Agricultural wastewater reuse in Sicily

This paper describes a long–term study on constructed wetland treatment and wastewater reuse for irrigation in Sicily.

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Abstract

In Mediterranean countries, water shortage is becoming a problem of high concern affecting the local economy, mostly based on agriculture. In addition, often the problem is not only the scarcity of water in terms of average per capita, but the high cost to make water available at the right place, at the right time with the required quality. In these cases, an integrated approach for water resources management including wastewater is required. The management should also include wastewater reclamation and reuse, especially for agricultural irrigation. This study evaluates and compares the efficiency of two full-scale Horizontal SubSurface Flow Constructed Wetlands (H-SSF CWs), located in Southern Italy (Sicily), both in terms of water quality improvement (removal percentage) and achievement of Italian wastewater discharge and irrigation reuse limits. Moreover, the impact on tomato crops of drip and sub-drip irrigation with treated municipal wastewater, as well as effects of wastewater reuse on main production features, microbial soil and products contamination were investigated. The analysis of the reuse scenario confirms that, under controlled conditions, low-quality wastewater can be used to increase tomato crops production in water-scarce Mediterranean environments.

Introduction

The economical sustainability of the agricultural sector in Sicily (Southern Italy) has to cope with the availability and management of water resources for irrigation. Crop water requirements are, generally, unfulfilled for relevant percentages and the need to use alternative water sources, like urban treated wastewater (TWW), is urgent. Moreover, reusing these discharged effluents can significantly reduce or completely remove the impact of these effluents from receiving environments.

The monitoring campaign carried out in Sicily (Barbagallo et al., 2012) evidenced the potential presence of 523 urban wastewater treatment plants (WWTPs), of which 259 actually in operation, 89 not in operation, 32 abandoned, 47 under construction and 96 just planned by the public administration. Figure 1 depicts the 523 urban WWTPs in the Sicilian territory by evidencing their operation. In particular, 49% of WWTPs in operation treat wastewater (WW) coming from urban areas with person equivalent (P.E.) (e.g. evaluated on the basis of the organic load) between 2,000 and 10,000, while more than 60% of the planned WWTPs will serve urban communities smaller than 2,000 PE.

The WW volume produced by WWTPs in Sicily amount to $155 \cdot 10^6$ m^3 (plants in operation) and $48 \cdot 10^6$ m^3 (plant under construction). The total volume available in the short term is therefore about 27% of the irrigation needs of the island, estimated at about $750 \cdot 10^6$ m^3/year, taking into account areas served by both collective irrigation

Technical data:

The Constructed Wetlands treatment plant for wastewater reuse:

- system is designed for about 2200 inhabitants
- flow rate: 4 L/s
- surface area: about 4,000 m^2
- irrigation area from 200 to 1,550 m^2
- cultivar of tomato plant “Incas” and “Missouri”
- total amount of irrigation volume from 5,500 to 6,000 m^3/ha during each year of the trial.

