The Effect of Municipal Wastewater Irrigation on the Yield and Quality of Vegetables and Crops

Josef ZAVADIL

Research Institute for Soil and Water Conservation, Prague-Zbraslav, Czech Republic

Abstract: The effect of municipal wastewater irrigation on the yield and quality of vegetables and crops was studied by means of pot and lysimetric experiments. The pots were seeded with lettuce salad, radishes, and carrots in all experimental years; the lysimeters were planted with early potatoes in 2005 and 2007, and with sugar beet in 2006. Secondary-treated wastewater (in 2005) or only primary-treated wastewater (in 2006 and 2007) were used in the experiments. The control treatment involved the irrigation with water from a local well (in 2005) or public water supply (in 2006 and 2007). Contrarily to the secondary-treated wastewater, the primary-treated wastewater increased the yield of all vegetables and crops, the increase having been statistically significant in most cases. The irrigation with secondary-treated wastewater increased only the sodium content in radishes and carrots. However, the irrigation with primary-treated wastewater led to a statistically significant increase in the sodium content in the consumable parts of all vegetables, sugar beet bulbs, and potato tubers in both years, and in 2007, in the nitrate contents in lettuce salad and radishes as well. A high bacterial contamination of vegetables and crops irrigated with this wastewater was found out, but there was no evidence for the contamination with pathogens. Also, no risk was shown of contamination of the crops with intestinal nematodes.

Keywords: primary-treated municipal wastewater; secondary-treated municipal wastewater; pot experiments; lysimetric experiments; lettuce salad; radishes; carrots; potatoes; sugar beet; nutrients; hazardous elements; microbial contamination

Municipal wastewater is an important alternative source of water for irrigation. However, apart from plant nutrients, it may contain various potentially toxic elements and organic matters with highly harmful effects on human and animal health. Municipal wastewater contains relatively high amounts of sodium, which can be accumulated in the soil during irrigation with this wastewater and display toxic effects on the plants. If this wastewater is not disinfected or treated in stabilisation ponds, it is highly contaminated with microorganisms. Therefore, the utilisation of municipal wastewater for the irrigation of crops is associated with a number of risks. Very serious risks are those of crop yields reduction, crops quality deterioration, crops contamination with pathogens and intestinal helminths. It is, however, possible to achieve high yields of crops without deterioration of their quality by using treated wastewater for the irrigation of crops under controlled conditions. This is evident from a number of papers – e. g. Shende – ex Mara and Cairncross (1989), Jimenez (2005), Stehlík (1966, 1980), Esmailiyan *et al.* (2008), Najafi *et al.* (2003), Munir and Ayadi (2005).

Excessive contents of heavy metals in crops irrigated with wastewater have not been reported. This is explained by a relatively good binding of heavy metals in the soil. Higher absorption of some risk elements by various crops irrigated with municipal wastewater can, however, be observed

Supported by the Ministry of Agriculture of the Czech Republic, Project No. MZE 0002704901.

Table 1. Average values of parameters of physicochemical and microbiological properties of municipal wastewater and control water used in the experiments

Sort of irrigation water	Primary-treated wastewater	Secondary-treated wastewater	Local well	Public water supply
Number of collected and analysed samples	33	16	5	5
pH	7.56	7.43	7.53	7.41
Conductivity (μS/cm)	1 402	1 063	1 146	664
TSS (mg/l)	234	< 1	< 1	0.2
TDS (mg/l)	737	701	885	482
COD_{Cr} (mg/l)	258	42	13	15
Ammonium-N (mg/l)	62.7	2.9	0.07	0.09
Nitrite-N (mg/l)	0.04	0.10	0.012	0.0062
Nitrate-N (mg/l)	1.8	< 1.3	22.7	1.6
Organic-N (mg/l)	6.1	2.0	1.6	1.4
Total P (mg/l)	18.6	5.6	0.20	0.51
K (mg/l)	21	19	7.3	3.1
Mg (mg/l)	14	15	9.2	11.8
Ca (mg/l)	121	112	193	115
Na (mg/l)	75	90	26	8
Mn (mg/l)	49	< 0.20	< 0.20	1
Fe (mg/l)	0.16	0.22	0.11	< 0.10
Hg (μg/l)	0.20	< 0.10	< 0.10	0.06
Cd (μg/l)	0.61	0.25	< 0.20	< 0.20
Pb (μg/l)	4.3	1.4	2	1
As (μg/l)	1.6	1.0	1	< 1.0
Cr (μg/l)	2.9	0.9	< 1	2.97
Ni (μg/l)	8.2	2.6	6	7
Cu (μg/l)	14.6	1.7	24	14
Zn (μg/l)	260	14	98	137
V (μg/l)	3.4	1.3	1.3	2.9
Co (μg/l)	5.3	< 5.0	< 5.0	2.0
Coliforms (CFU/ml)	1 504 063	32 694	12.2	< 0.01
Thermotolerant coliforms (CFU/ml)	275 156	1 968	0.5	< 0.01
Clostridium perfringens (CFU/ml)	2 735	20	0.2	< 0.01
Enterococci (CFU/ml)	35 844	810	3.5	< 0.01
Coliphages (PFU/ml)	494	6	0.4	0
Intestinal nematodes	not detected	not detected	not detected	not detected

TSS – Total suspended solids, TDS – Total dissolved solids, COD_{Cr} – Chemical oxygen demand using potassium dichromate, CFU – colony-forming units, PFU – plaque-forming units

(Feizi 2001; Panoras *et al.* 2003; Jimenez 2005; Wang *et al.* 2007). Bacterial contamination of crops irrigated with municipal wastewater was not detected if the wastewater had been treated in stabilisation ponds or disinfected, and if subsurface drip irrigation had been used (Vaz da Costa *et al.* 1996; Najafi *et al.* 2003; Panoras *et al.* 2003; Al-Lahham *et al.* 2003; Aiello *et al.* 2007). The experiments the results of which are reported here were aimed at assessing the possibility of using municipal wastewater from modern water treatment plants in the Czech Republic for the irrigation of agricultural crops.

