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REUSE OF MEMBRANE FILTERED MUNICIPAL WASTEWATER FOR IRRIGATING VEGETABLE CROPS

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SUMMARY - In the framework of a nationally relevant project named AQUATEC carried out in the period 2002-2006 and focused on innovative tools for mitigating the water-stress and/or scarcity in southern Italy, a technical scale investigation was performed to test the suitability of membrane filtration for agricultural reuse of municipal wastewater. Membrane filtration was tested at Cerignola (FG) where a test field was also operated and three different crops (processing tomato, fennel and lettuce) were grown in rotation. The experimental period considered in this paper spans between summer 2003 and spring 2005. Technological, water-quality and agronomic aspects were carefully investigated. Throughout the whole investigation the quality of treated wastewater was monitored (chemically and microbiologically) and compared with conventional water pumped from a local freatic well. Both water sources were used in parallel for irrigating two separate plots of the test field. Except for higher Cl^-, Na^+ and B concentrations, the average chemical quality of tertiary filtered municipal wastewater was comparable with that of conventional well-water. Irrigation with treated wastewater caused an increase of Na^+, Ca^{++} and EC values in the soil during summer periods that, however, were recovered during the following rainy seasons. From the microbial standpoint, unexpectedly, the plot irrigated with well-water resulted more contaminated than that irrigated with treated wastewater. The measured content of heavy metals in vegetables was independent of the water used for irrigation. Crops productivity did not show significant differences between the plot irrigated with treated wastewater and the one watered with well-water.

Keywords - Wastewater reuse, membrane filtration, alternative water resources, water scarcity management.

RESUME *- Dans la structure d'un projet nationalement pertinent, nommé AQUATEC, fait dans la période 2002-2006 et s'est concentré sur les outils innovateurs pour atténuer la stress d'eau et/ou la pénurie en Italie du sud, une enquête a été exécutée à l'échelle technique pour tester la convenance de filtration de la membrane pour la réutilisation agricole d'eau usée. La filtration de la membrane a été testée à Cerignola (FG) où une zone d'essai a aussi été opérée et trois récoltes différentes (tomate traité, fenouil et laitue) ont été grandi en rotation. La période expérimentale considérée dans ce papier a été déroulée entre été 2003 et printemps 2005. La qualité d'eau technologique et les aspects agronomiques ont été enquêtés avec soin. Partout dans l'enquête entière la qualité d'eau de rebut soignée a été dirigée (chimiquement et microbiologiquement) et bien comparé avec les eaux conventionnelles pompées d'un phréatique local. Les deux sources de l'eau ont été utilisées en parallèle pour irriguer deux intrigues séparées de la zone d'essai. À l'exception de la plus haute concentration en* Cl^-*,* Na^+ *et B, la qualité chimique moyenne de l'eau usée de filtration tertiaire était bien comparée avec celle conventionnel. L'irrigation avec eau usée traitée a causé une augmentation de la valeur de* Na^+*,* Ca^{++} *et EC dans le sol pendant les périodes estivales qui, cependant, s'est été remises pendant les saisons pluvieuses suivantes. Du point de vue microbien et de façon inattendue, l'intrigue irriguée avec les eaux de puits est plus contaminé que celui irrigué avec les eaux usées traitées. Le contenu mesuré de métaux lourds dans les légumes était indépendant de l'eau utilisée pour l'irrigation. La productivité des récoltes n'a pas montré de différences considérables entre l'intrigue irriguée avec les eaux usées traitées et celui arrosé avec les eaux des puits.*

Mots-clé *- réutilisation de l'Eau usée, filtration de la membrane, ressources de l'eau alternatives, gestion de la pénurie de l'eau.*

INTRODUCTION

In Italy, an overall annual water inflow around 155 billions m^3 yields only 52 billions m^3 of resources actually utilizable. However, because of the geographically uneven rainfalls distribution, in southern regions such figures drastically decrease as rainfalls are much lower (even 30 % less) than the national average (980 mm/y) (IRSA-CNR, 1999). Furthermore, in such areas, very often, only part (15-20%) of the already scarce water resources is actually available because of the out-of-date local water distribution systems. Accordingly, most of such regions have to face major problems related to water shortage for agriculture and, in some cases, even for drinking purposes.

