Constructed Wetland as a Low Cost and Sustainable Solution for Wastewater Treatment Adapted to Rural Settlements: The Chorfech Wastewater Treatment Pilot Plant

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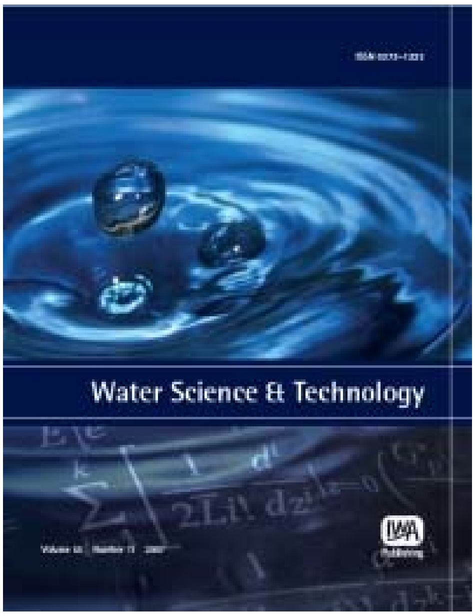
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Constructed wetland as a low cost and sustainable solution for wastewater treatment adapted to rural settlements: the Chorfech wastewater treatment pilot plant

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ABSTRACT

The paper presents the detailed design and some preliminary results obtained from a study regarding a wastewater treatment pilot plant (WWTPP), serving as a multistage constructed wetland (CW) located at the rural settlement of 'Chorfech 24' (Tunisia). The WWTPP implemented at Chorfech 24 is mainly designed as a demonstration of sustainable water management solutions (low-cost wastewater treatment), in order to prove the efficiency of these solutions working under real Tunisian conditions and ultimately allow the further spreading of the demonstrated techniques. The pilot activity also aims to help gain experience with the implemented techniques and to improve them when necessary to be recommended for wide application in rural settlements in Tunisia and similar situations worldwide. The selected WWTPP at Chorfech 24 (rural settlement of 50 houses counting 350 inhabitants) consists of one Imhoff tank for pre-treatment, and three stages in series: as first stage a horizontal subsurface flow CW system, as second stage a subsurface vertical flow CW system, and a third horizontal flow CW. The sludge of the Imhoff tank is treated in a sludge composting bed. The performances of the different components as well as the whole treatment system were presented based on 3 months monitoring. The results shown in this paper are related to carbon, nitrogen and phosphorus removal as well as to reduction of micro-organisms. The mean overall removal rates of the Chorfech WWTPP during the monitored period have been, respectively, equal to 97% for total suspended solids and biochemical oxygen demand (BOD_5), 95% for chemical oxygen demand, 71% for total nitrogen and 82% for $P\text{-}PO_4$. The removal of *E. coli* by the whole system is 2.5 log units.

Key words | constructed wetland, low cost, rural settlement, sustainability, wastewater treatment

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INTRODUCTION

The Tunisian cities, with a population superior to 5,000 inhabitants are already or presently being equipped with wastewater treatment plants. Given the lack of sanitation in rural and small villages, the government is now paying particular attention to develop the sanitation in these areas representing a serious risk for the environment and human health. About 40% of the Tunisian population lives in rural areas in small villages or isolated habitat with an access to drinking water for almost all of them. 83% of this population still has very poor sanitation services and their wastewater is discharged directly without treatment. Only 3.2% of the rural population has a sewerage system, albeit without treatment; and 13.5% has a sanitary pit or septic tank (Sellami *et al.* 2007). For all these reasons a few experiences were conducted in Tunisia by researchers to identify the best wastewater treatment technology for small settlements (Kouki *et al.* 2009; Lahjouj *et al.* 2007; Sellami *et al.* 2007).

The technologies must be as robust, simple and low-tech as possible, and need to guarantee a very high water quality at the discharge point as requested by the stringent Tunisian regulation for release of treated wastewater into water bodies, which seems to be unavoidable at least during certain periods of the year. Constructed wetland (CW)

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systems can play this role and have proven to be a good technology, ensuring appropriate performances even with a low technical profile in the wastewater management for villages and small communities (Conte *et al*. 2001; Masi 2007; Masi & Martinuzzi 2007; Masi *et al*. 2010; Molle *et al*. 2006).