MATERIALS AND METHODS

The effect of municipal wastewater on the yield and quality of crops was investigated by precise growth pot and lysimetric experiments. Wastewater from the treatment plant of the Mělník town was used. This wastewater treatment plant operates on the basis of primary and secondary treatments, with a previous anaerobic section for biological elimination of phosphorus complemented with chemical precipitation of phosphorus and subsequent circulation biological activation with simultaneous denitrification and partial aerobic stabilisation of the sludge. Wastewater entering the plant consists of ca 62% sewage and 38% industrial wastewaters. In 2005, secondary-treated wastewater and in 2006 and 2007 only primary-treated wastewater were used in the experiments. The characteristics of these two kinds of wastewater are given in Table 1. The pot experiments lasted one year, i.e., every year the pots were filled with new soil. To fill the 5-liter pots, we used topsoil from the experimental area of the Research Institute for Soil and Water Conservation, v.v.i. (RISWC) in the Mělník town. The pots were placed in an open vegetation hall with the roof of a PVC foil. The lysimetric experiments were conducted in zero-tension circular lysimeters of 1.28 m diameter and 0.8 m height from the bottom. The bottom of the lysimeter was covered by geo-textile, overlaid with 0.05 m river sand with 0.5–1 mm grain size, then with 0.4 m subsoil and 0.3 m topsoil – the same that was used in the pot experiments. According to the classification WRB (2006), the soil used in the experiments was Haplic Chernozem. The characteristics of the soil used in the experiments are given in Table 2. According to Novák's classification scale (Klika *et al.* 1954), the topsoil was medium-heavy, loamy-sandy. Its pH was neutral, humus content was medium, calcium content was high and, according to the evaluation criteria for the nutrient contents (Trávník *et al.* 1999), phosphorus content was very high. Its potassium content was high and that of magnesium was adequate. In all the years of the study, the pots were seeded with lettuce salad, radishes, and carrots. In the lysimetric experiments, early potatoes were used in 2005 and 2007 and sugar beet in 2006. Soil moisture in the lysimeters was measured at 0–0.3 m and 0.3–0.6 m depths by the TDR method, using CS 616 sensors from Campbell Scientific, Inc. (http://www.campbellsci.com/soilvol.html). The soil moisture was recorded continually by dataloggers Modulog 2031 of the company Environmental Measuring Systems Brno, Czech Republic (http://www.emsbrno.cz). The irrigation rates were calculated so that the water content in soil should be filled up to 80% of the field capacity (20% was reserved for the retention of pertinent rain water in soil) to minimise the risk of washing out nitrates and another matters from the soil. In each experiment a control treatment was carried out using the irrigation with well water from a local well in 2005, and with water from the public water supply in 2006 and 2007. The characteristics of these two kinds of water are shown in Table 1. The irrigation amounts of the

Table 2. Properties of the soil used in the experiments

Depth soil profile (m)		0–0.3	0.3–0.6
Soil particles (%)	< 0.001 mm	10.8	10.3
	< 0.01 mm	20.1	15.7
	0.01–0.05 mm	11.8	10.2
	0.05–0.25 mm	33.4	38.7
	0.25–2 mm	34.7	35.5
Exchangeable pH		7.16	7.40
Carbonates (%)		1.2	0.3
C oxidable (%)		1.67	0.47
N total (%)		0.16	0.06
Available nutrients - Mehlich III (mg/kg)	P	503	194
	K	333	141
	Mg	106	57
	Ca	4 553	2 319
Na in H_2O extract (mg/kg)		5.5	6.1

Table 3. Irrigation amounts of control water (CW) and wastewater (WW)

Crop	Treatment	Irrigation water	Irrigation amount (mm)		
			2005	2006	2007
Lettuce salad	control	CW	160	200	180
	experimental	CW	100	140	120
		WW	60	60	60
		Total	160	200	180
Radish	control	CW	180	210	190
	experimental	CW	130	130	120
		WW	60	50	70
		Total	190	180	190
Carrot	control	CW	830	470	720
	experimental	CW	560	330	680
		WW	130	270	300
		Total	690	600	980
Early potatoes 2005 and 2007 Sugar beet 2006	control	CW	178	483	220
	experimental	CW	124	339	43
		WW	87	249	227
		Total	211	587	270

wastewater and control water used for the irrigation of individual vegetables and crops are given in Table 3. The irrigation amounts of wastewater were given by the irrigation needs in the terms of the collection of samples for analysis, because only analysed water was used for irrigation. Considering the methodology of microbial analyses, the samples of wastewater were collected just on Mondays or Tuesdays. The irrigation amounts of wastewater in the lysimeters were also dependent on the irrigation rates determined by the water balance in the soil.

