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Performance of a vertical flow constructed wetland treating domestic wastewater for a small community in rural Tunisia

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ABSTRACT

Several least-cost wastewater treatment technologies and decentralized systems are being tested to be implemented in Tunisian rural areas. This study demonstrates the system performances of a pilot-scale subsurface vertical flow constructed wetland designed to enhance living sanitation conditions for several dwellings located in the rural area of Boujrida, north-east of Tunisia. Constructed in 2004, the plant consists of a septic tank followed by a vertical constructed wetland planted with common reed *Phragmites Australis*. The plant was monitored from June 2004 to April 2006. The analysis is based on the following parameters: TSS, COD, BOD_5, TKN, NH_4^+, NO_3^-, PO_4^{3-} and sulphates. Other in situ parameters are considered as well. In general, the treatment performances of the constructed plant are lower than those expected and the effluent did not meet the Tunisian standard of discharge. However, the system showed better removal efficiency after a period of rest. The overall results showed high concentrations in raw wastewater, good performances in the septic tank and variable removal rates in the constructed wetland. Conclusions are drawn from the experimental results and from literature.

Keywords: Wastewater treatment; Vertical flow constructed wetland; Treatment efficiency; Rest period

1. Introduction

Many small communities located in rural Tunisia lack adequate domestic wastewater treatment facilities. Wastewater collection and treatment are problematic in these areas due to the habitat typology, the cost effectiveness of wastewater handling in small communities and other institutional issues related to the maintenance of these small structures. In addition, wastewater treatment by traditional on-site systems such as septic tank and/or soil absorption design, are sometimes not feasible because of soil type, adverse topography and/or inadequate availability of land.

Approximately 40% of the Tunisian population resides in rural areas characterized by a relatively dispersed habitat with an access to drinking water for almost the totality of the rural population. On the other hand, it is estimated that 83% of the population in rural Tunisian medium evacuate their effluents in the natural next to 3.2% of the residences connected to a collective sewage network and 13.5% having personal pits or septic tanks.

At present, six small-size wastewater treatment plants were implemented in rural localities using different designs including sand and/or gravel infiltration beds,

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activated sludge system, and constructed wetland systems such as vertical-flow and hybrid systems in order to evaluate their treatment efficiencies.

A Tunisian federal research project was initiated under the request of the National Sanitation Office to assess the performances of the existing plants in rural areas and to propose solutions taking into account local climate and social settings. It is within this framework that the plant of Boujrida village based on a sub-surface vertical flow constructed wetland with treatment capacity of 72 person-equivalents is one of the selected plants for performance assessment. In fact, this technology is usually considered as a wastewater treatment solution for small settlements or individual houses in suburban areas of large cities, as well as for rural settlements [1]. When constructed wetlands are properly designed and effectively operated, they have many advantages from both economical and ecological engineering perspectives [2].

The main purpose of this study was to examine the performance of each component of the treatment plant, to characterize the influent and effluent and to analyse the system operation and layout.

2. Materials and methods

2.1. Description of wastewater treatment plant

The wastewater treatment plant under study is located in a little village called Boujrida, in the north-eastern part of Tunisia, characterized by a semi-arid climate. The average annual temperature varies between 12°C in the winter and 27°C in the summer and the annual rainfall is around 350 mm/y.

The wastewater treatment plant was built in June 2004 by the Tunisian national sanitation office as a pilot plant with twofold: enhancing the living and sanitation conditions of the areas near the coastal zone and testing the low cost technology of constructed wetlands for the Tunisian local conditions.

The plant collects domestic wastewater for 72 person-equivalents. It consists of two main structures placed in series: (a) a sedimentation tank and (b) a subsurface vertical flow constructed wetland. The septic tank has a total volume of 14 m^3 divided into 3 chambers with the first one representing 50% of the total volume and the remaining volume is evenly distributed between the second and third chamber.