With the aim to tone down water stress in these areas, a national relevant and strategic R&D and Training project whose acronym is AQUATEC has been carried out in five Regions (Campania, Apulia, Sicily, Calabria and Basilicata) in the period 2002-2006. The project was mainly focused on developing and/or testing innovative tools for contributing to mitigate the chronic water-stress and/or scarcity peculiar of these areas.

Referring to Apulia, it is a southern east region extended for about 20,000 km^2 with 800 km of coasts and about 4,500,000 inhabitants. At national level, it is the region with the lowest rainfall average value (i.e. about 660 mm) and, because of its orography and its hydro-geological subsoil features, its average runoff coefficient value (0.23) is also the lowest (IRSA-CNR, 1999). Nevertheless, the economy of the region, mainly based on two water demanding activities, agriculture and tourism, is ranked as one of the best in the south of the Country. This is possible thanks to the Apulian water aqueduct (AQP), the largest in Europe, which imports water from three bordering regions: Campania, Lucania and Molise. AQP is a complex multi-purposes and multi-reservoirs system with 19,635 km of distribution networks; it serves 4,623,349 inhab. and distributes, net of leakages, 309,416,113 m^3 of drinking water (*http://www.aqp.it/home.htm*).

As for the Apulian agricultural sector, it must be pointed out that in spite of the scarce regional rainfalls, most (78.8%) of the Apulian land is used for agricultural purposes (i.e., 15,239 km^2 over a total area of 19,332 km^2). However, only 23.8 % (i.e., 3,653 km^2) of the cultivated area is irrigated. Although such a small portion of irrigated land, in order to satisfy the agricultural water demand, in addition to the resources provided by large irrigation-water distribution consortia, in the region relevant amounts of water are withdrawn from local aquifers as a negative gap of about 700 Mm^3 exists (Portoghese *et al.*, 2005). In practice, to fill this gap, it has been estimated that regional farmers have drilled, more or less legally, about 140,000 wells and because of such an extensive groundwater over-exploitation, particularly in coastal areas, a sharp salinity increase, with peaks such high as 20,000 µs/cm, has taken place due to sea water intrusion phenomena (Maggiore *et al.*, 2001).

Taking into account that agricultural reuse of municipal wastewater is an appropriate tool for mitigating local scarcity of water resources (Lazarova, 2003) and that in the whole Apulian region about 250 Mm^3/y of treated wastewater could be reused for partially filling the above gap, within the AQUATEC project a specific activity has been planned and carried out in Apulia testing the suitability of membrane filtration technology for agricultural reuse of municipal wastewater. At a test field located in the Municipality of Cerignola (FG), three different crops (processing tomato, fennel and lettuce) were grown in rotation. Membrane filtration was chosen as viable technology due to its claimed efficiency for treating wastewaters with variable characteristics and removing pathogenic microrganisms. The main beneficial features of such a technology are the possibility of avoiding chemical disinfection and its toxic by-products as well as maintaining fertilizing species such as ammonia and phosphate ions in treated effluents.

This paper just reports the main results recorded during the investigation carried out in Apulia within the AQUATEC project.