The treatment using wastewater irrigation and the control treatment were done in triplicates. The vegetables in the pots and the crops in the lysimeters were irrigated to the ground and sprinkled after irrigation with the applied water. After the crop harvest, the yield of the crops was determined by weighing the consumable parts and collecting samples for analysis. The analyses of wastewater, control water, soil, vegetables, and crops were done according to the standard operation procedures in the laboratories of the following organisations: RISWC (physical and chemical soil analyses, chemical analyses of crops), T. G. Masaryk Water Research Institute, v.v.i. (microbiological water analyses), National Health Institute sited in the Prague city (parasitological water analyses), and National Health Institute sited in the Kolín town (microbiological examination of the crops). All these laboratories are accredited by the Czech Accreditation Institute, o.p.s., according to the standard ČSN EN ISO/IEC 17 025 (2005). The methods of soil analyses: soil particles – ISO 11277 (1998), exchangeable pH – ISO 10390 (2005), carbonates – ISO 10693 (1995), C oxidable – ISO 14235 (1998), total N – ISO 11261 (1995), available P, K, Mg, Ca – Mehlich III (see Trávník *et al.* 1999), Na in water extract – 10 minute water extraction and determination by AAS method. The characteristics of the water quality were determined using these methods: pH – ČSN ISO 10523 (1995), conductivity – ČSN ISO 27 888 (1996), total dissolved solids – ČSN 757346 (1998), total suspended solids – gravimetric method after evaporating, chemical oxygen demand using potassium dichromate – TNV 757520 (2002), ammonium ions – ČSN ISO 7150-2 (1994), nitrites and nitrates – ČSN EN ISO 13395 (1997), organic nitrogen – ČSN EN 25663 (1994), total phosphorus – ČSN EN ISO 15681 (2005), K – ČSN ISO 9964-2 (1995), Mg and Ca – ČSN ISO 7980 (1994), Na – ČSN ISO 9964-1 (1995), Mn – ČSN 830530-28, Fe – ČSN 830530-27, Hg – ČSN 75 7440 (2009) – analyzer AMA 254, Cd – ČSN EN ISO 5961 (1995), As – ČSN ISO 11969 (1997) – hydride technique, Cr – ČSN EN 1233 (1997) – ETA-AAS, Pb, Ni, Cu, Zn, and Co – ČSN ISO 8288 (1994) – AAS – ETA, V – AAS – ETA, coliforms – TNV 757837 (2003), thermotolerant coliforms – TNV 757835 (1999), Clostridium perfringens – Council Directive 98/83/EC (1998) and Decree No. 252/2004 Coll. (2004) in the sense of change 178/2005 Coll., enterococci – ČSN EN ISO 7899-2 (1993), coliphages – ČSN EN ISO 10705-2 (2002). The methods used for the analyses of vegetables and crops: dry matter – ČSN 467092-3 (1998), nitrates – flow analyzer Skalar, Na – ČSN 467092-15 (1998), Hg – analyzer AMA 254, As – hydride technique, Cd, Pb, Cr, Ni and Cu – AAS – ETA, Mn and Zn – FAAS, thermotolerant coliforms – TNV 757835 (1999), Salmonella – ČSN EN ISO 6579 (2003), dry mater of potatoes – ČSN 46 7092-3 (1998), reducing sugars – ČSN 46 7092-22 (1998), starch – according to Ewers, sugar content – using polarimetry, content of K and Na in beet bulbs – by flame photometry, alfa-aminonitrogen – by photometric technique.

The differences between the control treatment and the treatment using wastewater irrigation were assessed using the unifactorial analysis of variance (ANOVA).

RESULTS AND DISCUSSION

Effect of municipal wastewater on yields

Secondary-treated municipal wastewater used for the experiments in 2005 was poor in nutrients – the average content of total nitrogen was ca 5 mg/l, total phosphorus 5.6 mg/l, potassium 19 mg/l and magnesium 15 mg/l (Table 1). Low contents of nutrients, however, particularly nitrogen and phosphorus, in the secondary-treated wastewater can be expected in the case of all modern, properly designed and operated wastewater treatment plants because the removal of nitrogen and phosphorus compounds from wastewater is one of their main goals. The secondary-treated wastewater had low contents of elements and compounds with potential

Table 4. Statistical evaluation of crop yields in the experiments using municipal wastewater at the 0.05 significance level (α)

Wastewater treatment	Crop	Average yield (t/ha)[1]		α calculated	Evaluation of differences
		control water irrigation	wastewater irrigation		
Secondary (2005)	lettuce salad	49.0	46.8	0.4304	NS
	radishs	30.9	29.3	0.6071	NS
	carrots	85.4	83.1	0.5800	NS
	early potatoes	74.4	70.6	0.6398	NS
Primary (2006)	cettuce salad	27.7	32.8	0.0122	*
	radishs	12.1	22.0	0.0008	***
	carrots	77.1	133.1	1.50E-08	***
	sugar beet	98.8	104.2	0.2714	NS
Primary (2007)	lettuce salad	43.0	55.1	3.31E-05	***
	radishs	19.7	22.3	0.1204	NS
	carrots	60.4	128.4	2.10E-06	***
	early potatoes	45.8	60.1	0.014	*

[1]from three replicates, yield per 1 ha recalculated from the yield per area of the growth container (0.0314 m^2) or lysimeter (1.27 m^2), NS – non-significant at P = 0.05, *significant at P = 0.05, **significant at P = 0.01, ***significant at P = 0.001

