

Effects of Irrigation with Recycled Water on Biomass, Root system, Yield and Quality of Winter Wheat and Summer Corn

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Abstract: The recycled water irrigation district area has been reached for about 40000 hm² in Beijing China. As mainly crops, effects of irrigation with recycledwater after second treatment on biomass, root system, yield and quality of winter wheat and summer corn were studied for 5 years in field experiment. Experimental results illustrated that the height and total leaf area for per plant had no significant difference between treatments. The root length, root weight and root surface area in unite volume soil all decreased with the increase of soil depth for all treatments, and above indexes had no significant difference between treatments in the extent of 0~100cm soil(p=0.05). Irrigation with recycledwater did not influence the depth of main root, the root distributed in 0~20cm soil mainly and the root quantity in 0~70cm soil was the 95 percent of total root quantity. According to experimental results, the yields of winter wheat and summer corn which irrigated with recycledwater increased by 6.49% and 5.42%, respectively, compared with those of local groundwater irrigation treatment. There was no significant difference between recycledwater irrigation treatment and localground water irrigation treatment(p=0.05). The main quality indexes of winter wheat and summer corn with recycled water irrigation had not been significantly influenced(p=0.05). The total nitrogen content in grains of winter wheat, total nitrogen and total phosphorus contents in grains of summer corn were increased slightly, but the total phosphorus and total potassium contents in grains of winter wheat, total potassium content in grains of summer corn had no significant variation with recycledwater irrigation. Furthermore, the contents of As, Cd, Cr, Hg, Cu, and Pb for recycledwater irrigation treatment all were lower than the limited criterion value in Chinese national standard of <Hygienic standard for grains >(GB 2715-2005). As a result, the recycledwater after second treatment could be used in agricultural irrigation for winter wheat and summer corn safely.

Key words: recycled water; irrigation; water resources; winter wheat; summer corn; biomass; yield; quality

1Introduction

Using recycled water in agricultural irrigation has become a successful measure in mitigating water shortage in many countries around the world^[1]. The safety issue of using recycled water in irrigation is always a common concern by management, researchers and producers all over the world. To study potential problems in the usage of recycled water in irrigation, researchers have conducted numerous studies on the long-lasting effects of recycled water irrigation on organic pollutants, pathogenic microbes and ecological risks, as well as the effects of recycled water irrigation on environmental factors such as soil, surface water, groundwater and crops^[2-7]. Crops are an important ecological environmental factor that provides necessary food for people, and at the same time has an important ecological function^[8], therefore,

the effects of recycled water irrigation on crops has become a hot issue in the field. The main research subjects include the effects of recycled water irrigation on the distribution of heavy metals in the soil-crop system^[9], seed germination and seedling growth^[10], soil physical and chemical properties^[11,12] and on grain quality^[13-15] in China. Study of the influence of recycled water irrigation on crops started earlier in America, Japan and Australia, and is more systematic. The research often includes the effects of recycled water irrigation on crop growth, yield, the quality of the soil environment, soil moisture distribution and the quality of the grain or fruit, and the research develops deeply into the mechanisms^[16-21].

There is a lack of reports about the long-term effects of recycled water irrigation on crop growth, yield, quality and root development. The root system is an important functional organ that supports crop growth above ground, absorbs nutrients and connects the soil-crop system as a whole. Yield and quality are essential in the determination of the economic value of food crops and food safety. Among the main crops in the Beijing area of China, grain crops rank first in sown acreage and accounted for 60.4% of the total sown crop area^[22]. It is important to understand the effects of recycled water irrigation on crops given that the area for the growth of grain crops in Beijing is large, and research on the effects of recycled water irrigation on the roots of crops is lacking. We studied the long-term effects of recycled water irrigation on the development of the root system, and on the yield and quality of winter wheat and summer corn in the Beijing area in order to enrich the theoretical system on recycled water irrigation, and to provide reliable scientific evidence to ensure the safe usage of recycled water in irrigation.

2 Materials and methods

2.1 Basic statistics and experimental design

This experiment was carried out in the test-pits at the Beijing Water-Saving Irrigation Testing Station at Yongledian town, Tongzhou district, Beijing, China. The experiment station is located at latitude 39°20', longitude 114°20', and is 12 m above sea level. The average rainfall of the area is 565 mm, the average annual evaporation is 1140 mm, the multi-year average temperature is 11.5°C and the frost-free period is 185 days. The test-pits are bottomless pits with a uniform size of three by two m. The test-pits were surrounded by a 1 m deep isolation geomembrane to eliminate the effects of lateral soil water flow. The soil is silt loam. The local underground water

depth is approximately 8 m, therefore the water absorbed by the plant from the groundwater is negligible.

We tested the long-term effects of recycled water irrigation on root system development of winter wheat from September 2000 to mid-June 2006. There were four different treatment groups in this experiment: the clean water irrigation treatment T1-1; the recycled water irrigation treatment T1-2; three years of irrigation with recycled water followed by three years of irrigation with clean water treatment T1-3 and three years of irrigation with clean water followed by three years of irrigation with recycled water treatment T1-4. Each treatment had three replicates and the treatment plots were randomly arranged. The winter wheat and summer corn were planted in rotation each year in the test-pits. During the experimental period, a total of six crops of winter wheat were planted (the growing period was from the end of September of one year to the middle of June of the next year), and five crops of summer corn were planted (the growing period was from mid-June to the end of September each year). The irrigation system used each year was based on local farming practices. The irrigation of winter wheat in each treatment and rainfall conditions are shown in Table 1.

