

CONSTRUCTED WETLANDS SYSTEMS FOR WASTEWATER TREATMENT IN POLAND

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Abstract

Constructed wetland systems for treatment of wastewater from rural aeries could be an interesting alternative for conventional wastewater treatment plant.

The objective of this paper was to evaluate the performance and efficiency of organic pollutants removal of hybrid constructed wetlands in the Gdańsk region working in temperate climate and under different loadings. Facility consisting of septic tank and vegetated subsurface bed (willow or reed) could be recommended for treatment of wastewater in rural areas. Hybrid Constructed Wetland (HCW) provides efficient and stable both organic matter and nitrogen removal with the efficiency up to 95.7% of BOD₅ and 78.0 % of N_{Tot}. It was indicated that mass removal rates (MRRs) of organic matter (BOD, COD) for analysed HCW were independent of applied configuration in contrast to the MRRs of total nitrogen. The highest MRR of nitrogen (1.06 gNm⁻²day⁻¹) was observed for vertical flow beds in Wiklino facility with unit area of 4.0 m²pe⁻¹.

There is a farther need to explain the main processes responsible for nitrogen removal and relationship between discharging loads and configurations of hybrid constructed wetlands.

Streszczenie

Oczyszczalnie hydrofotowe mogą stanowić interesującą alternatywę dla konwencjonalnych rozwiązań gospodarki ściekowej na terenach o rozproszonej zabudowie.

Celem pracy była ocena działania i skuteczności usuwania zanieczyszczeń w hybrydowych systemach hydrofitowych pracujących w rejonie Gdańska, w klimacie umiarkowanym. Technologiczne rozwiązanie składające się z osadnika gnilnego oraz złoża hydrofitowego z podpowierzchniowym przepływem ścieków może być zalecane do oczyszczania ścieków bytowo-gospodarczych powstających na terenach wiejskich. Hybrydowe systemy hydrofitowe (HSH) zapewniają efektywne i stabilne w czasie usuwanie zarówno substancji organicznej (95.7%) jak i azotu ogólnego (78.0%). Wykazano, że wydajność usuwania substancji organicznej z 1m² złoża nie zależała od konfiguracji systemu, podczas gdy wydajności usuwania azotu uzależniona była od zastosowanej konfiguracji. Największą wydajnością usuwania azotu charakteryzował się obiekt w Wiklinie (1.06 gNm⁻²d⁻¹) w którym kwatery zraza pionowego (2.0 m²M⁻¹) zasilane były ściekami okresowo.

Keywords: Sewage treatment; Constructed wetland; Vertical flow; Contamination load.

1. INTRODUCTION

In rural areas of Poland the awareness of solving problems connected with wastewater treatment increases. There is a huge gap between water supply and wastewater treatment in the countryside. It is

estimated that about 1 km³year⁻¹ of untreated wastewater in these regions is discharged to surface water or to the soil.

Scattered localization of farms combined with an irregular inflow of wastewater causes that the tradi-

tional wastewater treatment systems applied in municipal areas are inadequate in the rural ones. Recently an idea of treating wastewater in the constructed wetland systems has emerged. These systems have been operating in Poland for about 15 years.

Implementation in 2002 less restrictive requirements for discharged sewage create better condition for constructed wetland methods. According to the new standards treated sewage from less than 2000 pe and above 50 pe has to fulfil following criteria: $BOD_5 \leq 40 \text{ mg O}_2 \cdot \text{l}^{-1}$, $COD \leq 150 \text{ mg O}_2 \cdot \text{l}^{-1}$, and $SS \leq 50 \text{ mg} \cdot \text{l}^{-1}$ [1].

