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Evaluation of the Simultaneous Removal of Organic Matter, Nitrogen and Suspended Solids in a SSHF Constructed Wetland in Capinha, Portugal

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1. Introduction

Comparing with other countries there is still a lack of experience in applied constructed wetlands for wastewater treatment in Portugal. Among all Mediterranean countries only France and Italy established the guidelines on Constructed Wetlands (CWs). In most of those countries as well as in Portugal there are no specific regulations and design criteria of CWs for the treatment of wastewater [1]. Most of the CWs applied in Mediterranean countries were designed basing on northern countries experience; therefore there is a great need to establish regulations suitable for warm climate conditions. Additionally, the extending popularity of CW systems and a need to make more researches is forced by the *Urban Wastewater Treatment* Directive (91/271/EEC) and *Water Framework Directive* (2000/60/EEC), which set the goals to achieve certain standards of discharge water in Europe by the 2015 year.

The advantages of CWs application in Portugal are unquestionable: low energy and maintenance requirements, low cost and appropriateness for domestic wastewater treatment for small and rural communities. Moreover, the land availability and temperature are not the limiting factors. As almost 25% of the population of central Portugal lives in small and rural agglomerations CWs seem to be very attractive solution. The majority of constructed wetlands in Portugal are designed as surface horizontal flow systems for secondary treatment of municipal and domestic sewage [2, 3]. There is very little date on the treatment efficiency of CWs in Portugal so far, however it had been reported that they show good performance in terms of BOD_5 , TSS and lower effectiveness for total P and N removal. High capacity to remove low concentration of organic substances was also observed [2]. Data obtained on the treatment efficiency of CWs in Mediterranean countries also proved good potential of CWs to organic removal (COD, BOD_5, and TSS) as well as to ammonia removal, which enabled meeting discharge criteria set by governments [1]. The survey conducted for CWs in Spain reported that the loadings applied for horizontal flow systems were in range of 0.8÷20.3 g BOD_5 /m^2day and 3÷17 g TSS/ m^2day [4]. Data obtained in Spain showed that the average load applied to horizontal flow constructed wetlands is higher that ones cited in the literature and proved that those systems perform very well in terms of organic matter removal comparing to the other European countries [4]. This conclusion could also apply to Portugal due to similar climate conditions, close localization and similar regulations and criteria taken into account for sizing. However, more accurate data must be provided in order to approve it and to establish the most guidelines criteria.

The objective of the paper was to evaluate the performance of the subsurface horizontal flow (SSHF) submerged constructed wetland in Capinha, located in the central Portugal, mostly in terms of organic matter (COD), nitrogen forms (total N, ammonia and nitrate) and suspended solids (TSS). The aim of the work was also to study the effect of loads on the removal of above pollutants.

2. Material and Methods

The constructed wetlands system of Capinha

The Wastewater Treatment Plant (WWTP) of Capinha (central Portugal) is designed for pe of 800. Preliminary treatment includes sand traps, the measurements of flow and Imhoff tank. As secondary treatment facilities two beds of constructed wetland with horizontal subsurface flow were built. Each CW is 50 m long and 15.5 m wide, filled with gravel (bottom layer) and sand (top layer). Total depth of the bed is 1.0 m, whereas submerged depth is 0.65 m. The bottom of each CW was covered with an impermeable material. The CW was planted with common reed (*Phragmites australis*). In order to allow variable water flow an adjustable outlet tube was installed. At the time of monitoring the WWTP of Capinha had been in operation for a period of 3 years.

Operating conditions of the constructed wetland of Capinha for an affective area are presented in Table 1.

Table 1. Operating conditions of the CW of Capinha
Tabela 1. Warunki pracy obiektu hydrofitowego w Capinha

Parameters	Range of values
Flow rate m^3/day	40-90
Hydraulic loading cm/day	6.5-14.6
Hydraulic retention time day	4.5-10.0
BOD_5 mg O_2/l	210-350
COD mg O_2/l	300-500
Organic loading g COD/m^2d	38.8-43.7

Experimental procedure

All the measurements were carried out for a period of 4 months, which included spring period (May and June) and summer period (July and August). Samples of the sewage were taken once a week and averaged before the analyses. During each measurement four samples were taken: raw influent sample (1), influent of the CW (2) and effluent of the CW 1 (3) and CW 2 (4). However, this paper will only analyze data from the influent to the CWs and the effluent from the CW 1. Only data for the CW 1 will be presented in this paper as the representative ones. The flow rate was measured at the inflow to the CW and at the outflow of the CW.

Approximately 1.5 L of sample was taken at each point. DO, pH and temperature of wastewater (T) were done on – site. The samples were stored at 4°C in the dark and transported to the laboratory to do remaining analyses. Most of the parameters were performed immediately: CODt (total COD), CODs (soluble COD), ammonia, nitrate, TSS (total suspended solids) and VSS (volatile suspended solids).

The analyses of DO, pH values and temperature were carried out directly after sampling using WTW Multi 340i.

The CODt and CODs (after sample filtration) were analyzed with the cuvette tests and the spectrometer (CADAS 50) of the Dr. Lange Company. The following tests were used: LCK 314 (15 - 150 mg/L), LCK 514 (100 - 2000 mg/L) and LCK 014 (1,000 – 10,000 mg/L). These tests use the oxidation with potassium dichromate, following DIN 38049-4.

