Application of subsurface vertical flow constructed wetlands to reject water treatment in dairy wastewater treatment plant

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Abstract

The paper presents the effects of applying subsurface vertical flow constructed wetlands (SS VF) for the treatment of reject water generated in the process of aerobic sewage sludge stabilization in the biggest dairy wastewater treatment plant (WWTP) in Poland. Two SS VF beds were built: bed (A) with 0.65 m depth and bed (B) with 1.0 m depth, planted with reeds. Beds were fed with reject water with hydraulic load of 0.1 m d^{-1} in order to establish the differences in treatment efficiency. During an eight months of research period, high removal efficiency of predominant pollutants was shown: BOD_5 88.1% (A) and 90.5% (B), COD 84.5% (A) and 87.5% (B), TSS 87.6% (A) and 91.9% (B), TKN 82.4% (A) and 76.5% (B), $N-NH_4^+$ 89.2% (A) and 85.7% (B), TP 30.2% (A) and 40.6% (B). Higher efficiency in removal of organic matter, TSS and TP was observed in bed (B), while $N-NH_4^+$ and TKN in bed (A). However, the differences between beds were not statistically significant.
The research indicated that SS VF beds could be successfully applied to reject water treatment in dairy WWTPs. The study proved that the use of SS VF beds in full scale in dairy WWTPs would result in a significant decrease of pollutants load in reject water. In the analyzed case decreasing the load of ammonia nitrogen was of greatest importance, as it constituted 58% of the total load treated in dairy WWTP and posed a hazard to the stability of the treatment process.

Keywords: aerobic stabilization, dairy wastewater treatment plant, filter press dewatering, reject water, subsurface vertical flow constructed wetlands.

Introduction

Sewage sludge as a by-product of wastewater treatment can be stabilized in aerobic or anaerobic conditions. In both cases the reject water is generated from sewage sludge in the processes of thickening and mechanical dewatering [1,2]. It is usually returned to the beginning of the sewage treatment process. In municipal WWTPs which apply aerobic sludge stabilization the quantity of reject water ranges between 2.1 and 2.9% of raw wastewater quantity. An increase from 2.7 to 7.0% can be observed in the case of anaerobic sludge stabilization (digestion) [3]. The difficulty in reject water treatment stems from a high irregularity of its generation and a large fluctuation of pollutant concentrations, mainly nitrogen, organic matter and TSS [4-7]. In case of WWTPs with sewage sludge digestion, 15–20% of the nitrogen load is redirected with reject water [4,5,8]. The load of pollutants present in reject water from municipal WWTPs plays an insignificant role in the total load, thus there is no need for its separate treatment. Returning the reject water to the beginning of a treatment process usually does not cause any major operation problems [6].

More excessive sludge is produced in dairy WWTPs than in municipal ones. Most of dairy WWTPs in Poland apply aerobic sewage sludge stabilization. The quantity of generated reject water reaches up to 10% of the raw sewage quantity. Reject water is usually returned to the beginning of the treatment process which results in a decrease of treatment efficiency. This is mainly due to a high load of ammonia nitrogen in reject water [9]. The concentration of ammonia nitrogen in reject water ranges from 4.9 to 26.4 mg $N-NH_4$ l^{-1}, while in the raw dairy wastewater from 1.1 to 8.3 mg $N-NH_4$ l^{-1} [10]. The load of ammonia nitrogen contained in reject water is a substantial part of the total WWTP dairy sewage load. This justifies the use of a separate system for its treatment.

There are a lot of known methods for separate reject water treatment but the most widely applied is the SHARON method (Single Reactor System for High-Rate Ammonia Removal Over Nitrite). Its features are high effectiveness but also high capital costs [2,4,11]. Separate reject water treatment applying a high-tech unit processes might be recommendable only in specific cases of upgrading WWTPs [8]. An alternative could be a low-cost method based on constructed wetlands.

The constructed wetlands method for sewage treatment is a biological process which occurs with the help of heterotrophic microorganisms and aquatic plants known as hydrophytes, which exist in specially designed facilities. Pollutants removal is possible thanks to creating specific conditions allowing the plants' growth, as well as intensifying the processes of oxidation, reduction, sorption, sedimentation and assimilation. The main processes include: changes in carbon compounds, changes in nitrogen compounds and mechanisms responsible for phosphorous compounds retention. Removing suspended solids occurs during sedimentation, filtration, accumulation, adhesion and adsorption processes [12].

