

Wastewater treatment through constructed wetlands: the influence of vegetation

Joana F. Mavioso^a, Ana F. Galvão^b

^a Master student in Environmental Engineering, IST, Lisboa, Portugal

^b Assistant Professor, IST, Lisboa, Portugal (agalvao@civil.ist.utl.pt)

Abstract

Horizontal subsurface constructed wetlands (HFCW) are examples of an appropriate technology for wastewater treatment, particularly for small agglomerations.

This study investigates the role of plants in organic matter removal and included the implementation of nine experimental constructed wetlands with subsurface horizontal flow at the pilot scale with physico-chemical data monitoring (pH, temperature, redox potential, dissolved oxygen and electrical conductivity) and COD, collected for about eight months. The constructed wetlands were fed daily with synthetic sewage.

The main objective of the work was to study the performance of two types of macrophytes – *Phragmites australis* and *Scirpus* – in COD removal. The statistical significance analysis showed that there are no significant performance differences between the two species regarding organic matter removal.

After applying peak concentration at the inflow, constructed wetlands tend to have a COD removal similar to regular operation conditions; the beds fed with potable water developed biofilm that provided organic matter removal.

1 Introduction and background

Constructed wetlands aim to reproduce, in a controlled environment, the phenomena and mechanisms of degradation of pollutants that occur in natural wetlands (Kadlec & Knight, 1996). The implementation and optimisation of these systems depend on the knowledge of natural organic removal processes. Subsurface flow (SSF) constructed wetlands (CW) consist of four main components: water, soil, plants and microorganisms (Kadlec et al., 2000), and there is a close relationship between them. The removal of any pollutant depends on these four components and involves many mechanisms. The influence of these four factors has been extensively studied. The species of plants used may be an important variable for wetland efficiency. Although there are many researchers studying this factor (Akratos and Tsihrintzis, 2007; Calheiros et al., 2007; Taylor et al., 2010), some question the role played by the use of a specific species instead of another.

Plants can be involved, either directly or indirectly, in the removal of almost all typical pollutants present in domestic wastewater. It is generally accepted that plants increase the amount of oxygen transported from the atmosphere into the water. This paper describes a study on the effects of different plant species on the operating conditions and results obtained in pilot scale horizontal subsurface flow constructed wetlands (HSSF). Also, constructed wetlands treatment efficiencies are compared in terms of the removal of organic matter for different plant species.

Although the positive role of macrophytes on the removal efficiency of constructed wetlands is well established, the possible performance differences between plants species of comparable life forms and sizes are difficult to demonstrate.

Organic matter is removed in a subsurface flow constructed wetland by aerobic bacteria attached to the porous media and plant roots (Al-Omari and Fayyad, 2003; Greenway and Woolley, 1999; Steer et al., 2002; Vymazal, 2002). Plant roots, beyond providing the necessary surfaces for bacteria to grow, also provide oxygen to them (Brix, 1994; Reed et al., 1995).

2 Materials and methods

2.1 Characterization of the pilot-scale wetlands

The pilot scale experimental installation used in this study is situated in a laboratory located at Instituto Superior Técnico, in Lisbon, and includes nine beds of subsurface flow horizontal flow (HSSF).

The system was fed discontinuously, with the average flow for each bed of 10 L/day, corresponding to a theoretical detention time of seven days. The average water level was of 0,25 m, about 0,10 m below the surface of the support material, preventing the proliferation of diseases and contact with the water. The distribution of the effluent is carried out through a perforated pipe inside the bed, located halfway up the support material (gravel). A discharge valve and a perforated tube of larger diameter to allow for additional measurements were also installed.

The PVC boxes used to encase the beds measure 1200 × 800 × 760 mm each.

The experimental installation is organized into three groups, A, B and C and each group is composed by three beds: one without vegetation, another colonized by *Phragmites australis*, and the third colonized with *Scirpus*. The beds without vegetation acted as control. Table 1 presents the species planted in each bed, inside each group.

Table 1 – Species planted in each bed, inside each group.

GROUP	BED	PLANTS USED
A	L1	Unplanted
A	L2	<i>Scirpus</i>
A	L3	<i>Phragmites australis</i>
B	L4	<i>Phragmites australis</i>
B	L5	<i>Scirpus</i>
B	L6	Unplanted
C	L7	<i>Phragmites australis</i>
C	L8	Unplanted
C	L9	<i>Scirpus</i>

2.2 Macrophytes planting

The plantation of the macrophytes began in November 2009, using previously grown seedlings. Adaptation growth was slow at first, probably due to the vegetation's growth cycle.

