.486	0.386
Co	0–20	0.155	0.272	0.366	0.395	0.366	0.433	0.366
	20–40	0.132	0.275	0.341	0.250	0.291	0.291	0.385
	40–80	0.130	0.233	0.208	0.275	0.275	0.191	0.300
	80–120	0.123	0.266	0.325	0.241	0.241	0.225	0.292
Cd	0–20	0.037	0.025	0.025	0.033	0.025	0.033	0.025
	20–40	0.037	0.025	0.041	0.041	0.025	0.025	0.025
	40–80	0.025	0.033	0.050	0.033	0.025	0.033	0.033
	80–120	0.370	0.041	0.050	0.050	0.033	0.025	0.025
Pb	0–20	2.110	2.275	2.230	2.266	2.208	2.100	2.266
	20–40	2.000	2.191	2.160	1.050	1.808	1.858	2.610
	40–80	1.750	1.766	1.770	1.833	1.700	2.010	2.075
	80–120	1.610	1.541	1.425	1.633	1.575	1.816	1.375
Mn	0–20	10.77	13.38	15.68	12.87	15.98	16.62	13.490
	20–40	5.03	11.59	11.45	7.030	8.990	10.09	11.880
	40–80	2.81	3.067	3.000	3.083	2.850	3.390	3.110
	80–120	1.96	1.910	2.290	2.110	2.160	2.140	1.920

ter had a significant effect on the accumulation of soil Mn compared to the beginning of growing season. Also, in the wastewater treatment, the accumulation of Mn increased significantly compared with the ground water treatment (Table 4). The average Cu concentration in the soil is 0.64 and 0.58 mg/g for the beginning and end of growing stage, respectively. The distribution of Cu is uniform in the soil profile. Application of wastewater treatment having 0.01 mg/l Cu, had no significant

Table 4. The effect of irrigation water treatment with wastewater on the increase of heavy metals in soil compared with the beginning of growth stage

Heavy metals	Fe	Mn	Zn	Cu	Pb	Cd	Ni	Co
Amount of increase (mg/kg)	0.08	2.36**	0.03	0.06	0.03	0.002	0.03	0.16**

*significant at 0.05 level, **significant at 0.01 level

effect on the amount of soil Cu compared with the beginning stage and with the groundwater treatment (Table 4). Saber (1986) reported that a seven-year application of wastewater had no significant effect on the concentration of Cu in the soil. Also, Adriano (1986) stated that Cu is stabilized in soil by clay minerals, organic matters and Fe, Al and Mn oxides. The average Zn concentration in the soil is 0.71 and 0.74 mg/kg for the beginning and end of growing stage, respectively. Zinc concentration decreases with increasing soil depth. Application of wastewater treatment had no significant effect on the accumulation of soil Zn compared with the beginning stage. However, in the wastewater treatment, the Zn concentration increased compared with the groundwater treatment (Table 4). Boll et al. (1986) reported that using wastewater irrigation for 16 years increased the concentration of Zn to toxic levels in the soil. Application of wastewater treatment had no significant effect on the accumulation of soil Ni compared with the beginning stage. However, in the wastewater treatment, Ni concentration increased compared with the groundwater treatment (Table 4.). Application of treated wastewater had no significant effect on the accumulation of soil Cd compared with the beginning stage and with the groundwater treatment (Table 4). The accumulation of Co decreases with increasing of soil depth. Application of wastewater treatment having 0.055 Co, mg/l had significant effect on the amount of soil Co compared with the beginning of the growing season and with the groundwater treatment. Pescod and Arar (1985) reported that application of wastewater for irrigation for a period of 47 years caused the total and available Co in soil to increase significantly.

Effect of irrigation system. Irrigation system did not have significant effects on accumulation of DTPA-extractable heavy metals except for Co in soil (Table 5). The significant differences for Co compared to the beginning of growing season are due to the concentration of Co in the treated wastewater, which is more than standard threshold level (Table 6).