MATERIALS AND METHODS

Membrane filtration pilot plant

Wastewater tertiary treatment by membrane filtration was carried out at the pilot scale by a hollow fiber submerged system (Zenon Environmental Inc., Canada). The membrane fibers were assembled in a module (ZeeWeed®) having a total membrane surface of 23.5 m^2. The module was plunged into a 1.5 m^3 steel tank fed with municipal secondary effluent and was operated *out-in*, i.e. the permeate was extracted from the internal surface of the fibers by imposing a negative pressure (never exceeding 0.7 bar) to both ends of the module, where the extremities of all fibers were connected. Hollow fibers have an external diameter of about 1.9 mm, internal diameter around 1.0 mm, and nominal (average) pore size of 0.03 μm. Operational cycles included extraction of the permeate (300 sec), and backwash (60 sec). The latter step was carried out by pumping, under positive pressure, a fraction of the permeate inside the fibers to unclog their pores. Coarse bubble aeration was also provided in the filtration tank to increase the shear stress and limit biofilm formation on the external surface of the hollow fibers. Operational parameters such as transmembrane pressure (TMP) and permeate flux (J) were regularly recorded. The pilot plant had a maximum productivity of about 0.7 m^3/h and was installed at the municipal wastewater treatment plant of Cerignola, a town of 50,000 PE in South-Eastern Italy. A fraction of the secondary effluent of the full scale plant was sent to the pilot for tertiary filtration, and the permeate was stored into six tanks (5 m^3 each). Although each irrigation required about 15 m^3 of water, a total stored volume of 30 m^3 was always available in order to match the continuous production with the discontinuous demand for irrigation. The test-field was located about 100 m away from the pilot plant and was connected to the storage tanks through a pipeline (Pollice *et al.*, 2004).

Experimental field

Two-year studies (2003-2004) were carried out to compare the effects on soil and crops of two types of water, tertiary filtered municipal wastewater ("Treated Wastewater", TW) and conventional water (control) pumped from a freatic well ("Conventional Source", CS), on three crops in succession. The three crops chosen for the investigation were processing tomato, fennel and lettuce.

Processing tomato (*Lycopersicon esculentum* Mill.) was transplanted in June 2003 in double rows 160 cm apart from each other, realizing a theoretical plant density of 3.1 plants/m^2, and was harvested in September 2003. Fennel (*Foeniculum vulgare* Mill.) was transplanted in October 2003 in single rows, 0.3 m apart from each other, realizing a theoretical plant density of 11.1 plants/m^2, and was harvested in April 2004. Lettuce (*Lactuca sativa* L.) was transplanted in April in single rows, 0.4 m apart from each other, realizing a theoretical plant density of 6.25 plants/m^2, and was harvested in July 2004. For all crops, drip irrigation was used by placing the dripping lines between each couple of tomato rows and every other row of fennel and lettuce.

The three crops were irrigated when the soil water deficit (SWD) in the root zone was equal to 35% of the total available water (TAW). Irrigation was scheduled based on the evapotranspiration criterion, providing water to the crops when the following conditions were met:

$${}_1\Sigma^n (E_{tc} - R_e) = 30 \text{ mm for tomato, and 25 mm for fennel and lettuce}$$

where:
n = number of days required to reach soil water deficit limits starting from the last watering;
E_{tc} = crop evapotranspiration (mm);
R_e = rainfall (mm).

Evapotranspiration was expressed as follows:

$$E_{tc} = E{*}K_p{*}K_c$$

with
E = "class A" pan evaporation (mm);
K_c = crop coefficient;
K_p = pan coefficient (0.8).

The experimental field was cultivated according to the methods commonly adopted by the local farmers.

Analyses

Tertiary filtered wastewater and conventional water samples were collected on every watering and analysed according to standard methods (Eaton *et al.*, 1995). The measured parameters were TSS, COD, $N\text{-}NH_4^+$, NO_3^-, $P\text{-}PO_4^{3-}$, electrical conductivity (ECw), total and faecal coliforms, *Escherichia coli* and *Salmonella.* Moreover, metals such as Ca, Mg, Na, K, B, Fe, Mn were monitored in both the filtered effluent and the conventional well water.

Soil samples were taken from each plot after every crop cycle, at depths decreasing from 0 to 0.8 m, every 0.2 m. They were analyzed for N, P_2O_5, K, organic matter (O.M.), pH, electrical conductivity on saturated paste extract (ECe), SAR, alcalinity (as $CaCO_3$), and exchangeable sodium percentage (ESP) according to standard procedures (Sparks, 1996).

Microbiological analyses (total and faecal coliforms, *Escherichia coli,* and *Salmonella*) were also carried out on soil samples at depths of 0-0.1 m and on tomato fruits, fennel heads and lettuce leaves, according to standard methods (Scharf, 1966; Woomer, 1994).