Table 1 Irrigation and rainfall for all treatments during experiment

Year	The irrigation water quantity, type and time for experiment				Irrigation time	Total rainfall during experimental period/mm
	T1-1	T1-2	T1-3	T1-4		
2000~2001	Q5	Z5	Z5	Q5	Sowing time, Overwintering period, Turning green period, Shooting period, Pustulation period	83.6
2001~2002	Q5	Q1,Z4	Q1,Z4	Q5	Sowing time, Overwintering period, Turning green period, Shooting period, Pustulation period	158.0
2002~2003	Q5	Z5	Z5	Q5	Sowing time, Overwintering period, Turning green period, Shooting period, Pustulation period	156.0
2003~2004	Q3	Z3	Q3	Z3	Overwintering period, Turning green period, Pustulation period	218.2
2004~2005	Q4	Z4	Q4	Z4	Overwintering period, Turning green period, Shooting period, Pustulation period	161.9
2005~2006	Q4	Z4	Q4	Z4	Sowing time, Overwintering period, Shooting period, Pustulation period	97.4

Note: Z and Q are the irrigation water types. Z refers to recycled water irrigation, Q refers to local groundwater irrigation; the numbers after Z and Q indicate the irrigation frequency. For example, Z1 indicates a one-time irrigation with recycled water and the same with all others. The one time clean water irrigation in the experiment conducted from 2001 to 2002 in test T1-2 and T1-3 was applied at the sowing time.

The annual irrigation quota was $450\text{m}^3/\text{hm}^2$ from 2000 to 2004 ^[9] and $600\text{m}^3/\text{hm}^2$ from 2004 to 2006. From 2004 to 2005 the wheat variety planted was *Lunxuan 987*. Compound fertilizer was applied with $750\text{kg}/\text{hm}^2$ as the base fertilizer. Urea fertilizer was applied with $300\text{kg}/\text{hm}^2$ as a fertilizer topdressing at the jointing stage of wheat. From 2005 to 2006 the wheat variety planted was *Lunxuan 987*, but the fertilization composition was changed. Compound fertilizer was applied with $375\text{kg}/\text{hm}^2$ as the base fertilizer and urea was applied with $375\text{kg}/\text{hm}^2$ as a fertilizer topdressing at the jointing stage. During the testing period, the same management measures were applied for each of the test pits except for the irrigation treatment.

The testing period of the long-term effects of recycled water irrigation on the growth, yield and quality of winter wheat and summer corn was from mid-June in 2003 to the end of September 2007. The sowing time and harvesting time, planting test-pits of experimental winter wheat and summer corn is the same as the above experiment. Four crops of winter wheat and five crops of summer corn were planted during the testing period. The three testing treatments were the recycled water irrigation treatment (T2-1), equal intervals of recycled water and clean water irrigation (T2-2), and the local groundwater irrigation treatment (CK). Each process was repeated three times and the treatment plots were randomly arranged. The specific test cases are shown in Table 2.

Table 2 Experimental treatments and irrigation schedule

Crop	Period of duration	Total irrigation amount/mm	Irrigation times	Treatments
Winter wheat	03/09/29—04/06/15	165	3	T2-1, T2-2, CK
	04/09/28—05/06/15	300	5	T2-1, T2-2, CK
	05/09/30—06/06/15	225	4	T2-1, CK
	06/10/02—07/06/14	300	5	T2-1, T2-2, CK
Summer corn	03/06/13—03/09/26	45	1	T2-1, CK
	04/06/15—04/09/28	0	0	Rainfall being abundant, without irrigation
	05/06/15—05/09/27	45	1	T2-1、T2-2、CK
	06/06/17—06/09/27	45	1	T2-1、CK
	07/06/17—07/09/28	75	1	T2-1、T2-2、CK

During the testing period the same management measures were applied for each test-pit, except for the different irrigation treatments. From 2003 to 2006 the annual winter wheat cultivar planted was the same as showed in Table 1. *Lunxuan 987* was the winter wheat cultivar planted in

2006 to 2007, *Nongda 84* and *Nongda 86* were the summer corn cultivar planted in 2003 and 2005, respectively and *Nongda 958* was the summer corn cultivar planted in 2006 and 2007.

The recycled water used in the test was secondary effluent from the Gaobeidian Sewage Treatment Plant, which is located in Gaobeidian town, Tongzhou district, Beijing, China. The water used for the CK was from the local groundwater.

The indicators of the water quality measurement of each irrigation group included the total salt (TDS), the suspended solids (SS), BOD₅, COD_{cr}, nutrients, heavy metals, and pH. The general water quality of the recycled water was in agreement with the provisions in “Water Quality of the Urban Wastewater Recycle, Reuse and Farmland Irrigation Water Usage” (GB20922-2007)^[23]. The results of the water quality test are shown in Table 3.

Table 3 Quality of ground water and recycled water

Serial No	Water quality indicators	Recycled water	Ground water
1	BOD ₅ /(mg·L ⁻¹)	3.9~45.6	8.91
2	COD _{cr} /(mg·L ⁻¹)	39.2~89.3	15.6
3	Suspended Solids /(mg·L ⁻¹)	1.21~32	0.2
4	TN/(mg·L ⁻¹)	16.2~32	1.75~8.45
5	NH ₃ -N/(mg·L ⁻¹)	0.67~4.2	0.02~0.42
6	pH	7.3~8.46	7.5~8.18
7	Total Cd/(mg·L ⁻¹)	0.00003	0.000005
8	Cr ⁶⁺ /(mg·L ⁻¹)	0.011~0.079	0.014~0.017
9	Coliforms, Fecal/100 mL ⁻¹	102~988	0
10	Ascaris eggs/L ⁻¹	0	0
11	Total salt content /(mg·L ⁻¹)	880~1050	610~760
12	Chlorid/(mg·L ⁻¹)	148~300	49.3~96.2
13	Sulfide/(mg·L ⁻¹)	0.18~0.19	<0.004

1.2 Experimental measurements and methods

1) Wheat root system: A root drill was used to collect root samples on and between rows on June 17th 2006 - the day of wheat harvest. Wheat was planted in dense rows. Sampling on the row refers to sampling directly below the wheat plant, whereas sampling between rows refers to sampling between two rows of wheat. The tube diameter of the root drill was 7 cm, the tube height was 10 cm and the length of the drill pipe was 120 cm. The root samples were taken from 10 cm below the surface until 100 cm below the surface, which included a total of 10 layers. The column of the root sample removed was 7 cm in diameter and 10 cm in height. Each sample was placed into a Ziplock plastic bag and marked individually. After the samples were brought back to the laboratory, they were sieved with a 0.5 mm sieve. All roots in the soil column from

different layers were washed clean with water and collected with a 0.25 mmsieve, then the root would be picked together. The WinRHIZ0-Reg-LA root analysis system made in Canada was used to scan the root sample layer-by-layer. The supporting software was used to obtain the parameter values of the root length, diameter and the surface area. After the scan was completed, the roots were placed in a manila envelope and baked to constant weight at 75°C. An analytical balance with an accuracy of 1/10000 was used to weigh the dried roots. The layer-by-layer root length density, root weight density and the root surface area per unit volume of soil were calculated based on the root analysis result and the dry weight.

