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Agricultural wastewater reuse in southern Italy

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Abstract

Within a strategic R&D project, since April 2002, membrane filtration, simplified treatments, storage reservoirs and constructed wetlands technologies are under investigation, at field scale, to evaluate their effectiveness for treating municipal effluents to be reused in agriculture. So far, the main results recorded have been the following: membrane filtration — the microbial quality of treated effluents was higher than that of local well-water used for irrigation; simplified treatment — in order to save the agronomic potential of organic matter and nutrients present in urban wastewater, olive trees were irrigated with effluents produced by skipping biological processes and this resulted in a yield increase of 50%; storage reservoirs — TSS, BOD_5, COD and nutrients concentrations achieved the in force Italian limits for WW agricultural reuse; constructed wetlands — recorded average efficiencies for TSS, BOD_5, COD, TN and TP removals were 85%, 65%, 75%, 42% and 32% respectively.

Keywords: Wastewater reuse; Membrane filtration; Constructed wetlands; Wastewater storage reservoirs

1. Introduction

For mitigating water stress in southern Italy, a strategic R&D and training project is currently ongoing in three regions: Apulia, Sicily and Basilicata. The translated title of the project is "Innovative and sustainable technologies for facing water emergency in Southern Italy" and its acronym is AQUATEC. The project, coordinated by the Italian Water Research Institute (IRSA) of the National Research Council (CNR),

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has been financed by the European Community (50%) and the Italian Government (50%) with about €19,000,000 for a four-year duration (April 2002–March 2006). In addition to IRSA-CNR, the participants are five universities (Bari, Naples, Catania, Basilicata, Calabria) and three large private R&D enterprises [Enel-Hydro (Sicily), Hydrocontrol (Sardinia), Iside (Campania)]. Local stakeholders are also involved. The overall goal of the project is to identify feasible technological solutions to be implemented in Southern Italy in the following areas: control and management of water resources; efficiency and safety of integrated water management; groundwater restoration and wastewater reuse. This paper specifically deals with the intermediate results obtained in this latter area. In practice, at four sites (Cerignola, Ferrandina, Caltagirone, S. Michele di Ganzaria) different because of their specific local peculiarities (economy, population density, land availability, etc.), the efficiencies of four technological options (membrane filtration, simplified treatments, wastewater storage reservoirs, constructed wetlands) are evaluated, at demonstrative scale, as viable alternatives for reusing reclaimed municipal effluents in agriculture.

2. Reuse of membrane filtered municipal wastewater for irrigation of vegetable crops

An experimental investigation was carried out to test membrane filtration for the treatment of municipal wastewater prior to agricultural reuse. The results reported here refer to the first two years of tertiary hollow fiber filtration of a municipal effluent and irrigation of three different seasonal crops.

Membrane filtration was chosen as a test technology due to its claimed efficiency for treating wastewaters with variable characteristics and for removing pathogenic microrganisms [1]. This aspect was especially interesting in relation to the possibility of avoiding conventional chemical disinfection, which tends to form toxic by-products [2]. Municipal effluents directed to irrigation may usefully contain easily biodegradable organics and readily absorbable nutrients, therefore the possibility of limiting disinfection by-products without losing microbiological quality and agronomic potential was considered as attractive.

Two types of water were compared in the experimental activity: tertiary filtered municipal wastewater (TFMW) and conventional water (control) pumped from a freatic well (WW). Processing tomato, fennel and lettuce were the three crops grown in succession at the clay-soil test field.

2.1. The 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 module (ZeeWeed®) had a total surface of 23.5 m^2 and was plunged in a 1.5 m^3 steel tank fed with municipal secondary effluent. Each hollow fiber had external diameter of about 1.9 mm, internal diameter around 1.0 mm, and nominal pore size of 0.03 μm. The module 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 the fibers were connected. Operational cycles included extraction of the permeate (90–360 s) and backwash (30–40 s). 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 for increasing the shear stress and limiting 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 50,000 inhabitants town 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 have a buffer of treated water in case of possible equipment failures. The test-field was located about 100 m away from the pilot plant and was connected to the storage tanks through a pipeline [3].