Up till middle nineties mainly one stage Constructed Wetlands with Horizontal Flow (HF CWs) of wastewater were applied in Poland. One stage systems were applied both for individual household and for local communities up to flow of $90.0 \text{ m}^3 \cdot \text{day}^{-1}$. The major characteristics of the HF CWs for individual household were as follows (i) the area of the bed was based on the surface area per capita loading $4.5 \text{ m}^2 \text{ pe}^{-1}$, which means that specific surface loading of a bed was approximately $29 \text{ cm}^3 \text{ m}^{-2} \cdot \text{day}^{-1}$, (ii) length of the bed equals $L=20.0 \text{ m}$ at all facilities, (iii) the width W of the beds was variable, depending on the number of persons; $W = 1.0 \text{ m}$ for 4 pe and $W = 1.5$ for 8 pe, respectively (iv) the average depth of the bed of individual system was equal 1.0 m and the slope of the bed bottom 1.0% [2]. The BOD_5 loading ranged between 1.21 and $5.76 \text{ g O}_2 \text{ m}^{-2} \cdot \text{day}^{-1}$ and the loading of COD ranged from 2.79 to $9.06 \text{ g O}_2 \text{ m}^{-2} \cdot \text{day}^{-1}$. The loading of organic nitrogen varied from 0.09 to $0.72 \text{ g} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. Total phosphorus loading in investigated plants was between 0.09 and $0.47 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$. Mass removal rate of organic compounds expressed as BOD_5 and total nitrogen ranged from 0.4 to $8.2 \text{ g BOD}_5 \text{ m}^{-2} \cdot \text{day}^{-1}$ and 0.6 to $1.1 \text{ g N}_{\text{tot}} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. The removal efficiency of organic matter was very high and varied from 68.1 to 99.0% , while total nitrogen removal efficiency varied significantly from 22.4 to 62.3% and in many cases was insufficient [2]. According to *Sardon et al.* in case of HF CW removal efficiency of 86% in BOD_5 has been achieved with the loads of $21.0 \text{ g BODm}^{-2} \cdot \text{day}^{-1}$ [3].

The improper operation of septic tanks and lack of good link between the subsequent units were the most frequent reasons for recontamination of sewage and lower efficiency of wastewater treatment in case of one stage HF CWs. While according to *Alvarez et al.* high effective pre-treatment of raw wastewater (e.g. anaerobic pre-treatment) could minimize the danger of clogging and improve the efficiency of pol-

lutants removal, in CWs as well as it could result in reduction of $30\text{-}50\%$ of the necessary wetland area [4].

In case of application of local one stage HF CWs the unit area per person ranging from 2.7 up to 10.0 m^2 and the depth from 0.4 to 0.9 m were applied. Similarly to single family household, CWs the efficiency of BOD removal was quite satisfactory up to 78.7% whilst total nitrogen efficiency did not exceed 44.7% . Mass removal of organic compounds expressed as BOD_5 and total nitrogen rate for local CWs ranged from 1.0 to $4.5 \text{ g BODm}^{-2} \cdot \text{day}^{-1}$ and 0.2 to $0.9 \text{ g N}_{\text{tot}} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ [2].

Problems with clogging and unstable efficiency of nitrogen removal caused interest in VF CW beds due to better oxygen condition enhanced by intermittent loadings [5, 6, 7]. Single-stage VF CW, with unit area of $4 \text{ m}^2 \text{ pe}^{-1}$, may provide effective organic matter removal even for loadings of $40 \text{ g COD m}^{-2} \cdot \text{day}^{-1}$ and the effluent meets Austrian requirements irrespective of season and air temperature (COD below $90 \text{ mg O}_2 \text{ l}^{-1}$ and BOD $25 \text{ mg O}_2 \text{ l}^{-1}$) [8]. According to *Sardon et al.* in case of VF CW 95% of performance in BOD_5 have been achieved with loads of $22.1 \text{ gBODm}^{-2} \cdot \text{day}^{-1}$ [3]. In recent years the increase of interest in hybrid constructed wetland systems (HCWs) has been observed [9, 10, 6]. These systems are composed of two or more filters with mixed flow direction of sewage. Apparently in the HCWS the benefits of both types of bed are merged, resulting in better effluent quality (lower organic matter concentration, complete nitrification and partial denitrification) [11, 10, 4]. In Europe two configurations of the hybrid constructed wetlands (HCWs) are used, with either vertical-flow bed or horizontal-flow bed at the beginning of biological treatment process. In Poland only configurations proposed by *Johansen and Brix et al.* 1993, with horizontal-flow bed at the beginning, were used [9].