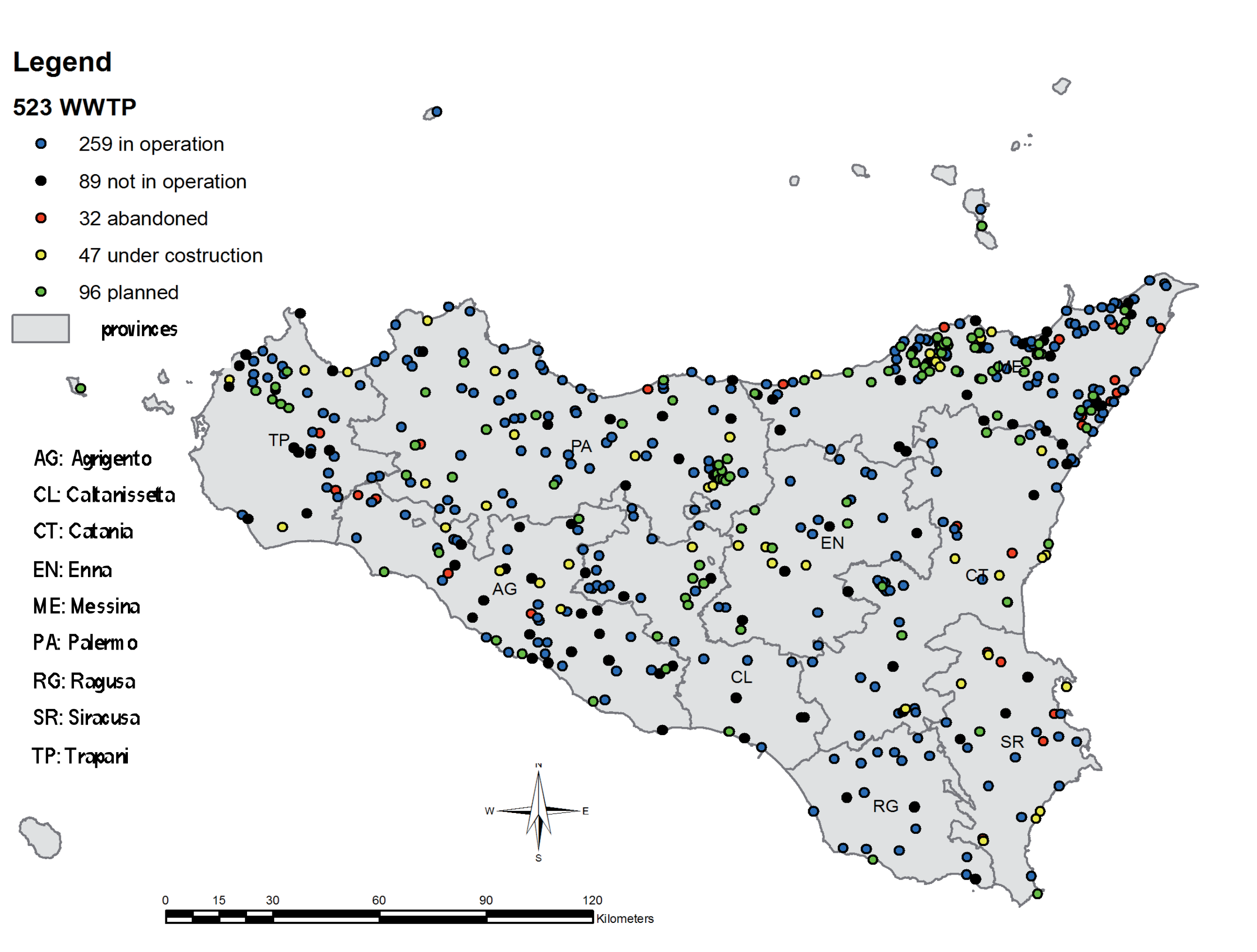


Figure 1. Location of the 523 urban WWTPs in the 9 Sicilian provinces

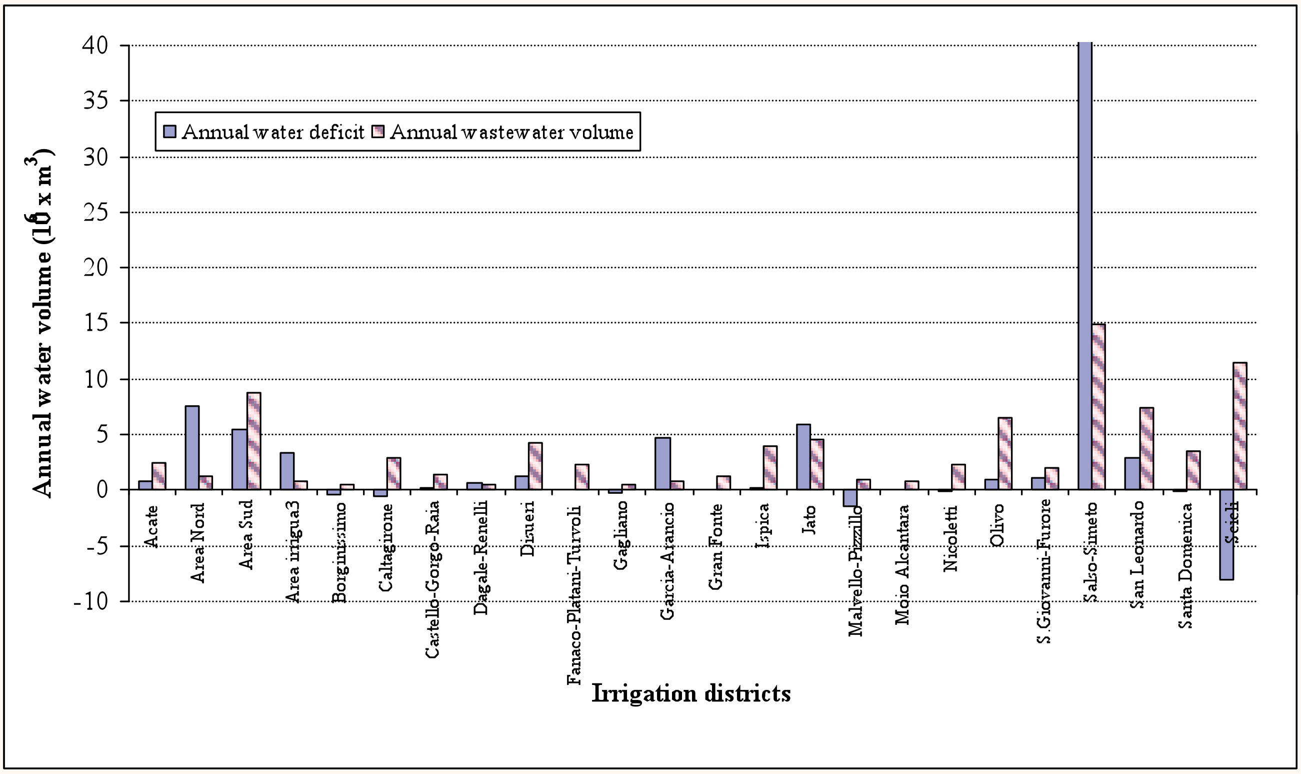


Figure 2. Annual water deficit and wastewater volume for each irrigation district

systems operated by public Consortia and private water sources.

But, a hampering factor to the development of TWW reuse is related to the total cost (construction, operation and maintenance) requested for reclamation, in addition to the cost for water distribution and the monitoring of the whole reuse system since WWTPs are often far from the irrigation area. On the basis of selection criteria (based on altitude, available flow rate, distance) and by the use of Geographical Information System (GIS), in Barbagallo et al. (2012) the area where it is economically viable to plan and design the infrastructures needed for the reuse of TWW have been identified. As a result, 24 of 37 irrigation areas operated by Consortia were eligible to receive TWW from 59 WWTPs (in operation or under construction). In particular, through the use of TWW ($87 \cdot 10^6$ m^3/year) 10 districts could cover the deficit and gain a surplus of water resources, 8 districts having no deficit could increase water availability, 6 districts could partially be able to meet water needs (Figure 2).

Although the reuse of WW is potentially beneficial, it raises soil contamination and public health concerns. As a consequence, these practices have to be regulated according to WW reuse norm limits that, in some countries, have become increasingly stringent. For example, the Italian law regarding the quality of water to be reused in agriculture (Decree No. 185, 12/06/2003, Ministry for Environment) has extremely tight limits, especially for microbiological parameters (Escherichia coli and Salmonella) (Barbagallo et al., 2011). Consequently, the adoption of