The constructed wetland consists of a subsurface vertical flow measuring 9 m wide, 10 m length and 1.2 m deep. The bed is planted with the common reed (*Phragmites Australis)* The filter bed is filled from top to bottom with gravel (30 cm of 15–40 mm) followed with a 70 cm sand filter and a 20 cm of 15–35 mm gravel layer. Septic tank effluent was diverted from the septic tank to the wetland using a submersible pump via 12 perforated PVC pipes placed in the top of the bed.

2.2. Water quality monitoring study and analysis methods

Field measurement following sample collection were taken roughly bimonthly throughout eight months from June 2005 to April 2006 with the exception of 26 d, from July to August 2005, due to a break in the pump. This period is considered as a rest period for the filter bed.

Influent and effluent samples were collected at 3 locations: influent entering the septic tank, effluent discharged from the septic tank (STE) and discharged from the vertical flow constructed wetland (VFCWE). Six hours composite samples were taken in high-density polyethylene bottles and carried to the laboratory in cold boxes within 1 h.

Dissolved oxygen and pH were measured in situ with a HI 9146 model portable dissolved oxygen meter and a Metrohm 704 model pH meter. A WTW conductivity model was used to measure water sample conductivity and temperature in situ. Analyses of total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), total Kjeldahl nitrogen (TKN-N), total nitrogen (TN-N), ammonium nitrogen (NH_4^+-N), nitrates nitrogen (NO_3^--N) and orthophosphates phosphorus (PO_4^{3-}-P) were performed according to the Standard Methods of APHA [3] to evaluate the removal efficiencies of the current plant.

3. Results and discussion

3.1. Characteristics of the raw wastewater

The raw wastewater of Boujrida show high concentrations for most elements. In fact, the comparison of the measured values to the reported values of raw wastewater of some European countries given in Table 1, confirm these observations.

The only exception is noted for TP-P where the reported values are 3–12 times higher depending on the country. Further, the analyses present high variability as expressed by the standard deviation and the large variation between the max and min pollutants concentrations values (Table 1). Such variability of the influent pollutants is expected because of its total dependence on various householder activities. TSS, BOD_5 and COD varied considerably with an average value of 1037, 605 and 1097 mg l^{-1} respectively. Total nitrogen (TN-N) in the influent ranged between 72 and 147 mg l^{-1} with an average value of 125 mg l^{-1}, while Kjeldahl nitrogen (TKN-N) represents between 87% and 92% of TN-N. At the same time, Ammonia (NH_4^+-N) is representing about 65% of TKN-N with an average value of 74 mg l^{-1}, while nitrates (NO_3^--N) are present in traces with an average concentration value of 5.5 mg l^{-1}.

3.2. Characteristics of the septic tank effluent (STE)

The septic tank of the Boujrida wastewater treatment

Table 1
Average concentrations of the Boujrida raw wastewater compared to these of some European countries (mg l^{-1})

	This study	Max–min	SD*	France [4]	Germany [4]	Danmark and UK [5]	Czech Rep. [5]	Typical values [6]
TSS	1037	2150–790	384	225	—	98.6	64.8	100
COD	1097	1656–879	272	495	430	264	211	250
BOD_5	605	837–451	124	215	248	97	87.2	220
NH_4^+-N	74.0	86 –55	11	25.00	80.50	21.00	28.10	25.00
TKN-N	115	144–66	13	—	—	—	—	—
NO_3^--N	5.50	7.4–1.25	1.82	2.85	1.90	—	—	0.00
TN-N	125	147–72	13	46.00	115	36.6	46.4	40.00
TP	1.25	2.1–0.6	0.50	8.50	15.90	8.60	6.57	8.00

plant reduces BOD_5, COD and TSS almost by 50% averaging to 320 mg l^{-1}, 595 mg l^{-1} and 390 mg l^{-1} respectively (Table 2). Similar results for TSS removal in septic tank in Turkey were reported by Korkuzus et al. [7], but lower removal rate for BOD_5 and COD (15%) was reported by the same author. Moreover, septic tanks may provide removal rates greater than 65% for BOD_5, and greater than 70% for TSS [8].