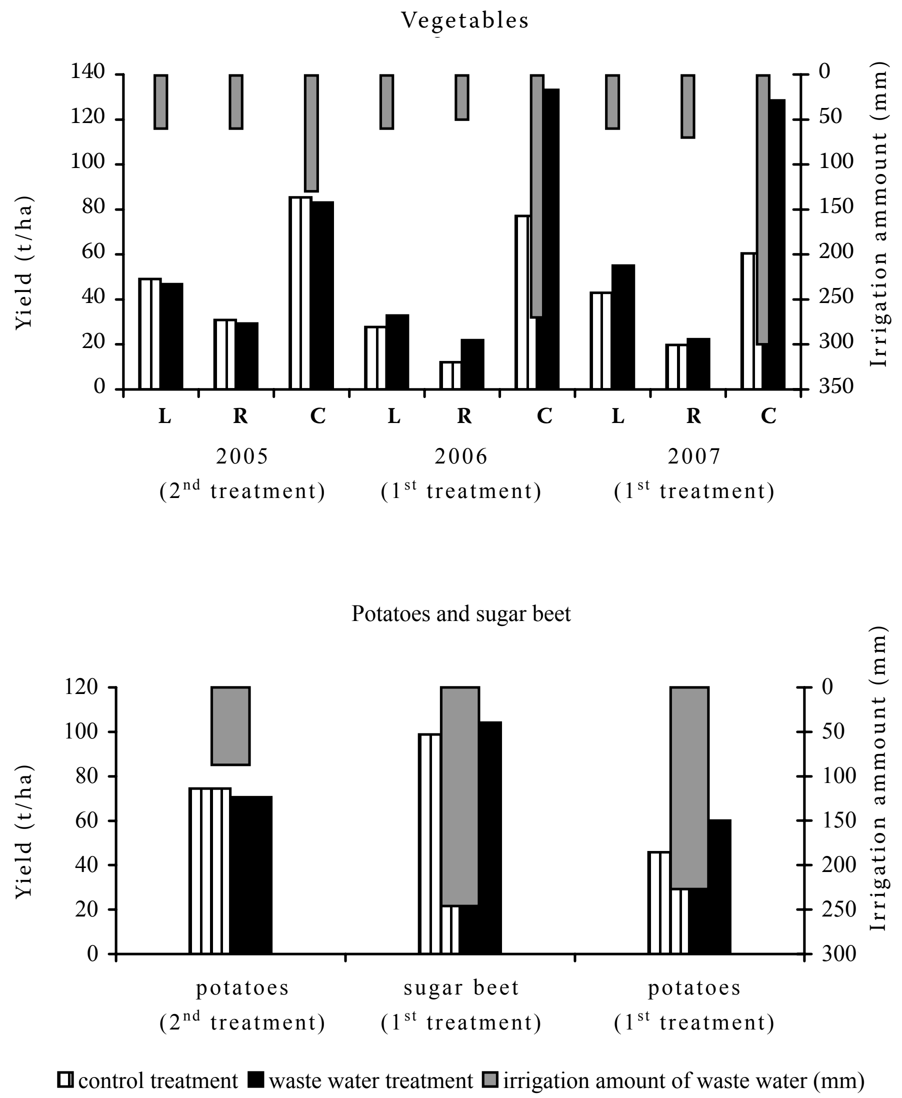

Figure 1. Effect of municipal wastewater irrigation on the yields
L– lettuce salad
R –radishes
C – carrots

phytotoxic effects (Table 1), even much lower than given for the limits for long-term-use of reclaimed waters for irrigation as recommended by US EPA (2004), and the limits permitted by the standard ČSN 75 7143 (1991) for irrigation water of class I quality, i.e. suitable for irrigation. Compared with the control treatment, i.e. irrigation with control water, the wastewater did not have any statistically significant effects on the yields of vegetables and early potatoes (Table 4). Somewhat higher yields of vegetables and early potatoes in the control treatment as compared with the wastewater-irrigated treatment (Figure 1) can be explained by the significantly higher nitrogen content in the control water from the local well (Table 1) and therefore its higher doses (Table 8).

Primary-treated wastewater contained on average ca 14fold amount of total nitrogen (70.6 mg/l, 89% in ammonia form), 3fold that of total phosphorus (18.6 mg/l), and roughly the same amounts of potassium and magnesium as the secondary-treated wastewater. The main plant nutrient in this wastewater was therefore nitrogen, as a rule. Its content varied between the values given in the literature (e.g. Huibers & van Lier 2005). The irrigation with primary – treated wastewater led to high amounts of nitrogen applied to carrots, sugar beet, and potatoes, i.e. plants with long vegetation periods and therefore high irrigation amounts of wastewater (Table 8). The fertilising effect of this wastewater was demonstrated with all vegetables and crops used for the experiments. The increased yield of the marketed parts of the crops as compared with the control treatment was, except for the experiments with radishes in 2007 and sugar beet in 2006, statistically significant at the 0.05 significance level (Table 4). In 2007, radishes displayed a particularly high increase in the weight of the leaves. The small differences between the sugar beet yield obtained on irrigation with primary-treated wastewater and that obtained on the control treatment were not very probably caused by phytotoxic effects of potentially harmful elements contained in the wastewater, because their contents were lower than the limits for the utilisation of regenerated waters for irrigation recommended by US EPA (2004) and those permitted by standard ČSN 75 7143 (1991) for irrigation water of class I quality. A negative effect of sodium on the soil or its phytotoxic effects are not probable because sugar beet is one of the crops with a high resistance to sodium – much higher than that of the vegetables used in the pot experiments (see ČSN 75 7143 1991; Ayers & Westcot 1989). Nitrogen applied with the wastewater probably displayed a very weak effect in the experiment. Since the amounts of nitrogen leached from the soil in the control treatment and in the treatment using wastewater irrigation were the same (45 kg/ha, 99.7% in nitrate form), it is evident that sugar beet was not able to utilise fully the nitrogen applied by waste water. The content of nitrate nitrogen in the soil irrigated with wastewater was twice that in the soil on the control treatment (11.2 and 5.2 mg/kg, respectively). Phosphorus applied with the wastewater (ca 47 kg/ha) displayed rather a weak effect because the soil used in the experiments abounded in it. Before seeding sugar beet, its total content in the leach Mehlich III was 460 mg/kg, while "a very high content" in arable land according to the content-evaluating criteria (Trávník *et al.* 1999) means an amount exceeding 185 mg/kg. The primary-treated wastewater had a slightly negative effect on the technological quality of sugar beet, but because of a higher yield of bulbs, the yields of refined sugar in the control treatment and that in the treatment using the irrigation with wastewater were practically the same (Table 5). The detected positive effect of the primary-treated wastewater on the crop yields is in agreement with the data in the literature (Shende – ex Mara & Cairncross 1989; Jimenez 2005; Stehlík 1966, 1980, and others).