Subsurface vertical flow constructed wetland (SS VF) beds have been used worldwide for the treatment of municipal and some industrial wastewaters, as well as reject water from sludge stabilization in municipal WWTPs and landfill leachate. This is due to their simplicity and low construction and operating costs [12-15]. The studies on low-cost methods for dairy wastewater, reject water and sludge treatment are especially important in a region where the milk production is one of the largest in Europe [16]. The application of a SS VF system for the treatment of reject water from aerobic sludge stabilization in dairy WWTP is a new conception and no publications on this subject are known. The experiments which are the closest reference to this problem are the ones concerning the application of constructed wetlands to the treatment of reject water from anaerobic stabilization in municipal WWTPs [17]. The hybrid system built of two SS VF beds working in series, followed by an SS HF, provided high removal efficiency of dominant pollutants (COD 76.0% and $N-NH_4^+$ 93,6%). It has been proved that SS VF beds ensured effective removal of nitrogen compounds, especially $N-NH_4^+$, whereas SS HF provided a good environment for the decomposition of hardly degradable Org-N and COD. The outflow from the beds minimized the impact of reject water on the final effluent from municipal WWTPs [17]. Research conducted in China was based on the application of alum sludge which is a by-product of coagulation in

water treatment process. It was used as a medium in a multi-stage constructed wetland for reject water treatment [18]. The results show that average removal efficiency was at: COD 65.4%, BOD$_5$ 67.8%, TN 33.6% and TP 99.5%.

The aim of the study was to evaluate removal efficiencies of SS VF beds for the treatment of reject water in dairy WWTPs.

Methods

Characteristics of WWTP

A dairy WWTP located in Wysokie Mazowieckie belonging to Mlekovita is the biggest dairy WWTP in Poland. In the summer period the plant processes between 3 and 4 million liters of milk per day. Increased production in dairy plants is observed from March through October. It causes an increase in the quantity of produced sewage, sludge and reject water. At this point problems occur with the stability of system operation, resulting from returning a significant load of ammonia nitrogen present in reject water to the beginning of the treatment process. Since these are seasonal disturbances long-term modernization projects are not reasonable to be carried out. In order to assess the possibility of solving the problems caused by reject water, SS VF beds were applied for its treatment. Figure 1 shows a scheme of a dairy WWTP with the reject water treatment installation indicated (11).
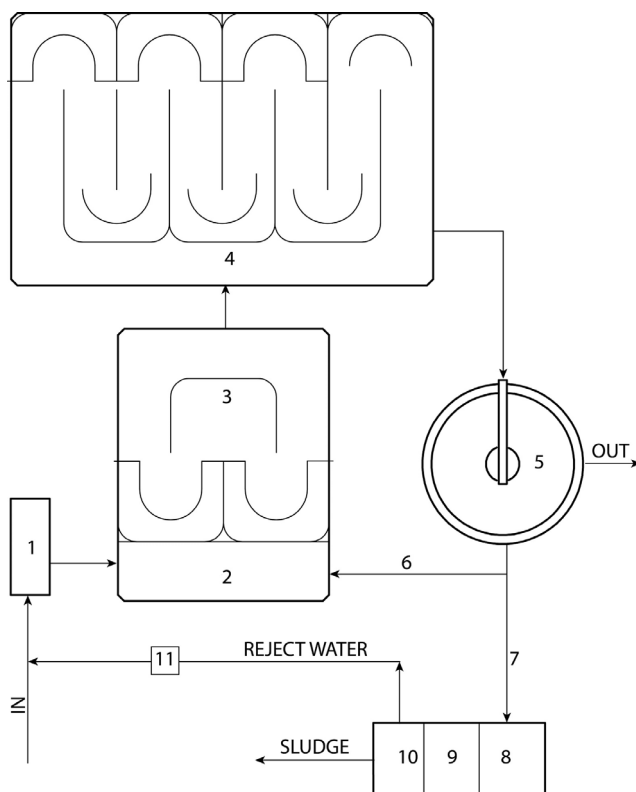
Figure 1. Scheme of dairy WWTP in Wysokie Mazowieckie