Even though the septic tank performs well, the STE applied to the CW still contains very high concentrations of BOD_5, COD and TSS as well as very high concentration of NH_4^+-N (77 mg l^{-1}) which is the predominant N form in the STE representing approximately 62% of the total Kjeldahl nitrogen (TKN-N). Further, TKN-N, NH_4^+-N and nitrate nitrogen (NO_3^--N) concentrations in STE did not change significantly compared to theirs initial concentrations in the raw wastewater (influent). This is due to the prevailing anaerobic conditions in the septic tank.

The main mechanisms for COD, BOD_5 and TSS removal in septic tank are sedimentation and microbial degradation. Septic tank removal efficiency is conditioned also by the raw wastewater quality and by the wastewater arrival pattern. On one hand, the studied influent is characterized by high organic and nitrogen loads, and on the other hand, it is discharged directly into the septic tank without going through an inlet structure which caused turbulence due to peak flows and disturbed the sedimentation process.

The PO_4^{3-}-P concentration values of the influent (1.25 mg l^{-1}) increased after the primary treatment in the septic tank to 3.6 mg l^{-1} (Table 2). This increase is explained by the conversion of long-chained polyphosphates to short-chained phosphates during the sedimentation phase.

Table 2
Average characteristic of the septic tank effluent (STE)

Parameters	Average influent (mg l^{-1})	Average STE (mg l^{-1})	Average removal (%)
TSS	1037	390	62.39
COD	1097	595	45.76
BOD_5	605	320	47.10
NH_4^+-N	74	77	—
TKN-N	115	125	—
NO_3^--N	5.50	6.50	—
TN-N	125	140	—
TP	1.25	3.6	—

3.3. Characteristics of the constructed wetland effluent (CWE)

3.3.1, Organics removal (BOD_5, COD and TSS) in the CW

Due to low cost of construction and operation, CWs have generally been regarded as an effective method of removing nutrients from domestic wastewater, especially sub-surface flow CWs, which have gained increased attention for on-site treatment of domestic wastewater [9]. The potential of SVFCW for organics removal in different countries and under different conditions has been demonstrated. In Italy, a general performances of reed beds treatment systems, planted with Phragmites australis, were respectively 84% for TSS, 94% for COD and BOD_5, 86% for NH_4^+, 60% for total nitrogen, and 94% for total phosphorus [10]. In Morocco, organic removal of 48–62% and TSS of 58–67% were obtained in reed beds planted with *Phragmites australis* [11]. Removal efficiency of VFCW in Spain, operating under organic load from 22.8 to 29.8 gBOD_5 m^{-2} d^{-1}, ranged from 80 to 95% for BOD_5 and COD [12]. Better performances in organics removal were obtained in France where COD and TSS removal in VFCW reached 91% and 95% respectively [13].

In this study, the relationship between average BOD_5, COD and TSS loads applied to the VFCW and their corresponding effluent concentrations (CWE), shown in Fig. 1, demonstrates that VFCW is operating under high variable organic load with a range of 3.5–21 gBOD m^{-2} d^{-1}, 7–40 g COD $m^{-2}d^{-1}$ and 6–23 g TSS m^{-2} d^{-1}.

There is a general trend between increased BOD_5 and COD loadings and increased effluents concentrations (Fig. 1). Even though, the system is receiving the lower BOD_5 and COD loadings rates (0–7 g BOD_5 m^{-2} d^{-1} and 0–10 g COD m^{-2} d^{-1} respectively), CWE remained above 30 mg l^{-1} for BOD_5 and above 100 mg l^{-1} for COD. Fig. 1 reveals also an opposite general behaviour of the system regarding TSS loading rate and TSS CWE comparing to those of BOD_5 and COD. It seems that increasing TSS loading rate decreases TSS outlet concentrations. When TSS load exceeds 8 g m^{-2} d^{-1}, CWE seems to be steady at an average value of 130 mg l^{-1}. This is due to the solids accumulation near the surface of the VFCW that decreased the hydraulic conductivity and increased the filtration strength of the filter media.