The objective of this paper was to evaluate the performance and efficiency of organic pollutants removal of hybrid constructed wetlands in the Gdańsk region working in temperate climate and under different loadings.

2. METHODS

In the period from 1995 to 2007 the measurements of pollutants removal in 3 hybrid reed wetland systems (composed of HF-CW and VF-CW filters) in Wiklino, Wieszyno and Sarbsk in Pomerania Region

Table 1.
Characteristics of hybrid constructed wetland systems

Plant	Q[m ³ day ⁻¹]	Configuration	Area [m ²]	Depth[m]	Hydraulic load [cm ³ m ⁻² day ⁻¹]	Unit area [m ² pe ⁻¹]
Wiklino	18.6	HF I	1050	0.6	17.7	7.0
		VF	2×312	0.4	46.9	2.0
		HF II	540	0.6	34.4	3.4
		Σ	2 214		8.4	Σ 12.4
Wieszyno	24.5	HF I	600	0.6	40.8	3.0
		VF	300	0.6	81.7	1.5
		HF II	600	0.6	40.8	3.0
		Σ	1 500		16.3	Σ 7.5
Sarbsk	29.7	HF I	1610	0.6	18.5	8.5
		VF	520	0.5	38.6	2.6
		Σ	2 130		13.9	Σ 9.1

were carried out (Table 1). Analysed hybrid constructed wetlands (HCWs) differ significantly as to the unit area per person as well as working condition of Vertical Flow beds (VF-CW) [12].

Composited samples of influent (sewage after mechanical stage before the constructed wetland), effluent (sewage after the constructed wetland) and after subsequent stages of biological treatment in all systems were analysed. Samples were collected once or twice a month. In order to evaluate the efficiency of organic matter and nitrogen removal in subsequent stages of treatment the following parameters were measured: organic matter (COD and BOD₅), total nitrogen, ammonium nitrogen (NH₄⁺ - N), nitrate, nitrite according to Polish standards. The measurements of the inflow of sewage to subsequent treatment stages were very important.

Analyses were carried out according to the procedures presented in the Polish Standards and the recommendations stated in the Environment Ministry Decree [1].

Removal efficiency was calculated as a quotient of pollutants concentration difference at the influent (C_{inf}) and at the effluent (C_{eff}) after subsequent stages of treatment in constructed wetland and the concentration at the influent (C_{inf}), $\eta = (C_{inf} - C_{eff}) / C_{inf}$ using data in Table 2.

Mass removal rate (MRR) was calculated on the basis of the following equation :

$$MRR = [(C_{inf}Q_{inf}) - (C_{eff}Q_{eff})] / A \quad [g \ m^{-2}day^{-1}] \quad (1)$$

where:

A – area of CW, m²,

Q_{inf} and Q_{eff} – average values of wastewater discharged at the influent and effluent, m³ day⁻¹

C_{inf} and C_{eff} – average concentration of contamination at the influent and effluent, mg l⁻¹.

3. HYBRID CONSTRUCTED WETLANDS (HCWs) PERFORMANCE

The comparison of mean values of characteristic pollutants in wastewater influent and effluent with standard deviation for analysed HCWs is given in Table 2.

In analysed measurement period very efficient organic matter and suspended solids removal took place in the facilities (Table 2). The highest removal efficiency of BOD was observed in CW Wiklino and the lowest in CW Wieszyno:

$$Wiklino > Sarbsk > Wieszyno$$

$$BOD_5 \quad 95,7\% > 95,5\% > 86,9\%$$

The highest efficiency of total nitrogen removal was observed in Wiklino and the lowest in Wieszyno. The average total nitrogen removal efficiencies could be described as follows (Table 2):

$$Wiklino > Sarbsk > Wieszyno$$

$$N_{tot} \quad 78,0 \% > 64,3 \% > 23,4 \%$$

Table 2.
Mean values of pollutants in HCWs (in influent *and effluent **)