tertiary treatments downstream of conventional WWTPs may be required to comply with legal limits. The adoption of natural systems, such as constructed wetlands, a natural WW treatment system, combined with conventional treatment plants, seem to be a suitable solution to improve water quality and it could be a cheap alternative for urban WW treatment especially in small and medium communities where low maintenance and operation needs are essential (Puigagut et al., 2007).

This paper describes the removal performance of two horizontal subsurface flow (H-SSF) constructed wetlands (CWs) designed to treat the secondary effluent of municipal wastewater with different operation lives: 8 and 3 years. Moreover, the paper reports the results of six years of research on irrigating tomato crops with the effluent coming from the tertiary-constructed wetland treatment.

Material and methods

Constructed wetland treatment plant

The research was carried out in a full-scale constructed wetland treatment plant located in San Michele di Ganzaria (Eastern Sicily), a rural community of about 5,000 inhabitants, 90 km South-West of Catania. The area is characterized by a Mediterranean semi-arid climate, with a mean annual rainfall of 600 mm and a mean daily temperature of 18°C in the observation period. The experimental plant consists of two horizontal subsurface flow (H-SSF) constructed wetlands (CWs) working in parallel that have an almost equal surface area (about 2,000 m^2) but with different operation life: H-SSF1 in operation since 2001 and H-SSF2 since 2006 (Cirelli et al., 2007). The constructed wetland treatment plant is used for tertiary treatment part of the effluent (about 4 L/s) of a conventional wastewater treatment plant (trickling filter) (Figure 3). Both wetlands are 0.6 m deep, were filled with 8-10 mm gravel and were planted with Phragmites australis.

