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Original Research

Speciation of Organic Matter in Vertical Flow Constructed Wetlands

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Abstract

The object of our research were vertical flow constructed wetlands (VFCWs) that are a component of biological treatment of two hybrid hydrophyte systems located in Wieszyno and Wiklino, near Słupsk, Poland. The facilities that are subject to analyses are unified in terms of structure (filtration material, depth of bed and time of operation), but they differ in organic matter load, amounting respectively to: 8.0 gCOD/m^{2}day and 31.0 gCOD/m^{2}day.

The intensity of oxygenation of the facilities resulting from diffusive flow of oxygen to the soil was determined based on the measurements of oxygen diffusion coefficient in the soil (D_g). The analysis of the quality of organic matter in wastewater was concentrated on determining concentrations of the following four fractions: in suspended solids and in dissolved phase both decomposable and non-decomposable ones.

The investigation proved that the increase in load of organic matter resulted in deterioration of oxygen conditions in the bed, which in turn led to a decrease in efficiency of pollutant removal. Higher load of organic matter in the facility of Wieszyno as compared with Wiklino was the direct cause of VFCW clogging.

Keywords: constructed wetlands, vertical flow, speciation of organic matter, efficiency of removal, clogging of beds

Introduction

Recently, increasing interest in hydrophyte systems with vertical flow constructed wetlands (VFCW) has been observed. VFCWs may create suitable conditions for nitrification, and their efficient oxygenation also leads to efficient removal of organic matter [1, 2]. Research carried out by [3] in facilities in Poland proved that the capacity of VFCW to remove organic matter expressed in BOD_5 and total nitrogen amounted, respectively, to 97.4% and 41.6%. In comparison (for similar facilities located in Belgium) the following results were achieved: removal of COD – 94.0%, and suspended solids – 98.0% [4]. Likewise, in Germany [5] showed that the efficiency of organic matter removal expressed in COD in VFCW supplied by domestic wastewater with frequency of 3-12 times a day was high and amounted to 90.0%. However, experience with the operation of facilities in Germany shows that VFCW loaded with higher organic matter expressed in COD (exceeding: 20 gCOD/m^{2}day) were subject to gradual clogging of the beds [6]. According to [7], effective air flow – so-called "good aeration" – is only possible when upper layers of the bed have appropriate hydraulic features and the surface of the bed undergoes good drainage between successive doses of wastewater supplying the bed. Many authors, for example [7-10], have proven that blocking gas spaces in filtrating material due to the influent of suspended matter caused limitation of oxygen influent to soil filters.

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Table 1. Characteristics of analyzed facilities.

Surface [m^2]	Depth [m]	Material			Wastewater influent [m^3/day]	Hydraulic load [mm/day]	Number of supplies per day	Duration of supply [min.]
		Filling	Granining coefficient, $U=d_{60}/d_{10}$	Air-filled porosity of the soil (n_g)* [cm^3/cm^3]				
Wiklino								
624.0	0.6	Coarse grained sand	3.4	0.18-0.36	18.6	42.8	6	2
Wieszyno								
300.0	0.6	Coarse grained sand	3.4	0.06-0.30	24.5	77.6	3	15

* n_g = no – θ, where: n_o- total porosity [cm^3/cm^3]; θ - moisture [cm^3/cm^3]

Problems related to clogging of VFCW were described, among others, by [11, 12]. According to these authors the efficiency of pollutants removal in clogged beds decreases by 35.0% for COD as compared with initial values. As proven in research, subject to faster clogging are wetlands of high load of organic matter. It has been shown that the maximum allowable load of organic matter that can be supplied to the wetland in climate conditions typical for middle Europe is 25 g COD/m^2·day. According to [13], accumulation of suspended solids in the bed initially depends only on influent load of pollutants and capacity to retain them in the bed.

Influent of air to VFCW also depends on the presence of free spaces in soil pores and on the structure of the soil [14, 15]. For coarse-grain and structural soils the influent of oxygen will be greater than for firm, very humid and non-structure soils [14].

This paper attempts to make an assessment of the exploitation of VFCW depending on the quality and concentration of different fractions of organic matter in wastewater.

Materials and Methods

Study Facilities

Research subjects were VFCWs located in Wiklino and Wieszyno, close to Słupsk, in Pomorskie Voivodship. The analyzed facilities are supplied with domestic wastewater from rural areas. The VFCWs are unified in terms of filtrating material, their depth and exploitation time of 9 years. They differ in the method of supplying the wastewater, in hydraulic load and the load of supplied organic matter. The characteristics of analyzed VF-beds are shown in Table 1.