Parameters	Unit	Wiklino, n=88	Wieszyno, n=18	Sarbsk, n=38
TSS	mg l ⁻¹	<u>539.3±127.2*</u> 36.3±17.2**	<u>1269.5±167.6</u> 106.4 ±31.7	<u>819.9±208</u> 45.6 ±49.9
COD	mg O ₂ l ⁻¹	<u>466.3±92.7</u> 31.5±8.9	<u>1021.9±251.2</u> 175.9±99.3	<u>687.6±162.9</u> 44.2 ± 15.9
BOD ₅	mg O ₂ l ⁻¹	<u>265.2±51.7</u> 10.9±4.1	<u>657.3±118.5</u> 85.9±53.6	<u>420.0±87.2</u> 19.0 ± 1.7
N _{tot}	mg l ⁻¹	<u>104.1±10.2</u> 21.7±5.5	<u>114.0±22.1</u> 87.3±14.8	<u>73.8±21.9</u> 27.6 ± 8.5
NH ₄ ⁺ -N	mg l ⁻¹	<u>87.3±9.0</u> 6.0±4.3	<u>84.8±15.3</u> 67.1±14.2	<u>47.1±13.7</u> 16.8 ±11.2
NO ₃ ⁻ -N	mg l ⁻¹	<u>0.8±0.2</u> 9.6±6.7	<u>1.0±0.4</u> 0.6±0.3	<u>0.93±0.12</u> 5.03 ±9.38
Norg	mg l ⁻¹	<u>16.2±5.3</u> 4.3±1.7	<u>27.9±8.9</u> 19.53±12.91	<u>25.9±7.3</u> 5.8 ±2.3
P _{tot}	mg l ⁻¹	<u>15.2±0.7</u> 7.2±1.6	<u>20.1±1.2</u> 14.6±3.9	<u>11.9±0.9</u> 8.9±3.1

n- number of samples

Table 3.
Load of pollutants and flow of sewage to hybrid constructed wetlands, kg day⁻¹

WIKLINO				
	Inflow	After HF-CW I	After VF-CW	After HF-CW II
Q _{rd} , m ³ day ⁻¹	18.15±0.37	15.46±0.53	14.57±0.26	11.40±0.23
L _{COD}	8.46±2.02	1.24±0.55	0.81±0.96	0.29±0.10
L _{BOD5}	4.92±1.01	0.66±0.38	0.24±0.11	0.16±0.20
L _{tot}	1.83±0.21	0.94±0.23	0.61±0.24	0.23±0.14
L _{-NH4+}	1.56±0.12	0.61±0.20	0.30±0.16	0.06±0.03
L _{org}	0.028±0.022	0.028±0.022	0.015±0.012	0.008±0.008
WIESZYNO				
	Inflow	After HF-CW I	After VF-CW	After HF-CW II
Q _{rd} , m ³ /d	24.14±0.15	23.85±0.34	23.81±0.36	23.47±0.44
L _{ODCr}	23.68±3.86	9.68±3.37	6.98±2.75	4.88±2.48
L _{OD5}	15.08±3.02	4.55±1.67	3.31±1.19	1.99±1.47
L _{tot}	2.76±0.50	2.46±0.51	2.18±0.40	2.01±0.44
L _{-NH4+}	2.01±0.42	1.81±0.36	1.59±0.40	1.50±0.45
L _{org}	0.068±0.045	0.060±0.048	0.222±0.040	0.046±0.031
SARBSK				
	Inflow	After HF-CW	After VF-CW	
Q _{av} , m ³ /d	29.86±0.90	24.06±0.11	23.58±0.34	
L _{CODCr}	2.04±0.54	0.13±0.02	0.10 ±0.04	
L _{BOD5}	1.26±0.24	0.046±0.005	0.045 ±0.004	
L _{Ntot}	0.22±0.08	0.09±0.02	0.07 ±0.02	
L _{N-NH4+}	0.14±0.04	0.07±0.02	0.04 ±0.03	
L _{Norg}	0.08±0.04	0.02±0.01	0,01 ±0,02	

The HF-CW beds in Wiklino and Sarbsk were characterized by higher total nitrogen removal efficiencies (55.1% and 47.4% respectively) in comparison to the ammonium nitrogen removal efficiency (49.7% and 34.6%). The efficiencies of ammonium nitrogen removal in VF-CW beds were much better in comparison to HF-CW beds in the same facility: 70.0% for Wiklino and 45.5% for Sarbsk. Also removal efficiencies of total nitrogen for those beds were much lower: 34.6% and 28.9 %, respectively.