After mechanical treatment (screen and sand trap (1)), the sewage flew to a dephospatation chamber (2). Then it was directed to high-loaded and low-loaded activated aeration tanks with simultaneous nitrification and denitrification (3,4). Phosphorus precipitation by means of coagulant dosing took place at the outflow from the aeration tank to secondary sedimentation tanks (5). With the help of a recirculation system (6), part of the sludge from the secondary sedimentation tanks was directed to the phosphorous removal chamber. Excess sludge (7) was led to sludge treatment line, which in 2012 was based on aerobic sludge stabilization. Excess sludge after mechanical thickening (8) outflew to an aerobic stabilization chamber (9). The stabilization time ranged from 5 to 8 days, the process was exothermal. The stabilization temperature was 30-36°C. In order to reduce the temperature rise in chambers and ensure proper air exchange, air was pumped under the cover of every chamber. After aerobic stabilization, sewage sludge was dewatered with a filter press (10). Part of reject water from dewatering was discharged onto SS VF beds (11). The rest of the reject water was returned to the beginning of the treatment process.

Research installation

In 2006 a pilot scale installation was built in the biggest dairy WWTP in Poland in Wysokie Mazowieckie in order to treat part of reject water. The main assumption of the design of SS VF beds was based on experiences of scientists and exploiters running full scale installations [19,20]. Furthermore, the results of laboratory analyses of reject water generated at the dairy WWTP in Wysokie Mazowieckie were included. They indicated that the dominant pollutant was nitrogen, mainly in the form of Kjeldahl nitrogen. Therefore, the assumption for the design of the installation was to remove ammonia and organic nitrogen effectively.

Two types of SS VF beds were built: bed (A) with 0.65 m depth and surface area 10 m^2 and bed (B) with 1.0 m depth and surface area 5m^2. The filtration bed media was composed of four layers according to Figure 2.
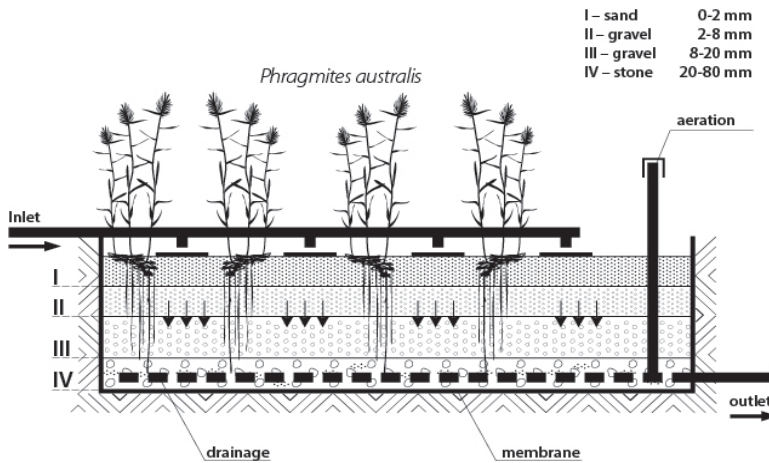
Figure 2. Cross section of beds A and B

The bed's bottoms and sides were supported with tiles and sealed with waterproof pool membrane. A spreading system built from PVC ø50 mm pipes was installed on the bed's surface. In order to protect the filling from washing out by the stream of outflowing reject water, the pipe outlets were secured with concrete tiles [21]. A collecting drainage system made of ø50 mm drain pipes and covered with stones was installed on the bottom of the bed. A system of six vertical pipes connected with the collecting drainage system ensured gravitational ventilation. No artificial aeration system was applied. A control well which was installed in the bed allowed for constant monitoring of physical and chemical parameters.

The beds were planted with reeds (*Phragmites australis*). This species is recommended and was not mixed with any others [19,22,23]. Three-year-old seedlings in pots were used for planting, which allowed a fast start-up of the constructed wetlands. The beds were located in a sunny area which enhanced plants growth. Figure 3 presents the research installation in July 2012.