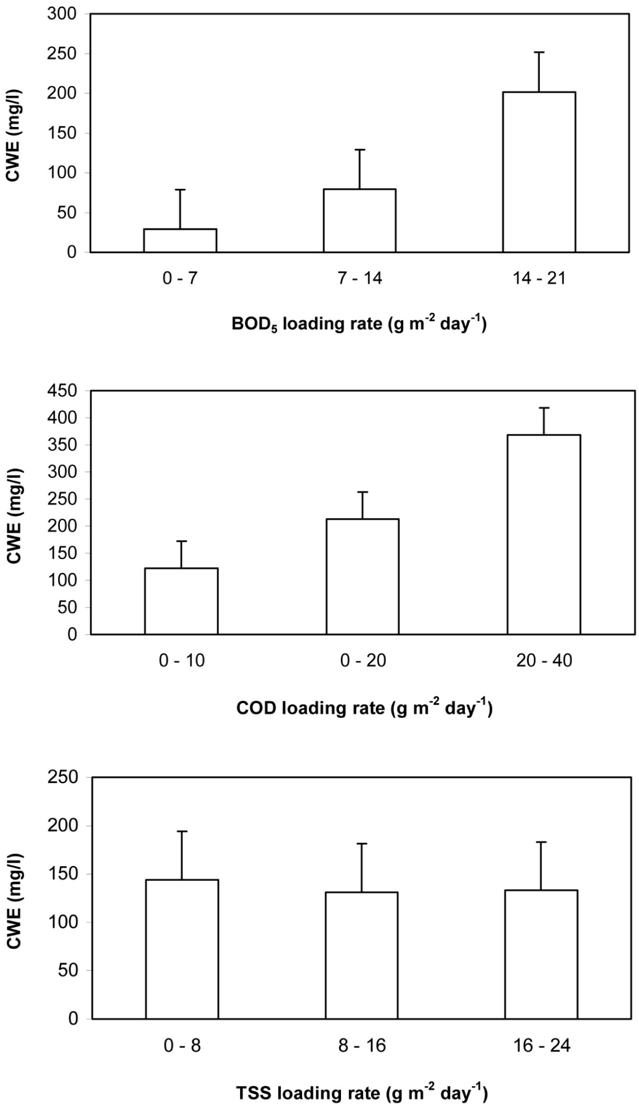

Fig. 1. Average outlet organics concentrations (CWE) as a function of organics loads applied to the constructed wetlands.

Despite the high variability of the organic load applied to the CW, significant improvement in reducing BOD_5, COD and TSS was observed after the rest period reaching respectively 97%, 92%, and 91% instead of 86%, 80% and 58% recorded before the break (Fig. 2). Effluent concentration of BOD_5, COD and TSS decreased and ranged from 17.8–46 mgl^{-1}, 72–235 mgl^{-1} and 68–105 mgl^{-1} respectively. This increase is an indicator for a better oxygenation and advanced oxidation state of organic matter due to the disclogging of the filter bed. BOD_5 and COD outlet concentrations values (17.8 and 72 mgl^{-1} respectively) recorded after the rest period, were lower than the Tunisian required discharge standard (BOD_5 30 mgl^{-1} and COD 90 mg l^{-1}) only when respective loadings rates were about 4.58 g BOD_5 m^{-2} d^{-1} and 19 g COD m^{-2} d^{-1}. However, the outlet TSS concentrations were above the standard discharge value (30 mgl^{-1}) even though the lowest TSS loading rate (6 g m^{-2} d^{-1}) was applied. Fig. 2 reveals also that the system was not able to fulfil steady removals rates. After 7 weeks since feeding operation of the CW was restarted, BOD_5 and COD removal efficiency declined respectively to 60% and 50% while TSS removal remained steady until the end of the monitoring period at a level of 88%. In fact, trapped suspended solids reinforce the filtration strength of the media and enhance the effluent quality but at the same time, decrease the oxygen transfer from the atmosphere into the wetland matrix and reduce the organic matter removal efficiency. In addition, the high loadings rates of BOD and COD, applied to the filter, might lead to excess sludge production of the involved micro-organisms and further clogging [14].