The samples for CODs analysis were filtered with glass fibre pre–filters (Chromafil GF/PET-45/25, Macherey-Nagel) with a pore size of 45µm.

The ammonia, nitrate, TSS and VSS were determined according to the Standard Methods for the Examination of Water and Wastewater [5]. Filter paper (MN GF-3, Macherey-Nagel) were dried at 100°C and buried at 550°C in a muffle furnace for 15 minutes for solid tests.

Removal efficiency was calculated as difference of concentration in influent (C_{infl}) and effluent (C_{effl}) to the system divided by concentration in influent and multiplied by 100 per cent.

Mass removal rate was calculated on the basis of following equitation:

Mass removal rate = $[(C_{infl} * Q_{infl}) - (C_{effl} * Q_{effl})]/A$ [g/m^{2}day]

A – effective area of the single bed

Q_{infl}, Q_{effl} – influent and effluent wastewater flow respectively [m^3/day]

C_{infl}, C_{effl} – concentration of pollutants in the influent and effluent [mg/L]

2. Results and Discussion

Operating conditions and removal efficiencies

The quality and the quantity of sewage at the inlet and characteristics of the effluent from the CW are presented in the Table 2 and Table 3. Two of the assays were not taken into account due to incomplete data, 14 assays were analyzed.

The results for the analyzed parameters describing the quality and the quantity of the sewage incoming to the system show that the influent was stable in time. In most cases standard deviations of the average values do not exceed 30% which indicate stabilized flow in time both in quality and quantity terms. Only data obtained for N-NO_3 indicate a strong changeability in time.

Different results were obtained for the sewage coming from the system. Standard deviations of the average values describing the quality of the sewage were quite high, especially for all analysed forms of nitrogen, which indicates unstable effluent quality.

The results obtained for all analysed pollutants during the monitoring period allow dividing it into two stages: first one – spring (May and June) and the second – summer (July and August). In the first period both the values for the concentration of COD in the influent and the effluent from the CW were higher than in the second period. The average total COD concentration in the first period in the influent was 493.5 mg O_2/L and in the effluent: 205.3 mg O_2/L. The average efficiency removal from that period was 57.8%.

In the second period the average influent COD was equal to 353.8 mg O_2/L, both the COD removal and the removal efficiency improved, reaching respectively: 108 mg O_2/L and 69.4%. The results for soluble COD followed that tendency.

Table 2. Quantity and quality of sewage at the inlet to CW
Tabela 2. Ilość i jakość ścieków wpływających do obiektu hydrofitowego

Date	Flow* [m^3/d]	COD t [mg O_2/L]	COD s [mg O_2/L]	N-NO_3 [mg/L]	N total [mg/L]	TSS [mg/L]	VSS [mg/L]	pH	T [°C]	DO [mg/L]
12.05	78.3	395.0	172.0	1.4	31.2	140.0	90.0	7.0	21.2	1.6
26.05	75.2	503.0	282.0	1.1	25.8	155.0	35.0	7.3	21.5	1.3
02.06	70.2	498.0	287.0	0.7	27.7	118.0	80.0	7.3	20.9	0.4
16.06	70.1	475.0	304.0	0.2	21.6	128.0	78.0	7.1	21.4	2.5
23.06	76.4	488.0	233.0	0.6	25.8	120.0	105.0	6.8	21.5	0.7
30.06	71.4	602.0	392.0	1.4	32.2	133.0	93.0	7.0	22.1	0.6
07.07	65.3	302.0	114.0	1.3	24.4	100.0	65.0	7.2	21.5	1.3
14.07	70.6	352.0	197.0	1.2	35.6	115.0	85.0	7.3	21.6	1.7
21.07	72.5	395.0	201.0	2.2	33.6	102.0	85.0	7.6	22.1	1.3
28.07	66.3	356.0	224.0	3.2	39.6	125.0	85.0	7.8	21.8	1.3
04.08	68.1	324.0	201.0	1.4	41.6	95.0	65.0	7.4	21.1	1.2
11.08	64.8	384.0	212.0	2.2	32.1	125.0	85.0	7.9	22.0	1.1
18.08	60.3	328.0	212.0	3.4	25.5	105.0	80.0	7.5	22.1	1.3
25.08	68.3	389.0	215.0	2.2	36.6	100.0	60.0	7.5	22.3	0.9
average	**69.8±4.9**	**413.6±86.4**	**231.9±66.9**	**1.6±0.9**	**31.0±6.0**	**119.0±17.3**	**78.0±17.1**	**7.3±0.3**	**21.7±0.4**	**1.2±0.5**

* measured for two beds

Table 3. Quantity and quality of sewage at the outlet
Tabela 3. Ilość i jakość ścieków wypływających