Finally, crops productions were compared and dried samples of the crops were extracted and analysed for their content of heavy metals in order to evaluate the differences due to irrigation with the two water sources.

RESULTS AND DISCUSSION

Pilot plant performance

The operational parameters of the membrane filtration pilot plant are summarized in *Table 1*.

Table 1. Operating parameters of the membrane filtration pilot plant.

Parameter	Unit	Operational value
Production (suction) time	sec	300
Backwash time	sec	60
Feed flowrate	L / h	2000
Production (suction) flowrate	L / h	300
Backwash flowrate	L / h	450
Frequency of chemical cleanings		For suction pressure > than 0.6 bar

During the considered experimental period, the pilot plant operated discontinuously according to the water demand for irrigation and to the management needs of the filtration system. In particular, the operating pressure of the system tended to increase over time due to the variable quality of the secondary wastewater. This pressure increase reflected the tendency of the membrane surface to foul, and was counteracted by periodical chemical cleaning of the module. This was done every time the operating negative pressure reached 0.6 bar, and consisted in sinking the module in a 200 mg /L NaClO solution for 4-6 hours. The solution was removed from the tank and the module rinsed before re-starting the plant's operation. Figure 1 shows the net flux of the filtration system (i.e. the net productivity of tertiary filtered wastewater) and the operating pressure over time. In the period between June and November 2003 the plant was operated by imposing higher permeate fluxes, and this resulted in more rapid decrease of membrane permeability (i.e. pressure increase). Chemical cleaning was required more often during this period than in the following ones when lower fluxes (and better influent quality) caused slower increase of the suction pressure (Fig. 1).

350 m^3 of the tertiary filtered wastewater produced by the pilot plant were used for irrigation of the first experimental crop (tomato) that was transplanted in June and removed in September 2003. The following experimental period spanned from February to April 2004, when the plant produced about

1000 m^3 of treated effluent, of which 150 m^3 were used for the irrigation of fennel. The last period started in June and ended in July 2004, and 100 m^3 of reclaimed wastewater allowed the experimental cultivation of lettuce.

The average quality of the tertiary filtered municipal wastewater was comparable with the well water conventionally used for irrigation (*Table 2*). Chemical, physical and microbial characteristics of the tertiary filtered municipal wastewater and the conventional well water showed similar concentrations except for Cl^-, Na^+ and B that were higher in the treated wastewater. On the contrary, the microbial pollution resulted higher in the well water. However, both chemical and microbiological parameters of the two water sources were below the regional limits for unrestricted irrigation except for the SAR. The higher salinity in the reclaimed wastewater was attributed to the presence of local preserved food industries, whose effluents partly reached the municipal sewer system.

The test field and the crops

Irrigation seasonal time-spans of tomato, fennel, and lettuce crops were of 57, 106, and 12 days respectively. The three crops were provided with 11, 4, and 3 waterings respectively (seasonal irrigation volumes 3300, 1000, and 750 m^3 ha^{-1} respectively).

Irrigation with tertiary filtered wastewater caused an increase of Na^+, Ca^{++}, SAR and EC along the soil profile (0-0.8 m) during summer 2003, when a higher number of waterings was provided. However, lower values were recovered in the soil during the following rainy season (Fig. 2).

Soil microbial contamination results show that the plots irrigated with the conventional well water were more polluted than those irrigated with the treated municipal effluent (Fig. 3). Salmonella was never found in either plots. Microbiological analyses performed on crop samples showed that total coliforms were the only indicator found on tomato fruits, fennel heads, and lettuce leaves (Fig. 4).

Irrigation with treated wastewater did not affect the productivity of the different crops, although the occasional presence of significant chlorine concentrations caused some effects on the plants. The unexpected occurrence of chlorine in the secondary effluent before chlorination was attributed to occasional management practices at the full scale plant.