3.3.2. Nitrogen removal in the CW

In VFCW the removal mechanisms for nitrogen include utilization, ammonification, nitrification, plant uptake and matrix adsorption [15]. Several studies showed that microbial nitrification is the major N removal mechanism [4]. Thus, our discussion will focus on the nitrification phase by monitoring NH_4^+-N and TKN normally used to determine N removal rates.

In this study, there is a significant difference in nitrogen removal (TKN-N and NH_4^+-N) before and after the rest period of the filter (Fig. 3). Before the rest period, nitrification was inactive in the system confirmed by very low concentrations of NO_3^--N (6 mg l^{-1}) and high concentrations of TKN-N (135 mg l^{-1}) and NH_4^+-N (85 mgl^{-1}). Despite the suitable conditions (pH of 7.4 and temperature of 24°C), the lack of nitrification is attributed to the clogging and to the prevailing of reductive conditions of the filter media. Many studies [16,17], reported that oxygen available in wetland matrix is primarily used by microbes to remove organic matter and consequently little amount of O_2 remains for nitrification indicating that significant nitrification takes place only when BOD_5 is below 200 mg l^{-1} which is not the case in our study.

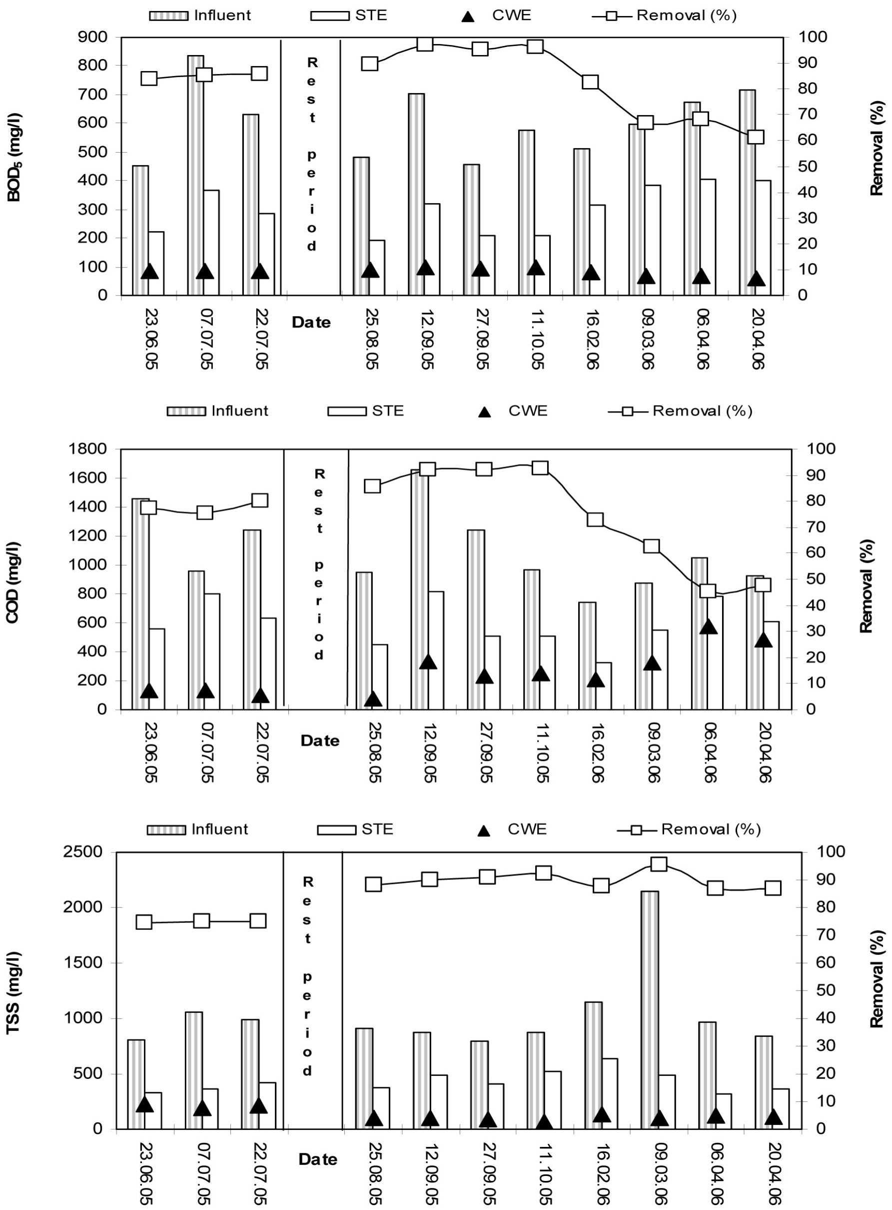