The major problem in assessing the effect of primary-treated and secondary-treated wastewaters on the crop yields seems to be the relatively high sodium content. Its average contents in the primary and secondary-treated wastewaters were 75 mg/l and 90 mg/l, respectively (Table 1). A long-term use of these wastewaters for irrigation could therefore result, in poorer fertility of the soil and thus in lower crop yields, namely in heavier soils without natural or artificial groundwater runoff. According to the limit values of the total content of dissolved compounds and electric conductivity given by FAO (1985) and Ayers and Westcot (1989), the use of primary-treated and secondary-treated wastewaters for irrigation requires slight to moderate limitations due to the negative effects on the soil. According to sodium adsorption ratio ($SAR = c(Na)/[c(Ca)+c(Mg)]^{1/2}$, where Na, Ca, and Mg are the concentrations of these elements in mmol/l), however, the primary-treated as well as the secondary-treated

Table 5. Technological quality of sugar beet and potatoes

Crop	Parameter	Control water irrigation	Wastewater irrigation	Evaluation of differences at the α = 0.05 level	
				α calculated	Significance of differences
Sugar beet	sugar content (%)	16.9	16.3	0.129	*
	potassium (mmol/100 g)	3.83	4.22	0.054	*
	sodium (mmol/100 g)	0.41	0.85	0.008	**
	alfa-aminonitrogen (mmol/100 g)	0.83	1.26	0.185	*
	yield of refined sugar (t/ha)	14.9	14.7	0.622	*
Early potatoes	reducing sugars (%)	0.3	0.3	0.976	*
	starch (%)	14.7	14.5	0.866	*

Evaluation of differences see Table 4

wastewater used in the experiments deserves a positive evaluation because their SAR were 1.7 and 2.1, respectively, which are lower than 3, the maximum permissible value for unlimited use of water for surface irrigation, considering sodium toxicity for the plants.

Effect of municipal wastewater on the crop quality

The compositions of the primary and secondary-treated municipal wastewaters used in the experiments (Table 1) show that the most important potential threat of irrigation with these waters to the crop quality is their microbial contamination. According to the criteria delineated in the standard ČSN 75 7143 (1991), even the secondary-treated wastewater is of degree III quality, i.e. unsuitable for irrigation. Its utilisation for irrigation is possible only after a treatment ensuring degree I quality, i.e. suitable for irrigation. Additionally, this wastewater does not fulfill the quality requirements for the unlimited and even limited uses for irrigation as defined in the second version of WHO guidelines (1989). Extensive literature data on microbial contamination of municipal wastewater show that the quality of wastewater used in our experiments did not substantially differ from these data, except for the parasitic contamination parameters. No sample collected from the wastewater contained germs of intestinal nematodes in the infectious phase. Contamination of crops with intestinal nematodes was therefore not assessed in our experiments.

The irrigation with the secondary-treated wastewater (Table 1) did not result in a statistically significant increase in nitrates content or in other potentially harmful element contents assayed in

Table 6. Results of crop analyses from experiments using secondary-treated municipal wastewater

Crop	Lettuce salad		Radish		Carrot		Potatoes	
Irrigation water	CW	WW	CW	WW	CW	WW	CW	WW
Dry matter (%)	10.99	11.13	12.36	13.02	11.78	12.05	16.96	17.28
Nitrates (mg/kg)	43	13	92	35	< 25	24	374	304
Na (g/kg)	1.10	1.14	1.30	**2.80	1.22	**1.8	0.06	0.07
Hg (mg/kg)	0.025	0.026	0.035	0.032	0.007	0.007	0.005	< 0.005
Cd (mg/kg)	0.56	0.55	0.26	0.25	0.19	0.19	0.07	0.07
Pb (mg/kg)	0.74	0.69	1.90	1.33	0.26	0.13	< 0.10	< 0.10
As (mg/kg)	0.40	0.40	0.49	0.50	0.12	0.15	0.05	0.06
Cr (mg/kg)	2.37	2.54	3.45	2.44	0.25	0.14	0.17	0.14
Ni (mg/kg)	1.31	1.47	2.51	1.99	0.29	< 0.20	0.23	< 0.20
Cu (mg/kg)	2.99	2.96	3.44	3.16	1.73	1.62	4.75	4.08
Mn (mg/kg)	27.6	29.8	22.9	21.3	5.0	5.1	5.4	5.1
Zn (mg/kg)	31.4	29.6	50.4	53.1	11.0	10.4	18.7	16.7
TC (CFU/g 100% of dry matter)	< 10	11	< 10	< 10	< 10	< 10	< 10	< 10
TC (CFU/100 g of original mass)	110	126	< 124	< 130	< 118	< 121	< 170	< 173
Salmonella (CFU/g 100% of dry matter)	N	N	N	N	N	N	N	N

CW – control water, WW – wastewater, TC – thermotolerant coliforms, CFU – colony-forming units, N – negative; evaluation of differences see Table 4; unmarked differences between the control and the wastewater-irrigation treatment are not statistically significant

Table 7. Results of crop analyses from experiments using primary-treated municipal wastewater