Water quality analyses

At the inlet and outlet of H-SSF1 (from 2001) and H-SSF2 (from 2007) the following physicochemical parameters were evaluated to December 2008 (about twice a month for H-SFF1 and weekly for H-SSF2) according to APHA (1998) methods: total suspended solids (TSS) at 105°C, BOD5, COD, total phosphorus (TP) and total nitrogen (TN). Microbiological parameters, such as E. coli and Salmonella were also evaluated. E. coli was counted according to APHA (1998) methods and Salmonella was examined according to Barbagallo et al. (2003).

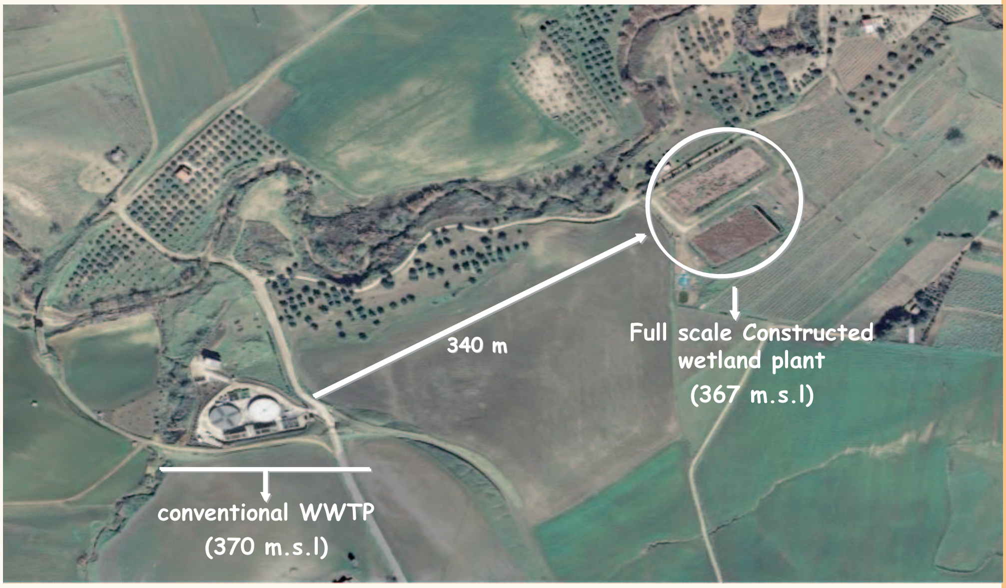


Figure 3. Experimental plants location

WW sampling has been done in different days for the two beds. For the physicochemical parameters, the evaluation of treatment performance was based on the removal efficiency percentage. For microbiological parameters log reductions were calculated.

Irrigation systems

A system using the effluent coming from the tertiary-constructed wetland treatment to irrigate tomato crops was build in the area during the irrigation seasons 2004-2009 (Figure 4).

The experimental field was moved during the years. In particular, the soil was sandy-loam during the first 4 years of the experiment (2004-2007) and clay (USDA textural soil classification) during the following period (2008-2009).