After planting, all beds were fed with tap water until the end of January 2010. On this date, beds of groups A and B began to be fed with synthetic wastewater prepared in the laboratory, while group C maintained the supply of tap water.

2.3 Duration of experiment

The study was carried out from January to July 2010 and was divided into three phases: Phase 1, Phase 2 and Phase 3, which had separate objectives, as presented in Table 2. The synthetic wastewater influent fed to group A and B differed, as explained in section 2.4. Samples of the discharged effluent were collected on a weekly basis. Each sample was analyzed regarding chemical oxygen demand (COD) while experimental conditions such as temperature (T), redox potential (ORP), pH and dissolved oxygen (DO) were also measured *in situ*, twice per week.

Table 2 – Experimental plan description of the stages involved in achieving the proposed objectives and associated periods.

Phase	Period	Objectives
1	February 9 to May 18	Influence of vegetation in the process of removing pollutants
2	May 18 to June 2	Influence of the variability of organic loads
3	June 2 to June 24	Perturbation of the system after application of peak inflow

2.4 Influent characterization

The composition of the synthetic effluent was defined in order to obtain a composition similar to typical wastewater in terms of organic matter and nutrients, ensuring also the presence of trace elements. The constituents and their dosage were based on synthetic wastewater described in Akratos and Tsihrintzis (2007) and Nopens et al. (2001) and include the following substances:

- i. Starch, as carbon source;
- ii. Milk powder, as carbon source;
- iii. Urea, as nitrogen source;
- iv. Sodium acetate, as carbon source, readily degradable;
- v. Soybean oil, as a source of oils and fats;
- vi. Peptone, as source of aminoacids;
- vii. Fertilizer as a source of nitrogen, phosphorus and trace elements (iron, zing, among others).

The characteristics of the synthetic wastewater are presented in Table 2, according to the phase of the experiment.

Table 3 - Composition of concentrated solutions, referred to the different phases of the experiment.

Compounds		Phase 1 e 3	Phase 2		
			Solution 2.1	Solution 2.2	Solution 2.3
Starch	[g/L]	15,00	45,00	20,00	5,00
Sodium acetate	[g/L]	15,00	45,00	20,00	5,00
Urea	[g/L]	13,20	35,00	13,00	4,40
Pancreatic peptone	[g/L]	6,00	9,00	6,00	2,00
Powdered milk	[g/L]	1,80	2,00	2,20	0,60
Oil	[g/L]	3,00	3,00	3,00	1,00
Fertilizer	[L]	0,25	0,25	0,15	0,075

2.5 Data analysis

The data were entered into a Microsoft Excel spreadsheet. All representative values were displayed by mean value and standard deviation (S.D.). Statistically significance differences inside each group

were assessed using analysis of variance (ANOVA), through software PASW18 (SPSS). A p-value of less than 0.05 was concluded to represent statistically significant differences.

3 Results and discussion

3.1 Operating conditions generated inside the wetlands

Table 4 presents the results obtained from measurements taken *in situ*, including DO, ORP, pH and conductivity. In the effluent, the temperature showed a reduced variability during the study, while conductivity showed a high variability of results.

It was observed that as the organic load increased, the conductivity also increased, i.e. for the group A the average conductivity was above the average value measured in group C.

Table 4 - Water measured variables in the influent and effluent in the pilot-scale wetland.

	Effluent		Influent					
	Mean	S. D.	Group A		Group B		Group C	
			Mean	S. D.	Mean	S. D.	Mean	S. D.
Temp. [°C]	17,03	3,72	18,75	2,51	19,16	2,45	18,71	3,00
DO [mgO ₂ /l]	1,87	2,17	6,12	1,59	5,68	1,44	6,19	1,55
pH	7,06	0,36	7,04	0,20	7,26	0,28	7,41	0,18
ORP [mV]	-16,78	15,37	-18,14	12,35	-30,73	14,77	-39,17	9,77
Cond. [μS/cm]	6,68E+02	3,61E+02	746,45	65,31	490,64	51,25	255,54	92,37

3.2 Overall performance statistics

3.2.1 Phase 1

Phase 1, between February 9 and May 13, aimed at examining the influence of vegetation in removing pollutants. Figure 1 presents the results of COD concentration in the effluent of each bed, during this period. Beds L7, L8 and L9 (Group C) showed values below the detection limit for COD (10 mg/l).