Crop	Lettuce		Radish		Carrot		Sugar beet	
2006								
Irrigation water	CW	WW	CW	WW	CW	WW	CW	WW
Dry matter (%)	11.36	12.94	11.16	10.28	11.22	10.11	22.58	21.44
Nitrates (mg/kg)	< 100	< 100	< 100	< 100	5	5	101	389
Na (g/kg)	0.61	***1.31	0.77	**1.63	0.96	***4.62	0.14	* 0.71
Hg (mg/kg)	0.025	0.019	0.035	0.022	0.008	0.007	< 0.005	< 0.005
Cd (mg/kg)	0.35	0.33	0.26	0.23	0.14	0.16	0.06	0.06
Pb (mg/kg)	1.39	0.78	2.06	1.14	0.25	0.15	0.14	0.23
As (mg/kg)	0.40	0.30	0.53	0.52	0.10	0.08	<0.05	< 0.05
Cr (mg/kg)	14.34	8.56	5.37	4.13	0.65	0.57	0.50	0.23
Ni (mg/kg)	8.42	4.35	9.20	7.85	0.39	0.33	0.23	< 0.20
Cu (mg/kg)	4.33	4.63	7.19	4.30	2.31	3.05	2.55	2.20
Mn (mg/kg)	27.3	22.8	13.1	9.3	4.1	4.5	3.4	5.1
Zn (mg/kg)	23.8	26.9	32.6	26.8	21.7	19.3	16.8	20.4
TC (CFU/g 100% of dry matter)	< 10	33	< 10	< 10	< 10	12	< 10	15
TC (CFU/100 g of original mass)	< 114	427	< 112	< 103	< 112	121	< 226	322
Salmonella (CFU/g 100% of dry matter)	N	N	N	N	N	N	N	N
Crop	Lettuce		Radish		Carrot		Potatoes	
2007								
Irrigation water	CW	WW	CW	WW	CW	WW	CW	WW
Dry matter (%)	6.97	5.88	8.58	9.23	11.46	11.24	20.11	19.98
Nitrates (mg/kg)	595	*3505	255	*1424	67	70	832	684
Na (g/kg)	684	***1218	704	***1477	99	***463	69	**120
Hg (mg/kg)	0.018	0.108	0.02	0.01	0.027	0.018	0.002	0.002
Cd (mg/kg)	0.68	0.55	0.24	0.24	0.14	0.16	0.07	0.07
Pb (mg/kg)	0.63	0.26	0.96	0.54	1.68	1.24	0.15	0.14
As (mg/kg)	0.18	0.13	0.19	0.16	0.30	0.27	0.02	0.02
Cr (mg/kg)	1.61	1.12	1.11	1.17	1.23	1.41	0.52	0.83
Ni (mg/kg)	1.75	0.74	1.90	0.81	0.28	0.22	0.31	0.20
Cu (mg/kg)	3.21	3.85	2.34	1.95	3.26	2.40	2.64	3.06
Mn (mg/kg)	23.0	18.9	8.0	8.1	10.2	7.4	5.4	5.8
Zn (mg/kg)	35.7	36.9	28.4	29.8	19.6	17.7	20.4	20.7
TC (CFU/g 100% of dry matter)	17	*183	< 10	377	< 10	27	77	320
TC (CFU/100 g of original mass)	< 117	**1047	< 86	3 474	< 115	303	1 522	6 489
Salmonella (CFU/g 100% of dry matter)	N	N	N	N	N	N	N	N

Glossary see Table 6

Table 8. Amounts of organic and inorganic nitrogen applied to the crops by irrigation

Year	Crop	Treatment	Amount of applied nitrogen in kg/ha			
			control water	wastewater	total	difference to the control
2005	lettuce salad	control	48.7	0	48.7	–12.3
		experimental	34.1	2.3	36.4	
	radish	control	51.2	0	51.2	–17.2
		experimental	31.7	2.3	34	
	carrot	control	114.5	0	114.5	–30.1
		experimental	80.4	4.0	84.4	
	early potatoes	control	53.0	0	53	–18.5
		experimental	29.9	4.6	34.5	
2006	lettuce salad	control	4.6	0	4.6	+25.1
		experimental	2.9	26.82	29.72	
	radish	control	5.2	0	5.2	+17.2
		experimental	3.8	18.55	22.35	
	carrot	control	24.0	0	24	+182.7
		experimental	16.2	190.5	206.7	
	sugar beet	control	13.8	0	13.8	+157.3
		experimental	9.7	161.4	171.1	
2007	lettuce salad	control	5.8	0	5.8	+43.3
		experimental	3.9	45.2	49.1	
	radish	control	6.1	0	6.1	+52.0
		experimental	3.9	54.2	58.1	
	carrot	control	23.2	0	23.2	+210.7
		experimental	21.9	212.0	233.9	
	early potatoes	control	5.2	0	5.2	+118.8
		experimental	1.4	122.6	124	

the consumable parts of the vegetables and potato tubers (Table 6). The only exception was a significant increase in sodium content in radish bulbs and carrot roots. Among the monitored microbiological parameters, at the time of harvest only the contamination of wastewater-irrigated lettuce salad with thermotolerant coliforms was higher than the contamination of control water-irrigated lettuce salad, but the difference was not statistically significant. Contamination of the crops by pathogenic bacteria of the Salmonella species was not found. The irrigation with primary-treated wastewater (characteristics see in Table 1) led to a statistically significant increase of sodium content in the consumable parts of vegetables, sugar beet bulbs, and potato tubers in both years, and of nitrate content in lettuce salad and radishes and thermotolerant coliforms content on lettuce salad in 2007 (Table 7). Sugar beet irrigated with wastewater only displayed a poorer technological quality (Table 5). Besides higher amounts of sodium, its bulbs also contained higher amounts of potassium and alfa-aminonitrogen, causing a lower extraction of sugar. The increased yield of bulbs obtained after irrigation with wastewater, however, led to the same yield of refined sugar in the wastewater treatment as in the control treatment. Microbial contamination of all vegetables and crops with wastewater was higher in 2007 than in 2006. There are large differences in the numbers of thermotolerant coliforms between the control treatment using irrigation with water from the public water supply and the treatment using irrigation with wastewater. The statistically non-significant difference between these treatments was caused by a high variability of the values measured in the individual replicates of these treatments. The number of thermotolerant coliforms on the crops irrigated only with primary-treated municipal wastewater was higher on lettuce salad, radishes, and potatoes than allowed by ICMSF (Blumenthal *et al*. 2000) for foodstuffs consumed in raw state. The contamination of the crops by pathogenic bacteria of the Salmonella species was not found, similarly as on irrigation with secondary-treated wastewater.