2.2. Irrigation of crops

In June 2003 processing tomato was transplanted in double rows 1.6 m apart from each other, realizing a theoretical plant density of 3.1 plants/m^2. In September 2003, after harvesting tomato, the soil was prepared for transplanting the second crop (fennel). Fennel was transplanted in October 2003 in single rows, 0.3 m apart from each other, and was harvested in April 2004. Lettuce was transplanted at the end of April in single rows, 0.4 m apart from each other, and was harvested in July 2004. For all crops, drip irrigation was used 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 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:

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

where n is the number of days required to reach the $SWD_{\lim}$ starting from the last watering; E_{tc} — crop evapotranspiration (mm); R_e — rainfall (mm).

Evapotranspiration can be expressed as follows

$$E_{tc} = E \cdot K_p \cdot K_c$$

with E — “class A” pan evaporation (mm); K_c — crop coefficient; K_p — pan coefficient (0.8).

The test field was cultivated according to the agronomical practices commonly adopted by the local farmers.

2.3. Sampling and analyses

Wastewater samples (before and after filtration) and conventional water samples were collected on every watering and analysed according to standard methods [4]. The measured parameters were TSS, COD, N-NH_4^+, TKN, P-PO_4^{3-} , Ca^{2+}, Mg^{2+}, Na^+, K^+, B, Cl^-, pH, electrical conductivity (ECw), total and faecal coliforms, *Escherichia coli,* faecal *Streptococci,* and *Salmonella.*

Soil samples were taken from each plot before and after every crop cycle, at depths decreasing from 0 to 0.8 m, every 0.2 m. They were analyzed for nitrogen (N), phosphorus (P_2O_5), organic matter (OM), pH, electrical conductivity on saturated paste extract (ECe), sodium absorption ratio (SAR), alcalinity (as $CaCO_3$), potassium (K) and exchangeable sodium percentage (ESP) according to standard procedures [5]. Microbiological analyses (total and faecal coliforms, faecal *Streptococci, 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, according to standard methods [6,7].

2.4. First results

Irrigation seasonal time-span of tomato, fennel, and lettuce crops resulted of 57, 106, and 12 days respectively. The three crops had 11, 4, and 3 waterings and seasonal irrigation volumes of 3300, 1000, and 750 m^3 ha^{-1} respectively.

Chemical, physical and microbial characteristics of the tertiary filtered municipal wastewater (TFMW) and well water (WW) are shown in Table 1. Concentrations of Cl^-, Na^+ and B are higher in TFMW than WW, whereas the other parameters are similar across the two water sources. It is worth to note that the microbial pollu-

Table 1
Average values of main physical, chemical and microbial parameters measured in the two types of waters during the research period

Parameters	Well water (WW)	Tertiary filtered municipal wastewater (TFMW)
TSS, mg/l	33	5
COD, mg/l	11	58
N-NH_4^+, mg/l	0	13.4
NO_3^-, mg/l	22	48.5
P-PO_4^{3-}, mg/l	2.3	2.3
Na^+, mg/l	124	328
Ca^{2+}, mg/l	44	44
Mg^{2+}, mg/l	27	51
Cl^-, mg/l	255	460
B, mg/l	0.1	1.0
E.C., dS/m	1.5	2.4
Total coliforms, cfu/100 ml	263	149
Faecal coliforms, cfu/100 ml	80	40
Escherichia coli, cfu/100 ml	10	10
Faecal *Streptococci*	148	75
Salmonella, cfu/100 ml	0	0

tion of well water was noticeable and much higher than that of filtered wastewater.

As observed along the soil profile (0–0.8 m), the use of TFMW for irrigation caused a slight increase of some parameters reprted in Table 2.

Soil microbial contamination was assessed by measuring total and faecal coliforms, *Escherichia coli*, faecal *Streptococci*, and *Salmonella* on samples taken at depths of 0–0.1 m, before and after each seasonal irrigation. Results show that plots irrigated with WW resulted more polluted than plots irrigated with TFMW. Salmonella was never found in either plots. Microbiological analyses performed on crop samples show that total coliforms were the only indicator found on tomato fruits, fennel heads, and lettuce (Table 3).