Date	Flow* [m^3/d]	COD t [mg O_2/L]	COD s [mg O_2/L]	N-NO_3 [mg/L]	N total [mg/L]	TSS [mg/L]	VSS [mg/L]	pH	T [°C]	DO [mg/L]
12.05	52.1	*208.0*	96.0	0.6	14.1	*85.0*	45.0	6.8	20.8	0.1
26.05	43.2	*199.0*	101.0	0.7	*18.3*	*50.0*	20.0	7.4	23.6	1.1
02.06	48.3	*148.0*	65.0	1.0	*20.3*	*50.0*	35.0	7.0	21.5	0.6
16.06	48.6	*238.0*	114.0	0.1	3.4	*74.0*	28.0	6.8	21.6	2.8
23.06	44.6	*217.0*	108.0	0.6	*19.3*	*60.0*	40.0	6.7	21.1	1.0
30.06	51.3	*222.0*	103.0	0.3	5.3	*45.0*	20.0	6.8	21.6	2.6
07.07	40.2	102.0	55.0	0,7	5.2	35.0	20.0	6.8	22.3	2.3
14.07	40.9	95.0	64.0	0.3	8.1	*40.0*	30.0	6.8	22.5	2.2
21.07	50.6	102.0	54.0	0.7	2.2	*55.0*	30.0	6.7	23.4	1.3
28.07	39.3	88.0	32.0	0.3	3.6	*60.0*	40.0	6.9	23.6	2.1
04.08	38.1	77.0	54.0	0.2	4.5	30.0	15.0	6.7	23.1	2.5
11.08	36.5	*133.0*	95.0	0.2	2.6	*45.0*	20.0	6.7	23.4	1.6
18.08	38.6	*142.0*	102.0	0.5	5.3	*55.0*	25.0	6.6	23.5	2.1
25.08	40.1	124.0	75.0	0.2	4.6	*40.0*	15.0	6.8	23.8	1.9
average	**43.7±5.4**	**149.7±56.1**	**79.9±25.8**	**0.5±0.3**	**8.3±6.6**	**52.0±14.9**	**27.0±9.7**	**6.8±0.2**	**22.6±1.1**	**1.7±0.8**

Values exceeding the standards in Urban Wastewater Directive (27/91/EEC)
* measured for two beds

Table 4. Removal efficiency of pollutants in the CW
Tabela 4. Efektywność usuwania zanieczyszczeń na obiekcie hydrofitowym

Date	Removal efficiency [%]						
	COD t	COD s	N-NH_4	N-NO_3	N total	TSS	VSS
12.05	47.3	44.4	54.8	53.7	54.8	39.3	50.0
26.05	60.4	64.2	20.6	37.5	29.1	67.7	42.9
02.06	70.3	77.2	18.5	0.0	26.7	57.4	56.3
16.06	49.9	62.5	94.1	31.3	84.3	42.2	64.5
23.06	55.5	53.6	27.6	11.1	25.2	50.0	61.9
30.06	63.1	73.7	85.2	75.0	83.5	66.0	78.4
07.07	66.2	52.1	84.5	47.2	78.7	65.0	69.2
14.07	72.9	67.4	82.4	79.0	77.2	65.2	64.7
21.07	74.2	73.0	95.8	69.2	93.5	46.1	64.7
28.07	75.2	85.7	96.3	92.1	90.9	52.0	52.9
04.08	76.2	73.1	91.3	83.1	89.2	68.4	76.9
11.08	65.4	55.1	91.5	90.5	91.9	64.0	76.5
18.08	56.7	51.9	78.0	86.6	79.2	47.6	68.8
25.08	68.1	65.0	88.5	89.3	87.4	60.0	75.0
Average	**64.4±9.3**	**64.2±7.4**	**72.1±29.0**	**65.0±60.4**	**70.8±25.6**	**56.5±10.5**	**64.5±10.8**

The average N-NO_3 concentration in the influent was 1.6 mg/L and was unstable in time, especially in the first period. The average efficiency removal for the first period was 35% whereas in the second 80%.

Similar tendency in terms of total nitrogen removal efficiency and overall concentration in the effluent, was observed. The average N concentration in the first period was 13.5 mg/L, whereas in the second 4.5 mg/L; removal efficiency from the first period was 50.6% and it improved significantly in the second (86%).

In the first period of analyses the average concentration of TSS in the influent was a bit higher than in the second period (starting from July) and was 132.2 and 108.4 mg/L respectively. In spite of the differences in those two periods the average removal efficiency did not show this tendency and was similar for both with the overall of 56.5%. The VSS concentration in the effluent of the CW was quite stable in time with the average of 27.3 mg/L; the average removal efficiency was 64.5%.

Comparing removal efficiencies of COD, TSS and nitrogen removal in Capinha system with similar data for horizontal flow systems in Spain, it can be concluded that CW in Capinha performed differently [4]. Although the COD removal was in the range reported for systems in Spain (50.0-95.0%) it was still quite low with the average of 64.4%. Furthermore, TSS removal in CWs from Spain was in range from 70.0 to 95.0%, whereas in Capinha the average removal efficiency was 65.5%. However, Capinha system performed very well in term of nitrogen removal. In comparison with other systems, i.e. Spanish where the average efficiencies for nitrogen removal (N_{tot}, $N\text{-}NH_4$, $N\text{-}NO_3$) are not higher than 50.0%, the results obtained in Capinha were very high with the average above 60% for all forms of nitrogen.

DO concentration both in the influent and effluent was unstable in time (high standard deviation - Table 2 and 3). The average DO concentration in the influent was 1.22 mg/L while the average DO concentration in the effluent from the system was 1.72 mg/L. An increase indicated that the oxygen concentration was not a limiting factor for nitrification. Higher DO values in the effluent comparing to the influent could be due to higher plants activity and their lower oxygen demand; DO values from the effluent do not respond to the values inside of the bed, which were not measured. Moreover, the values of DO incoming to the system by diffusion and plant transport were not estimated during the monitoring period.