The purpose of this study is to show the performances of the WWTPP of Chorfech 24 (small rural village) using a CW combining horizontal and vertical flow for wastewater treatment. The design of the plant has been developed in close consultation with the community, local and national authorities by a team of experts within the framework of a project for sustainable water management. While there were cheaper solutions with similar performances, the present one has been selected from a range of propositions as the most appropriate design regarding national regulations, not least concerning wastewater reuse in agriculture. Experiments were performed in order to evaluate the preliminary performance of each part of the plant.

MATERIALS AND METHODS

WWTPP

Chorfech 24 is a rural settlement where 350 inhabitants live in around 50 houses. It is situated about 24 km northwest of Tunis (36 °57′11,33″ N, 10 °03′59,66″ E). The average rainfall is about 470 mm/year. The average temperatures of the coldest month (December) and the warmest month (August) of the year are 13.7 and 28.3 °C, respectively. Before the construction of the wastewater treatment pilot plant, the raw wastewater collected in the conventional sewage network linked to a septic tank, was discharged directly into a drainage channel. The daily flow was monitored during one week.

Pre-treatment: Imhoff tank

To reduce the amount of solids in the inflow and to minimize the risk of clogging of the CWs (filter bed), a pre-treatment by an Imhoff tank with an effective volume of 20 m^3, is applied before the CWs system. The sludge settling in the digester chamber has to be removed from time to time (twice per year). It is transferred to a sludge treatment CW. Its removal becomes necessary when the sludge volume reaches a height of 2/3 of the useable height in the settling chamber. Finally the ‘sludge treatment CW’ for treating and composting the primary sludge accumulated in the Imhoff tank allows the reuse of the nutrients as high quality fertilizer of crops.

CW system

Figure 1 shows the general layout of the WWTPP of Chorfech. The wastewater, after a primary treatment in the Imhoff tank, flows into a first submerged horizontal flow CW as a secondary treatment (1st stage), then into a vertical

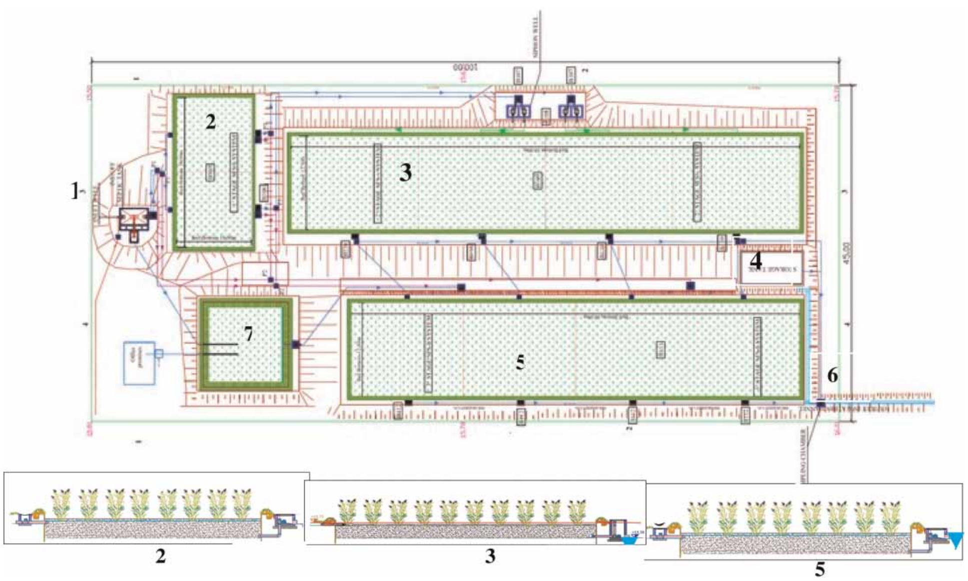

Figure 1 | General layout of WWTPP, Chorfech 24. 1: Imhoff tank; 2: 1st stage HF-CW; 3: 2nd stage VF-CW; 4: Reservoir of treated wastewater; 5: 3rd stage HF-CW; 6: Treated wastewater outlet to the drainage channel; 7: Sludge composting bed CW.

flow CW (2nd stage) and finally into a second horizontal flow CW (3rd stage).