3. Simplified treatments for agricultural wastewater reuse

Basically, simplified treatments partially exclude biological processes for organic matter and nitrogen removal in order to recover the nutritive and fertilising principles from wastewater and to avoid the cost related to the biological oxidation and to the removal, dehydration and disposal of biological sludges.

Approximately, avoiding the costs for the organic matter and nitrate removal, it is possible to lower costs of treatment and disposal under the ones required for simple discharging into natural basins.

The reuse of wastewater, in addition to the economical aspect, has a relevant impact on environment protection because of the reduction of the exploitation of natural sources, in particular of the slow-recharging water layer [8].

Table 2
Average values of selected parameters measured over the research period along the soil profile. ECe and SAR were determined on saturated paste, ESP values were calculated

Parameters	03/04/2003		03/10/2003		29/04/2004		12/07/2004	
	WW	TFMW	WW	TFMW	WW	TFMW	WW	TFMW
Na, meq/l	4.74	4.73	6.21	9.81	5.95	6.5	3.9	5.15
Ca, meq/l	2.82	3.78	1.73	1.81	1.3	1.4	1.57	1.85
Mg, meq/l	1.24	1.12	2.74	2.44	1.97	1.85	1.26	1.55
ECe, dS/m	1.01	1.09	1.42	1.89	1.1	1.3	0.8	1.3
SAR	3	3	5	7	5	5	4	4
ESP	4	4	5	8	6	6	4	5

Table 3
Average values of various microbial indicators as detected on tomato fruits, fennel heads and lettuce at harvesting time, expressed per unit weight of marketable yield

Parameter	Tomato		Fennel		Lettuce	
	WW	TFMW	WW	TFMW	WW	TFMW
Total coliforms, cfu/g	164	220	0	5	830	1375
Faecal coliforms, cfu/g	85	166	0	0	8	8
Escherichia coli, cfu/g	79	57	0	0	3	0
Faecal *Streptoc*., cfu/g	1	1	0	0	1	0
Salmonella, cfu/25 g	Absent	Absent	Absent	Absent	Absent	Absent

3.1. Technological issues and first results

The results of the activity carried out at the pilot site of Ferrandina (Basilicata Region, southern Italy) are illustrated in the following. A pilot treatment unit has been designed and realised at the Sanitary Engineering laboratories of the University of Basilicata. In Table 4 the principal characteristics of the pilot plant parts are reported [9].

In the activity period the plant operated in different configurations producing, on average, 30 m^3/ d of water, subsequently used for olive growing application. In Table 5 the meaningful data coming from different treatment periods are shown.

Olive trees irrigation was carried out using reclaimed wastewaters coming from both treatment schemes, 2 (20%) and 3 (80%). Waters produced by scheme 1 have been distributed to the olive trees for limited periods to simulate plant malfunctioning that could cause microbial load increases.

The results obtained by the tests on pilot plant, relatively to scheme 2, have conducted to the definition of an alternative treatment scheme able to operate a selective removal of the organic substance (quickly biodegradable fraction) and a partial removal of the nitrogenous charge. For such scheme the costs of treatment of waters are smaller than the conventional schemes of treatment (up to 30%); the consequent economic advantages must be added to the recovery of the fertilisers.

3.2. Irrigation of crops and first results

As reported before, the treated wastewater was used for the irrigation of an olive orchard of mature trees (cv Maiatica, a dual purpose variety) vase trained and planted at a distance of about 8 m × 8 m, located near the pilot plant. The climate of the area was classified as semi-arid, with an average annual rainfall (1921–1970) of 597 mm mostly concentrated in winter. The soil of the experimental field

Table 4
Characteristics of the pilot plant

Collection and pre-treatments	Centrifuge endorser open pump - range 1 - 10 m^3/h Bottle-holder grate manual-cleaning — passing diameter 3 mm
Sedimentation/flocculation	Net surface 6.25 m^2, net volume 12.5 m^3, max perimeter 8.8 m Equipped with dosing, reacting system and rapid mixer (0.5 kW) Hydraulic system of sludge extraction
Filter	Pressure unit with one-layer sand bed. Diameter 1.5 m. Height 2 m.
Disinfection	Contact tank (only liquid products) Net volume 2.5 m^3. Rapid mixer 0.5 kW.