Determined values of characteristic load pollutants infolded into subsequent stage of treatment in analysed hybrid constructed wetlands are given in Table 3.

The CW in Wieszyno received several times higher loads of contaminations in comparison to loads discharged to two other CWs (Table 3). Basing on literature studies and authors' experience it is concluded that vertical beds play a very important role in removal of organic substances and nitrogen. To ensure the best operation conditions of such beds it is necessary to optimize hydraulic and contamination loads. Platzer reported that even though higher hydraulic load equal $300 \text{ cm}^3\text{m}^{-2}\text{d}^{-1}$ was discharged to VF-CW, effective nitrification and removal of nitrogen compounds was still observed [13].

Müller and Lützner proved that CW designed with larger unit areas per person equivalent (for example in Austria the unit area is $5 \text{ m}^2\text{pe}^{-1}$) are more resistant to clogging caused by oxygen depletions [14].

Problems connected with clogging of vertical beds were described by Kunst and Flasche as well as by Platzer and Mauch [15, 16]. According to Kunst and Flasche efficiency of contamination removal in clogged beds decreased to about 35% of former efficiency for COD and to about 76.2% for ammonium, while concentration of inorganic forms of nitrogen (mainly N-NO_3^-) decreased over 70 times. Platzer and Mauch proved that the beds with low hydraulic loads and higher loads of organic matter are less resistant to clogging. According to these authors permissible maximum load of organic matter discharged to the bed is equal $25 \text{ g COD m}^{-2}\text{day}^{-1}$ in climate conditions of central Europe [15, 16].

Designed unit area for HF-CW bed for first stage of treatment in CW Wiklino was equal $7.0 \text{ m}^2\text{pe}^{-1}$ and in Sarbsk it was $8.5 \text{ m}^2\text{pe}^{-1}$. Both values were higher than minimal recommended unit area $A_h \geq 5 \text{ m}^2\text{pe}^{-1}$ [17, 18, 19, 20, 21]. In CW Wieszyno the unit area equalled $3.0 \text{ m}^2\text{pe}^{-1}$ only. Similar unit areas for VF-CW beds

were designed (in Wiklino $2.0 \text{ m}^2\text{pe}^{-1}$ and in Sarbsk $2.6 \text{ m}^2\text{pe}^{-1}$) to ensure proper conditions for nitrification process. According to Cooper unit area of VF-CW designed for organic matter removal only should be above $1.0 \text{ m}^2\text{pe}^{-1}$, while for efficient nitrification over $2.0 \text{ m}^2\text{pe}^{-1}$ is necessary [19].

The third stage of treatment in CWs Wiklino and Wieszyno takes place in HF-CW beds with unit areas equal $3.4 \text{ m}^2\text{pe}^{-1}$ and $3.0 \text{ m}^2\text{pe}^{-1}$, respectively. According to Cooper the unit area of HF-CW beds located in such a position in the course of treatment should be between 0.7 to $1.0 \text{ m}^2\text{pe}^{-1}$ [20]. According to Birkedal et al. if only a VF-CW bed with sewage recirculation is applied after HF-CW bed effective removal of total nitrogen and allows for decreasing of the unit area of the total facilities to $10.0 \text{ m}^2\text{pe}^{-1}$. Total unit area of the facility in Sarbsk was higher and equalled $11.1 \text{ m}^2\text{pe}^{-1}$ [21].