2) Plant height and leaf surface area of the winter wheat: Typical sample plants were selected based on the proportion of growth levels. A plastic ruler or steel tape was used to measure the plant height and leaf surface area. 10 sample plants were selected from each pit. The monitoring period was from April 26, 2006 (the jointing stage) to June 1, 2006 (the grain filling stage), and measurements were conducted once every one to two weeks.

3) Yield of the winter wheat and summer corn: The winter wheat and summer corn were harvested and threshed. After air-drying, the grains were weighed and the relative crop yield index was determined seasonally.

4) Grain quality: Sample grains were selected after air-drying each year. The nutrient contents of the grain, including crude protein, soluble total sugars, vitamin C (VC), crude ash, and crude starch, were measured. The content of total soluble sugar was measured using hydrochloric acid and a copper reduction direct titration method, the content of VC was determined using a 2,6-dichloro indophenol titration method, the content of crude protein was determined using the Kjeldahl method, the content of the crude starch was determined using the starch Glucoamylase-acid hydrolysis method, crude ash was determined using the dry ashing method, the total nitrogen (TN) was determined using H₂SO₄-H₂O₂ digestion-distillation titration method, the total phosphorus (TP) was determined using H₂SO₄-H₂O₂ digestion-V-Mo yellow colorimetry, the total potassium (TK) was determined using H₂SO₄-H₂O₂ digestion-flame photometry, the content of As was determined using the hydride generation-atomic fluorescence spectrometry (HG-AFS) method, the content of Cd, Cr, Cu, Pb, and Zn were determined using the high resolution inductively coupled plasma mass spectrometry (HR-ICP-MS), and the content of Hg was determined by cold vapor generation-atomic fluorescence spectrometry (CV-AFS).

2. Results

2.1 Effects of recycled water irrigation on plant height and leaf surface area of winter wheat

On April 26th, May 11th, May 18th, and June 1st in 2006, the plant height and leaf surface area of treatment 1-1 (T1-1), treatment 1-2 (T1-2), and treatment 1-3 (T1-3) were determined. The results are shown in Table 4.

Table 4 Height and total leaf area of winter wheat for T1, T2 and T4

日期	Plant Height/cm			Leaf surface area of one plant/cm ²		
	T1-1	T1-2	T1-4	T1-1	T1-2	T1-4
2006-04-26	31.7	34.2	32.4	46.5	51.8	46.1
2006-05-11	57.4	59.2	59.3	57.6	64.0	58.2
2006-05-18	63.6	65.4	64.5	48.5	47.9	44.1
2006-06-01	63.2	68.0	66.7	30.6	35.5	29.3

Leaves are the vital organs for photosynthesis, transpiration and respiration in winter wheat. The development condition of leaves made a direct impact on the efficiency of water usage in the plant. Some of the leaves were wilted to varying degrees when the winter wheat entered the booting stage after mid-May, which resulted in a decrease in the total leaf surface area per plant. By using the average value of a two paired sample analysis, the plant height and the total leaf-surface-area per plant between different treatments were analyzed. The results from these four measurements showed that plant height and total leaf-surface-area per plant among the different treatments at different growth periods showed no significant differences. This indicates that there were no significant effects of the recycled water irrigation on plant height and leaf surface area after the jointing stage of winter wheat.

2.2 Effects of recycled water irrigation on winter wheat root development

Roots are vital organs that uptake nutrients and support the upper portion of the plant. In this study, the root development of winter wheat from four different irrigation treatments were analyzed for the vertical spatial distribution of the root length, root dry weight, and root surface area.

2.2.1 Effects of recycled water irrigation on root density

2.2.1.1 Effects of recycled water irrigation on root length density

Figure 1 and 2 show the characteristics of the vertical distributions of the root length density of winter wheat, on or between rows from the surface to 100 cm below the surface under different irrigation treatments. Under different treatments, the root length densities of the winter wheat, on

or between rows, decreased with increasing soil depth. In the soil layer from 0 to 30cm, there was a sharp decrease in root length densities, of which, the root length density between rows was reduced from 3.015 to 0.625cm/cm³ in T1-1, from 2.171 to 0.183cm/cm³ in T1-2, from 2.079 to 0.679cm/cm³ in T1-3, and from 2.329 to 1.128cm/cm³ in T1-4. The root length density on the rows was reduced to about 0.4cm/cm³ from 4.176cm/cm³ in T1-1, 5.639cm/cm³ in T1-2, 3.904cm/cm³ in T1-3, and 5.309cm/cm³ in T1-4, respectively. In addition, the root length densities on the rows in the soil layer from 0 to 20cm were significantly higher than the root length densities between the rows. The root length densities on or between rows in the soil layer from 20 to 100cm had both highs and lows. However, the overall root length densities at the soil depth of 0 to 100cm showed no significant differences between different treatment groups, indicating that at harvest time, the recycled water irrigation showed no significant effect on winter wheat root length densities within 1 m of soil.