Fig. 2. Performance removal of BOD_5, COD and TSS in the wastewater treatment plant. STE is septic tank discharge and CWE is constructed wetland discharge.

After the rest period, the TKN–N and NH_4^+-N removal increased and reached a maximum rate of 36% and 38% respectively while NO_3^--N effluent concentration increased to 14.7 mg l^{-1}.

However, this nitrification was limited as shown by the rapid decline of NH_4^+-N removal (Fig. 3) and by the low NO_3^--N concentrations values measured in the CWE. Nitrogen removal in the current system is poor compared to others vertical constructed wetlands systems in others countries. The limited nitrification capacity of the studied VFCW was attributed to enhanced oxygen transfer from the atmosphere to the filter media. However, this available oxygen might have been used for organics removal instead of ammonia oxidation. Moreover, the high concentrations of nitrogen in the STE applied to the VFCW can inhibit the nitrification process.

Fig. 4 shows interactions between ammonia removal, nitrates and sulphates concentrations in the CWE recorded after the rest period. Significant correlations exist between sulphate concentration in the CWE and ammonia removal (R^2 = 0.78), and between sulphate and nitrates (R^2 = 0.91) as well as nitrates and ammonia removal (R^2 = 0.89). The increase in ammonia removal, after the rest period, is accompanied by an increase for both nitrates