Depending on the objectives of treatment, the reuse or the discharge into the channel, it is possible to skip the 3rd stage and to stop treatment at the level of the 2nd stage for conservation of nutrients (nitrogen and phosphorus) for irrigation. In this case, the treated wastewater is stored in a reservoir for reuse. There is no limitation for the nitrogen in the case of reuse for irrigation (Tunisian Standards for Wastewater Reuse NT 106.03). The nutrients will be conserved in the effluent for agriculture valorization (reuse of nutrients). If there is no reuse, the outlet quality for treated wastewater to be discharged into the aquatic environment (drainage channel) has to be satisfactory (Tunisian Standards for Wastewater Discharge NT 106.02). In this case the use of the 3rd stage is necessary for denitrification and nitrogen removal.

The bottom and the walls of the basins are correctly waterproofed using a sandwich of a membrane (high density polyethylene membrane, HDPE 1.5 mm) between two layers of geo-textile. The technical specification and characteristics of the WWTPP are presented in Table 1. All the CWs were planted with reed, *Phragmites australis* (4 plants per m^2).

Monitoring and measurements of the water quality parameters

The water quality parameters have been monitored during normal operation between May and July 2010. The influent and effluent water samples of WWTPP were taken periodically. Physical chemical and microbiological analyses were performed on the same day according to the standard methods (APHA/AWWA/WEF 2005). pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), phosphate (PO_4^{3-}-P), total nitrogen (TN) and *E. coli* were monitored.

RESULTS

Table 2 shows the water quality at every part of the WWTP and the removal rate linked to physical, chemical and

Table 1 | Characteristics of the WWTPP of Chorfech 24

	Unit	1st stage horizontal flow HF-CW	2nd stage vertical flow VF-CW	3rd stage horizontal flow HF-CW	Sludge treatment CW
Total bottom surface	[m^2]	200	850	750	100
Bottom length	[m]	10	12.5	12.5	10
Bottom width	[m]	20	68	60	10
Retention time	[d]	3	0.5	10	
Average medium height	[m]	0.8		0.8	
Inlet medium height	[m]	0.75		0.74	
Outlet medium height	[m]	0.85		0.86	
Bank slope	[°]	90	90	90	45
Medium porosity (gravel 5–10 mm), clean medium		0.35		0.35	
Average water level	[m]	0.7		0.7	
Bottom slope	%	1	0.5	1	0
Filling material height (VF-CW)	[m]		0.95		
composed of (from bottom to top):					
Gravel 40–70 mm	[m]		0.15		
Gravel 5–10 mm	[m]		0.1		
Coarse sand 0.2–1 mm	[m]		0.5		
Gravel 5–10 mm	[m]		0.2		
Drainage layer height (gravel 20/40 mm)	[m]				0.2
Filter layer height (gravel 3/8 mm)	[m]				0.3
Top filter layer height (coarse sand 0.3/0.5 mm)	[m]				0.05

bacteriological parameters. The interval variation of the flow rate ranged between 14.14 and 21.60 m^3/day and the average value is 17 m^3/day corresponding to 48 L/(c.d). This wastewater flow includes all discharges to sewer from farm activities. The monitored parameters show high concentrations in the raw wastewater of Chorfech village compared to standard municipal wastewater. This is linked to characteristics of the rural area and their activities (low water consumption).

Organic matter and manure were evacuated through the sewerage network which partly explains the high values of TSS, COD, BOD and nitrogen in the influent. These results regarding the characteristics of wastewater were confirmed by Sellami *et al.* (2007) on wastewater of the rural village of Boujrida in Tunisia. In the Imhoff tank, wastewater receives initial treatment. Anaerobic bacteria begin to break down organic matter, and solids settle to form a sludge layer in the bottom compartment of the Imhoff tank, while grease and oils float to form a scum layer. The clarified middle layer (effluent) travels to the CW system.

The mean overall removal rates performed by the WWTPP of Chorfech 24 during the monitored period were, respectively, 97% for TSS and BOD, 95% for COD, 71% for TN, and 82% for phosphorus (P-PO_4). Compared to the literature, these rates remain high, independently of the quality of the final effluent. In Table 2 we can notice that the main part of COD reduction takes place in the 1st and 2nd stages (horizontal flow constructed wetland (HF-CW) and vertical flow constructed wetland (VF-CW)). The most important part of TSS removal is achieved by the Imhoff tank and the 1st stage (HF-CW). The concentration of TSS at the entrance of the 1st HF-CW remains high and could clog the bed in the long term. The first stage of treatment is the hydraulic limiting factor due to the high deposit layer and biomass development. The role of reeds and batch frequencies on infiltration capacity was pointed out. It is crucial to predict the maximum hydraulic load which is acceptable without endangering the filter longevity (Molle *et al.* 2006). Management and optimization of TSS removal before the 1st stage is necessary to reduce clogging phenomena on the CW system. A weak decreasing of the quality of effluent, especially for BOD and phosphorus, has been noticed after 2nd HF-CW (increase of parameters). This phenomena is linked to the release of organic debris by plants which can influence the turbidity and the quality of effluent.