In terms of pH value changes (Table 3) the systematic increase in the influent (with the average of 7.33) was observed. Comparing that with ammonia and nitrate changes in the influent which showed the same tendency, it can be concluded that during that period system was receiving some additional loading. However, it did not have an influence on the overall work of the system. The pH value in the effluent remained on the stable level, with the average of 6.82. The decline of the pH value in the influent may indicate the presence of nitrification process during which H^+ ions are realised and alkalinity is consumed.

According to the *Urban Wastewater Treatment Directive* (91/271/EEC) the system showed good results in case of nitrogen removal. Minimal efficiency required to fulfil the total nitrogen requirements was 51.5% and the results obtained were around 70%. Nitrate concentration in the effluent was low and the efficiency removal was good, however it should be noticed that the initial nitrate loading to the system after the Imhoff tank was also considerably low. Ammonia results for the effluent concentration and efficiency removal were also very good in spite of the considerably high concentration entering the system.

In terms of COD removal the average effluent concentration was a bit higher than the one recommended by the Urban Wastewater Directive (271/91/EEC), which is 125.0 [mg/L]. The average concentration in the effluent was 149.7 mg/L whereas the removal efficiency was 64.4%. Although the removal efficiency recommended by the Directive is 75%, the minimal efficiency required to achieve the goal of 125 mg/L COD is near 70%. It is important to notice that there was a significant difference in the values from the first period of investigation (May and June) and the second (July and August) and that the initial values of COD entering the system were considerably high, especially in the first period of monitoring and two times exceeded the highest value of 500 mg/L from the design criteria.

Although in the first period most of the values exceeded the require concentration with the average of 205.3 mg/L (table 3)and the removal efficiency of 57.8%, the second period showed much better results of the average concentration of 108.0 mg/L and the removal efficiency of 69.4%.

The expected value for COD removal reported in German Guideline "DWA A-262" from 2005 is 85% which is even higher than the value from the Urban Wastewater Directive (75%). Efficiency around 85% should easily enable a COD effluent concentration below 150 mg/L (comparing to required 125 mg/L by the Urban Wastewater Directive). This concentration value can be reached only if the inlet COD concentration does not exceed 1000 mg/L, which in the Capinha system was on the average level of 413.6 mg/L [10].

The values obtained from the horizontal CW in Italy showed much better results in terms of COD and TSS removal [12]. It is worth to compare the data from that system with the Capinha system because of the similar climate conditions, however HRT in the system in Italy was slightly shorter (6 days) comparing to the average in Capinha of 7.1 d and was receiving much stronger sewage with the average COD concentration of 1100 mg/L and TSS concentration of 150 mg/L, which could account for higher removal efficiencies. The average removal efficiency thought was very high and for COD reached 93% and for TSS – 81%.

The overall TSS concentration in the effluent was higher than the one recommended by the Directive. The average TSS concentration in the effluent was 51.7 mg/L with the 35 mg/L required by the Directive. The average efficiency removal was 56.5% with the 90% required by the Directive, however to achieve the concentration goal of 35 mg/L 70.5% removal efficiency is enough. Worldwide experience for TSS removal in the subsurface wetland system reports the values in the range of 50 to 95% with the best results (80% - 90%) for the influent TSS concentration not higher than 300 mg/L [6]. Taking into account than the average TSS concentration in the influent to the system was 118.6 mg/L, it could be concluded that the system could have reached much better removal efficiency than it did.

Mass removal of organic matter, nitrogen and suspended solids

Mass loadings in relation to the removal rate of selected pollutants are presented in the Figure 1÷4.

In all analyzed cases there is a strong dependency between the mass loading and the removal rate; however only with respond to $N\text{-}NO_3$ the relation is linear.

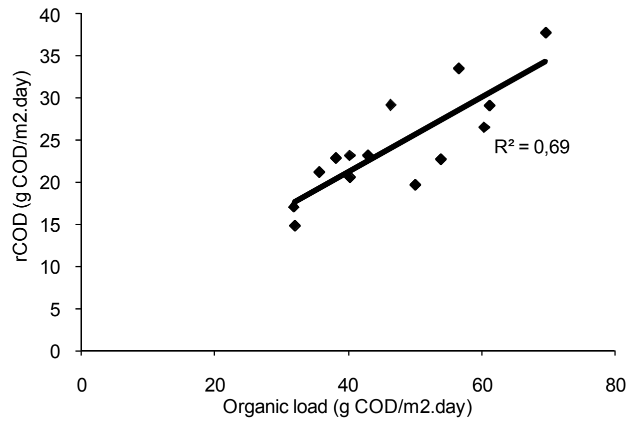

Fig. 1. COD mass loading vs. removal rate
Rys. 1. Zależność obciążenia ChZT od efektywności usuwania