Table 5
Characteristics of waters produced during different treatment periods

Treated water	Treatment scheme	Average content of fertilising substance (mg L^{-1})			Disinfection		Residual contained microbial (MPN/100ml)	
		COD	N_{tot}	P_{tot}	Agent	mg L^{-1}	Total *coli*	*Streptococci*
Sewers waters Scheme no. 1	Chain driven-screens Microscreen Flocculation–filtration–disinfection	300	50	10	PAA NaOCl	5–15 5–25	100–10^5 100–10^5	10–100 10–100
Out of denitrif. unit Scheme no. 2	Sedimentation–flocculation–filtration–disinfection	250	35	8	PAA NaOCl	2–10 5–10	10–1000 10–1000	0–10 1–10
Out of final sedimentation Scheme no. 3	Flocculation–filtration–disinfection	60	15	2	PAA NaOCl	0.5–2.5 1–5	0–100 0–100	0 0

is a sandy loam soil. On average (0–60 cm layer), organic matter content was 1.2%, total N 0.8 g kg^{-1}, available P 11.7 mg kg^{-1} and K 104 mg kg^{-1}. Available water, calculated as the difference between the values of soil water content at field capacity and irreversible wilting point, was 12%.

The olive grove was micro-irrigated (drip irrigation), pruned slightly yearly and its ground was covered by natural vegetation.

Meteorological parameters (temperature, rainfall, humidity, etc.), measured by a standard weather station placed close to the trial field, and ETo (reference evapotranspiration) were taken by the web-page of the Extension regional service (www.alsia.it). In order to define water volumes, ETc (crop evapotranspiration) was calculated multiplying ETo by reduction coefficient (K_r = 0.7) [10] and crop coefficient (K_c ranged from 0.50 to 0.65).

Samples of treated wastewater were collected from the drippers in the middle and at the end of the irrigation season. Physical, chemical and microbiological (faecal coliform) analyses of the effluent were performed according to standard Italian methods [11].

Before the beginning of the irrigation season, in the middle and at the end, composite soil samples were collected from the wet area at different depths in the irrigated plot in order to carry out physical, chemical and microbiological analyses according to standard methods [12].

Fruits, collected directly from the canopy and from nets put on the ground for harvest, were also analysed to verify possible faecal pollution.

For comparison, soil chemical, physical and microbiological analyses were carried out on soil and fruit samples collected, at the same dates and with the same methods, from a nearby control plot managed according to the common practices in the research area (not irrigated, tilled, and pruned strongly every two years or more). Yield per plant was measured at the harvest time. Pruning material per tree was determined.

Seasonal water volume applied during the experimentation ranged from about 2200 to more than 3000 m^3 ha^{-1} according to the climate conditions. During the trial ETo reached 1400 mm y^{-1}. Water deficit, calculated as the difference between ETo and the total rainfall, ranged, in the years, from about 600 to more than 1000 mm y^{-1}.

Taking into account the chemical analyses of the treated wastewater, the amount of mineral

Table 6
Comparison between mineral element needs of olive trees in a bearing year (10 t ha^{-1}) and nutrients carried by wastewater treated by the pilot plant in Ferrandina (3000 m^3 ha^{-1})

Mineral elements	Plant needs (kg ha^{-1})	Nutrients carried by treated wastewater (kg ha^{-1})
N	118	55
P	9	3
K	100	51
Mg	9	41
Ca	87	203

elements distributed by irrigation satisfied the plant nutrient requirements except for N (Table 6). Nitrogen fertigations were carried out during fruit set and pit hardening phases.