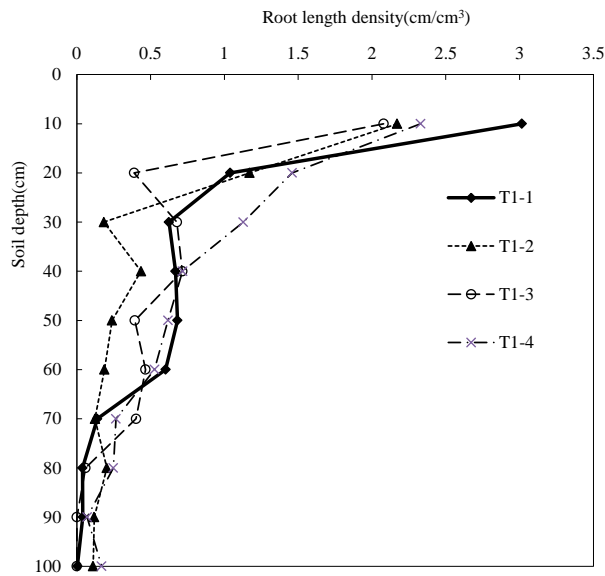


Figure 1 Vertical trend of root length density between lines for all treatments

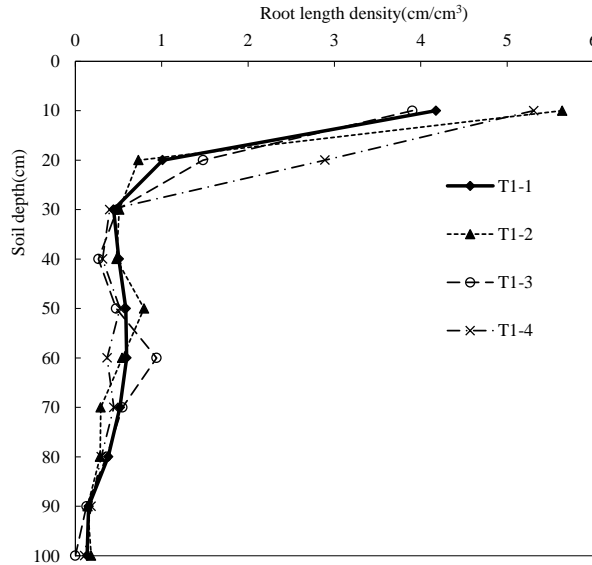


Figure 2 Vertical trend of root length density on lines for all treatments

2.2.1.2 Effects of recycled water irrigation on root weight density

Figures 3 and 4 show the characteristics of the vertical distributions of root weight density of winter wheat, on or between rows, from the surface to 100 cm below the surface under different irrigation treatments. The changes of the distribution of the root weight density were similar to the distribution of the root length density. The distribution of the root weight densities of winter wheat, on or between rows, decreased with the increase of soil depth. From 0 to 20 cm, the root weight densities decreased rapidly. From 20 to 100 cm, the root weight densities slowly decreased. The root weight densities at the soil layer from 0 to 10 cm were the highest among different treatments. The root weight densities between rows were 0.334 mg/cm^3 for T1-1, 0.263 mg/cm^3 for T1-2, 0.223 mg/cm^3 for T1-3, and 0.246 mg/cm^3 for T1-4. The root weight densities on the rows were 1.774 mg/cm^3 for T1-1, 1.439 mg/cm^3 for T1-2, 1.790 mg/cm^3 for T1-3, and 1.245 mg/cm^3 for T1-4, which were approximately 80% higher than the root weight densities between rows. In addition, at the soil layer from 0 to 20 cm, the root weight densities on the rows were significantly higher than root weight densities between rows. At the soil layer from 20 to 100 cm, the differences on or between rows were not significant. The overall root weight densities in soil depths from 0 to 100 cm showed no significant differences between different treatment groups, indicating that at harvest time, the recycled water irrigation showed no significant effect on winter wheat root weight densities within 1 m of soil depth soil.

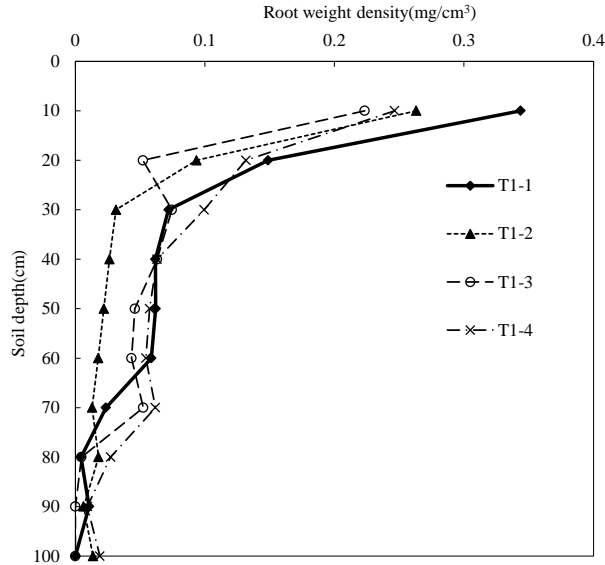


Figure 3 Vertical trend of root weight density between lines for all treatments

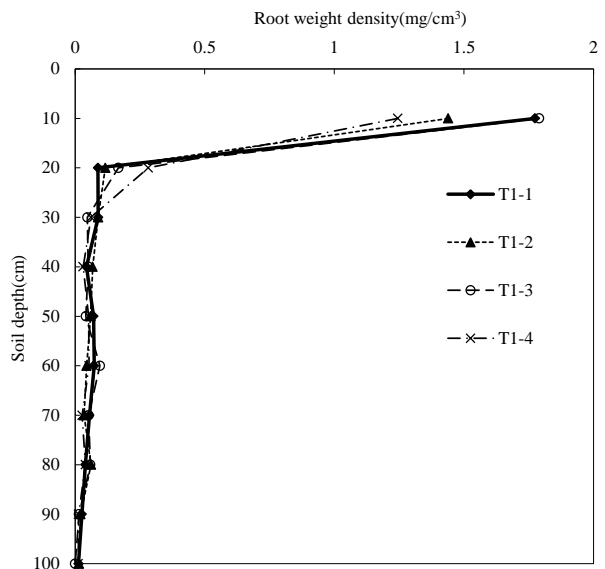


Figure 4 Vertical trend of root weight density on lines for all treatments

2.2.2 Effects of recycled water irrigation on the major root distribution depth

Based on the analysis above, there was no significant difference in the root length density and root weight density between different treatment groups. In order to determine the primary depth of the root system of winter wheat, the average value of the root length densities on and between rows at each soil depth layer were used as representative values of the root length in a particular soil layer. This was used to analyze the vertical distribution trend by calculating the ratio of the accumulation of the root length density layer-by-layer with the sum of total root length density in the 1 m soil layer (r_{li}), as shown in Figure 5. Also, the average root weight density