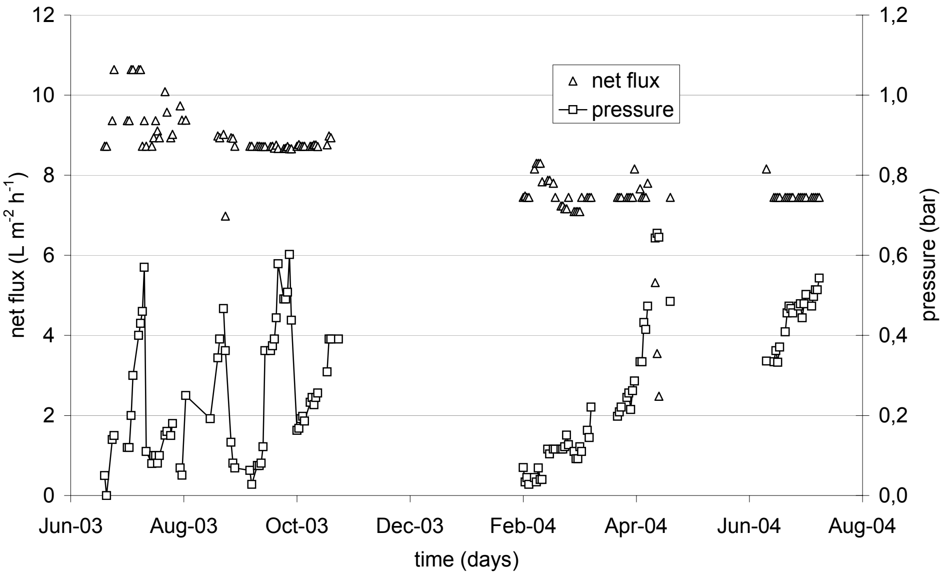
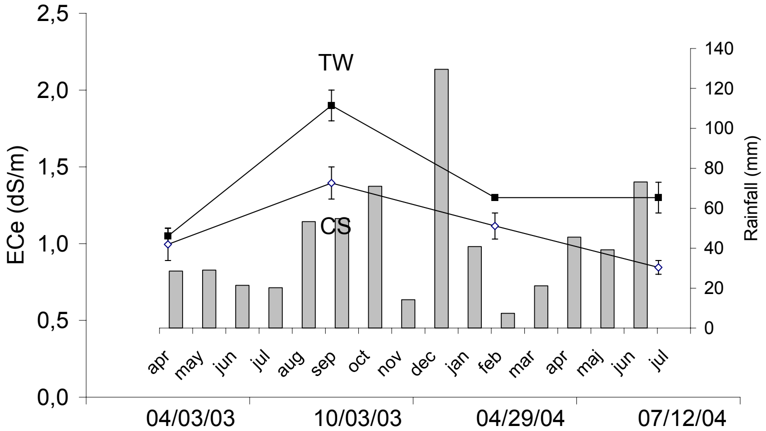


Fig. 1. Behaviour of the membrane filtration pilot plant over the investigated period in terms of productivity (net flux) and energy/maintenance requirements (trans-membrane pressure).

Table 2. Average values of the main physical, chemical and microbial parameters measured, over the research period, in the two types of compared water.

Parameter	Unit	Treated Wastewater	Conventional Source	Regional limits (*)
TSS	mg/L	< d.l.	< d.l.	10
COD	mgO_2/L	43	32	50
$N\text{-}NH4^+$	mg/L	1.0	0.3	2
NO_3^-	mg/L	9.5	5.8	
$P\text{-}PO_4^-$	mg/L	2.3	2.3	10
Na^+	mg/L	329	124	
Ca^{++}	mg/L	45	44	
Mg^{++}	mg/L	27	51	
Cl^-	mg/L	460	256	500
K^+	mg/L	30	18	
B	mg/L	1.0	0.1	2.0
Fe	mg/L	0.0	0.0	2.0
Mn	mg/L	0.0	0.0	0.2
ECw	dS/m	2.4	1.5	3.0
S.A.R.		13	4	10
Total coliforms	Cfu/100mL	146	293	
Faecal coliforms	Cfu/100mL	38	73	
Escherichia Coli	Cfu/100mL	11	9	10
Salmonellae	Cfu/100mL	0	0	0

(*) Limits established by Apulia Region for unrestricted reuse of municipal wastewater in agriculture.