In Wiklino the wastewater was supplied to VF-beds periodically by a pump, and in Wieszyno the wastewater was carried gravitationally.

Methods

Samples of wastewater and filtrating material were taken once a month for a period of 21 months. Wastewater was sampled at the inlet and outlet from analyzed wetlands. Filtrating material was sampled from each bed separately from a number of places. Samples of soil were taken along the profile of the bed from four depths: 0-2.5 cm, 2.5-5.0 cm, 5-10 cm and 10-30 cm. Soil samples were always taken two hours after the wastewater was supplied to the bed.

Quality of organic matter present in the wastewater was determined on the basis of measurement of concentration of organic matter expressed in COD and BOD_5. Speciation of organic matter was carried out for the purpose of determining the participation and type of dissolved of biodegradable (S_S) and non-degradable (S_I) organic compounds as well as biodegradable (X_S) and non-degradable (refractory) suspended matters (X_I), according to the practice given in German guidelines [16].

Microbiological degradation capacity of organic matter was determined on the basis of constant rate of wastewater biodegradation (k) [17]. It was described based on the rate coefficient (k) value that was calculated from equation (1):

$$k=-\ln[(L_o-BOD_t)/L_o]/t, \quad (1)$$

...where: k – the empirical coefficient dependent on the quality of organic matter in wastewater, 1/day; L_o – total BOD at the first stage of biodegradation, mgO_2/l; BOD_t – BOD at time t, mgO_2/l; t – time, day.

The degree of wastewater dispersion was determined on the basis of the ratio of biodegradable fractions in the form of suspended matter and dissolved substances (X_S/S_S).

In order to determine the oxidation capacity of filtrating material, measurements of the oxygen diffusion coefficient in the soil (D_g) were carried out. Measurements of D_g coefficient were carried out in independent tests, using a measuring system built for this purpose [17].

The values of the coefficients characterizing the structure of filtrating material of analyzed beds (marked with symbols γ and μ) were determined on the basis of the relation between oxygen diffusion coefficient in the soil (D_g), oxygen diffusion coefficient for atmospheric air (D_o) and air-filled porosity of the soil (n_g):

$$D_g/D_o=\gamma\cdot n_g^{\mu}$$

Coefficient γ is dependent on gas porosity of the soil, and coefficient μ depends on the continuity and sinuosity of soil pores. When presenting the value D_g/D_o in the function of gas porosity in a logarithmic coordinate system, a straight-line dependence was obtained. The tangent of inclination angle of this straight equals to the value of μ, and the value D_g/D_o extrapolated to the value $n_g = 1$ corresponds with the value γ.

Results and Discussion

Quality of Wastewater

Fig. 1 presents average values of COD fraction concentrations in wastewater inflowing and outflowing from analyzed facilities. Wastewater flowing into the bed in Wieszyno was characterized with concentration values of all analyzed fractions a number of times higher than that inflowing to Wiklino. The fraction of hardly biodegradable suspended matters (X_S), amounting to 47.6% of total COD, dominated in wastewater on the effluent to VFCW in Wieszyno, whereas the percentage of this fraction in Wiklino in inflowing wastewater was almost twice as low and amounted to ca. 24.2% of total COD. Furthermore, the fraction of easily biodegradable dissolved substance (S_S) dominated in wastewater inflowing to the VF-bed in Wiklino, making more than 40% of total COD. It can be observed in Fig. 1 that the values of concentration of one COD fraction after treatment in both wetlands were not altered. This was the fraction of refractory dissolved substances (S_I). This fraction was not removed from wastewater in analyzed facilities.