Organic loading rates

The COD load applied to the first stage (1st HF-CW) is high and reaches 245 g (m^2 day). The calculated organic loads (BOD_5), applied to the CWs system at Chorfech, ranged from 10.2 to 246.5 from 0.57 to 13.6 and from 0.4 to 0.7 g BOD_5/(m^2/day) for the 1st HF-CW (alone), the VF-CW and the 2nd HF-CW, respectively. The load applied to the overall

Table 2 | Quality of water and reduction rates achieved by the consecutive stages of the WWTPP of Chorfech

						Removal (%)		Standards	
	N[a]	Min.	Average	Max.	Standard deviation	Each stage	All system	NT.106.02[(a)]	NT.106.03[(b)]
Flow (m^3/day)	6	14.41	17.00	21.60	2.69				
pH									
Raw wastewater	3	5.51	6.03	6.41	0.46				
Imhoff tank	6	5.71	5.95	6.23	0.24				
1st HF-CW	5	6.67	6.83	7.15	0.19				
VF-CW	4	7.33	7.62	7.88	0.29			6.5–8.5	6.5–8.5
2nd HF-CW	8	7.08	7.58	8.50	0.50				
TSS (mg/L)									
Raw wastewater	5	1015	1851	3016	750				
Imhoff tank	8	156	679	1580	523	63.3			
1st HF-CW	8	75	174	285	91	74.4			
VF-CW	7	20	86	356	121	50.6		30	30[(c)]
2nd HF-CW	10	19	53	130	40	38.4	97.1		

(*continued*)

Table 2 | continued

	N[a]	Min.	Average	Max.	Standard deviation	Removal (%) Each stage	All system	Standards NT.106.02[(a)]	NT.106.03[(b)]
COD (mg O_2/L)									
Raw wastewater	5	2300	3072	5040	1112				
Imhoff tank	8	2150	2876	5052	941	6.4			
1st HF-CW	8	384	1647	5204	1586	42.7			
VF-CW	6	102	234	410	123	85.8		90	90[(c)]
2nd HF-CW	10	124	167	214	30	28.6	94.6		
BOD (mg O_2/L)									
Raw wastewater	3	1000	1620	2300	652				
Imhoff tank	4	120	1350	2900	1392	16.7			
1st HF-CW	4	25	197	600	271	85.4			
VF-CW	3	20	26	35	8	86.8		30	30[(c)]
2nd HF-CW	4	40	45	50	6	(–)73.1[b]	97.2		
N total (mg N/L)									
Raw wastewater	3	50	125	256	113				
Imhoff tank	5	4	70	264	110	44.0			
1st HF-CW	5	9	65	128	51	7.1		NO_3 : 50	No
VF-CW	3	28	69	98	37	(–)6.2[b]		NO_2 : 0.5	Limitation
2nd HF-CW	7	13	36	90	30	47.8	71.2	Org. + NH_4: 1	
P-PO4 (mg P/L)									
Raw wastewater	5	30.23	33.35	35.12	2.15				
Imhoff tank	5	24.60	29.51	34.09	3.40	11.51			
1st HF-CW	5	16.50	18.28	21.80	2.07	38.08			No
VF-CW	6	0.50	4.22	14.57	5.65	76.91		0.1	Limitation
2nd HF-CW	7	0.80	5.95	11.11	4.55	(–)40.99[b]	82.2		
E. Coli (log FU/100 mL)						Log removal			
Raw wastewater	5	6.45	6.67	7.08	6.64				
Imhoff tank	8	6.20	5.73	7.08	6.52	0.94		FC: 3.30/100 mL	
1st HF-CW	8	5.32	5.38	7.48	7.04	0.35		FS: 3.00/100 mL	
VF-CW	7	4	4.66	5.26	4.76	0.72		N < 1/l[(d)]	N < 1/l[(d)]
2nd HF-CW	9	2.48	4.23	5.18	4.74	0.43	2.45		