Compared to the olive trees grown in rainfed conditions, irrigation caused mitigation of the alternate bearing phenomenon and, on an average, a yield increase of 50% (about 11 t ha^{-1}). Irrigation practice improved fruit characteristics such as weight and flesh to pit ratio which are very important parameters for table olives.

With regards to a sustainable soil management, total organic matter (expressed as COD) distributed on the soil by the treated wastewater was, on average, 0.12 t ha^{-1}; this amount and the one coming from other organic sources internal to the olive orchard (old leaves, pruning material and grass cover) could produce about 2.3 t ha^{-1} y^{-1} of humus.

Faecal coliforms tended to be higher in the irrigated soil than in the non irrigated one. Soil faecal contamination ranged from 0.37 to 270 cfu g^{-1} d.w, according to the hygienic quality of the water, and it seemed not able to go deep into the soil profile and to spread over the wet area under the dripper. No faecal contamination was recorded on the fruit picked directly from the canopy. Only in one case a very weak pollution (10 cfu 100 g^{-1} f.w) was measured on a fruit sample collected from the nets.

4. Wastewater storage reservoirs

In the past few years many on-farm reservoirs have been built in Sicily, mainly in the eastern part of the island, to store both treated and untreated urban wastewater in the fall–winter season [13]. This section describes the experimental activity carried out on a small reservoir (maximum capacity 100,000 m^3) for tertiary treatment and reclamation of municipal wastewater for agricultural reuse. The overall objective of the research is to develop design criteria and rules of management of small wastewater storage reservoirs (WWRs) in Mediterranean condition in order to improve their pollutants removal efficiency.

4.1. WWR description

The experimental facility is located at Caltagirone, a municipality of about 35,000 PE in the Eastern Sicily. This town is equipped with a secondary wastewater treatment plant (WWTP) by activated sludge system. A part of the flow, about 30 L/s, is pumped in a wastewater reservoir (WWR) and used, after the storage, for irrigation of citrus orchards. The WWR, built in concrete, has a surface area of about 2.1 ha (140 × 140 m), and a maximum capacity of 80,000 m^3 with a depth of 3.75 m. The WWR is operating in continuos modality with a nominal detention time of about 30 days. The WWR inflow and outflow are equal a part of infiltration and evaporation losses. The WWR has been equipped with a volumetric gauge in the inlet, an electronic flow meter with a data logger in the outlet, a refrigerated automatic sampler (for composite sampling both in the inlet and in outlet), an integrated weather station (monitoring: air temperature, rainfall, solar radiation, air humidity, wind velocity).

4.2. Methods

Water samples were taken from WWR with a weekly or biweekly frequency. Sampling locations were: at the WWR inlet (corresponding to the outlet of WWTP); at an internal point, located about 20 m from the inlet point, at two depths (0.20 m below the water surface and 0.50 m from the bottom of the reservoir); at the WWR outlet. The WWR inlet sample was collected over 24 h by an automatic sampler, the others were grab samples. The following physicochemical parameters were measured in laboratory according to standard methods: TSS (at 180°C), BOD_5, COD, total phosphorus (TP), total nitrogen (TN), electrical conductivity (EC), pH, dissolved oxygen (DO) and temperature. Microbiological analysis included: total coliforms (TC), faecal coliforms (FC), *Escherichia coli*, faecal *Streptococci* (FC), *Salmonella* and helminth eggs (nematodes).

Temperature, DO, pH and EC, were also measured in situ at six points in the WWR along the profile of the water column by a portable instrument (Horiba U10). The hydraulic detention time has been evaluated by means of pulse-input tracer tests (using a Rhodamine B solution).

4.3. First results

The average values of physicochemical and microbiological parameters with removal efficiencies in the inflow and outflow wastewater are reported in Figs. 1a and 1b respectively.