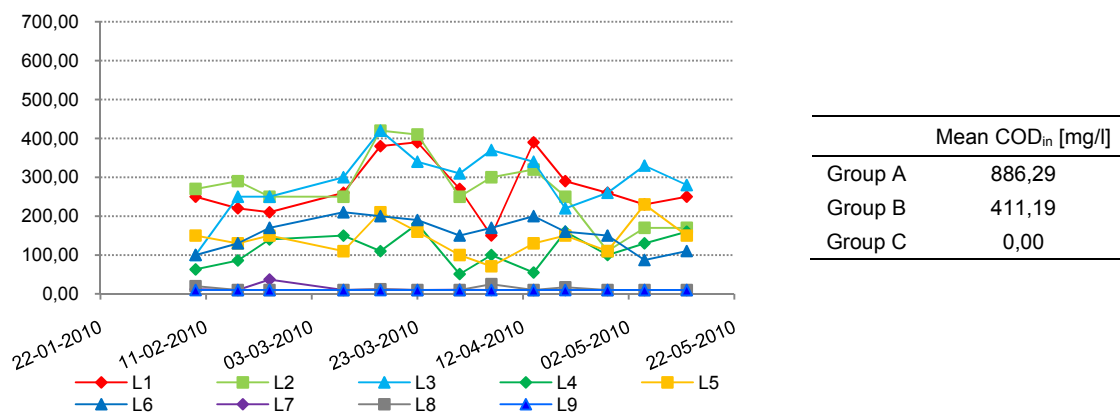


Figure 1 - Evolution of output COD concentration for L1-L9 beds. Phase 1 (February 9 to May 13).

Table 4 presents the average value for each parameter and each section and the corresponding removal efficiencies. There is a slight increase in COD removal for all planted beds compared to beds without plants (L1, L6 and L8). It is generally accepted that constructed wetlands with subsurface horizontal flow which are planted improve COD removal due to a combination of phenomena favoured by plants (Soto et al., 1999; Stottmeister et al., 2003), due to factors such as biofilm growth on root

surface, absorption of certain organic pollutants, or the potential for substrate aeration provided by plant roots.

Table 5 – Input and output average concentrations of constructed wetlands, regarding COD. Removal efficiency during Phase 1 (February 9 to May 13, 2010).

Parameter	CONSTRUCTED WETLANDS								
	L1	L2	L3	L4	L5	L6	L7	L8	L9
	Group A			Group B			Group C		
Species	un.	<i>Scirpus</i>	<i>Ph. a.</i>	<i>Ph. a.</i>	<i>Scirpus</i>	un.	<i>Ph. a.</i>	un.	<i>Scirpus</i>
COD _{in} [mg/l]	886,29	886,29	886,29	411,19	411,19	411,19	0,00	0,00	0,00
COD _{out} [mg/l]	273,08	266,15	302,31	112,92	142,38	155,92	18,00	12,62	0,00
Efficiency [%]	69,2	70,0	65,9	72,6	65,4	62,1	-	-	-

un. – unplanted

Mass removal rates were also calculated, and the results are presented in Table 6.

Table 6 - COD mass removal associated with each constructed wetland. Input and output loads. Phase 1.

CW	COD _{in} [g/ (day.m ²)]	COD _{out} [g/ (day.m ²)]	COD mass removal [g/ (day.m ²)]
L1	9,23	2,84	6,39
L2	9,23	2,77	6,46
L3	9,23	3,02	6,21
L4	4,28	1,19	3,09
L5	4,28	1,48	2,80
L6	4,28	1,62	2,66
L7	0,00	0,19	-0,19
L8	0,00	0,13	-0,13
L9	0,00	0,10	-0,10

Given that within each group differences in mass removal are only slight, it was considered appropriate to carry out a more detailed statistical analysis, to ascertain their statistical significance.

Table 7 - Results of ANOVA for testing the difference between the average output of COD inside each group: p-value.