on and between rows at each soil layer were used as the representative value of the root weight of that soil layer, and this was used to analyze the vertical distribution trend of the ratio of the accumulation of the root length density layer-by-layer with the sum of total root length density in the 1 m soil layer (r_{wi}), as shown in Figure 6.

r_{li} was calculated using Formula 1.

$$r_{li} = \rho_{li} / \rho_{li} = \frac{\sum_{n=1}^i \rho_{ln}}{\sum_{n=1}^{10} \rho_{ln}} \quad \text{Formula(1)}$$

In the formula, r_{li} is the ratio of the accumulation of the root length density of the soil layer from 0 to i in the total root length density in the 1 m soil layer; $i=1,2,3, \dots, 10$; ρ_{li} is the accumulation of the root length density of the soil layer from 0 to i ; ρ_{li} is the total root length density of the 1 m deep soil layer; ρ_{ln} is the average of the root length density on and between rows at n^{th} soil layer.

r_{wi} was calculated using Formula 2.

$$r_{wi} = \rho_{wi} / \rho_{wt} = \frac{\sum_{n=1}^i \rho_{wn}}{\sum_{n=1}^{10} \rho_{wn}} \quad \text{Formula (2)}$$

r_{wi} is the ratio of the accumulation of the root weight density of the soil layer from 0 to i in the total root weight density in the 1 m deep soil layer; ρ_{wi} is the accumulation of the root length density of the soil layer from 0 to i ; ρ_{wt} is the total root length density of the 1 m deep soil layer; ρ_{wn} is the average of the root length density on and between rows at the soil layer n .

Figure 5 and 6 showed that root length at the soil layer from 0 to 20 cm was 60% of the total root length from the 1 m deep soil layer, and the root weight was 78% of the root weight from the 1 m deep soil layer. Therefore, this soil layer was the main layer where the roots of winter wheat were distributed. In the soil layer from 0 to 70 cm, the root length and root weight were both 95% of those from the 0 to 100 cm soil layer from all treatments, therefore irrigation with recycled water did not affect the winter wheat root distribution at the harvest time.

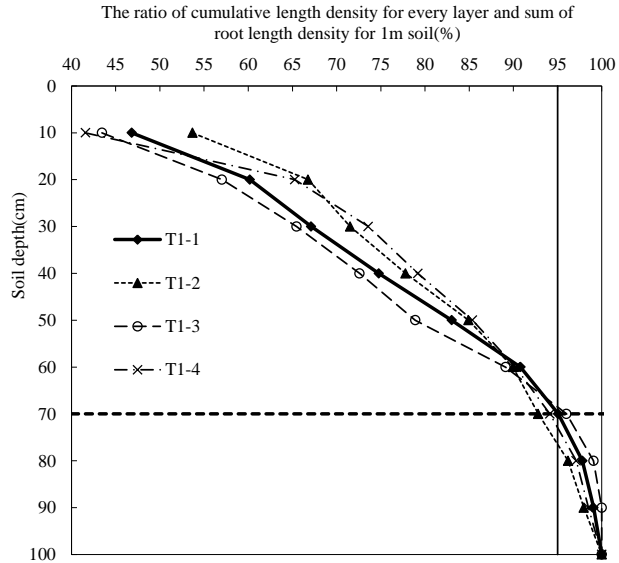


Figure 5 Vertical trend of cumulative root length density for all treatments

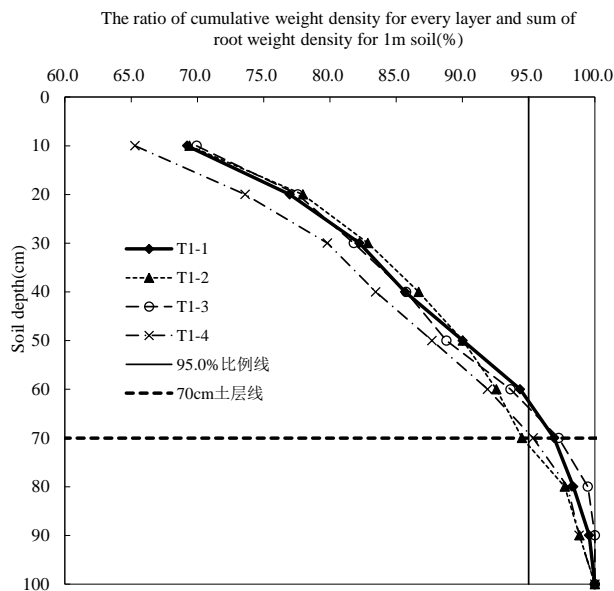


Figure 6 Vertical trend of cumulative root weight density for all treatments

2.3 Effects of recycled water irrigation on the yield of winter wheat and summer corn

2.3.1 Effects of recycled water irrigation on the yield of winter wheat

As shown in Table 5, the yield of winter wheat in 2003 to 2004 was significantly lower compared with other years, which was largely caused by quality issues with the winter wheat seed. From 2004 to 2007, the yields of winter wheat T1 were 5516.9, 4182.7, and 5416.9 kg/hm², respectively. Compared to the CK group, the changes of the yields were 0.1%, 12.87%, and 12.72%, respectively, which indicates an average of 6.5% increase in the yield of winter

wheat when irrigated with recycled water compared with those irrigated with groundwater over four years. From 2003 to 2007, results showed that there was no significant change in the yields among treatment groups ($\alpha=0.05$). This conclusion is in line with recent similar research^[24-25].