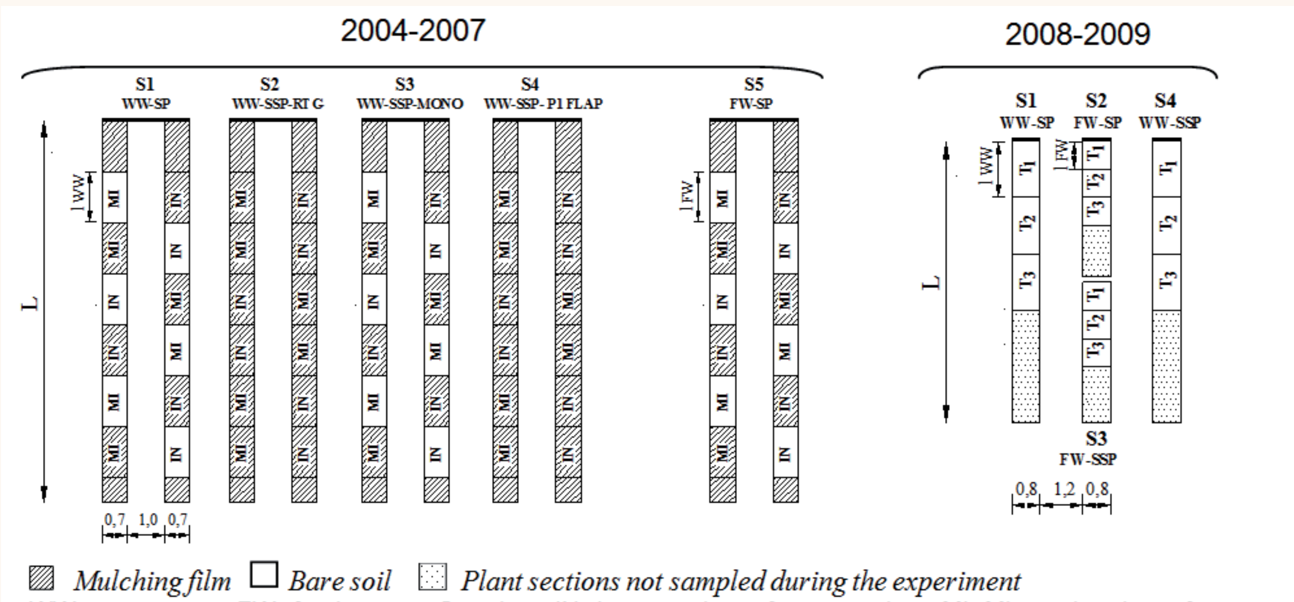
Monitoring period 2004-2007. In 2004, the site was equipped with two parallel testing systems, each one of four plots supplied by WW (plots S1…S4 were replicated two times; in Figure 4 just one testing system is reported). Four different drip lateral types were evaluated. A control system, supplied with fresh water (FW) was also installed. Two cultivar of tomato plant “Incas” and “Missouri” were transplanted into the open field. Irrigation scheduling was based on a simplified soil water balance method, by recording climatic data and evaporation rates through a Class A pan evaporimeter.

The total amount of irrigation volume measured by volumetric meters was of about 6,000 m^3/ha during each year of the trial.

Monitoring period 2008-2009. Figure 4 reports the experimental system design during 2008-2009 monitoring periods. In the scheme, two plots (S1 and S4) were supplied by WW and two (S2 and S3) by FW. All plots were equipped with surface (SP) or subsurface (SSP) polyethylene laterals. The chosen drip laterals were the same (P1 and MONO) showing the highest performance during the 2004 monitoring program. Irrigation scheduling was based on the advection-aridity model as function of evapotranspiration rates (Parlange and Katul, 1992), rainfall, soil water content (evaluated by time domain reflectometry method). The total amount of irrigation volume measured by volumetric meters was of about 5,500 m^3 during each year of trial. More information can be found in Cirelli et al. (2012).

Soil contamination analysis. During 2004-2006 monitoring period, soil contamination analyses were carried out to assess E.Coli, Enterococcus Faecalis (EF) and Salmonella concentrations within soil columns (from 0.1 to 0.4 m of depth) collected close to emitters (Aiello et al., 2012).

Crop yield features and microbiological contamination. The effect on crop production features due to water qualities (treated WW and FW), drip lines (SP and SSP) and soil coverage (just during 2004) and their interactions were evaluated during the trials. Marketable yield (MY), marketable fruits number (MN), fruit mean weight (MW) and unmarketable fruits number (UMN) were determined and processed. Analyses of variance (2-ways ANOVA) identified the effects of main factors and their interactions. Treatment means were compared



WW: wastewater; FW: fresh water; Sx: plots; IN: Incas variety of tomato plant; MI: Missouri variety of tomato plant; T1…T3: tomato crop replicates in 2008-2009; SP: surface pipe; SSP: subsurface pipe; SSP-RTG: P1 Rootguard subsurface light pipe; SSP-MONO: Mono subsurface rigid pipe; SSP-P1 FLAP: P1 Flap subsurface light pipe; l_{WW}: length of WW sections (6 m in 2004-2007 and 2009; 8 m in 2008); l_{FW}: length of FW sections (6 m in 2004-2009; 4 m in 2008 and 3 m in 2009); L: total length (45 m in 2004-2007; 40 m in 2008 and 31 m in 2009)

Figure 4. Experimental irrigation system at S. Michele di Ganzaria (Sicily, Italy) during 2004

by the least significance test, considering * for P<0.05, ** for 0.01<P≤0.05 and *** for 0.001<P≤0.01. The methodology followed to assess the microbiological contamination is described in Aiello et al. (2012).