FACTOR	UNPLANTED	PHRAGMITES AUSTRALIS	SCIRPUS
	Group A		
UNPLANTED		0,844	1,000
PHRAGMITES AUSTRALIS			0,629
SCIRPUS			
	Group B		
UNPLANTED		0,434	0,999
PHRAGMITES AUSTRALIS			0,870
SCIRPUS			
	Group C		
UNPLANTED		1,000	1,000
PHRAGMITES AUSTRALIS			1,000
SCIRPUS			

The analysis above indicates that the influence of vegetation inside each group was not significant. Further analysis was carried out to quantify the contribution of vegetation for COD removal. The procedure assumes that the removal of mass load in beds without vegetation is due to biofilm formation and therefore the presence of microorganisms. Thus, these beds provide a default value for

the organic load removal due to microorganisms-only activity, based on the method used by Camacho et al. (2007). Applying the methodology developed by these authors, the difference between planted and unplanted beds' removed load can be considered an indicator of the effect of vegetation on the decomposition of organic matter.

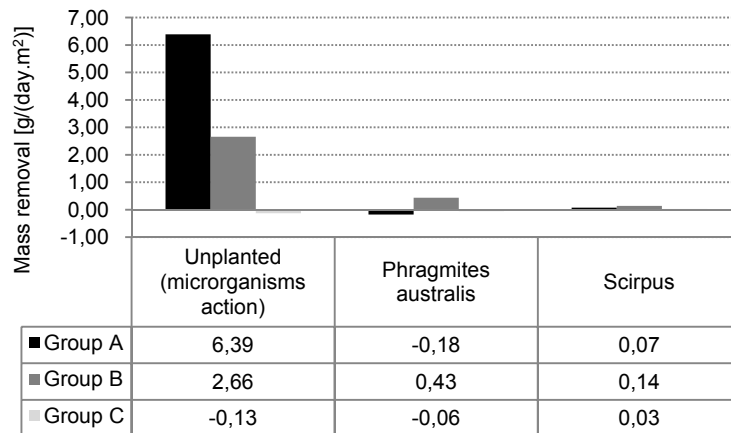


Figure 2 - Average COD mass removal associated with each species of macrophytes and microorganisms (unplanted beds) for each group (Group A, Group B and Group C). Phase 1 (February 9 to May 13, 2010).

Indeed, the increasing organic loads enhance the microbial growth, increasing organic removal (Ragusa et. al., 2004). Moreover, there is a limit of biomass removed for a given bed, corresponding to the bed's maximum carrying capacity (Galvão, 2009).

In beds colonized by *Phragmites australis* there is a greater mass removal for Group B (intermediate load) compared to Group A and Group C. in fact, for both groups A and C the influence of vegetation was apparently negative. However, since values obtained were very close to zero, it is safe to conclude that the presence of *Phragmites australis* has no significant effect on treatment, at least for the conditions of this study, supporting the above findings. This may be due to weak vegetation development during the monitoring period.

For the beds colonized with *Scirpus* there is a higher mass removal in Group B. However, the low values recorded for the contribution of vegetation lead to a situation similar to *Phragmites australis* beds (minor influence).

3.2.2 Phase 2 and 3

Phase 2, between May 17 and June 24, 2010 aimed to study the effects of charges related to variability in the removal of pollutants. Phase 3 follows Phase 2, corresponding to the establishment of "normal" conditions of operation. During Phase 2 and start of Phase 3, the collection of samples in each bed for COD analysis was carried out twice-weekly frequency, to better detect changes in the behavior of the beds.

Group B could not be fully studied for the effect of increasing concentrations since the inherent variability of the synthetic wastewater used resulted in COD mean values lower than expected (increase of only 7 % compared to Phase 1).

Figures 3 and 4 present the output COD concentrations obtained in each bed for Phase 2 and 3, respectively.

