Ecological Engineering 98 (2017) 365–371

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

# Reliability of nitrogen removal processes in multistage treatment wetlands receiving high-strength wastewater

Ewa Wojciechowska*, Magdalena Gajewska, Arkadiusz Ostojski

*Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, ul. Narutowicza 11/12, Gdańsk, 80-233, Poland*

ARTICLE INFO

*Article history:*
Received 21 January 2016
Received in revised form 23 May 2016
Accepted 6 July 2016
Available online 21 July 2016

*Keywords:*
Landfill leachate
Reject water from sewage sludge dewatering
Nitrification
Denitrification
Ammonium adsorption
Biodegradability

ABSTRACT

Treatment wetlands have been proved to be more effective than conventional treatment processes in case of high-strength wastewater containing high concentrations of ammonium nitrogen and recalcitrant organic matter. In this study nitrogen removal processes and reliability of nitrogen removal at two identical pilot-scale multistage treatment wetlands (MTWs) receiving real, non-synthetic wastewater were discussed. The wastewater discharged to pilot-scale subsurface flow MTWs contained high ammonium nitrogen concentrations and limited biodegradable organic matter (OM) concentrations. One of the pilot MTWs was fed with landfill leachate (LL) and another one with reject water from sewage sludge centrifugation (RW). In the first season of operation both MTWs reached very high (95–99%) efficiency of total nitrogen (TN) removal, which was explained by adsorption to the substrate. In the later period, TN was removed in a sequence of nitrification and denitrification processes with lower efficiency (40–86%). The denitrification process was the limiting one at the LL treating site because of too low carbon supply. Still, during the whole investigation period TN outflow concentrations were at the level that allows for co-treatment of the effluent in municipal wastewater treatment plants without risk for biological treatment processes. In 90% of samples TN concentration was below 200 mg/l and in 60% of samples it was below 145 mg/l.



## 1. Introduction

The treatment of wastewater containing high concentrations of recalcitrant organic matter (OM) and ammonium nitrogen, like landfill leachate (LL) or reject water from mechanical dewatering of sewage sludge after the digestion process (RW) is hard to accomplish in conventional treatment processes. Poor biodegradability indicates proportions of easily biodegradable OM (expressed in $BOD_5$) in total organic matter (expressed in COD) and total Kjeldahl nitrogen (TKN) usually determines the failure of activated-sludge or SBR reactors (Wiesman, 1994). However, the treatment wetlands (TWs) have been reported to perform better and offer reliable treatment results in case of high-strength wastewater like LL (Kadlec, 2003; Kinsley et al., 2006). This significant difference between the conventional biological treatment and treatment wetlands is explained to be the result of more complex processes occurring in the wetland systems and the unique capacity of wetland systems in providing endogenous sources of biodegradable OM (Crites et al., 2006; Kadlec and Wallace, 2009; Gajewska et al., 2015).

Experiences with the application of TWs for LL indicated that significant reduction of BOD, COD and nitrogen concentrations, as well as BTEX is possible. Surface flow systems (SF) have proved to be very effective in LL treatment due to long hydraulic retention time and complex removal processes. (Johnson et al., 1999; Waara et al., 2008; Obarska-Pempkowiak et al., 2015). The removal of extremely high ammonium nitrogen concentrations generally requires a sequence of nitrification and denitrification processes (Makinia et al., 2009; Vymazal, 2009). In case of horizontal subsurface flow systems (HSSF), nitrification is limited due to anaerobic conditions, which could be overcome by additional aeration (Nivala et al., 2007). In vertical subsurface flow systems (VSSF) oxygen transfer is good enough and creates favourable conditions for nitrification of ammonium nitrogen presence in LL (Obarska-Pempkowiak et al., 2010; Yalcuk and Ugurlu, 2009; Lavrova and Koumanova, 2010). On the other hand denitrification requires anoxic conditions, as well as the presence of easily biodegradable carbon. Multistage TWs offer a solution with nitrification going on in VSSF beds and denitrification running in HSSF beds (Molle et al., 2008; Masi et al., 2013; Gajewska et al., 2015). Kadlec and Zmarthie (2010) recommend LL treatment in vertical subsurface flow beds (VSSF), willingly followed by a SF system for denitrification. The final SF system can be replaced by a HSSF bed, while a

* Corresponding author.
*E-mail address:* ewa.wojciechowska@wilis.pg.gda.pl (E. Wojciechowska).

http://dx.doi.org/10.1016/j.ecoleng.2016.07.006

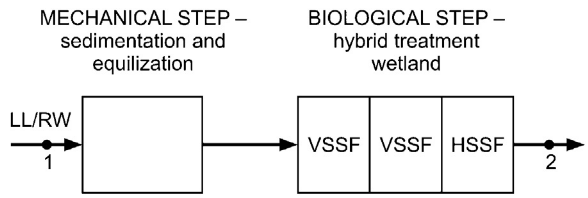


**Fig. 1.** Scheme of twin MTWs for LL and RW treatment with marked sampling points (1–inflow, 2–outflow).

sequence of two VSSF beds working in a series (instead of a single bed) can provide full nitrification of enormous ammonium nitrogen load (Obarska-Obarska-Pempkowiak and Gajewska, 2011).