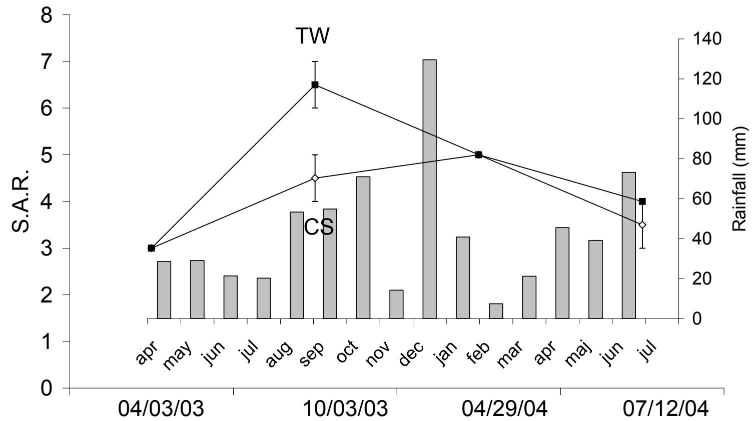


Fig. 2. Average values of soil Electrical Conductivity (ECe) and SAR versus time recorded over the research period and compared with rainfall in plots watered with conventional source (CS) and treated wastewater (TW). Histograms represent the rainfall.

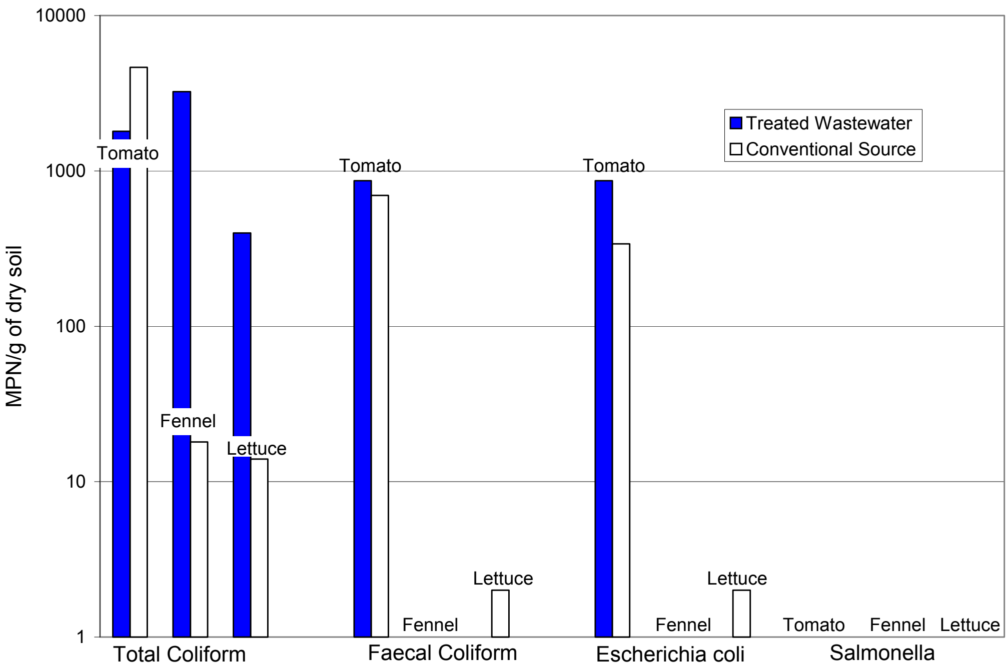


Fig. 3. Average values of total and faecal coliforms, *Escherichia coli* and *Salmonella* (as MPN/g of dry soil) measured at harvesting time in soil samples from plots watered with conventional source (CS) and treated wastewater (TW).