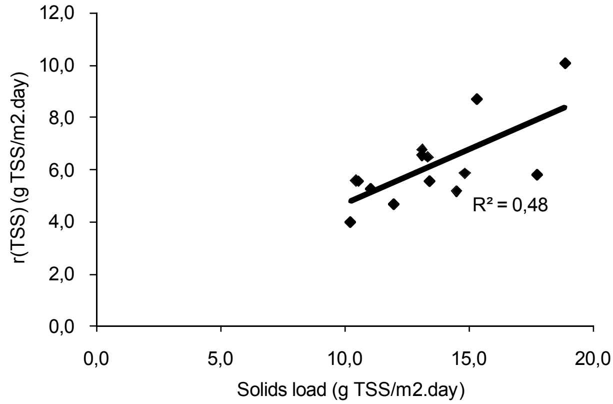

Fig. 2. TSS mass loading vs. removal rate
Rys. 2. Zależność obciążenia zawiesiną ogólną od efektywności usuwania

Similar correlation of COD removal rate and mass loading was reported for several systems in Germany, however the dependency was much stronger and linear [13]. Along with the higher COD mass loading the amount of organic matter removed increased. The range of COD mass loading was from 2 to 22 g COD/m^{2}day with the average of 6 g COD/m^{2}day comparing to 47.1 in Capinha.

According to studies on mass reduction with correlation to organic loading it was reported that higher organic loading rate favors heterotrophic microorganisms and consequently increases the COD mass removal rate. It had been demonstrated previously in several studies that microbial degradation is the major mechanism responsible for organic carbon removal (i.e. COD). Moreover, at higher organic loading more bacterial substrates is supplied which results in higher heterotrophic production rates [8].

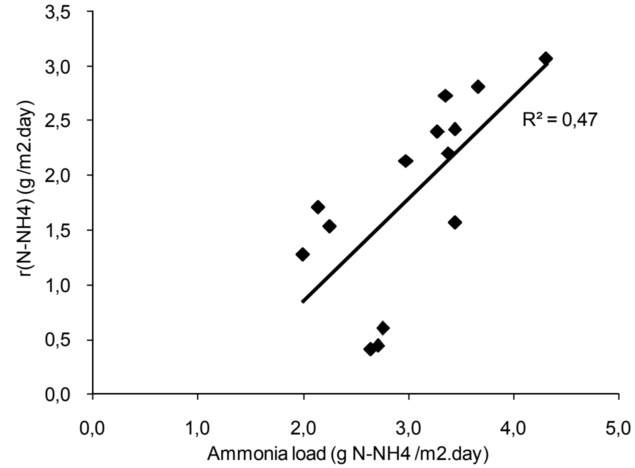

Fig. 3. N-NH_4 mass loading vs. N-NH_4 removal rate
Rys. 3. Zależność obciążenia N-NH_4 od efektywności usuwania

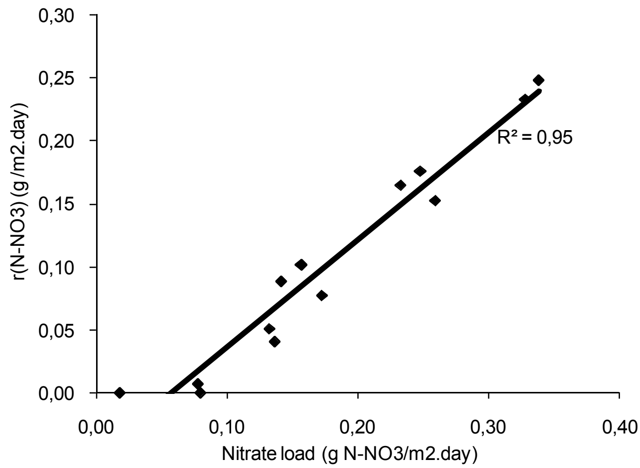

Fig. 4. N-NO_3 mass loading vs. N-NO_3 removal rate
Rys. 4. Zależność obciążenia N-NO_3 od efektywności usuwania

Comparison of mass loadings, removal rates and removal efficiencies between the system in Capinha and other reporter in the literature is presented in the Table 5.

The organic removal rates and organic loading rates varied significantly in the first (May and June) and second (July and August) period of monitoring (Figure 5).

During all the assays of the first period organic loading was higher than in the second with the average value of 58.6 g COD/m^{2}day whereas in the second was 38.5 g COD/m^{2}day. The difference can be partly explained by the different quality of the raw sewage in favour of the second period (lower concentration and organic loading).

Table 5. Comparison between mass loadings, removal rates and removal efficiencies in Capinha and systems reported in the literature
Tabela 5. Porównanie obciążenia, ilości usuwanych zanieczyszczeń i efektywności usuwania zanieczyszczeń w Capinhii i innych systemach z literatury

Pollutant	System	Mass loading [g/m^{2}day]	Removal rate [g/m^{2}day]	Removal efficiency %
TSS	New Zealand [9]	8.5	-	78
	Poland [6]	5.2-7.4	-	89
	Czech Republic [7]	5.4	4.2	-
	Portugal – Capinha	**13.5**	**6.1**	**56.5**
COD	Poland [6]	-	8.5	-
	Czech Republic [7]	-	15.0	-
	Portugal – Capinha	**47.1**	**24.4**	**64.4**
Ntot	Worldwide [14]	mean 1.8	mean 0.7	40-55
	Poland [6]	-	2-6	-
	Germany [15]	0.7-1.7	0.15-0.7	-
	Tanzania [16]	17.8	8.6-8.9	48-50
	Portugal – Capinha	**3.5**	**2.0**	**70.8**
N-NH$_4$ (nitrification rate)	Worldwide [14]	mean 1.1	mean 0.4	50
	Germany [15]	1.1-1.6	0.5-0.6	-
	Tanzania [16]	10.9	3.0	27-28
	Portugal – Capinha	**3.0**	**1.8**	**72**