Figure 3. View on research installation, Sept. 2012

Apart from constructed wetlands, the research installation also included a 1 m^3 retention tank (inflow sampling point) and two collecting wells (outflow sampling points). Moreover, the installation enabled recirculation of the treated reject water (Figure 4).
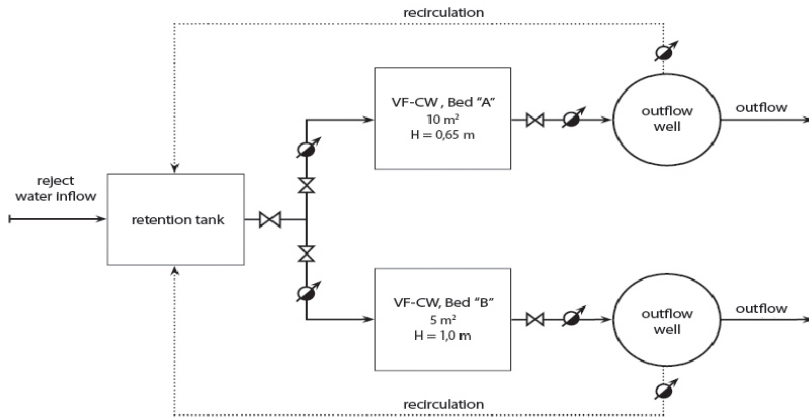

Figure 4. Scheme of research installation

Beds (A) and (B) were fed with reject water simultaneously with the same hydraulic load of 0.1 m d^{-1} in order to establish the differences in treatment efficiency. Organic load was on average at 13.2 g BOD m^{-2} d^{-1}, while ammonia nitrogen load was 2,6 g N-NH_4^+ m^{-2} d^{-1}. Reject water temperature was stable and ranged between 23 and 26°C, whereas air temperature varied from 4°C to 26°C.

Sampling and scope of the determination
In the research conducted in the dairy WWTP in Wysokie Mazowieckie the qualitative and quantitative characteristics of dairy sewage and reject water (before and after treatment in beds A and B) were evaluated.

The study was carried out from March to October 2012. The 24-h-composite samples were collected four times a month (dairy sewage, reject water inflowing and outflowing from beds A and B).

Concentration of the following pollutants was measured:
- organic matter (BOD_5, COD, TOC), total suspended solids (TSS),
- nitrogen forms (total Kjeldahl nitrogen TKN, ammonium nitrogen N-NH_4^+, nitrate nitrogen N-NO_3^- and nitrite nitrogen N-NO_2^-)
- total phosphorus (TP)

Determinations were conducted in a certified laboratory in accordance with the procedures set out in the Regulation of the Environmental Protection Minister from 18th November 2014 [24]. Tests for the analysis of COD, TOC, TKN, N-NH_4^+, N-NO_3^-, N-NO_2^- and TP recommended by Merck were applied. Spectrophotometer Spectroquant Pharo 100 was used. BOD_5 was determined using OXI-TOP®.

Removal efficiency was calculated as a concentration reduction according to the terminology given by Kadlec & Wallace [12]. The results were statistically evaluated using the StatSoft STATISTICA 8.0. Statistic tests were carried out concerning the average values of unit removed pollutants load ($g\ m^{-2}d^{-1}$) in beds A and B. The normality of variables was checked using the Shapiro-Wilk test with significance level $\alpha=0.05$. To assess the difference in the efficiency of the beds A and B, t-Student tests were performed.

Results and discussion

Table 1 presents quantity and quality characteristics of Mlekovita dairy WWTP in Wysokie Mazowieckie.

Table 1. Basic parameters of Mlekovita dairy WWTP, average values, 2012.

Parameter	Unit	Value
Sewage quantity	$m^3\ d^{-1}$	5840
Sewage sludge quantity	tons of dry mass d^{-1}	6.2
Person Equivalent of sewage	-	274480
Load of ammonia nitrogen in raw sewage	$kg\ N\text{-}NH_4^+\cdot d^{-1}$	10.5
Reject water quantity	$m^3\cdot d^{-1}$	560
P.E. of reject water	-	1232
Load of ammonia nitrogen in reject water	$kg\ N\text{-}NH_4^+\cdot d^{-1}$	14.6

The average pollutants concentrations in raw dairy sewage were at: 2820 mg BOD_5 l^{-1}, 4650 mg COD l^{-1}, 630 mg TSS l^{-1}, 1.8 mg $N\text{-}NH_4^+$ l^{-1}, 161 mg TKN l^{-1} and 32.2 mg TP l^{-1}. The BOD_5/COD ratio varied between 0.35 and 0.66.