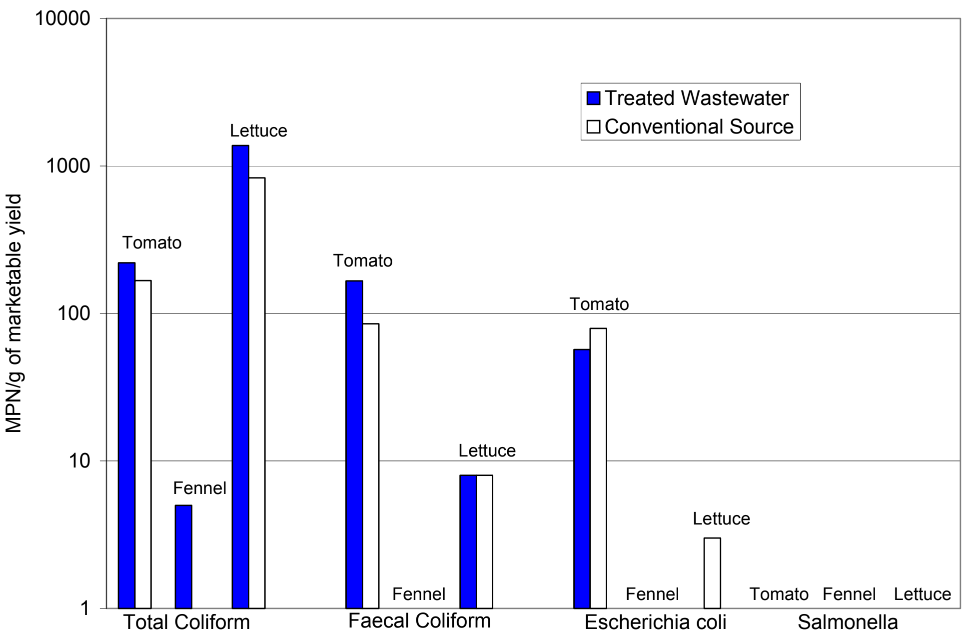


Fig. 4. Average values of total and faecal coliforms, *Escherichia coli* and *Salmonella* (as MPN/g of marketable parts of vegetables) measured at harvesting time on tomato fruits, fennel heads and lettuce in plots watered with conventional source (CS) and treated wastewater (TW).

The content of heavy metals in the vegetables was observed to be independent of the water source used for irrigation. Higher levels of some specific metals were occasionally measured in the crops irrigated with treated wastewater, but these concentrations were below those considered to cause acute toxicity (*Table 3*).

Table 3. Heavy metals average concentrations in crops irrigated with well water (CS) and treated wastewater (TW).

		Tomato fruits		Fennel heads		Lettuce leaves		Common range	Toxic range
Metal	Unit	CS	TW	CS	TW	CS	TW		
Fe	mg/kg	12	13			5	10	30-300	
Al	mg/kg	4.0	1.2					7-75	75
Cu	mg/kg	0	0			3	4	3-20	25-40
Zn	mg/kg	0.4	2.0	9	10	6	6	15-150	500-1500
Pb	mg/kg	0	0	0	0	0	0	2-5	400-200
Mn	mg/kg	0	0	92	101	90	48	15-150	

CONCLUSIONS

The main results obtained during a two-year field investigation aimed at evaluating the feasibility of using membrane filtered secondary effluents for irrigating vegetable crops (tomato, fennel, lettuce), were the following:

- Except for higher Cl^-, Na^+ and B concentrations, the tertiary filtered municipal wastewater was comparable with the well water conventionally used for irrigation in terms of average quality. Chemical and microbiological parameters of both water sources were below the local limits fixed for unrestricted irrigation, except for SAR. Wastewater salinity was due to uncontrolled effluent dumping into the sewer from local industries.

- Irrigation with tertiary filtered wastewater caused an increase of Na^+, Ca^{++}, SAR and EC values along the soil profile when higher volumes of water were provided (in summer), but these values returned to the background level during the rainy season.

- From the microbial contamination standpoint, unexpectedly, the plots irrigated with well water resulted more polluted than those irrigated with treated municipal effluent, possibly due to untreated wastewater discharge into the water table that caused groundwater faecal contamination. Also, the only indicator found on the irrigated crops were total coliforms.

- The content of heavy metals in the vegetables was independent of the water source.

- Irrigation with treated wastewater did not affect crops productivity except when unscheduled spikes of relevant amount of chlorine occurred in the secondary effluent due to operational practices at the full scale plant.

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