The average quality of WWR inflow (i.e. WWTP outflow) was high. TSS, BOD_5 and COD concentrations were, in most samples, down the limits fixed for wastewater disposal by the EU directive 271/91. The storage period in WWR caused a further improvement in wastewater quality: TSS, BOD_5, COD and nutrient concentrations in WWR outflow achieved the Italian legislation limits for agricultural reuse. Average TSS concentrations (57 mg/L in WWR influent) dropped to 8 mg/L during the storage in WWR, with a mean removal efficiency of about 83%. The mean reduction of organic matter concentration during the detention period in the WWR was about 61%. The WWR effluent had BOD_5 with a mean value of 8.2 mg/L (±SD = 2.25), and COD with a mean value of 17.3 mg/L (±SD = 3.44). The nutrient concentration was very low in WWR inflow and consequently removal efficiency during storage period was 15% for TN and 7% for TP.

The average number of TC, FC and *E. coli* found in WWR inflow was 10^5¸10^6 CFU/100 mL. During the storage period microorganism indicators showed an average decrease of 2–3 log units (removal about 99–99.9%). *Salmonella*, found in WWR inflow, with a mean value of 28.2 MPN/100 mL, was detected in WWR effluent only in 2 samples (about 5% of total samples) with a maximum concentration of 4 MPN/100 mL. Helminth eggs, detected in 80% samples with an average

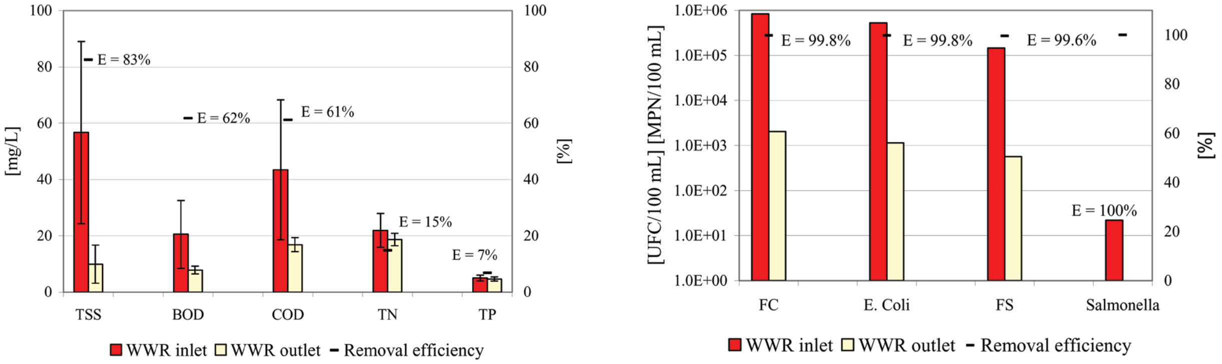

Fig. 1. Wastewater characteristics in WWR inlet and outlet: a) average values (±SD) and removal efficiencies (±SD) of TSS, BOD_5, COD, TN and TP; (b) average values and removal efficiencies of FC, *E.coli*, FS and *Salmonella.*

value of 4.1 per liter and a maximum of 30 per liter in the WWR inflow, were not detected in the outflow.

These experimental results will be used for modeling the kinetics of removal of selected pollutants (*E.coli*, BOD_5 and COD) by a new operational parameter: Mean Residence Time of the Fresh Effluents (MRTFE) for a range of fresh effluents varying between 5% and 100% [14].

The first tracer tests performed to evaluate the actual detection time and modeling the stabilisation processes in order to improve the design and operation rules of WWRs, has showed that the actual detention time is significantly shorter (7 days) than the nominal one (30 days). This is probably due to hydraulic short circuiting. If this result will be confirmed an improvement in microbiological quality of WWR outflow will be easily achieved by reducing the percentage of fresh effluents, i.e. with a change of operational rules.

5. Constructed wetlands for agricultural wastewater reuse

Some municipalities in the district of Catania (Eastern Sicily) are involved in wastewater reuse projects for irrigation purposes [15] focused on tertiary treatment performed by constructed wetlands (CW) and/or stabilisation reservoirs (SR). One of such full-scale CW, based on a horizontal subsurface flow (H-SSF), is under investigation within the AQUATEC project together with a pilot-scale CW system. The main goals of the overall research are to analyse the performances of the wetlands, to investigate their hydraulic behaviour and to model the contaminants removal processes. This section reports the first results obtained through the above full-scale wetland.