Dairy sewage characteristics varies greatly among plants and it is not easily predictable even when information on processing operations is available. The contribution of milk products to the sewage streams is underestimated [25]. In the case of wastewaters from some unitary production processes, significant concentrations of butyric acid and caproic acid may be found [26].

In spite of the above, high concentrations of biogenic compounds, which are reported in the literature (COD values from 800 to 7000 mg O_2 l^{-1}), was observed in the research [27-29]. The low value of BOD_5/COD ratio points to the high content of easily biologically biodegradable substances. Due to the high concentration of easily decomposing organic matter it, can be concluded that nutrients are highly susceptible to removal during the biological wastewater treatment process [25].

During the research period, the sludge production ratio in the examined WWTP was at 1.06 Kg dry mass of sludge per m^3 of treated dairy sewage. The quantity of reject water was up to 10% of the total quantity of the treated sewage (Table 1).

The average value of sludge production ratio in smaller dairy WWTPs in Podlaskie province did not exceed 0.72 Kg dry mass of sludge per m^{-3} of treated

sewage. In case of municipal sewage it was 0.25 Kg dry mass of sludge per m^{-3}[30]. The quantity of reject water generated in the dairy WWTP in Wysokie Mazowieckie is from 3 to 5 times higher than in municipal WWTPs that apply aerobic sludge stabilization [3].

The average chemical composition of reject water during the research period was: 138 mg BOD$_5$ l^{-1}, 235 mg COD l^{-1}, 134 mg TSS l^{-1}, 26.0 mg N-NH$_4^+$ l^{-1}, 39.2 mg TKN l^{-1} and 8.6 mg TP l^{-1}. BOD$_5$/COD ratio varied from 0.50 to 0.62, while BOD$_5$/TN ratio from 2.6 to 3.4. The BOD$_5$/COD and BOD$_5$/TN ratios give information about biodegradability. These values decrease as decomposition progresses.

The presented results are similar to those achieved during research on reject water in dairy WWTPs using aerobic sludge stabilization in Podlasie province in Poland. In 2008 nine individual dairy WWTP that used simultaneous or separate aerobic digestion of excessive sludge were examined. The study found that the average value of BOD$_5$ in reject water amounted to 114 mg O$_2$ l^{-1}, ammonia nitrogen to 18.2 mg l^{-1} and total phosphorus to 7.3 mg l^{-1} [31]. These values are considerably lower than the ones observed in reject water from anaerobic sewage sludge stabilization in Gdansk WWTP, in which the average concentrations of pollutants were at: 429 mg BOD$_5$ l^{-1}, 1213 mg COD l^{-1}, 526 mg TSS l^{-1}, 705 mg N-NH$_4^+$ l^{-1}, 791 mg TKN l^{-1} [17]. The BOD$_5$/COD ratio in reject water from anaerobic sewage sludge stabilization in municipal WWTPs is lower than the one observed in dairy WWTPs. It is equal to 0.25–0.32 for reject water from the WWTP in Gdansk (Poland) [17] and 0.2 for reject water from the WWTP in Minworth (Great Britain) [5]. Furthermore, low BOD$_5$/COD ratio reflects low degradability of the organic compounds. BOD$_5$/TN ratios in WWTP in Gdansk ranges from 0.37 to 0.54. It indicates that the content of easily degradable organics is not sufficient for the conventional path of nitrogen removal. It is due to a very high content of ammonia nitrogen [17].