Table 5 Yield of winter wheat for each treatment

Year	Yield/(kg·hm ⁻²)			Changes of the yield compared with the CK/%	
	T2-1	T2-2	CK	T2-1	T2-2
2003—2004	1 675.1	1 983.4	1 666.8	0.50	18.99
2004—2005	5 516.9	5 739.2	5 522.5	-0.10	3.92
2005—2006	4 182.7	—	3 705.7	12.87	—
2006—2007	5 416.9	5 222.5	4 805.8	12.72	8.67

Note: "—" represents the test was not conducted for that season.

As shown in Table 6, compared with the CK group, the variation of the thousand-grain quality of the winter wheat irrigated with recycled water in T2-1 was 2.88% and -3.28% from 2004 to 2005, and 2005 to 2006, respectively. This indicates that the effect of the recycled water irrigation on the 1000-grain quality of the winter wheat is negligible.

Table 6 1000-grain weight of winter wheat for each treatment

Year	1000-grain weight/g		Changes of the 1000-grain yield weight compared with the CK/%
	CK	T2-1	T2-1
2004—2005	39.90	41.05	2.88
2005—2006	33.55	32.45	-3.28

2.3.2 Effects of recycled water irrigation on the yield of summer corn

As shown in Table 7, from 2003 to 2007, the yields of summer corn in T1 were 9056.5, 5569.7, 7925.4 and 10094.9 kg/hm², respectively.

Table 7 Yield of summer corn for each treatment

Year	Yield/(kg·hm ⁻²)			Changes of the 1000-grain yield weight compared with the CK /%	
	T2-1	T2-2	CK	T2-1	T2-2
2003	9 056.0	—	8 767.1	3.30	—
2005	5 569.7	5 275.3	5 353.0	4.05	-1.45
2006	7 925.4	—	8 019.8	-1.18	—
2007	10 094.9	8 717.1	8 739.3	15.51	-0.25

Note: "—" represents the test was not conducted for that season. In 2004, the rainfall was abundant and the summer corn was not irrigated with recycled water, therefore it is not listed in the table.

Compared to the CK group, the changes of the yields were 3.3%, 4.05%, -1.18%, and 15.51%, respectively. The increase in the yield of summer corn irrigated with recycled water was 15.51% compared with the yield of the treatment irrigated with groundwater in 2007. This may

be related to the soil fertility accumulation when using recycled water irrigation and the increased recycled water irrigation in that year. The changes of the yield in the other three years were all below 5%. The summer corn yields for the four years showed no significant differences between different treatment groups ($\alpha=0.05$).

2.4 Effects of recycled water irrigation on the grain qualities of winter wheat and summer corn

2.4.1 Effects of recycled water irrigation on grain quality of winter wheat

As shown in Table 8, five winter wheat quality indexes were analyzed. 1) Crude protein (CP): The crude protein content of the winter wheat grain over two years were 12.4% and 11.9% in T1, 12.1% and 13.1% in CK. There was a change of 2.48% and -9.16% over the two-year span. 2) Total soluble sugar: The total soluble sugar from 2004 to 2005 of the winter wheat irrigated with recycled or clean water was very similar: 0.82% and 0.81%, respectively. From 2006 to 2007, the soluble sugar content of T2-1 was 13.33% higher than that of the CK group. The average increase over the two years was 7.28%, possibly due to the increased photosynthetic capacity of the winter wheat with recycled water irrigation. 3) Crude ash: The crude ash content of winter wheat in T2-1 and the CK were 1.63% and 1.56%, respectively, with an increase of 4.49% from 2006 to 2007. 4) Crude starch: The crude starch content of the winter wheat in T2-1 and the CK were 75.7% and 73.2%, respectively, with an increase of 3.42% from 2006 to 2007. 5) Reduced Vc: The contents of reduced Vc of T2-1 over the two years were 5.18 and 10.1 mg/kg, respectively. Compared to the CK, there was a decrease of 3.18% and 8.18%, respectively, with an average decrease of 5.68%. Overall, the analysis showed no significant negative impacts on the nutrient contents of the winter wheat grain irrigated with recycled water.

Table 8 Grain nutrients of winter wheat for each treatment

Year	Treatment	Crude protein	The total soluble sugar	Crude ash	Crude starch/	Reduced Vc
		%	%	%	%	mg·kg ⁻¹
2004—2005	T2-1	12.4	0.82	—	—	5.18
	CK	12.1	0.81	—	—	5.35
	The change of content compared with the CK/%	2.48	1.23	—	—	-3.18
2006—2007	T2-1	11.9	1.53	1.63	75.7	10.1
	CK	13.1	1.35	1.56	73.2	11.00
	The change of content compared	-9.16	13.33	4.49	3.42	-8.18

with the CK /%

Note: "—" represents the test was not conducted for that season.

2.4.2 Effects of recycled water irrigation on the grain quality of summer corn

As shown in Table 9, five summer corn quality indexes were analyzed: 1) Crude protein: Compared with clean water irrigation, the changes of the content of crude protein of the summer corn irrigated with recycled water were from -0.51% to 18.41%, with an average variation of 5.67%. 2) Total soluble sugar: In 2003 and 2005, compared with the groundwater irrigation treatment, the contents of the total soluble sugar reduced 8.06% and 12.77%, respectively, but in 2006 and 2007, they increased 10.19% and 19.48%, respectively. The average percentage of variation over the four years was 2.21%. 3) Crude ash: The crude ash contents in the summer corn irrigated using recycled water compared to summer corn irrigated with groundwater changed from -0.97% to 5.33%, with an average increase of 1.19%. 4) Crude starch: The starch content of the summer corn irrigated using recycled water was -0.09% of corn irrigated using groundwater in over the three years tested. 5) Reduced Vc: The reduced Vc contents were the same among different treatment groups in the years 2003 and 2005. The Vc content reduced 17.55% in 2006 and increased 16.34% in 2007. The average reduction was 0.30% over the four years tested. Overall, the results of the significance test on the quality indicators including, crude protein, soluble total sugar, crude ash, starch, and reduced Vc showed that irrigation using recycled water had no significant effects on the summer corn grain quality ($\alpha=0.05$).