Results

Constructed wetland performances

As the water flew through the constructed wetlands, an improvement on wastewater quality was achieved since a decrease in concentrations for all physicochemical and microbiological parameters was observed (Table 1 and Table 2). A generally better performance for H-SSF1 in BOD5 and COD was observed for the overall operation. The mean organic matter removal was about 60% in H-SSF1 and 40% in H-SSF2. This could be explained by alga growth and decomposition occurring in the free water surface area at the end of the H-SSF2 (the last 3 meters of the bed functions as a free water surface with an area of about 190 m^2) which increases organic concentration in the effluent. Another possible explanation is that starting from the start-up of 2007. The mean influent concentrations detected were generally lower than in previous years, giving overall lower removal efficiency for the two beds. Except for few deviations, both systems produce a final effluent with TSS concentration less than 20 mg/L regardless of input level (up to 120 mg/L for H-SSF1 and 113 mg/L for H-SSF2). This performance was very stable over their entire operational periods (8 years for H-SSF1 and 3 for H-SSF2) and does not show any decrease. The mean TSS removal in H-SSF2 (67% ±20) was lower than that obtained in H-SSF1, but it is to note that lower was the mean TSS concentration detected at the H-SSF2 influent. There is very little or no difference in the results for H-SSF1 and H-SSF2 for E. coli reduction. Similar E. coli treatment trends of both wetlands were observed with a mean reduction more than 2.5 log units. In particular, E. coli, were reduced to a mean value of 2.7 Ulog (± 0.8) (incoming range 4.5-5.3 Ulog) in the effluent of H-SSF1 and a mean value of 2.6 Ulog (± 0.8) in H-SSF2 (incoming range 5.3-5.4 Ulog). Despite plant uptake of nitrogen and phosphorus generally being non significant for their removal, a positive effect of the plants was observed. In the first year of H-SSF2 operation, its average removal efficiency of nutrients (60% to 46% for TN and TP) was higher than that in the H-SSF1 bed in 2001 (29% to 31% for TN and TP) (Table 1 and Table 2). These differences in removal efficiency during the start-up of the plants, is probably related to the sampling period. Samples were collected at the beginning of plant growth in H-SSF1, while the sampling survey began when the plants were already fully developed in H-SSF2.

Table 1. Mean influent (±SD) and effluent (±SD) wastewater concentrations and mean (±SD) pollutant removal efficiencies (R) throughout the monitoring period in H-SSF1

		TSS		BOD_5		COD		TN		TP		*E. coli**	
2001	in (mg/L)	66	(18)	35	(10)	76	(21)	26	(3)	6	(<1)	5.3	(0.4)
	out (mg/L)	12	(4)	11	(4)	18	(4)	18	(4)	4	(1)	3.1	(0.8)
	R (%)	81	(6)	68	(11)	75	(5)	29	(11)	31	(10)	2.2	(0.5)
2002	in (mg/L)	95	(17)	44	(16)	92	(22)	21	(4)	7	(3)	5.1	(0.4)
	out (mg/L)	11	(3)	13	(4)	19	(4)	10	(7)	5	(1)	3.1	(0.9)
	R (%)	88	(4)	68	(13)	78	(6)	56	(22)	32	(23)	2.1	(0.8)
2003	in (mg/L)	82	(15)	42	(8)	84	(14)	23	(5)	7	(2)	5.1	(0.3)
	out (mg/L)	12	(3)	11	(3)	17	(5)	12	(5)	4	(1)	3.0	(0.7)
	R (%)	85	(4)	72	(8)	79	(5)	50	(16)	37	(15)	2.0	(0.5)
2004	in (mg/L)	39	(35)	16	(8)	37	(15)	31	(6)	7	(1)	4.5	(0.7)
	out (mg/L)	5	(2)	8	(2)	16	(4)	25	(8)	6	(<1)	2.0	(0.7)
	R (%)	77	17)	37	(28)	51	(20)	20	(16)	17	(6)	2.5	(0.5)
2005	in (mg/L)	41	(16)	25	(9)	48	(16)	-	-	-	-	4.8	(0.4)
	out (mg/L)	3	(2)	8	(2)	16	(4)	-	-	-	-	1.5	(0.6)
	R (%)	92	(5)	63	(13)	63	(15)	-	-	-	-	3.5	(0.5)
2006	in (mg/L)	69	(8)	54	(13)	87	(18)	-	-	5	(1)	5.0	(0.1)
	out (mg/L)	10	(5)	19	(1)	34	(3)	-	-	3	(1)	2.6	(0.6)
	R (%)	86	(7)	63	(10)	61	(5)	-	-	31	(12)	2.4	(0.5)
2007	in (mg/L)	36	(12)	24	(7)	44	(9)	31	(7)	7	(1)	5.1	(0.4)
	out (mg/L)	14	(6)	16	(5)	29	(10)	25	(10)	6	(<1)	2.4	(0.1)
	R (%)	84	(15)	50	(27)	59	(21)	49	(19)	16	(6)	2.6	(0.4)
2008	in (mg/L)	34	(26)	21	(9)	36	(14)	20	(7)	8	(3)	5.2	(1.1)
	out (mg/L)	13	(7)	15	(7)	27	(14)	9	(4)	7	(2)	2.6	(1.1)
	R (%)	54	(24)	29	(19)	26	(18)	56	(16)	12	(8)	2.4	(0.9)
Overall period	in (mg/L)	62	(31)	32	(15)	64	(28)	23	(6)	7	(2)	5.0	(0.5)
	out (mg/L)	10	(5)	11	(4)	20	(8)	13	(7)	5	(2)	2.7	(0.8)
	R (%)	80	(17)	58	(22)	63	(22)	45	(20)	27	(16)	2.5	(0.8)