Excessive contents of heavy metals in the crops irrigated with municipal wastewater were not observed in the experiments and had not been reported in the available literature.

CONCLUSIONS

The results of the experiments have confirmed a potential high bacterial contamination of the crops irrigated with municipal wastewater, but have not revealed their contamination with pathogens. The water used in the experiments did not present a risk of contamination of the crops with intestinal nematodes, because their germs in infectious stage have not been found in the samples of wastewater. From the microbiological point of view, the higher quality of municipal wastewater in the Czech Republic, as compared particularly to the developing countries where this wastewater is mainly used for irrigation, is caused namely by better health conditions of the population. However, a certain risk exists of the contamination of the population by infectious diseases and parasites through the consumption of crops irrigated with only secondary-treated municipal wastewater. To use this water for irrigation, the guidelines must be observed given in the standard ČSN 75 7143 (1991) and particularly WHO guidelines (1989, 2006).

References

Aiello R., Cirelli L.G., Consoli S. (2007): Effect of reclaimed wastewater irrigation on soil and tomato fruits: A case study in Sicily (Italy). Agricultural Water Management, **93**: 65–72.

Al-Lahham O., El Assi N.M., Fayyad M. (2003): Impact of treated wastewater irrigation on quality attributes and contamination of tomato fruits. Agricultural Water Management, **61**: 51–62.

Ayers R.S., Westcot D.W. (1989): Water quality for agriculture. FAO irrigation and drainage paper 29. Available at http://www.fao.org/DOCREP/003/T0234E/T0234E00.htm (accessed March 6, 2007)

Blumenthal U.J., Peasey A., Ruiz-Palacios G., Mara D.D. (2000): Guidelines for wastewater reuse in agriculture and aquaculture: recommended revisions based on new research evidence. Well study. Task No. 68. Part 1. Available at http://www.lboro.ac.uk/well/resources/well-studies/full-reports-pdf/task0068i.pdf. (accessed February 21, 2007)

Council directive 98/83/EC (1998): Council directive on the quality of water intended for human consumption. Official Journal No. L 330, 1–32.

ČSN 75 7143 (1991): Water Quality for Irrigation. Czech Standards Institute, Prague. (in Czech)

ČSN 46 7092-3 (1998): Testing method for feeding stuffs – Part 3: Determination of moisture content. Czech Standards Institute, Prague. (in Czech)

ČSN 46 7092-15 (1998): Testing method for feeding stuffs – Part 15: Determination of sodium. Czech Standards Institute, Prague. (in Czech)

ČSN 46 7092-22 (1998): Testing method for feeding stuffs – Part 22: Determination of sugar content. Czech Standards Institute, Prague. (in Czech)

ČSN 75 7346 (1998): Water quality. Determination of dissolved substances. Czech Standards Institute, Prague. (in Czech)

ČSN 75 7440 (2009): Water quality – Determination of total mercury by thermal decomposition, amalgamation and atomic absorbing spectrometry. Czech Standards Institute, Prague. (in Czech)

ČSN EN 25663 (1994): Water quality. Determination of Kjeldahl nitrogen. Method after mineralization with selenium (ISO 5663:1984). Czech Standards Institute, Prague. (in Czech)

ČSN EN 1233 (1997): Water quality. Determination of chromium – Atomic absorption spectrometric methods. Czech Standards Institute, Prague. (in Czech)

ČSN EN ISO 5961 (1995): Water quality. Determination of cadmium by atomic absorption spectrometry

(ISO 5961:1994). Czech Standards Institute, Prague. (in Czech)

ČSN EN ISO 13395 (1997): Water quality Determination of nitrite nitrogen and nitrate nitrogen and the sum of both by flow analysis (CFA and FIA) and spectrometric detection. Czech Standards Institute, Prague. (in Czech)

ČSN EN ISO 10705-2 (757871) (2002): Water quality – Detection and enumeration of bacteriophages – Part 2: Enumeration of somatic coliphages. Czech Standards Institute, Prague. (in Czech)

ČSN EN ISO 6579 (2003): Microbiology of food and animal feeding stuffs – Horizontal method for the detection of *Salmonella* spp. Czech Standards Institute, Prague. (in Czech)

ČSN EN ISO 15681 (2005): Water quality – Determination of orthophosphate and total phosphorus contents by flow analysis (FIA and CFA) – Part 2: Method by continuous flow analysis (CFA). Czech Standards Institute, Prague. (in Czech)

ČSN ISO 7899-2 (1993): Water Quality. Determination and Enumeration of Faecal Streptococci. Part 2: Method by Membrane Filtration. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 7150-2 (1994): Water Quality. Determination of Ammonium. Part 2: Automated Spectrometric Method. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 7980 (1994): Water quality. Determination of calcium and magnesium. Atomic absorption spectrometric method. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 8288 (1994): Water quality. Determination of cobalt, nickel, copper, zinc, cadmium and lead. Flame atomic absorption spectrometric methods. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 9297 (1995): Water quality Determination of chloride. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 9964-1 (1995): Water quality. Determination of sodium and potassium. Part 1: Determination of sodium by atomic absorption spectrometry. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 9964-1 (1995): Water quality. Determination of sodium and potassium. Part 2: Determination of potassium by atomic absorption spectrometry. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 10523(1995): Water quality. Determination of pH. Czech Standards Institute, Prague. (in Czech)

ČSN ISO 27888 (1996): Water quality. Determination of electrical conductivity (ISO 7888:1985). Czech Standards Institute, Prague. (in Czech)

ČSN ISO 11969 (1997): Water quality. Determination of arsenic – Atomic absorption spectrometric method (hydride technique). Czech Standards Institute, Prague. (in Czech)

Decree No. 252/2004 Coll. (2004): Laying down the health requirements for drinking and hot water and the frequency and extent of control of drinking water. The Law Collection of the Czech Republic, 82/2004 Coll. Ministry of Health of the Czech Republic, Prague. (in Czech)

Esmailiyan Y., Heidari M., Ghanbari A. (2008): Effect of Municipal Wastewater with Manure and Chemical Fertilizer on Grain Yield and Yield Components in Corn KoSc 704. Journal of Agronomy, **7**: 227–280.