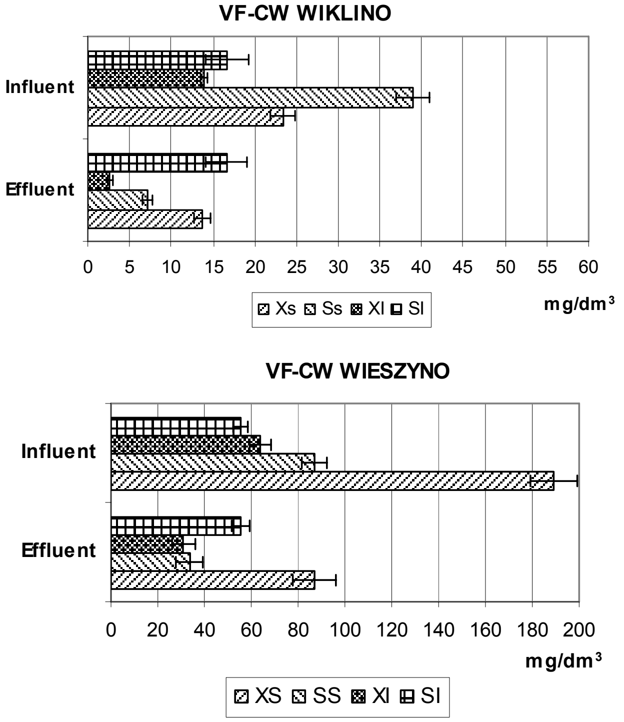

Fig. 1. Changes in COD fraction concentrations in wastewater on the influent and effluent from analyzed wetlands.

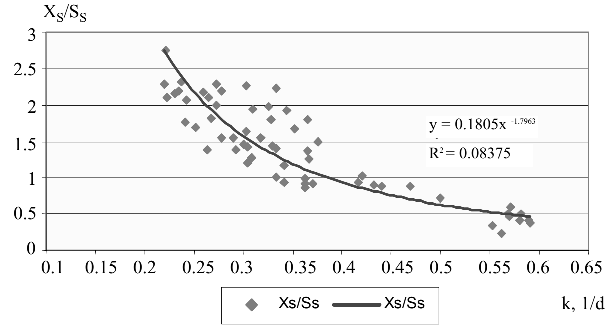

Fig. 2. Dependence between wastewater degradation rate coefficient, k, and dispersion degree of organic matter (X_S/S_S).

On the basis of our research it has been stated that suspended solids were of great impact on the capacity of wastewater to undergo biodegradation described with "k" coefficient. The degree of wastewater dispersion was determined as the ratio of participation of suspended solid fraction versus dissolved substance fractions susceptible to biodegradation (X_S/S_S). In Fig. 2, the values of X_S/S_S ratio are marked on the Y axis, and k coefficient values are given on the X axis. Analyzing the wastewater influent to the facilities it was stated that in Wieszyno were the most suspended solids, and in Wiklino – dissolved substances susceptible to biodegradation.

The wastewater flowing to Wieszyno in which suspended solid concentrations exceeded the double of concentration of biodegradable dissolved substances was characterized with k coefficient value equalling 0.25 1/day. As for the wastewater inflowing to Wiklino, a higher value of k coefficient was found (varying from 0.38 to 0.57 1/day), because dissolved substances fraction was dominant. The dependence presented in Fig. 2 also allows for stating that the wastewater characterized with higher participation of suspended solids were subject to degradation reactions considerably more slowly than organic dissolved substances.

Efficiency of Pollutant Removal

Figs. 3 and 4 show linear dependence between the removal of different COD fractions and surface load of VFCW in Wiklino and Wieszyno. When surface load increases, the amount of degraded X_S, X_I and S_S per surface unit increases. Increases of inclination angle of obtained straights correlated with the increase in efficiency of the removal of analyzed COD fractions. The VF-bed in Wiklino was characterized with high efficiency of COD fraction removal from the wastewater.

The VFCW was the most efficient in terms of removing SS fractions from the wastewater. The average value was 89.2 ± 3.6% (Fig. 3a). Unit load of the bed with S_S fraction varied from 0.9 to 1.5 g/m²day. Efficiency of X_S and X_I removal from the wastewater amounted respectively to: 82.0 ± 3.6% and 80.1 ± 3.1% (Fig. 3b). Unit load of the bed with the fraction varied respectively: from 0.5 to 0.9 g/m²day for X_S and from 0.3 to 0.5 g/m²day for X_I.

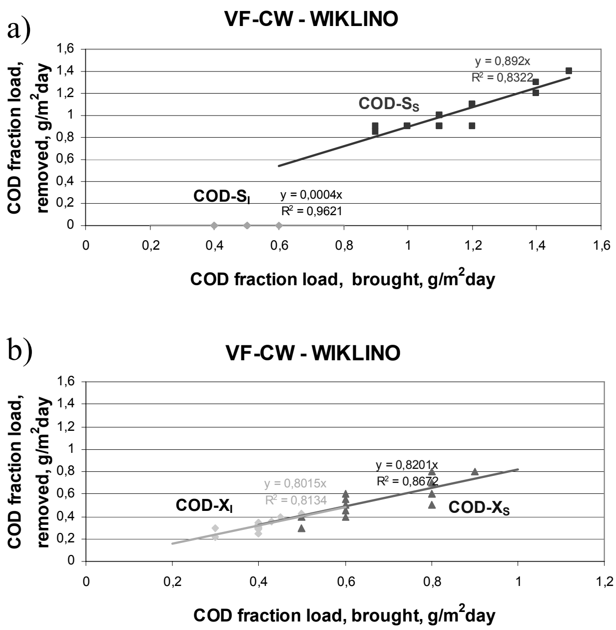

Fig. 3. COD fraction load: a) dissolved substances and b) in suspended solids, brought and removed from the VFCW in Wiklino.