While comparing the concentration of pollutants present in dairy sewage and reject water, it is noticeable that a distinctly higher concentration of ammonia nitrogen appears in reject water (over 14 times higher), whereas other parameters are substantially lower than in dairy sewage. In case of municipal WWTPs, the increase of ammonia nitrogen concentration in reject water from anaerobic sewage sludge stabilization is not so significant in comparison with its concentration in raw wastewater. However, the load of ammonia nitrogen from reject water usually contributes up to 20% of total nitrogen load [3-5,17,32]. Figure 5 shows the share of pollutants load contained in sewage and reject water in the total load of the treatment plant.
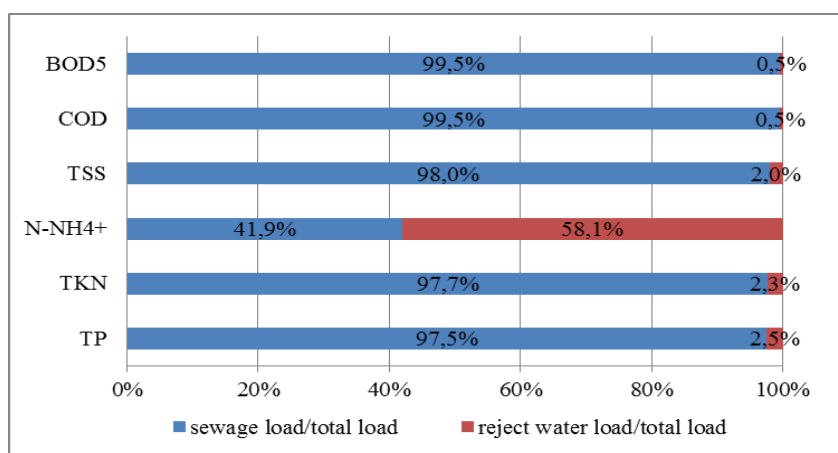
Figure 5. The share of pollutants load contained in sewage and reject water in the total load of dairy WWTP in Wysokie Mazowieckie

The analysis of the data presented in Figure 5 proves that the basic problem regarding the influence of reject water is the ammonia nitrogen load. The share of ammonia nitrogen load contained in reject water in relation to the total load in the analysed period was 58.1%, while TKN was only 2.3%. In case of other analyzed parameters, their share in the load in reject water was significantly lower than in dairy sewage and ranged from 0.5 to 2.5%. It confirms the purpose of designing reject water treatment systems based on ammonia nitrogen load.

Table 2 presents quality characteristics of reject water before and after treatment in SS VF beds. Table 3 includes mean values of removed pollutants load.

Table 2. Chemical characteristics of reject water before and after treatment

Parameters	Before treatment (n=32) [mg l^{-1}]	After treatment (n=32) [mg l^{-1}]
BOD$_5$	138.0/132.0 (105.0–146.0)	Bed A 15.1/15.7 (12.0–19)
		Bed B 12.9/12.6 (10.0–18)
COD	241.0/235.0 (215.0–249.0)	Bed A 35.2/36.5 (29.0-42)
		Bed B 29.0/29.3(25.0–40)
TOC	49.8/49.3 (41.5–52.8)	Bed A 11.9/11.4(9.6–15.0)
		Bed B 10.8/10.2(9.1–14.0)
TSS	130.0/134.0 (118.0–139.0)	Bed A 16.1/16.6(10.0-18)
		Bed B 11.4/10.8(9.0–17.0)
TKN	38.1/39.2 (26.0–41.4)	Bed A 7.1/6.9 (5.9–8.5)
		Bed B 9.3/9.2 (6.7-12.3)
N-NH$_4^+$	26.8/26.0 (19.2–31.4)	Bed A 2.6/2.8 (1.9-4.1)
		Bed B 3.8/3.7 (3.2-6.1)
N-NO$_3^-$	1.6/1.5 (0.5–0.6)	Bed A 8.6/8.8 (7.3-9.5)
		Bed B 6.0/6.1 (4.1-7.3)
N-NO$_2^-$	0.3/0.3 (0.1–0.3)	Bed A 0.2/0.2 (0.1-0.2)
		Bed B 0.2/0.2 (0.1-0.2)
TP	8.4/8.6 (7.2–8,9)	Bed A 6.2/6.0 (5.0-7.5)

Bed B 5.7/5.1 (4.8-6.1)

median/mean (minimum – maximum)

Table 3: Removed pollutant loads (mean values)