Table 9 Summer corn grain quality indicators under various conditions

Year	Treatment	Crude protein %	The total soluble sugar %	Crude ash %	Crude starch/ %	Reduced Vc mg·kg ⁻¹
2003	T2-1	8.81	11.4	12.4	—	18.8
	CK	7.44	12.4	12.5	—	18.8
	The change of content compared with the CK/%	18.41	-8.06	-0.80	—	0.00
2005	T2-1	8.56	1.23	—	83	7.12
	CK	8.38	1.41	—	80.5	7.12
	The change of content compared with the CK/%	2.15	-12.77	—	3.11	0.00
2006	T2-1	7.73	1.73	1.047	79.23	5.31
	CK	7.77	1.57	0.994	78.43	6.44
	The change of content compared with the CK/%	-0.51	10.19	5.33	1.02	-17.55
2007	T2-1	7.38	0.92	1.02	73.65	17.8
	CK	7.19	0.77	1.03	77.05	15.3

The change of content compared with the CK/%	2.64	19.48	-0.97	-4.41	16.34
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Note: "—" represents the test was not conducted for that season.

2.4.3 Effects of recycled water irrigation on the N, P and K contents of winter wheat and summer corn

As shown in Table 10, the total nitrogen content of the winter wheat in T2-1 over the three years tested were 2.34%, 2.12%, and 2.23%, respectively. Compared to the CK, the percentages of variation were 2.18%, 2.42%, and 25.99%, respectively, with an average increase of 10.2%. The variations of the TP content of the winter wheat in T2-1 compared to the CK were -7.22%, -3.7%, and 6.05% over the three years tested, with an average change of -1.6%. The variations of the TK content of winter wheat in T2-1 compared to the CK were -7.25%, 1.14%, and 1.1%, respectively, with no significant differences.

Table 10 Content of nitrogen, phosphorus, potassium of winter wheat grain for each treatment

Year	Treatment	Total nitrogen	Total phosphorus	Total potassium/
		%	%	%
2003—2004	T2-1	2.34	0.270	0.256
	CK	2.29	0.291	0.276
	The change of content compared with the CK/%	2.18	-7.22	-7.25
2004—2005	T2-1	2.12	0.260	0.356
	CK	2.07	0.270	0.352
	The change of content compared with the CK/%	2.42	-3.70	1.14
2006—2007	T2-1	2.23	0.298	0.368
	CK	1.77	0.281	0.364
	The change of content compared with the CK/%	25.99	6.05	1.10
Average	The change of content compared with the CK/%	10.2	-1.6	-1.7

Table 11 Content of nitrogen, phosphorus, potassium of summer corn grain for each treatment

Year	Treatment	Total nitrogen	Total phosphorus	Total potassium/
		%	%	%
2003	T2-1	1.41	0.29	0.20
	CK	1.19	0.22	0.21
	The change of content compared with the CK/%	18.49	31.82	-4.76
2005	T2-1	1.37	0.20	0.29
	CK	1.34	0.20	0.29
	The change of content compared with the CK/%	2.24	1.01	0

Average	The change of content compared with the CK/%	10.40	16.40	-2.40
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Note: "—" represents the test was not conducted for that season.

As shown in Table11, the TN content of the summer corn inT2-1 over the two years tested were 1.41% and 1.37%, respectively. Compared to the CK, the average TN content variation was 10.4%. The average TPcontent variation was16.4%. Compared to the CK, the TK content in T2-1 TKreduced by 2.4%. We believed that the increased utilization of nitrogen and phosphorus when using recycled water is the main reason for the increase in TN and TP in winter wheat and summer corn grain.

2.4.4 Effects of recycled water irrigation on the content of heavy metals in the grain of winter wheat and summer corn

As shown in Table12, the contents of Hg, As,Pb,Cd and Cr in winter wheat T2-1 in 2006-2007were all higher than the control group, except the Zncontent, which had no significant difference. Compared to the standard limitationsset by China’s “Hygiene standards of food” (GB2715-2005), all of the heavy metal contents from the grains irrigated with recycled water are1 to 2orders of magnitude below the standard limitations and are in the safe range.

Table 12 Content of heavy metals of winter wheat grain for each treatment unit: mg/kg

Year	Treatment	Indexes					
		Hg	As	Pb	Cd	Cr	Zn
2006-2007	T2-1	0.0046	0.091	0.025	0.008	0.22	7.7
	CK	0.0011	<0.010	<0.005	<0.002	0.17	7.54
	The change of content compared with the CK /%	318.18	-	-	-	29.41	2.12
《Hygienic standard for grains》 (GB2715-2005)		0.02	0.1	0.2	0.1	-	-

Note: "—" represents the test was not conducted for that season.

Table 13 Content of heavy metals of summer corn grain for each treatment unit: mg/kg

Year	Treatment	Indexes						
		Hg	As	Pb	Cd	Cr	Cu	Zn
2007	T2-1	0.0040	0.013	0.014	<0.002	0.28	1.22	11.0
	CK	0.0068	<0.010	0.029	<0.002	0.33	1.26	11.0
	The change of content compared with the CK /%	-41.8	-	-51.72	-	-15.15	-3.17	0.00

《Hygienic standard for grains》 (GB2715-2005)	0.02	0.2	0.2	0.1	-	-	-
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Note: "-" represents the test was not conducted for that season.

As shown in Table13, in 2007, all of the heavy metal contents of summer corn T2-1 were not significantly different or lower than the CK, except As, which was significantly higher. Compared to the standard limitations by China’s “Hygiene standards of food” (GB2715-2005), all of the heavy metal contents from the grain irrigated with recycled water are 1 to 2orders of magnitude below the standard limitations and are in the safe range.