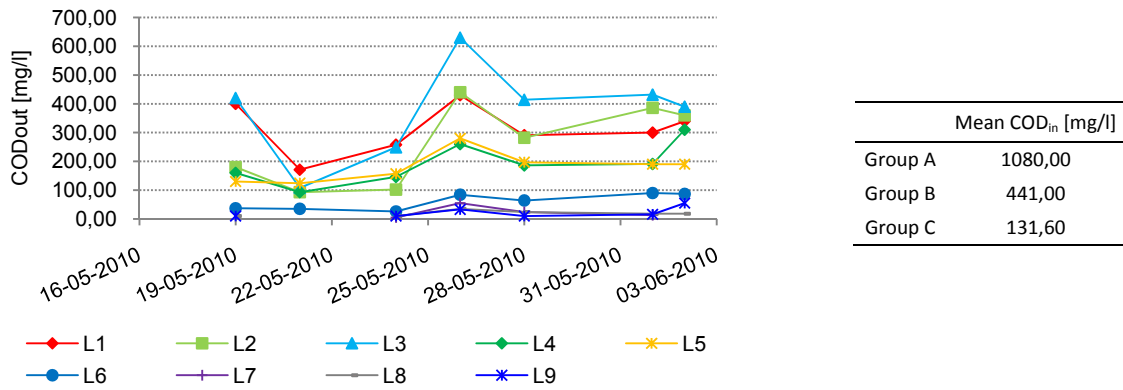


Figure 3 - Evolution of output COD concentration for L1-L9 beds during Phase 2 (May 17 to June 2, 2010).

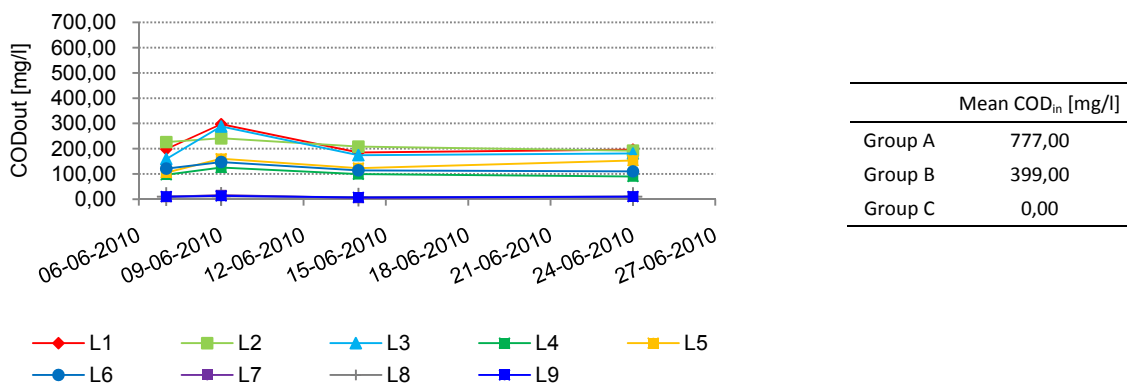


Figure 4 - Evolution of output COD concentration for L1-L9 beds, during Phase 3 (June 7 to June 24, 2010).

Although input organic load has been constant during each phase, the adjustment of the bed to higher organic loads occurred after the first week of Phase 2, which is why the COD removal efficiencies do not increase at first. In fact, there was an increased concentration of output COD in most beds only at the end of May. Furthermore, Figure 4 shows the influence of Phase 2 and the variability due to the initial hydraulic retention time of approximately seven days. Indeed, from mid-June onward, the concentrations of output COD appeared to stabilize to values similar to those observed during Phase 1. Still, a longer monitoring period would be necessary to confirm these inferences.

COD mass removal rates for Phase 2 and Phase 3 are presented in Table 8.

Table 8 - COD mass removal associated with each constructed wetland. Input and output loads. Phase 2.

CW	COD_{in} [g/ (day.m ²)]	COD_{out} [g/ (day.m ²)]	COD mass removal [g/ (day.m ²)]
L1	11,25	3,26	7,99
L2	11,25	2,74	8,51
L3	11,25	3,93	7,32
L4	4,59	2,00	2,59
L5	4,59	1,89	2,71
L6	4,59	0,63	3,96
L7	1,37	0,25	1,12
L8	1,37	0,25	1,12
L9	1,37	0,36	1,01

During Phase 2 group A and B showed an increase in COD mass removal rates when compared to Phase 1. However, this result may not entirely represent the adjustments of this phase since it was very short and the retention time influenced the response of the system. Group C showed a positive mass removal during Phase 2, while Phase 1 feeding was exclusively with tap water. The rapid response of beds L7, L8 and L9 to increased organic loads may indicate the presence of an established microbial community during feeding with tap water. This phenomenon resembles to one described in sand filters, in production of drinking water, assessed by Urfer and Huck (2001). Phase 3 mass removal rates are shown in Table 9. Due to the reduced monitoring period few values were considered in the calculation, taking into account only the last values were there was no influence from Phase 2.

Table 9 - COD mass removal associated with each constructed wetland. Input and output loads. Phase 3.