Parameters	Removed load
BOD$_5$	Bed A: 11.7 g BOD$_5$ m^{-2} d^{-1}
	Bed B: 12.0 g BOD$_5$ m^{-2}d^{-}
COD	Bed A: 19.9 COD m^{-2}d^{-1}
	Bed B: 20.6 COD m^{-2}d^{-1}
TOC	Bed A: 3.8 TOC m^{-2}d^{-1}
	Bed B: 3.9 TOC m^{-2}d^{-1}
TSS	Bed A: 11.7 TSS m^{-2}d^{-1}
	Bed B: 12.3 TSS m^{-2}d^{-1}
TKN	Bed A: 3.2 g TKN m^{-2}d^{-1}
	Bed B: 3.0 g TKN m^{-2}d^{-1}
N-NH$_4^+$	Bed A: 2.3 g N-NH$_4^+$ m^{-2}d^{-1}
	Bed B: 2.2 g N-NH$_4^+$ m^{-2}d^{-1}
TP	Bed A: 0.26 g P m^{-2}d^{-1}
	Bed B: 0.35 g P m^{-2}d^{-1}

The calculated treatment efficiency was on average at: BOD$_5$ 88.1% (bed A) and 90.5% (bed B), COD 84.5% (bed A) and 87.5% (bed B), TOC 76.9% (bed A) and 79.3% (bed B), TSS 87.6% (bed A) and 91.9% (bed B), TKN 82.4% (bed A) and 76.5% (bed B), N-NH$_4^+$ 89.2% (bed A) and 85.7% (bed B), TP 30.2% (bed A) and 40.6% (bed B).

After the treatment in SS VF beds, the average ratios of BOD$_5$/COD and BOD$_5$/TN decreased significantly and ranged from 0.29 to 0.46 for bed A and from 0.25 to 0.44 for bed B. Such low values indicate the presence of hardly decomposable form of organic matter. The main form of total nitrogen in the influent was ammonia nitrogen, while in the effluent nitrate nitrogen. Its average concentration was equal to 7.5 mg l^{-1}, while in the raw dairy sewage discharged to a WWTP it was a trace contamination. Ammonia nitrogen in reject is a product of ammonification process. Nitrate nitrogen after treatment in SS VF beds is caused by nitrification process.

The treatment of reject water from aerobic stabilization is more effective when compared with anaerobic sludge stabilization in municipal WWTPs. The average effectiveness of the process present in literature was on average at 70% for BOD$_5$, 65% for TSS and 40% for N-NH$_4^+$ [17].

Similar values were achieved while applying SS VF beds for the treatment of other highly concentrated wastewater, including septage [33]. It might be due to lower pollutants concentration in reject water from aerobic sludge stabilization in

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dairy WWTPs in comparison with reject water from anaerobic sludge stabilization in municipal WWTPs.

On the basis of the results from the Shapiro-Wilk test, normal distribution of unit removed loads might be concluded (p value > 0.40), which allows conducting parametric tests. The results of t-Student test showed that the differences between the loads removed in beds A and B are statistically insignificant (p value > 0.20).

The removal efficiency remained constant throughout the study period. Although the beds has been operating since 2007, clogging has not been observed. Due to high temperature of reject water, which exceeded 20°C, high treatment efficiency was observed also in the winter.

It is confirmed by other authors that constructed wetlands can provide long-term removal of pollutants along with stability and high efficiency at low operating costs [15,19,35-38].

The real scale system for reject water treatment at dairy WWTP in Bielsk Podlaski (PE 20 000) was designed and constructed based on research presented in the paper. High efficiency of this facility justifies the use of similar systems also in larger dairy WWTPs.

Conclusions

The study showed a high efficiency of SS VF beds for removing main pollutants from the reject water generated in aerobic sludge treatment in dairy WWTPs. It was respectively: 88.1-90.5% for BOD_5, 82.4-76.5% for TKN, 89.2-85.7% for $N-NH_4^+$, 30.2-40.6% for TP.

Higher efficiency in removal of organic matter, TSS and TP was observed in bed (B) with 1.0 m depth, while $N-NH_4^+$ and TKN in bed (A) with 0.65 m depth. However, the differences between beds were not statistically significant.

The study proved that the use of SS VF beds in full scale in dairy WWTPs would result in a significant decrease of pollutants load in reject water. In dairy WWTPs decreasing the load of ammonia nitrogen is of greatest importance. In analyzed case it constituted 58.1% of the total load and posed a hazard to the stability of the biological sewage treatment process.

Applying constructed wetlands for separate reject water treatment might ensure stable and effective functioning of dairy WWTPs. In the case of numerous treatment plants it will also allow to avoid expensive modernization projects.

Acknowledgements

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