Effect of crop type. In general, there were no significant differences between DTPA-extractable heavy metals in soil for the two irrigation systems and three crops. However, some observed differences were probably mainly due to the rooting systems of the crops. Many studies have shown that vegetation is an important factor influencing the mobility of metals in soil, directly as well as indirectly (Caron et al. 1996, Shabanpour et al. 2000). Plants may increase metal mobility through the formation of preferential pathways along root channels or the complexation of metals with root exudates in the rhizosphere. On the other hand

Table 5. Effect of wastewater treatment on the accumulation of available heavy metals in soil for two irrigation system treatments compared with the first of growth stage

Irrigation treatment	Crop	Fe	Mn	Zn	Cu	Pb	Cd	Ni	Co
Sprinkler	sugar beet	7.02	7.49	0.78	0.61	1.82	0.03	0.65	0.30**
	corn	7.17	8.06	0.71	0.54	1.94	0.03	0.76	0.28*
	sunflower	7.43	7.60	0.72	0.60	2.08	0.02	0.72	0.33**
Surface	sugar beet	7.33	7.84	0.64	0.54	1.94	0.03	0.69	0.26**
	corn	7.46	8.10	0.77	0.58	1.89	0.04	0.65	0.31**
	sunflower	8.02	6.27	0.81	0.62	1.94	0.04	0.68	0.29**

*significant at 0.05 level, **significant at 0.01 level

Table 6. Comparison of the average of the available heavy metals (mg/kg) in soil for two irrigation system treatments and three crops

Irrigation treatment	Crop	Fe	Mn	Zn	Cu	Pb	Cd	Ni	Co
Sprinkler	sugar beet	7.33[ac]	7.48[a]	0.64[a]	0.54[a]	1.94[a]	0.03[c]	0.69[a]	0.26[a]
	corn	7.46[ab]	8.10[a]	0.77 [a]	0.58[a]	1.89[a]	0.04[ab]	0.65[a]	0.31[a]
	sunflower	8.02[a]	6.27[a]	0.81[a]	0.62[a]	1.94[a]	0.04[a]	0.68[a]	0.29[a]
Surface	sugar beet	7.02[a]	7.49[a]	0.78[a]	0.61[a]	1.82[a]	0.03[a]	0.65[bc]	0.30[a]
	corn	7.17[a]	8.06[a]	0.71[a]	0.54[a]	1.94[a]	0.03[a]	0.76[a]	0.28[a]
	sunflower	7.43[a]	7.60[a]	0.72[a]	0.60[a]	2.08[a]	0.02[a]	0.72[ab]	0.33[a]

Means with the same letter in each column are not significantly different at $P < 0.05$ according to Duncan Multiple Range Test

they may also retard metal leaching through reducing deep seepage by taking up water, adsorption of metals to root surfaces, plant uptake of metals, and simulated microbial immobilization in rhizosphere (McBride et al. 1997).

Effect of wastewater on soil physical properties

Infiltration rate. For the wastewater treatment the average infiltration rate at the beginning and end of growing season were 2.1 and 2.9 cm/h, respectively. Therefore, the application of wastewater caused an increase in the infiltration rate. For the groundwater treatment, the average of infiltration rate at the beginning and end of growing season were similar (Table 7).

Saturated hydraulic conductivity. As shown in Table 7, application of wastewater caused a decrease in the saturated hydraulic conductivity at depths of 0–15 and 15–30 cm. Suspended solids including organic matter in wastewater may have filled up some of the soil voids decreasing hydraulic conductivity of the soil. Also, in the wastewater treated plots, growth of microorganisms in the soil pores may result in the reduction of saturated hydraulic conductivity.

Soil bulk density. Soil bulk density increased significantly in both water treatments (Table 7). This was due to the particles dispersion and sedimentation of clay particles. Although the wastewater contains considerable organic matters but there was no effect on the soil bulk density. This could be because the period of experiment was short.

Porosity. The wastewater irrigation caused a reduction in the soil porosity; however there was no significant difference between the wastewater and groundwater irrigation treatments (Table 7). The average soil porosity, at 0–15 cm depth, in the wastewater and groundwater treatments is 48.6 and 48.4 percent, respectively. The reduction of soil porosity at the depth of 15–30 cm was significant as compared to the beginning of the growing season.