[a]N: number of samples; [b](-): negative removal, i.e., increase; (a) Tunisian standards into receiving waters; (b) Tunisian standards for reuse; (c): derogation can be obtained by authority; (d): 1 Nematode per liter.

system ranged between 1.13 and 27, with an average equal to 12.7 g $BOD_5/(m^2/day)$. According to the average the applied load still might be compared to the load rates cited in the literature. In a comparative study conducted by Puigagut *et al.* (2007) on CWs for small communities in Spain a variability in the applied organic loads has been shown. The VF-CW systems present the highest rates of all the types of systems analyzed with a range of 22.8–29.8 g BOD_5 m^2/day. These are followed by the HF-CW and the combined systems (HF-CW in combination with other processes).

Nitrogen and phosphorus compounds

The reduction rates of macronutrients or rather the concentration at the outlet of the system is insufficient compared to the Tunisian norms authorizing the discharge of treated wastewater into receiving waters. Biogeochemical cycling of nitrogen in treatment wetlands is complex involving inter conversions between different N species and transfers between storage compartments. Kadlec *et al*. (2005) investigated nitrogen processing in treatment wetlands by use of the stable isotope ^{15}N introduced as ammonium. The results demonstrated that the details of nitrogen in CWs include strong interactions between water, sediment and biofilm solids, and plant storage of nitrogen. Ammonium ^{15}N is rapidly sorbed into wetland solids in the inlet region of wetlands and subsequently gradually released for a major part back to the water.

According to Puigagut *et al*. (2007), the systems were not very efficient for nitrogen and phosphorus removal. They found a total average removal efficiency around 40–50%. In general, the analysis of CWs in Spain shows that although they operate with higher loads than in other European countries, their performance in terms of organic matter and nutrient removal remains within the usual range described in several studies.

The abiotic adsorption of phosphorus to the substrate has been reported as the major P-removal mechanism in CW by several researchers. Various physical–chemical properties including pH, redox potential, dissolved ions, calcium content, amorphous and poorly crystalline Al and Fe-oxides content of these substrates influence the P-sorption mechanisms onto their surfaces (several authors cited by Korcuzus *et al*. (2007)).

Bacteria removal

The removal of the *E. coli* by the whole system is about 2.5 log units (Table 2). This performance is low and less than the values cited in the literature. Keffala & Ghrabi (2005) studied the comparison between two series of CWs (planted by *Phragmites australis* and unplanted). The result shows that there is no significant difference. The removal of bacteria is about four logarithmic units.

Rivera *et al*. (1995) working on gravel media obtained the same results, with no significant difference between planted and unplanted system in bacteria elimination compared to bacteria elimination in the soil media. The elimination of bacteria through the two series is important with a removal rate of about 1 log unit for each bed. Bacteria removals implicate physical (mechanical filtration by roots) and chemical (biocides secretion) mechanisms. The latter, described by Batchelor *et al*. (1990), are directly related to the presence of plants. It has been noticed that biological processes such as antibioses, nematode predation, lytic bacteria attack and natural death are also implicated in the removal of bacteria (Vincent *et al*. 1994).

CONCLUSIONS

The preliminary results show the feasibility of the system and the WWTPP appears to be a powerful combination coupling the horizontal and vertical submerged flow CW after an Imhoff tank. Regarding the high removal rates obtained, the final quality of treated wastewater is still insufficient compared to the national norms authorizing the discharge of treated wastewater into receiving water or reuse. Those results have to be linked to the high pollution load of the influent observed in this rural settlement. It is expected that after plants (*Phragmites*) grow to a good cover of all the CW surface, the quality of treated effluent will improve to reach the Tunisian standards both into receiving waters and for reuse.

The main objective of the WWTP is to set up a robust technology adapted to rural areas but also to solve the problems related to the uncontrolled wastewater discharged into nature without treatment.

This WWTPP will provide the solution for improvement of sanitation at the village of Chorfech. The system could be considered as a demonstration action and a best practice example for rural settlements in Tunisia with low operation costs. It is also intended to increase the available water for agricultural purposes. The pilot activity will also build and reinforce the capacity building and experience with the techniques implemented under real conditions and improve them when necessary to be recommended for wide application in rural settlements in Tunisia, which are characterized by limited financial resources for water supply and sanitation services.

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