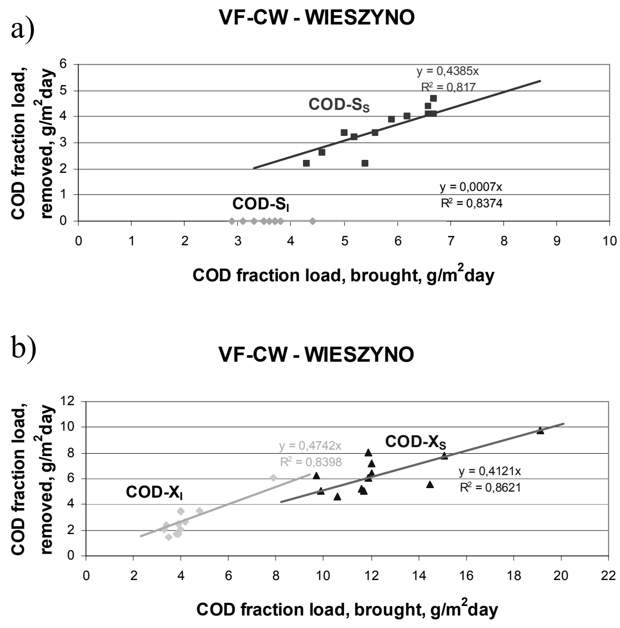

Fig. 4. COD fraction load: a) dissolved substances and b) in suspended solids, brought and removed from the VFCW in Wieszyno.

While the VF-bed in Wieszyno was removing COD fractions in suspended solids and in a dissolved form susceptible to biodegradation with lower efficiency as compared with the load in Wiklino (Fig. 4a and b). Efficiency in COD fraction removal from the wastewater amounted respectively to: 41.2 ± 2.9% for X_S; 47.4 ± 3.1% for X_I and 43.8 ± 1.7% for S_S. Unit load of the bed with COD fraction varied respectively: from 9.8 do 19.1 g/m^{2}day for X_S; from 3.2 to 7.9 g/m^{2}day for X_I and from 4.1 to 6.5 g/m^{2}day for S_S.

Influence of Organic Matter Quality in Wastewater on Oxidation in Filter Beds

The samples of the filtrating material of analyzed beds were characterized with variable moisture (θ), thus also with variable air-filled porosity of the soil (n_g) (despite maintaining the same conditions of soil sample taking, i.e. 2 hours after finishing the supply of wastewater to the wetland). This resulted on one hand from the quality of inflowing wastewater to the bed and on the other hand from existing atmospheric conditions (variable temperature, precipitation, etc.). Along with the increase of soil moisture, the influent of oxygen was reduced. For the VF-bed in Wiklino at moisture value amounting to 4.0% the value of diffusion coefficient was $6.8 \cdot 10^{-2}$ cm^2/s. When the moisture of the wetland increased to 23.0%, the value of diffusion coefficient decreased to $2.8 \cdot 10^{-2}$ cm^2/s. The VFCWs where moisture was higher than 35.0% were characterized with diffusion coefficient values varying from $7.0 \cdot 10^{-5}$ cm^2/s to $6.0 \cdot 10^{-4}$ cm^2/s. Similar observations were described by [18] who, based on research concerning changes in soil moisture depending on saturation with wastewater, determined the values of diffusion coefficient in the soil. The authors have shown that for a filter filled with sand (of particle diameter from 0.06 to 0.3 mm) after saturation with wastewater (amounting to 22.0%), the diffusion coefficient was $7.3 \cdot 10^{-2}$ cm^2/s, whereas with higher saturation (amounting to 85%) it was considerably lower and amounted to $3.17 \cdot 10^{-4}$ cm^2/s. The measurements also prove that the VFCW in Wieszyno, compared with the VF-bed in Wiklino, with the same moisture, was characterized with over four times lower value of diffusion coefficient D_g. For the average value of moisture amounting to ca. 10.0%, the coefficient Dg for the bed in Wiklino achieved the value of 0.0552 cm^2/s and for the bed in Wieszyno it achieved the value of 0.0132 cm^2/s.