Table 7. Average of soil physical properties for two irrigation water treatments and three crops

	Saturated hydraulic conductivity (cm/h)				Bulk density (g/cm³)				Porosity (%)				Final infiltration rate (cm/h)	
Soil depth (cm)	0–15		15–30		0–15		15–30		0–15		15–30			
Trial	B	E	B	E	B	E	B	E	B	E	B	E	B	E
Wastewater	3.80	3.45	3.70	3.50	1.19	1.29**	1.22	1.32**	54.48	48.59**	52.78	48.93**	2.09	2.92
Groundwater	3.56	2.34**	3.49	2.55**	1.20	1.30**	1.21	1.31**	52.68	48.35**	53.14	49.23*	1.86	1.94

B = beginning of growing season, E = end of growing season, *significant in 0.05 level, **significant in 0.01 level

There are different attributes of wastewater that may contribute to reduction in infiltration rates and hydraulic conductivity when wastewater irrigation is applied (Magesan et al. 1999). Some of reported mechanisms by researchers are: blockage of the inter-soil spaces by suspended material such as colloidal clay and algal cell particles (Berend 1967, Bouwer and Chaney 1974), formation of a biological mat or crust (Kristiansen 1981, Balks et al. 1997), biological clogging including microbial extracellular (Thomas et al. 1966, McAuliffe et al. 1982), collapse of soil structure due to organic matter dissolution (Nevo and Mitchell 1967, Vandevivere and Baveye 1992, Lieffering and McLay 1996). Infiltration rate and hydraulic conductivity may also decrease through physical blocking of soil pores as a result of high loads of suspended solids during land application of wastewater (Magesan et al. 2000). Although clay dispersion at the soil surface has been reported to increase the hydraulic conductivity of soils, generally in sandy soils with large soil pores that allow the clay particles to pass straight through (Frenkel et al. 1978), dispersion typically reduces the infiltration rate and hydraulic conductivity by blocking soil pores with fine clay particles (So and Aylmore 1993). However, as stated by Halliwel et al. (2001), dispersion would not normally occur during wastewater irrigation as long as the EC of the wastewater remains above the critical coagulation value.

Effect of irrigation system on soil physical properties

Infiltration rate. The effect of irrigation system on infiltration rate for both treatments was significant (Table 8). The average final infiltration rate for sprinkler system was higher compared to surface irrigation system. In the wastewater treatment with the surface irrigation system, the average final infiltration rate decreased at the end of growing season compared to the beginning of growing season (Table 9). Using the sprinkler system with wastewater, the final infiltration rate increased for sugar beet and corn but decreased for sunflower. Using the surface irrigation system, the final infiltration rate increased for sugar beet but decreased for corn and sunflower (Table 10).

Saturated hydraulic conductivity. In the sprinkler system with wastewater, the saturated hydraulic conductivity increased at 0–15 and 15–30 cm depth but decreased in the surface irrigation system (Table 9). This could be related to the less production of suspended materials in the sprinkler system and therefore, less possibility of the clogging of soil porosity. As mentioned before for surface irrigation system, the soil aggregates are dispersed and produced more fine particles.

Soil bulk density. The average of soil bulk density for surface irrigation system was higher as compared to the sprinkler system (Table 9). This is probably due to the movement of some soil fine particles to the soil porosity.

Porosity. The surface irrigation system reduced the soil porosity for both irrigation water treatments more than sprinkler irrigation system. This could be attributed to breaking of aggregates and filling of some of soil voids by fine particles. The coefficients and exponent of the Kostiakov infiltration rate model which was fitted to the average of three replications for each treatment are shown in Table 11. The Kostiakov model can properly predict the infiltration rate for all experiments and the exponent of the Kostiakov model for sprinkler system is small and close to zero as compared to the surface irrigation system. This is due to less possibility of changing the soil structure in sprinkler system and so less gradient of infiltration rate from initial to the final value. In other words, the infiltration rate decreases rapidly from initial to final value for surface irrigation system as compared to the sprinkler system (exponent is less). This phenomenon was observed for both irrigation water treatments. The initial infiltration rate in sprinkler system for both irrigation water

Table 8. Effect of two irrigation water treatments on the soil physical properties

	Final infiltration rate (cm/h)	Saturated hydraulic conductivity (cm/h)		Bulk density (g/cm^3)		Porosity (%)	
Soil depth (cm)		0–15	15–30	0–15	15–30	0–15	15–30
Wastewater	4.52**	3.12**	1.36**	0.07*	0.04*	2.99**	1.53*
Groundwater	2.53*	1.87**	0.99**	0.08**	0.02	2.87**	0.88

*significant in 0.05 level, **significant in 0.01 level

Table 9. Average of soil physical properties irrigated by wastewater and groundwater for two irrigation system treatments