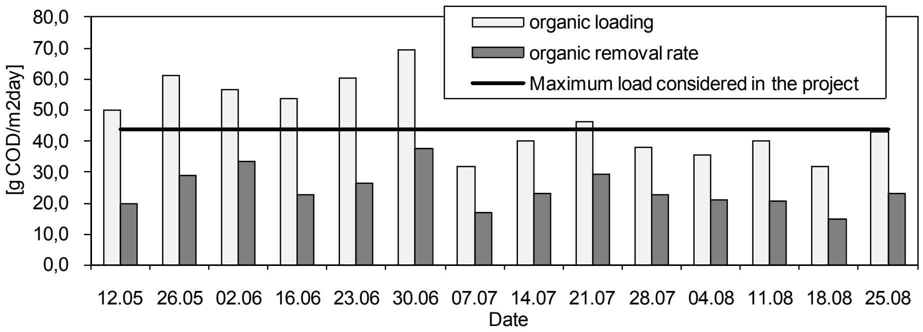

Fig. 5. Mass loading of COD and removal rate in time
Rys. 5. Obciążenie ChZT i efektywność usuwania w czasie

The greatest cause could be an increase in the work efficiency of the Imhoff tank in the second period. In May and June the average COD removal efficiency in the Imhoff tank was 25.4% whereas in July and August it was 36.9%. Such difference could be due to re-suspension of the bottom sludge in the spring period of monitoring. However, it is important to notice than in the first analyzed period the loading values were exceeded in comparison to the design criteria; therefore the system was more likely to fail to deal with that amount of COD in the influent.

The organic removal rate was higher in the first period with the average of 28.2 g COD/m^{2}day in comparison to 21.5 g COD/m^{2}day in the second which was mostly due to much higher organic loading in the first period. However, better removal rates in the first period proved that the removal capability of the system can be high (probably even higher) and that the system did not reach the maximum of its capability. Such occurrence could be explained by problems in exploitation of the CW, shown by clogging, probable existence of the dead zones inside of the bed and short – circuiting. That could lead to not enough growth of the biofilm where the main removal processes take place. It also seems that the effective area for organic matter uptake may be not enough to reach the desirable removal efficiencies.

However, according to Kowalik [6] one stage constructed wetland (as Capinha system) is able to remove about 15.0 g COD/m^{2}day and from 2.0 to 6.0 g N/m^{2}day. The average COD removal rate for Capinha was 24.2 g COD/m^{2}day whereas the average total nitrogen removal rate was 2.1 g COD/m^{2}day. Therefore the values for COD correspond to those from Kowalik quite well whereas low values for nitrogen was due to low nitrogen loading to the system (3.5 g COD/m^{2}day). According to worldwide experience reported by Vymazal [7], the average COD removal rate in horizontal flow constructed wetlands is 8.5 g COD/m^{2}day, which is much lower than the rate in the Capinha system.

The COD loading was 47.1 g/m^{2}day whereas the value recommended in the literature is less than 15.0 g/m^{2}day [3] or less than 16.0 g/m^{2}day [10]. The TSS loading was 13.5 g/m^{2}day whereas the one recommended in the literature is 5.4 g/m^{2}day [7], also the concentration of TSS according to the literature should not exceed the value of 100 mg/L [10] while the average TSS concentration in the influent was 118.6 mg/L.

The study of different organic loading 20, 27, 40 g COD/m^{2}day but for vertical flow constructed wetlands showed that only the system with the loading of 20 g COD/m^{2}day met the required effluent standards and removal efficiencies the whole year round [11]. Also in case of Capinha the first period with higher organic loading (average of 58.6 g COD/m^{2}day) did not perform well in terms of COD and TSS removal.

The case study from New Zeeland [9] presents the results for TSS removal for different mass loading, however the values are lower than the one from the Capinha system (the average loading is 13.5 gTSS/m^{2}day. For the most close mass loading (8.5 g TSS/m^{2}day) the removal efficiency was 78% and the concentration in the effluent was 33 mg/L and remained at the same level no matter the mass loading. Also the other data presented in the literature [6] for the TSS loading between 5.22 and 7.37 g TSS/m^{2}day shows much better results with the average removal of 89%. According to Vymazal [7] the average TSS removal rate in horizontal flow constructed wetlands all over the world, for the loading of 5.4 g TSS/m^{2}day, is 4.2 g TSS/m^{2}day. The average TSS removal rate in Capinha was 6.1 g TSS/m^{2}day.

The ammonia concentration and a mass loading in the influent was increasing in time, however it did not correspond with the effluent concentration which from the 6th assay was very stable. Comparing values for ammonia and DO variation (Table 3), the correspondence of DO concentration in the influent to the ammonia consumption can be found, especially noticeable during on the 16th of June when DO content increased sharply reaching the highest value. The ammonia value in the effluent decreased at that time sharply as well and reached one of the lowest concentration values (1.1 mg/L)) and one of the highest removal efficiency. Starting from the 7th assay DO content was more stable (above 1.0 mg/L) likewise the ammonia content in the effluent which from the 6th assay was very stable and low (between 1.2 and 5.2 mg/L). Taking into account the concentration value of the ammonia in the influent, it also can be noticed that the overall concentration in the effluent depends more on the DO concentration in the influent than on the initial concentration of in the influent.