FAO (1985): Guidelines: Land evaluation for irrigated agriculture. FAO Soils Bulletin No. 55. FAO, Rome. Available at http://www.fao.org/docrep/X5648E/x5648e00.htm (accessed October 5, 2006)

Feizi M. (2001): Effect of treated wastewater on accumulation of heavy metals in plants and soils. In: ICID Int. Workshop on Water Reuse Management. Seoul, 137–146.

Huibers F.P., van Lier J.B. (2005): Use of wastewater in agriculture: the water chain approach. Journal of Irrigation and Drainage Engineering – ASCE, **54**: 7.

ISO 10693 (1995): Soil quality – Determination of carbonate content – Volumetric method. ISO, Geneva.

ISO 11261 (1995): Soil quality – Determination of total nitrogen – Modified Kjeldahl method. ISO, Geneva.

ISO 11277 (1998): Soil quality – Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation. ISO, Geneva.

ISO 14235 (1998): Soil quality – Determination of organic carbon by sulfochromic oxidation. ISO, Geneva.

ISO 10390 (2005): Soil quality – Determination of pH. ISO, Geneva.

Jimenez B. (2005): Treatment technology and standards for agricultural wastewater reuse: a case study in Mexico. Journal of Irrigation and Drainage Engineering – ASCE, **54**: 23–33.

Klika J., Novák V., Gregor A. (ed.) (1954): Practicum of Phytocoenology, Ecology, Climatology and Pedology. Czechoslovak Academy of Sciences. Prague. (in Czech)

Mara D., Cairncross S. (1989): Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture. Measures for Public Health Protection. WHO, Geneva, 1–187.

Munir J.M. ,Ayadi M. (2005): Forage yield and nutrient uptake as influenced by secondary treated wastewater. Journal of Plant Nutrition, **27**: 351–356.

Najafi P., Mousavi S.F., Feizy F. (2003): Effects of using treated municipal wastewater in irrigation of tomato. In: Proc. ICID 20th European Regional Conf. Montpellier, September 14–19, 2003, 8.

Panoras A., Evgenidis G., Bladenopoulou S., Melidis V., Doitsinis A., Samaras I., Zdragkas A., Mathi Th. (2003): Corn irrigation with reclaimed municipal wastewater. Global Nest: the International Journal, **5**: 39–45.

Stehlík K. (1966): Municipal wastewater irrigation. Study information of the Institute of Scientific and Technical Information, Series Pedology and Soil Improvement, **2–3**: 1–160. (in Czech)

Stehlík K. (1980): Use of Wastewater for Irrigation II. Municipal Wastewater Irrigation. Ministry of Agriculture and Nutrition, Prague, 1–86. (in Czech)

TNV 757835 (1999): Water quality – Determination of thermotolerant coliform bacteria and *Escherichia coli*. Hydroprojekt CZ, JSC., Prague. (in Czech)

TNV 757520 (2002): Water quality – Determination of the chemical oxygen demand by dichromate CHSK. Hydroprojekt CZ, JSC., Prague. (in Czech)

TNV 757837 (2003): Water quality – Determination of coliform bacteria in undesinfected water. Hydroprojekt CZ, JSC., Prague. (in Czech)

Trávník K., Zbíral J., Němec P. (1999): Agrochemical testing of agricultural soils. Mehlich Method III. Central Institute for Supervising and Testing in Agriculture. Brno, 1–100. (in Czech)

US EPA (2004): Guidelines for Water Reuse. EPA/625/R-04/108. U.S. Environmental Agency and U.S. Agency for International Development, Washington, DC, 1–445. Available at http://www.epa.gov/ORD/NRMRL/pubs/625r04108/625r04108chap5.pdf (accessed August 21, 2006)

Vaz da Costa S.M., Bastos R.K.X., Mara D.D. (1996): Bacteriological aspects of wastewater irrigation. Tropical Public Health Engineering (TPHE) Research Monograph no. 8, University Leeds (Department of Civil Engineering), Leeds, UK. Available at http//leeds.ac.uk/civil/ceri/water/tphe/publicat/monogfiles/Res/mon8.doc (accessed February 14, 2007)

Wang J., Wang G., Wanyan H. (2007): Treated wastewater irrigation effect on soil, crop and environment: Wastewater recycling in the loess area of China. Journal of Environmental Sciences, **19**: 1093–1099.

WHO (1989): Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture. Report of a WHO Scientific Group. Technical Report Series No. 778. WHO, Geneva.

WHO (2006): Guidelines for the safe use of wastewater, excreta and greywater. Volume 2: Wastewater use in agriculture. Available at http://www.who.int/water_sanitation_health/wastewater/gsuweg2/en/index.html (accessed October 31, 2006).

WRB (2006): World reference base for soil resources 2006. A framework for international classification, correlation and communication. FAO, Rome, 1–182.

Received for publication September 26, 2008
Accepted after corrections July 2, 2009

Corresponding author:

Ing. Josef Zavadil, CSc., Výzkumný ústav meliorací a ochrany půdy, v.v.i., Žabovřeská 250, 156 27 Praha 5-Zbraslav, Česká republika
tel.: + 420 257 027 332, fax: + 420 257 921 246, e-mail: zavadil@vumop.cz