		Saturated hydraulic conductivity (cm/h)				Bulk density (g/cm^3)				Porosity (%)				Final infiltration rate (cm/h)	
Soil depth (cm)		0–15		15–30		0–15		15–30		0–15		15–30			
Trial		B	E	B	E	B	E	B	E	B	E	B	E	B	E
Waste-water	sprinkler	3.57	5.01**	3.67	4.18	1.20	1.26**	1.22	1.30**	52.3	50.09**	52.6	49.7*	2.05	5.38*
	surface	4.03	1.89*	3.74	2.82*	1.19	1.33**	1.22	1.34**	52.6	47.10**	52.8	48.1*	2.13	0.46**
Ground-water	sprinkler	3.75	3.28	3.53	3.04*	1.18	1.26	1.20	1.30**	52.9	49.70**	53.4	49.6**	2.42	3.24
	surface	3.36	1.41*	3.47	2.05*	1.21	1.32**	1.21.	1.32**	52.4	46.90**	53.0	48.8**	1.31	0.65**

B = beginning of growing season, E = end of growing season, *significant in 0.05 level, **significant in 0.01 level

treatments is more as compared to the surface irrigation system. These properties are changed in the surface irrigation system due to the breaking of soil aggregates in both irrigation water treatments and the existence of suspended materials in the wastewater.

The results indicated that irrigation system treatment had no significant effect on DTPA-extractable heavy metals in soil, except for Co, which is slightly higher than standard level proposed by FAO. This may be related to the concentration of Co in the wastewater treatment effluent, which is more than the recommended maximum concentration level.

Using wastewater for irrigation significantly increased Pb, Mn, Ni and Co concentrations in soil as compared with the groundwater treatment. Concentration of Pb, Mn, Ni, Co, Cu and Zn decreases with the soil depth. Using wastewater had no effect on increase of Fe, Cd, Ni, Cu and Zn as compared to the beginning stage of crop growth.

Applying surface irrigation, with wastewater decreased the final infiltration rate but a reverse effect occurred in sprinkler irrigation system. The irrigation system in both irrigation water treatments significantly affected the Kostiakov parameters (*a*, *b*). Applying wastewater with surface irrigation had significant effect on the coefficient of *a* and applying wastewater with sprinkler irrigation had significant effect on the exponent of *b*.

The irrigation system also had significant effect on soil bulk density, porosity and saturated hydraulic conductivity at 0–15 cm soil depth. The surface irrigation caused the soil bulk density to increase and soil porosity to decrease as compared to the sprinkler irrigation. Also, the surface irrigation decreased the saturated hydraulic conductivity but the sprinkler irrigation system increased the

Table 10. Final infiltration rate for two irrigation system treatments and three crops

Irrigation system		Wastewater		Groundwater	
Sprinkler	sugar beet	2.01	9.84*	2.70	5.63
	corn	2.11	4.46	2.65	2.48
	sunflower	2.02	1.82	1.90	1.60
Surface	sugar beet	1.58	0.35	1.55	0.82
	corn	2.28	0.52*	1.38	0.31*
	sunflower	2.53	0.52	1.00	0.80

*significant in 0.05 level, **significant in 0.01 level

Table 11. The parameters of the Kostiakov model based on the average of observed data at the end of growing season

Treatment	Irrigation system	Crop	*a*	*b*	*R*
Wastewater	sprinkler	sugar beet	34.27	–0.256	–0.98
		corn	21.76	–0.310	–0.99
		sunflower	4.93	–0.230	–0.92
	surface	sugar beet	7.38	–0.314	–0.97
		corn	5.31	–0.439	–0.97
		sunflower	3.66	–0.437	–0.86
Groundwater	sprinkler	sugar beet	18.69	–0.244	–0.98
		corn	18.35	–0.394	–0.98
		sunflower	9.50	–0.339	–0.86
	surface	sugar beet	6.79	–0.421	–0.94
		corn	5.89	–0.523	–0.99
		sunflower	4.49	–0.364	–0.95

saturated hydraulic conductivity. Irrigation system using wastewater treatment increased the soil bulk density and porosity at 15–30 cm soil depth. Using waste water for surface irrigation decreased the soil saturated hydraulic conductivity at soil depth of 15–30 cm but sprinkler irrigation increased the soil saturated hydraulic conductivity.

The positive effects of sprinkler system using wastewater on infiltration rate and saturated hydraulic conductivity are important findings which need to be studied in a long term experiment especially in the soils of central Iran which have very poor physical properties. Also, further research is required to investigate the effects of environmentally friendly and safer irrigation systems for farmers (such as trickle and underground systems) upon soil chemical and physical properties.

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