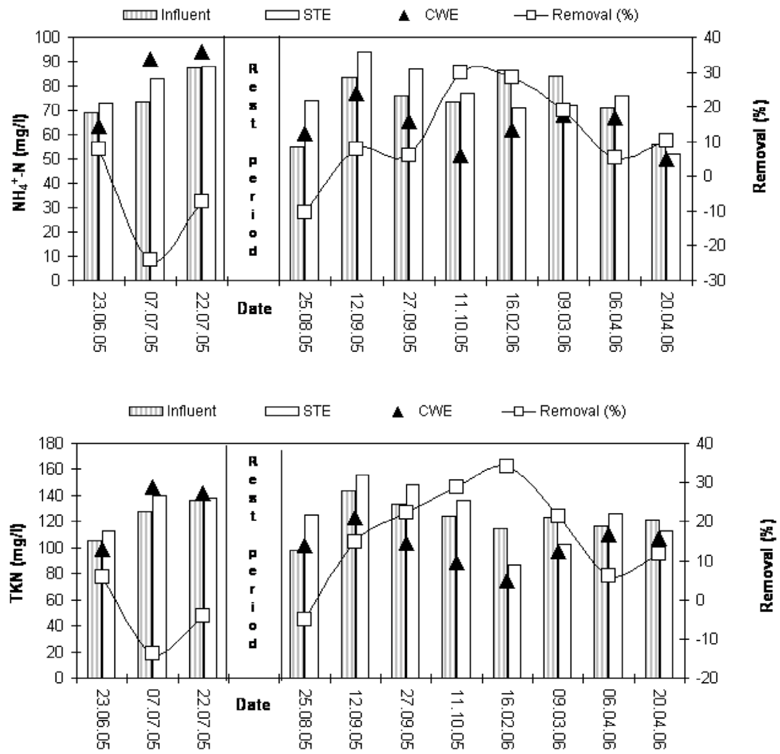

Fig. 3. Nitrogen removal in the wastewater treatment plant. STE is septic tank discharge and CWE is constructed wetland discharge.

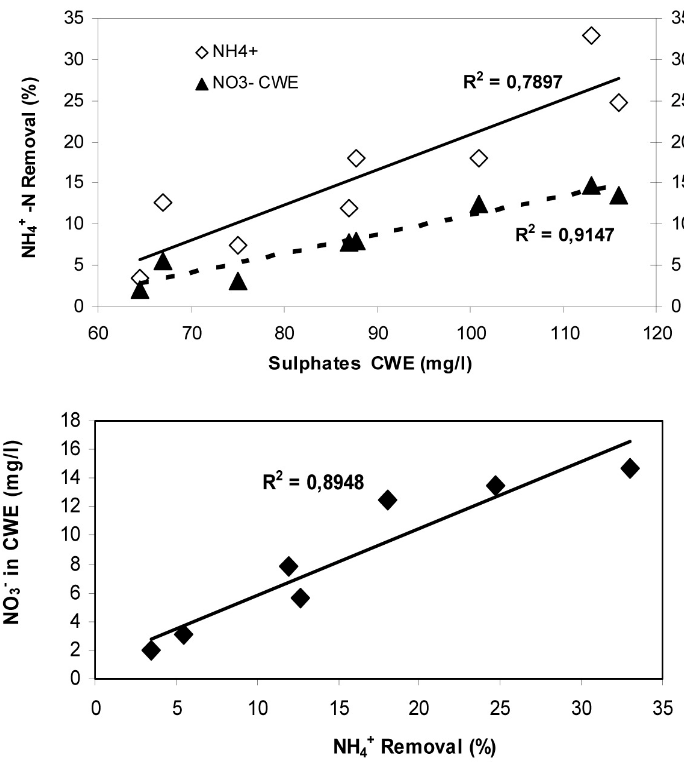

Fig. 4. Ammonia removal in the CW vs. sulphates and nitrates outlet concentrations.

and sulphates effluent concentrations. This result attests that nitrification was active only after the rest period and nitrates recorded in the effluent were the result of ammonia oxidation. In fact, when the CW is left for aeration for 26 d, organic matter and biofilm were naturally decomposed in the filter, permeability was recovered and oxygen transfer from the atmosphere into the wetland increased which improved nitrification.

3.3.2. Phosphorus (as orthophosphates) removal in the VFCW

Phosphorus removal mechanisms in subsurface flow constructed wetlands systems are until now not well recognised. The main mechanisms for P removal are adsorption, complexation and precipitation, plant absorption (plant uptake), and biotic assimilation.

In this study, P average removal was not steady. Average removal rate of the filter bed was about 13% and did not exceed 22%. In addition, P concentrations measured in the outlet of the CW show wide variation where values oscillate between 2.45 mg l^{-1} and 4 mg l^{-1} and remained higher than those measured in the influent (Fig. 5).