* Concentration and removal values in log units

Table 2. Mean influent (±SD) and effluent (±SD) wastewater concentrations and mean (±SD) pollutant removal efficiencies (R) throughout the monitoring period in H-SSF2.

		TSS		BOD_5		COD		TN		TP		*E. coli**	
2007	in (mg/L)	27	(24)	35	(5)	63	(9)	23	(5)	4	(<1)	5.3	(0.7)
	out	7	(3)	18	(7)	37	(13)	9	(3)	2	(1)	2.7	(1.0)
	R (%)	68	(17)	42	(22)	41	(23)	60	(19)	46	(20)	2.6	(0.7)
2008	in (mg/L)	41	(27)	30	(18)	50	(26)	34	(17)	7	(2)	5.4	(1.0)
	out	11	(7)	17	(8)	30	(15)	13	(7)	5	(3)	3.0	(0.8)
	R (%)	67	(23)	41	(16)	37	(19)	58	(15)	35	(31)	2.4	(0.7)
Overall period	in (mg/L)	35	(26)	31	(14)	55	(22)	29	(14)	6	(2)	5.4	(0.7)
	out	9	(6)	17	(8)	33	(15)	11	(6)	4	(3)	2.6	(0.8)
	R (%)	67	(20)	41	(19)	38	(20)	59	(16)	40	(27)	2.6	(0.8)

* Concentration and removal values in log units

Wastewater discharge and reuse limits

It could be deceptive to evaluate constructed wetland performance just according by removal efficiency. Constructed wetlands, and in general all wastewater treatment plants, are designed to meet discharge limits. For this reason, samples expressed as percentages below the Italian wastewater discharge limits into surface waters (D.Lgs. 152/2006) and for agriculture reuse (DM 185/2003) have been calculated (Barbagallo et al., 2011). In both effluents, COD and TSS concentrations were always below the Italian discharge concentration (35 mg/L and 125 mg/L respectively). Furthermore, the two wetlands always reduced COD to acceptable concentrations for irrigation (100 mg/L). Just a few samples (1 out of 80 for H-SSF1 and 5 out of 35 for H-SSF2) didn't comply with the BOD_5 limit of 25 mg/L for discharge into surface water. Both effluent nitrogen concentrations met the legal requirements for irrigation (35 mg/L) while the phosphorus limit (10 mg/L) was only exceeded by 3% (H-SSF1) and 5% (H-SSF2) of the samples. Despite constructed wetlands having shown good removal of microbial indicators (more than 2.5 log units) did not show the ability to produce effluent with E. coli levels matching Italian wastewater reuse standard (50 UFC/100 ml - Maximum value to be detected in 80% samples for natural treatment systems). Only 35% and 27% of samples collected at the outlets of H-SSF1 and H-SSF2, were below the maximum E. coli value limit imposed by the law. This result highlights the need for further treatment to achieve the Italian limits required for irrigation reuse. Following the WHO Guidelines (2006), in the 80% of samples E. coli contamination was in the range of 10^2-10^4 CFU 100 mL^{-1}, corresponding to a median risk rotavirus infection of 10^{-3} pppy, in an unrestricted irrigation and considering additional 2-3 log pathogen reductions by means of post-treatment control measures. So wastewater reclaimed by the constructed wetland system could be used for unrestricted crop irrigation if combined with some health protection measures, such as e.g. respect of withholding periods to allow pathogen die-off after the last wastewater application, in order to obtain the supplementary 2-3 log reduction needed to achieve the health based target of 10^{-6} DALY (Disability-Adjusted Life Years).