Ammonia loading during the analyzed time did not show any significant differences between the first and the second period, however a slightly higher loading was observed in the second period with the average of 3.2 g N-NH$_4$/m^{2}day whilst in the first it was 2.8 g N-NH$_4$/m^{2}day (Figure 6).

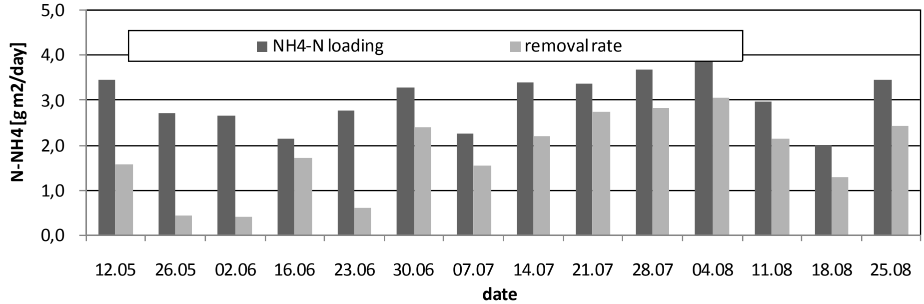

Fig. 6. Mass loading of $N\text{-}NH_4$ and removal rate in the period of investigation
Rys. 6. Obciążenie $N\text{-}NH_4$ i efektywność usuwania w czasie

However, the $N\text{-}NH_4$ removal rate in both periods varied significantly in favour of the second one. During May and June the rate was very unstable with the average value of 1.2 g $N\text{-}NH_4/m^2$day and the average removal efficiency of 43.8%. In July and August $N\text{-}NH_4$ removal rate stabilized and reached high values with the average of 2.3 g $N\text{-}NH_4/m^2$day and the removal efficiency of 89.1% which showed that the system worked very well in terms of ammonia removal in the summer period. Higher and more stabilized values in that period could be partly explained by slightly higher temperature of the sewage, which was 23.6°C in comparison to 22.6°C in the first one. Higher temperature increases kinetics rate, however in that case the temperature rise was not so significant. Temperature could also be one of the factors affecting organic removal rate. Although the kinetic ratio could be quicker, an organic loading seems to be more important factor. As it was lower in the second period, in spite of the higher temperature, the removal rate was also lower comparing to the first period.

Temperature factor is not enough to explain such low $N\text{-}NH_4$ removal rates in the first period. There is also no reason to assume that the plant uptake was responsible for a significant ammonia removal (between 5 to 10% according to [7]). Another important point to notice can be the differences of pH values between the first and the second analyzed period with the average of 7.09 and 7.51 respectively. As it is known that the optimum pH values for the nitrification process is around 7.6, therefore higher values in the second period could partly explain much better $N\text{-}NH_4$ removal rate.

The most important factor taken into account in case of $N\text{-}NH_4$ removal rate and carbon removal is oxygen concentration. Oxygen is necessary for the aerobic COD degradation, which is quicker and more effective than anaerobic one and does not produce toxic compounds. The oxygen concentration higher than 0.5 mg/L is essential for the nitrification process, therefore its lack may lead to the lower $N\text{-}NH_4$ removal rate and even to its inhibition. The average

DO concentration in the influent was 1.22 mg/L, however in the first period of analyses oxygen content was unstable reaching in few assays low values (near 0.5 mg/L) which could partly explain unstable N-NH_4 removal rates in that period. An important point to notice is that oxygen provided to the system was consumed both by the nitrification bacteria and the heterotrophic ones, decomposing carbon compounds. Therefore they must compete with each other about the oxygen available in the environment and heterotrophic bacteria overtake nitrification ones in the oxygen consumption which the data from Capinha system can confirm [7]. In the first period of monitoring (May and June) when the N-NH_4 removal rate was unstable and rather low, organic loading as well as organic removal rate were high. This occurrence could be partly explained by the fact that due to the higher organic loading there was a higher oxygen demand to remove both carbon and nitrogen compounds. Apparently available oxygen was only enough to remove a great deal of COD and was not enough to fully oxygenate ammonia present in the bed. Moreover, during the second period (July and August) when DO concentration in the influent was almost at the same level but the average organic loading was much lower (as well as organic removal rate), the nitrification rate was stable and satisfactory high.

However, the average N-NH_4 removal rate in both periods was 1.8 g N-NH_4/m^2day, which is much higher than the one reported by Vymazal [7] basing on worldwide experience, which is 0.36 g N-NH_4/m^2day.

There is a significant similarity between the ammonia and nitrate changes. Similar to ammonia, nitrate concentration and mass loading in the influent also increased with the time reaching the highest values at the end of monitoring (Fig. 7). However, the effluent concentration did not respond to those high values and stayed on the same level over the monitored period with the average concentration of 0.45 mg/L and the average removal efficiency of 59%.