CW	COD_{in} [g/ (day.m ²)]	COD_{out} [g/ (day.m ²)]	COD mass removal [g/ (day.m ²)]
L1	8,09	1,98	6,11
L2	8,09	2,08	6,01
L3	8,09	1,85	6,24
L4	4,16	1,07	3,09
L5	4,16	1,41	2,75
L6	4,16	1,28	2,88
L7	0,00	0,10	-0,10
L8	0,00	0,10	-0,10
L9	0,00	0,10	-0,10

The results presented in Table 9 show that mass removal rates are similar to Phase 1, where input concentrations were similar to Phase 3.

3.3 Simplified expressions to estimate effluent COD mass load

Testing in controlled laboratory environment often allows the establishment of equations that relate input and output conditions using regression techniques.

In this study, the overall analysis of Phase 1 results identified the influence of input load on COD removal. In this context, the calculation of regression equations between these two variables was performed, in order to analyze a correlation. The adjustment was made for three different expressions, including the following:

- Linear, in general form: $COD_{out} = a_1 COD_{in} + b_1$;
- Potential, in general form: $COD_{out} = a_2 COD_{in}^{b_2}$;
- Logarithmic, in general form: $COD_{out} = a_3 \ln COD_{in} + b_3$.

With a_i and b_i , $i \in [1, 2, 3]$, the parameters associated with each expression, and COD_{in} and COD_{out} the influent and effluent organic load (g / (day. M²)), respectively. The results obtained are presented in Table 10.

Table 10 – Regression equations (COD). Organic load as a function of effluent load.

Expression	R ²	a _i	b _i
	No plants		
$COD_{out} = a_1 COD_{in} + b_1$	0,8961	0,2872	0,0212
$COD_{out} = a_2 COD_{in}^{b_2}$	0,8595	0,3254	0,9177
$COD_{out} = a_3 \ln COD_{in} + b_3$	0,7241	1,0184	0,1668
	<i>Phragmites australis</i>		
$COD_{out} = a_1 COD_{in} + b_1$	0,9351	0,3323	-0,0346
$COD_{out} = a_2 COD_{in}^{b_2}$	0,9642	0,3435	0,9639
$COD_{out} = a_3 \ln COD_{in} + b_3$	0,7491	1,1731	0,1415
	<i>Scirpus</i>		
$COD_{out} = a_1 COD_{in} + b_1$	0,9164	0,2221	0,5250
$COD_{out} = a_2 COD_{in}^{b_2}$	0,9779	0,5054	0,7511
$COD_{out} = a_3 \ln COD_{in} + b_3$	0,9164	0,2221	0,5250

The power potential regression equations are the most suitable to estimate for the obtained results, particularly in planted beds. Moreover, in unplanted beds, the linear expression appears to reflect more accurately the results obtained.

4 Conclusions

Possible differences in performance between subsurface horizontal flow constructed wetlands (SHF-CW) planted with different species (*Phragmites australis* and *Scirpus*) can be attributed to different organic input load, particularly load peaks.

The present study was intended provide a contribution to the knowledge of those species as components of systems such as SHF-CW for COD removal.

Phase 1 aimed to study the influence of plants on organic matter removal in constructed wetlands-type SHF. Statistical significance analysis showed that there is no significant difference performance between species *Phragmites australis* and *Scirpus* regarding the removal of organic matter, for a given organic load mass. The average removal efficiencies ranged between 62% (unplanted bed) and 70% (*Scirpus*). The obtained values are generally lower than those obtained in other studies (Solano et al., 2004; Garcia et al., 2005; El Hamouri et al., 2007).

For increased discharges of organic loads (input peaks) submitted during Phase 2 of the study, the beds showed higher values of output COD in comparison with Phase 1.

The underlying effects were detected up to two weeks later (Phase 3), although the peaks of affluence have lasted about two weeks (Phase 2). After stabilization, the obtained mass removal was similar to those obtained in Phase 1, although with slightly lower loads charges. In non-peak input conditions, results show that vegetation was not relevant for the COD removal.

Group C was fed during Phase 1 with drinking water; organic loads were administered to these beds during Phase 2, which demonstrated effective COD removal. This result may indicate the presence of a microbial community, formed during Phase 1, which provides some treatment for the applied load.

The monitored SHF-CW experimental installation completed its first months of operation during the present study. Planted macrophytes had not completed a full vegetation cycle during the experiments, which could explain the obtained results.

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