Hygienic quality of tomato crops and soil

Table 3 reports the average hygienic quality of tomato crops washing solution evaluated over the years of trial. By analysing the microbiological data it is not easy to determine if such contamination was due to the fruits contact with TWW, to an environmental pollution or to an accidental contamination occurring during sampling. The former possibility could be realistic during 2004 and 2005 years of trial, because we operated in the worst case condition (tomato fruits sampled near the drippers). During 2006-2009 period, the fruits sampled not in contact with soil/plastic mulch showed a very weak E.Coli contamination (60 CFU 100 g^{-1}), which fell within the quality recommendations (≤100 CFU g^{-1} E.Coli for pre-cut fruits and vegetable ready to eat) established by the European Commission (Commission Regulation

Table 3. Average microbiological quality of tomato fruits over the years of trial

Year	Sampling procedure	*E.Coli* (CFU 100 g^{-1})	*EF* (CFU 100 g^{-1})	*Salmonella* (CFU 100 g^{-1})
2004	1	4×10^2	5×10^2	Absent
2005	1	1×10^2	2×10^3	
2006	1	4×10^2	4×10^3	
	2	8	1×10^3	
2007	1	1	1×10^4	
	2	0	2×10^3	
2008	1	6×10^1	5×10^1	
	2	0	0	
2009	1	6×10^1	4×10^2	
	2	0	7	

1: samples of tomato fruits in contact with soil/plastic mulch; 2: samples of tomato fruits not in contact with soil/plastic mulch. E.Coli: Escherichia Coli; EF: Enterococcus Faecalis

2073/2005). EF concentrations were generally not negligible, suggesting that the found contamination could depend on the contact with WW.

During 2004-2006 monitoring period, the analyses on soil samples collected between 0.1-0.4 m from the surface level evidenced a not negligible microbial content. In particular, a mean E.Coli content of about 3×10^3 CFU 100 g^{-1} was found, with a decrease of about 3 log units along the examined soil profile. EF concentrations were found in all investigated soil columns layers, with a mean of about 1×10^3 CFU 100 g^{-1}. During 2007-2009 monitoring period, the concentration of E.Coli measured in the soil sampled were very low. No Salmonella contamination was recorded.

Crop yield evaluation

The results of WW reuse for vegetable cultivation were different according to crop and cultivation seasons. Differences on crop production features between the trials may be related with the harvest operation modalities. Between the different tomato varieties analysed in the study, the genotype Missouri was more suitable for reclaimed WW. The marketable total yield (mean of 60 t ha^{-1} during the trials) resulted significantly ($P<0.05$) higher for WW irrigated tomatoes in 4 of the 6 available years (it was not possible to evaluate the parameter in 2008 due to the fact that the Phytophtora affected tomato plants). The unmarketable production (mean of 50 fruits m^{-2}) resulted significantly ($P<0.05$) lower for WW irrigated tomatoes in 3 of the 5 available years.

The adoption of SSP laterals determined a significant improvement of MY (+28%) that was related to the increase in marketable fruits (+18%) and mainly to the decrease in unmarketable fruits (-30%), especially during 2008-2009 period. Finally, on the agronomic point of view, the use of tertiary treated municipal WW is suitable for the cultivation of vegetable crops. The obtained qualitative and yield results were slightly influenced by water quality. However, the different WW quality features during the years of trial require further physical and chemical characterization analyses to optimize the reuse scenario.

Conclusion

The constructed wetlands located in San Michele di Ganzaria (Sicily), have proved to be efficient in removing the main chemical and physical pollutants from the secondary effluent of urban wastewaters treatment plant. The results of this study confirm the high reliability of CWs for tertiary wastewater treatment given that the H-SSF1 treatment capacity remained largely unchanged after eight years of operation.

Despite increasing pressure to make more efficient use of water resources, irrigation of food crops with reclaimed water still remains a contentious issue. The debate is complicated by the fact that reuse scenarios can vary substantially with respect to WW treatment level, irrigated crops, sampling procedures, etc. The presented study, based on a 6-years monitoring program, showed that municipal WW, reclaimed according to a Constructed Wetland system may be successfully used, under specific experimental conditions, to irrigate and grow tomato crops.

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