Fig. 5 demonstrates that aeration of the filter bed did not affect P removal. Many studies [18,19] showed that phosphorus may be bound to the media of the constructed wetland as a consequence of adsorption and precipitation reactions with calcium (Ca), aluminum (Al) and iron (Fe) in the sand or gravel substrate. The investigation of the filter medium understudy showed that the particle-size distribution of the sand on a weight basis have a d_{10} of about 0.25, a d_{60} of about 0.4 and a uniformity coefficient ($U = d_{60}/d_{10}$) equals to 1.6. The contents of clay and silt (particles less than 0.125 mm) are less than 0.2%. Thus, the sand texture makes it suitable to use as substrate in constructed reed bed systems. However, the concentrations of Ca (0.87 mg g^{-1} dw), Al (0.56 mg g^{-1} dw) and Fe (1.1 mgg^{-1} dw) were particularly low which can explain the low P removal rate observed during the monitoring period.

4. Discussion

The low removal rates of different pollutants in the system of Boujrida is both under sized and not normally operated. In fact, the system receives high organic and nitrogen loads, compared to values recommended in literature, without running to a regular rest period which led to the clogging of the filter bed. Basic principles related to design, application, operation and maintenance of subsurface vertical flow constructed wetland were set in different countries. Thus, the needed vertical CW area would vary between 200 m^2 and 230 m^2 for the 72 PE instead of the actual 90 m^2 based on several available European and USA-Environmental protection Agency vertical flow CW guidelines. However, given the wide variability in quantity and quality of the rural wastewater discharges, these cited guidelines may not be applicable directly in the Tunisian case. Further, there is a need to avoid clogging in the filter media by ensuring a better oxygenation and by monitoring the feeding operation.

5. Conclusion

The results of this investigation show that the organic load and nitrogen concentration measured in raw domestic water in a Tunisian rural settlement are higher than those reported in several literatures. The wastewater treatment system presented here was operating under high and variable organic and nitrogen loads. Reasonable removal rates were achieved in the Septic tank for COD, BOD_5 and TSS. Organic and nitrogen loads in the septic tank effluent, drained to the constructed wetland, remained high causing the clogging of the filter bed and reduced considerably the plant performance. In fact, the aeration of the filter bed was very interesting to overcome the clogging problems and to improve the elimination efficiency of organic and nitrogen loads.

This study suggests that constructed wetlands could be suitable for Tunisian rural wastewater treatment when are properly designed and effectively operated. Further

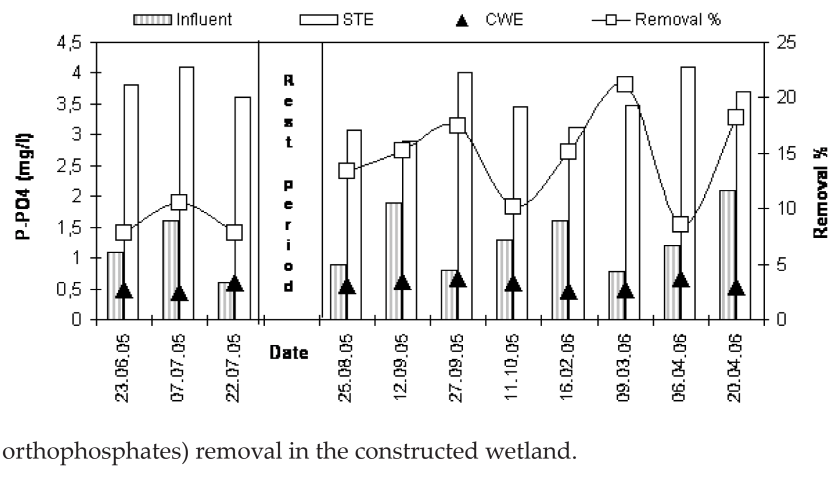

Fig. 5. Phosphorus (as orthophosphates) removal in the constructed wetland.

studies are being conducted to introduce technical improvements taking into account the raw wastewater quality, social and climate issues.

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