5.1. Wetlands description

The CW experimental facilities are located at San Michele di Ganzaria (Eastern Sicily), a rural community of about 5,000 inhabitants. Within a wastewater reuse project for the irrigation of about 150 ha of olive orchards, the local conventional WWTP (trickling filter) has been integrated with a full scale horizontal subsurface flow CW. The whole project foresees a tertiary system made of four H-SSF reed beds in parallel followed by three stabilisation reservoirs. Presently, only a single reed bed is used for the tertiary treatment of about 1,100 p.e., with a design flow rate of 1.75 L/s and a nominal hydraulic residence time of about 2 days. The wetland is 78 m long, 25 m wide and the surface bed area results 1,950 m^2 (about 1.7 m^2/p.e.) corresponding to an hydraulic loading rate of 0.077 m/d. The filtering bed, made of 8–10 mm gravel with a porosity of 0.38, is 0.6 m deep and the average water depth is 0.4 m. The wetland was planted with *Phragmites* sp. at density of four rhizomes per m^2.

As for the pilot-scale CW plant, it is made of four lines through 2-stage subsurface flow CW and it is able to work as main or tertiary treatment. The first stage, for each line, consists of a horizontal flow wetland, while in the second stage a vertical flow wetland operates for two lines and a horizontal flow wetland for the other two. Each wetland, sizing 1.5 × 3.0 m, is built in concrete and lined with an impermeable membrane. *Phragmites* sp. are used as vegetation in two lines while the others two are without vegetation. The horizontal flow systems are filled, to an average depth of 0.6 m, with gravel having a size of about 10–15 mm, while the vertical flow systems are filled with different medium layers ranging from 0.06–4 mm at the top of the filtering bed to 16–32 mm on the bottom. The pilot-CW plant will be essentially used for modelling: flow pattern, solute transport, biochemical removal and transformation processes of organic matter, nitrogen and phosphorus.

5.2. Methods

Full-scale CW influent and effluent were sampled and physical, chemical and microbiological characteristics of wastewater analysed. The following physicochemical parameters were measured in laboratory according to Standard Methods: TSS (at 180°C), BOD_5, COD, total phosphorus (TP), total nitrogen (TN), electrical conductivity (EC), pH, dissolved oxygen (DO) and temperature. Microbiological analysis included: total coliforms (TC), faecal coliforms (FC), *E. coli*, faecal *Streptococci* (FC), *Salmonella* and helminth eggs (nematodes). Moreover, to assess the actual flow conditions in the wetland, several pulse-input tracer tests (using a sodium chloride solution and sampling the electrical conductivity at the wetland outlet) have been carried out and the residence time distributions (RTDs) were evaluated [16].

5.3. First results

The average values of physicochemical parameters in the inflow and outflow wastewater of the wetland are reported in Fig. 2a for the whole reference period. In Fig. 2b, instead, the average removal efficiencies are shown.

Average TSS and BOD_5 values in CW influent (corresponding to WWTP effluent) resulted greater than the Italian limits for agricultural reuse (10 and 20 mg/L respectively). Average TSS concentrations (78 mg/L in CW influent) dropped to 10 mg/L showing a mean removal efficiency of about 85%. The mean reduction of organic matter concentration during the detention period in the CW was about 65% (with peaks over 80%) for the BOD_5 and 75% for the COD. The effluent provided BOD_5 values between 6 and 18 mg/L, with a mean value of 12 mg/L, and COD values between 10 and 25 mg/L, with a mean value of 18 mg/L, both compatible with law limits for reuse. The removal efficiency of nutrients was 42% for TN and 32 % for TP.

The average number of total coliforms, faecal coliforms and *E. coli* found in CW influent was $10^5 \div 10^6$ CFU/100 mL. During the observation period microorganism indicators showed an average decrease close to 2 log units (removal = 99%), with a maximum of 3 log units. Helminth eggs, detected in 80% samples with an average value of 12 per liter and a maximum of 54 per liter in the CW influent, were not detected in the effluent.