Those differences resulted from different speciation of organic matter in inflowing wastewater. High concentrations of hardly biodegradable suspended solids in inflowing wastewater in Wieszyno caused a blocking of bed pores and an increase in moisture, which in turn limited the inflow of oxygen [19].

According to [14] the soils characterized with oxygen diffusion coefficient values lower than $2.0 \cdot 10^{-2}$ cm^2/s are not oxidized enough and one should limit their intense irrigation. Taking the given value as the criterion of insufficient oxidation, the allowable suspended solids load was determined. Obtained results enabled determination of dependence between the value of diffusion coefficient and unit suspended solids load in the bed. Together with the increase unit load of suspended solids in the bed, the value of diffusion coefficient decreased. VFCW achieved critical value of diffusion coefficient when the unit suspended solids load amounted to 4.0 ± 0.3 g/m^{2}day (Fig. 5).

Based on the dependence describing the influence of the suspended solids on the oxidation of the bed, it can be observed that the Wiklino treatment plant was supplied with wastewater in doses not exceeding allowable loads.

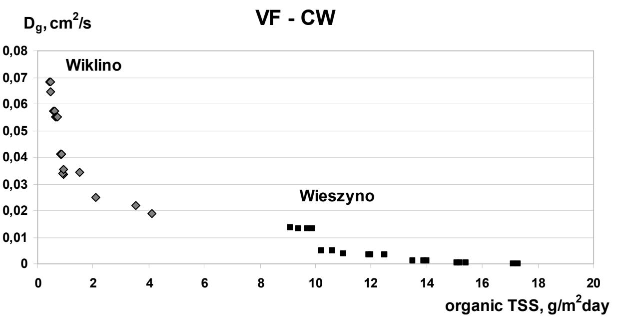

Fig. 5. Influence of suspended solid load in analyzed wetlands on their oxidation given by D_g.

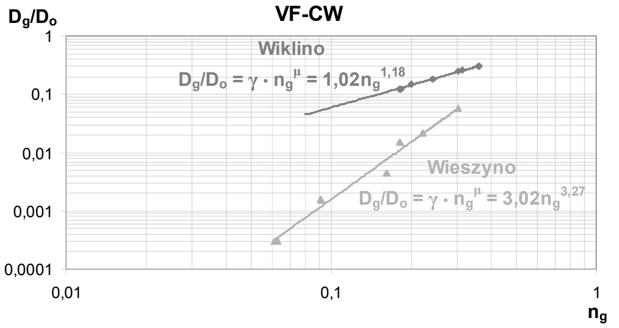

Fig. 6. Dependence $D_g/D_o = f(n_g)$ in logarithmic coordinate system for analyzed soil samples from VFCWs.

However, in Wieszyno the allowable values of organic suspended matter load were exceeded. As a consequence, the environment of this hydrophyte system was insufficiently oxidized and could cause accumulation of organic matter.

Influence of Oxygenation of VF-Bed on the Structure of Soil

Limitation of air influent to the soil filling the bed was the reason for modifications to its structure. In Fig. 6 the dependence $D_g/D_o = f(n_g)$ is presented in logarithmic coordinate system for analyzing soil samples from VFCWs. Based on obtained dependence, the values of γ and μ coefficients were determined.

The γ and μ coefficients for the soil sampled from Wieszyno were very similar to the values obtained by [14] and amounted respectively to $\gamma = 3.02$ and $\mu = 3.27$. According to the Author, the values of the coefficients equal to $\gamma = 3.0$ and $\mu = 3.0$ referred to heavy soils containing mud of devastated structure. As for Wiklino, the values of 1.02 and 1.18 were obtained for the γ and μ coefficients. These values showed that the analyzed material corresponded with the structure of sandy soils [14].

Conclusions

The following conclusions have been formulated based on the obtained results related to speciation of organic matter in influent wastewater on oxidation of analyzed VFCW and efficiency of pollutant removal:

1. Organic suspended solid loads below 4.0 g/m² day enable appropriate exploitation of VFCW with oxidation intensity at the level of at least $2.0 \cdot 10^{-2}$ cm²/s.
2. Suspended solid loads above 8.7 g/m² day in the facility in Wieszyno caused an increase in moisture up to 35.0%, as well as modification in bed structure quality.
3. The VFCW in Wieszyno was characterized by lower efficiency of organic matter removal from wastewater expressed in COD, as compared with Wiklino. The reason for the lower treatment efficiency of removal was the limited supply of oxygen (decrease of D_g value from 0.0552 cm²/s to 0.0132 cm²/s).

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