The average load of total nitrogen removed in the analysed CWs could be described as follows:

$$\begin{aligned} & \text{Wiklino} > \text{Sarbsk} > \text{Wieszyno} \\ N_{\text{tot}} & 1.44 \text{ kg day}^{-1} > 1.17 \text{ kg day}^{-1} > 0.49 \text{ kg day}^{-1} \end{aligned}$$

Applied configuration and the way of wastewater discharge to the beds in Wiklino and Sarbsk were appropriate for nitrification process. The results of this study confirm that additional aeration of wastewater caused by periodical dosing of sewage creates favorable conditions for nitrification process.

HCW in Wieszyno provided only efficient removal of organic matter, while removal of nitrogen was insufficient. VF-CW beds in Wieszyno are continuously supplied with sewage and the beds work in series. Total unit area of those beds was only $1.5 \text{ m}^2\text{pe}^{-1}$. To ensure the nitrification process the German ATV recommends minimal unit area of $3.0 \text{ m}^2\text{pe}^{-1}$ [22]. As a consequence, hydraulic load of the VF-CW in Wieszyno was the highest in comparison to facilities in Wiklino and Sarbsk and equalled $81.7 \text{ cm}^3\text{m}^{-2}\text{day}^{-1}$ (Table 1). Additionally, the oblong shape of the VF-CW beds ($3.0 \times 50.0 \text{ m}$ each) was very unfavourable for efficiency removal and that construction of wastewater discharge (point, gravitational discharge) did not provide uniform flooding of the beds. In the consequence, the whole bed area was not used and contamination removal efficiency decreased.

Table 4 presents average mass removal rate (MRR) from 1 m^2 of hybrid constructed wetlands. The MRRs for total nitrogen varied significantly from 0.04 to $1.06 \text{ g m}^{-2}\text{day}^{-1}$. According to Brix et al. the MRR not exceeded the value of $0.7 \text{ gN}_{\text{tot}} \text{ m}^{-2}\text{day}^{-1}$ given for systems in Denmark [9]. Obtained results suggest that

Table 4.
Average mass removal rates of contaminants in HCWs, $\text{gm}^{-2}\text{day}^{-1}$

Wiklino								
	HF-CW I		VF-CW		HF-CW II		TOTAL	
	Load	MRR	Load	MRR	Load	MRR	Load	MRR
COD	8.06	6.88	3.95	1.38	1.5	0.96	4.44	4.29
BOD	4.68	4.06	2.11	1.35	0.44	0.15	2.58	2.5
N _{Tot}	1.75	0.89	3.0	1.06	1.12	0.70	0.96	0.84
Wieszyno								
COD	39.47	23.33	9.0	9.0	3.5	3.5	19.73	15.5
BOD	26.13	17.55	4.13	4.13	2.2	2.2	12.56	10.9
N _{Tot}	4.6	0.5	0.9	0.9	0.15	0.15	2.3	0.62
Sarbsk								
COD	1.27	1.19	0.25	0.05	-	-	0.96	0.9
BOD	0.78	0.75	0.074	0.002	-	-	0.59	0.57
N _{Tot}	0.14	0.08	0.17	0.04	-	-	0.073	0.07

the MRR of pollutants from 1 m^2 changed proportionally to the loading value. At the same time, organic matter in hybrid constructed wetlands was removed highly effectively in the wide loading range, irrespectively of the applied HCW configuration, however, the MRR of nitrogen compounds was more related to the applied configuration than to the values of nitrogen loading applied.

4. CONCLUSIONS

1. Technological units for wastewater treatment consisting of septic tank and vegetated subsurface bed (willow or reed) could be recommended for treatment of wastewater in rural areas.
2. Analysed hybrid constructed wetlands (HCWs) ensured effective and stable removal of suspended solids and organic matter (BOD_5 and COD) in the wide loadings range: $0.9 - 4.3 \text{ g CODm}^{-2}\text{day}^{-1}$.
3. The efficiency of nitrogen removal varied from 23.4 to 78.0% in the wide loadings range: $0.14 - 4.6 \text{ gNm}^{-2}\text{day}^{-1}$.
4. Mass removal rates of organic matter (BOD, COD) for analysed HCW were independent of applied configuration in contrast to the MRRs of total nitrogen.
5. The most effective removal of nitrogen was in HCW (Wiklino) with VF beds compartments with intermittent loadings.

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