Also *Salmonella*, found in CW influent, with a mean value of 3 MPN/100 mL, was never detected in CW effluent, as required by law to reuse wastewater in agriculture.

The results of tracer tests highlighted, as in other studies, a residence time in the wetland significantly lower (about 0.5 times) than the nominal one currently used for design purposes. Also a large amount of flow dispersion in the wetland can be inferred on the basis of the detected residence time distributions [17]. These results can have relevant implications on wetland design criteria and removal efficiency modelling [18].

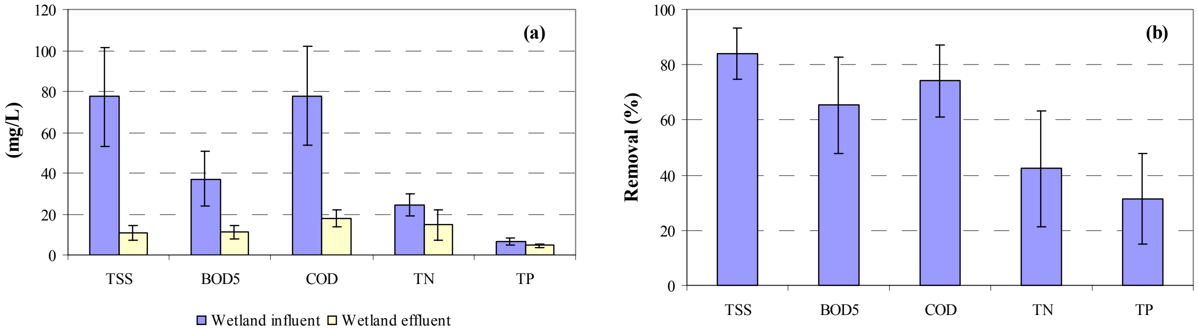

Fig. 2. TSS, BOD_5, COD, TN, TP: (a) average values (±SD) and (b) removal efficiencies (±SD).

6. Conclusions

Four feasible technological alternatives (i.e., membrane filtration, simplified treatments, storage reservoirs, constructed wetlands) have been tested in field to assess their effectiveness for producing reclaimed wastewater suitable to be reused in agriculture. For each alternative, the main results recorded after about half of a four years project named AQUATEC, have been the following:

Membrane filtration. The microbial quality of treated effluents was higher than that of the benchmark (i.e., local well-water conventionally used for irrigation). Total coliforms were the only microorganisms found on the irrigated crops (tomato, fennel and lettuce). Referring to soil contamination, particularly during summer periods, the irrigation with membrane filtered effluents caused an increase of Na^+, Ca^{2+}, EC, SAR and ESP.

Simplified treatments. Effluents obtained by skipping biological processes for saving the agronomic potential of organic matter and nutrients occurring in urban wastewater, once tertiary treated, had a microbiological quality not significantly worse than that of conventional secondary effluents also tertiary treated. Compared to olive trees grown in rainfed conditions, irrigation with the "simply" treated effluents caused a yield increase of 50% improving fruit characteristics very important for marketing table-olives such as weight and flesh to pit ratio.

Storage reservoirs. After appropriate storage periods: TSS, BOD_5, COD and nutrients concentrations achieved the in force Italian limits for WW agricultural reuse; Pathogens indicators showed an average decrease of 2–3 log units; Salmonella, from a mean value of 28.2 MPN/100 mL decreased up to 4 MPN/100 mL; Helminth eggs, detected in inflow wastewater with an average value of 4.1/L, were not detected in outflow effluents

Constructed wetlands. Recorded average efficiencies for TSS, BOD5, COD, TN and TP removal resulted 85%, 65%, 75%, 42% and 32% respectively. Microorganisms indicators showed an average decrease around 2 log units; Helminth eggs, detected with an average value of 12/L, were not detected in the effluent; Salmonella, found in influent with a mean value of 3 MPN/100 mL, was never detected in effluent.

Before the end of the project (March 2006), a comparative evaluation of the investigated options in terms of technological reliability, costs, environmental impact, potential stakeholders interest, mass media perception and the degree of political will to implement the proposed solutions will be carried out.

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