The objective of this paper is to discuss the nitrogen removal processes at two identical MTWs receiving wastewater with low biodegradable OM and high ammonium nitrogen concentrations. The study MTWs were the outdoor pilot scale installations placed at (i) landfill site and fed with real LL and (ii) municipal wastewater treatment plant and fed with real RW from digested sludge centrifugation. In our investigation "twin" installations gave the opportunity to analyze the differences in operation depending on the quality of inflow of RW and LL, as well as they allowed to find similarities in removal processes. The other distinction of our investigation is working with real, and not synthetic wastewater, which gave more complex results due to the presence of organic and inorganic fractions of solids, which could have influence on removal processes in MTWs. The TN removal rates and the reliability of removal processes during three years of operation of LL MTW and two years of operation of RW MTW were evaluated with respect to the adaptation and post-adaptation period, basing on the inflow and outflow pollutants concentrations. In this paper we would like to focus on MTWs consisting of three stages, but taken as a whole unit with regard to the removal process reliability, which is of significance for potential co-treatment of municipal wastewater.

## 2. Materials and methods

### 2.1. Study sites

Two identical multistage MTWs for LL and RW treatment consisted of three SSF beds, working in series: two VSSF (7.84 $m^2$ and 5.29 $m^2$) beds followed by a HSSF bed (3.19 $m^2$), all planted with *P. australis*. Washed gravel (4–8 mm) with the hydraulic conductivity of $4.2 \times 10^{-2}$ m/s was used as a substrate. One of the MTWs received leachate from the landfill in Chlewnica near Słupsk and another one treated reject waters from sewage sludge centrifugation at WWTP in Gdańsk. The VSSF beds were operated in batch mode (flooded and drained) except for the first operation season (adaptation period) at LL MTW, when both VSSF beds were continuously flooded to promote the development of *P. australis* that was damaged by birds breeding at the landfill site. The wastewater inflow was equal to 111 l/d. The scheme of twin MTWs is presented in Fig. 1. Further details of the investigation sites were provided in previous papers (Gajewska and Obarska-Pempkowiak, 2011; Wojciechowska and Gajewska, 2013).

### 2.2. Sampling and analytical procedures

The averaged samples of wastewater at the inflow and at the outflow were collected every 3–4 weeks during the vegetation seasons (from April to early November) in 1-l glass bottles and immediately transported to the laboratory in cooling containers. The analyses were conducted in three subsequent vegetation seasons (2009–2011) in the LL MTW and during the two subsequent seasons in RW MTW (2009–10). The first season of operation was regarded as an adaptation period. It was considered that the conditions during the adaptation of the beds (for instance intensively developing plants and "fresh" gravel media) can influence the treatment performance.

**Table 1**
The average RW and LL composition (in/out).

| Parameter | RW | | LL | |
|---|---|---|---|---|
| | inflow | outflow | inflow | outflow |
| total N [mg/l] | 1054 | 123 | 542 | 190 |
| $NH_4^+$-N [mg/l] | 941 | 96 | 434 | 103 |
| organic N [mg/l] | 113 | 23 | 77 | 35 |
| TKN [mg/l] | 1054 | 119 | 511 | 138 |
| N-$NO_3^-$ [mg/l] | 0.1 | 4.3 | 2.2 | 19.2 |
| COD [mg $O_2$/l] | 1208 | 264 | 1825 | 953 |
| $BOD_5$ [mg $O_2$/l] | 460 | 21 | 151 | 19 |

**Table 2**
The average COD/$BOD_5$, COD/TKN and $BOD_5$/TKN ratios in RW and LL.

| Parameter | RW | | LL | |
|---|---|---|---|---|
| | inflow | outflow | inflow | outflow |
| COD/$BOD_5$ | 2.63 | 12.50 | 9.09 | 33.33 |
| COD/TKN | 1.25 | 2.83 | 2.63 | 6.45 |
| $BOD_5$/TKN | 0.46 | 0.23 | 0.28 | 0.18 |
| $BOD_5$/TN | 0.44 | 0.17 | 0.28 | 0.10 |

The concentrations of COD, $BOD_5$, total nitrogen, ammonium nitrogen, organic nitrogen and nitrates were measured in samples (inflow and outflow) collected according to the hydraulic retention time.

The chemical analyses were performed by an independent laboratory (ISO certificate), according to Polish standard methods (Polish Environmental Ministry Regulations of 24th July 2006 with amendment of 18th January 2009; COD: PN-ISO 15705:2005; total N: PN-73/C-04576.14; ammonium N: PN-ISO 5664:2002, nitrates: PN-EN ISO 10304-1:2009). Polish standards are in agreement with the EU Framework Directive 2000/60/EC and are comparable with APHA (2005).

## 3. RESULTS and discussion

### 3.1. Composition of raw and treated wastewater

The composition of raw wastewater is summarized in Table 1. Both, LL and RW contained high concentrations of total N, mostly in the form of ammonium nitrogen, although the total nitrogen concentration in RW was twice as high as in LL. Organic nitrogen constituted approximately 11% and 14% of the total nitrogen present in RW and LL, respectively. Nitrates concentrations in raw wastewater were low. The outflow concentrations indicate effective removal of ammonium nitrogen from both LL and RW. Organic nitrogen concentrations of 23 mg/l (RW) and 35 mg/l (LL) remained in the effluent. The remaining organic nitrogen was supposed to be built up in the structure of complex organic compounds, like humic substances and thus unavailable for biotransformation processes (Kang et al., 2002; Obarska-Pempkowiak et al., 2015), which is in agreement with very high concentrations of recalcitrant OM in LL, expressed in high inflow/outflow COD concentration and high COD/$BOD_5$ ratio. The LL at the outflow contained nitrates, indicating incomplete denitrification.

The OM concentrations expressed in COD were very high, especially in LL. At the same time, the $BOD_5$ mean concentration was four times lower in LL than in RW. In Table 2 the values of characteristic ratios $BOD_5$/COD, COD/TKN and $BOD_5$/TKN are summarized. The high COD/$BOD_5$ ratio indicates that recalcitrant forms of organics were present in both types of wastewater. The LL COD/$BOD_5$