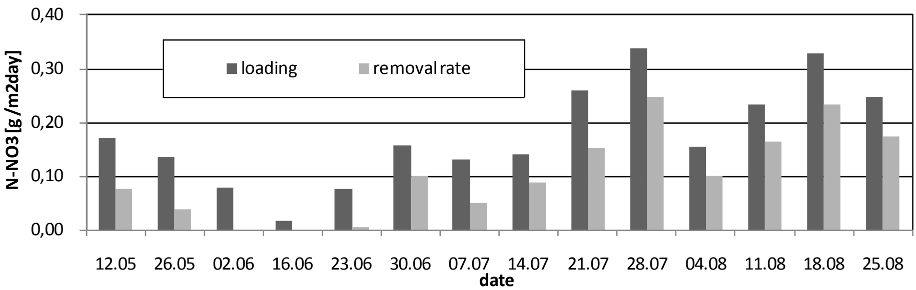

Fig. 7. Mass loading of N-NO_3 and removal rate in the period of investigation
Rys. 7. Obciążenie N-NO_3 i efektywność usuwania w czasie

5. Conclusions

In order to evaluate the performance of the Capinha Constructed Wetland, the analyses of biochemical and physical parameters of the sewage and of the system during 4 months period were performed and the following conclusions were drawn from this study.

1) In terms of chemical oxygen demand (COD) and (TSS) removal the average effluent concentration was higher than the one recommended by the Urban Wastewater Directive (271/91/EEC), which could be explained by the clogging of the system. The system showed lower removal efficiencies but higher removal rates than the ones observed in other international studies
2) System showed good results in terms of nitrogen removal (total N, N-NO_3, N-NH_4) of the average removal efficiency of 70% which is much higher that reported for the systems for similar climate conditions (average of 40-50%).
3) Good correlation between mass removal rates and mass loading was observed for all measured contaminants. In case of N-NO_3 removal the correlation was linear
4) High discrepancy between system performance in May – June and July – August was observed. Both mass removal rates and removal efficiencies were much higher in the second period, especially in case of nitrogen removal (total N, N-NO_3, and N-NH_4).

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Usuwanie substancji organicznej, związków azotu oraz zawiesiny w obiekcie hydrofitowym typu SSHF w miejscowości Capinha w Portugalii

Streszczenie

Wiejskie miejscowości w Portugalii, w porównaniu do miast, prezentują niski poziom infrastruktury do oczyszczania ścieków. Z tego względu szczególnie istotne jest zastosowanie rozwiązań technicznie i ekonomicznie uzasadnionych, takich jak systemy hydrofitowe. Obiekty te umożliwiają osiągnięcie jakości oczyszczonych ścieków zgodnych z Ramową Dyrektywą Wodną – 2000/60/EEC a także z Dyrektywą - 91/271/EEC. Wśród krajów basenu Morza Śródziemnego jedynie Francja i Włochy posiadają wytyczne do projektowania systemów hydrofitowych. Duża część takich systemów projektowana była według doświadczeń krajów o umiarkowanym klimacie. Z tego względu w dalszym ciągu istnieje potrzeba sformułowania wytycznych dla krajów ciepłego klimatu. W literaturze jest brak dostatecznych informacji odnośnie zachowania i efektywności systemów hydrofitowych w Portugalii. Z opublikowanych dotychczas danych wynika, że systemy te osiągały wysokie efektywności usuwania substancji organicznej, natomiast niższe w odniesieniu do związków biogennych. Celem pracy była ocena funkcjonowania systemu hydrofitowego z podpowierzchniowym przepływem wody (SSHF) usytuowanego w miejscowości Capinha w Portugalii, głównie pod względem usuwania substancji organicznej oraz związków azotu. Podczas czteromiesięcznego monitoringu obiekt wykazał nieregularność w usuwaniu zawiesiny ogólnej oraz substancji organicznej, wyrażonej w formie ChZT. Efektywności usuwania były mniejsze w porównaniu do wyników publikowanych wcześniej ale ładunek usuwanych zanieczyszczeń z powierzchni jednostkowej był zbliżony. Średnie stężenie substancji organicznej wyrażonej w formie ChZT na odpływie a także średnie stężenie zawiesiny ogólnych przekroczyło wartości podane w Ramowej Dyrektywie Wodnej. Przekroczenie wartości może wyjaśniać zjawisko kolmatacji, które miało miejsce na analizowanym obiekcie. Zaobserwowano także proporcjonalną zależność szybkości usuwanych zanieczyszczeń do ładunku zanieczyszczeń dopływających do systemu. Szybkość usuwania zanieczyszczeń organicznych z powierzchni wynosiła 28 g ChZT/m^2·d, chociaż powierzchnia efektywna wydaje się zbyt mała by osiągnąć zadowalającą efektywność usuwania zanieczyszczeń organicznych. W odniesieniu do usuwania azotu (Nog, N-NO_3, N-NH_4), uzyskano wysoką efektywność wynoszącą 70% oraz średnią szybkość procesu nitryfikacji na poziomie 1,8 g N-NH_4/m^2·d. Są to wartości znacznie wyższe niż wartość prezentowane w międzynarodowych publikacjach (średnie wartości wynoszą odpowiednio: efektywność – 40÷50% i szybkość procesu nitryfikacji – 0,4 g N-NH_4/m^2·d). Zaobserwowano również różnice w funkcjonowaniu systemu między okresem wiosennym (kwiecień, maj) a letnim (czerwiec, lipiec), co wynika przede wszystkim ze znacznych różnic między średnią temperaturą powietrza. Zarówno szybkość usuwania zanieczyszczeń, jak i efektywność usuwania były wyższe w okresie letnim, głównie w odniesieniu do związków azotu.