3. Discussion and Conclusions

Root system development has an important impact on grain yield and quality, it plays an important role in agro-hydrological microcirculation processes and has an important ecological function. The study on the effects of irrigation using recycled water on the development of the root system has great practical and theoretical values.

The effects of recycled water irrigation on winter wheat growth.In this study, recycled water irrigation had no significant effects on winter wheat plant height, total leaf surface area per plantor flag leaf surface area per plant. The recycled water used in this study is the secondary effluent from the Gaobeidian Sewage Treatment Plant. After treatment, the water quality is significantly improved. The total nitrogen and phosphorus in the recycled water are higher than the clean water, because the irrigation water volume is small compared to the fertilization volume. Thus the N and P from the recycled water that enters the soil is far below the N and P from fertilization, therefore the recycled water had no significantimpact on the growth of winter wheat.

The effects of recycled water irrigation on the root system of winter wheat.The results showed that the root system of winter wheat in 0 to 70 cm of soil contained 95% of the total root system in 1m of soil. Irrigation with recycled water had no significant effect on root length density, root weight densityand root surface area per unit volume of soil, which may be due to that the good water quality of the recycled water. Although the indicators of the recycled water are all higher than the groundwater and winter wheat may absorb more elements during the growing period, but recycled water irrigation did not significantly change the soil moisture content, therefore didn’t affect the winter wheat roots development. Yang *et al.* (2006) studied

the effects of recycled water on the soil physiochemical properties through an indoor soil column test and their results showed no significant influence of recycled water irrigation on soil secondary salinization ^[11]. Wu *et al.* (2006) studied the effects of short-term irrigation using recycled water on the distribution of heavy metals in soil and crops at the same location as this study. Wu *et al.* (2006) results showed no significant effect on the distribution and accumulation of heavy metals in soil when using recycled water for irrigation ^[9].

The results from this study also indicated that within the 0 to 20 cm soil layer, the root length of winter wheat was 68% of the total length of the root system and 78% of the total weight of the root system. This result was in line with previous reports by Ma *et al.* ^[6] and Zhao *et al.* ^[27].

In this study, the difference of the root system of the winter wheat on and between rows was analyzed. The results showed that within the 0 to 20cm soil layer, the root length density and the root surface area per unit soil volume on the rows were higher than between rows. The root weight density on the rows in the 0 to 20cm soil layer was significantly higher than between the rows. The differences of the root weight density on or between rows were smaller within the 20to 100cm soil layer. When studying a densely planted winter wheat root system using a root drill it is necessary to take samples on the rows and between rows.

The effects of recycled water irrigation on wheat yield. We studied the effects of recycled water for irrigation from 2000 to 2006 using the same test pits as used by previous studies From 2000 to 2001, a study conducted by Shao *et al.* ^[28] suggested that the yield of winter wheat with different irrigation water qualities was not significantly different. From 2001 to 2002, a study conducted by Qi *et al.* ^[29] showed that under the same water and fertilization conditions, the yield from the plots irrigated with sewage water were on average 22.3% higher than the yield from the control plots. From 2003 to 2004, a study conducted by Wu *et al.* ^[30] showed that irrigation with recycled water increased the yield of winter wheat, and suggested that during the experimental period the contents of TN and organic nitrogen in the recycled water was 100 times that found in clean water, which played a significant role in the increase in the yield of the winter wheat. From 2004 to 2006 the Beijing Hydraulic Research Institute conducted research on the effects of recycled water irrigation on the yield of winter wheat. The TN content of the recycled water used during the experimental period was only 3.8 times that found in clean water. The results showed

no significant difference in using recycled water on the yield of winter wheat in both seasons. From 2005 to 2006, the annual yield of winter wheat was significantly lower than from 2004 to 2005. This may be due to the reduced base fertilization in 2005 to 2006 (only 50% of the amount used in 2004 to 2005), as well as the reduced top-dressing fertilization used (40 to 50 kg/acre) compared to the amount used in the local agricultural process during the same period.

No significant effects of recycled water irrigation on grain quality. The winter wheat yields irrigated by recycled water over four years were 1675.1, 5516.9, 4182.7, and 5416.9 kg/hm², respectively. Compared to the CK group, the yield differences were 0.5%, -0.1%, 12.87%, and 12.72%, respectively, with no significant differences in yields between different treatment groups ($\alpha=0.05$). The summer corn yields from T1 over four years were 9056, 5569.7, 7925.4, and 10094.9 kg/hm², respectively. Compared with the CK group, the yield differences were 3.3%, 4.05%, -1.18%, and 15.51%, respectively, indicating that recycled water irrigation had no significant impact on the yields of summer corn ($\alpha=0.05$). The content of crude protein, total soluble sugar, crude ash, crude starch and reduced Vc of the winter wheat and summer corn irrigated using recycled water showed some variations, but did not show significant consistency. Irrigation with recycled water showed no significant impact on the quality indicators of winter wheat and summer corn ($\alpha=0.05$). The N content in the grains of winter wheat and summer corn saw a slight increase, which was related to the increased rate of N utilization when irrigated with recycled water. The heavy metal contents in the grains of the winter wheat and summer corn were all lower than the limitations of China's national food safety standards.

In summary, the impact of irrigation with recycled water on crop growth and yield were influenced by many factors such as fertilization volume, amount of irrigation water, water quality, irrigation times, soil status and the amount of rainfall. Therefore, a comprehensive study of the mechanism needs to be conducted, especially for the effects of recycled water irrigation on physiological factors such as photosynthesis, transpiration and stomatal activities. In addition, the mechanisms for the physiological and biochemical response of food crops to recycled water irrigation at different developmental stages needs to be studied.

Acknowledgments

We are grateful for the support by the projects 2012BAD08B02, 2012AA101404-1 and the Chinese National Science Fund 51339007.

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