Partial nitrification in a high-load activated sludge system by biofilter backwash water recirculation

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Abstract The South-Budapest Municipal Wastewater Treatment Plant (SBWWTP) based on the high-load activated sludge process (AS) was upgraded into nutrient removal in 1998–1999 in Hungary. Biofor® type nitrifying (NP) and denitrifying (DN) biofilters were implemented for nitrogen removal downstream of the (AS) stage in order to meet the required effluent standards characterized by 50 mgCOD l^{-1}, 10 mgBOI$_5$ l^{-1}, 10 mgTN l^{-1}, 1 mgTP l^{-1} and 35 mgTSS l^{-1}. Phosphorus removal is obtained by chemical addition. The study presented sums up the performance of the upgraded plant throughout 25 months. Besides the efficient pre-denitrification obtained in the AS basin, significant ammonium oxidation was observed in the aerated zone, upon the introduction of recirculation of nitrate rich water and backwash water. The introduction of biofilter backwash water, containing nitrifying biomass, has generated significant ammonium conversion in the aerated basins, where nitrification was observed previously to a very limited extent. Process parameters of the AS stage were: aerobic sludge age of 1.5–2.0 days, 1.5 hours hydraulic retention time, specific sludge load of 1.1 kgCOD kgMLSS^{-1} d^{-1}. The nitrification in the AS tank has significantly reduced below 16°C, however, denitrification efficiency was not as highly dependent upon temperature during the investigated period. The paper investigates the nitrogen balance of the plant in two aspects: (i) the effects of seeding on nitrification in the high load AS reactor and (ii) pre-denitrification potential in the anoxic zone of the AS tank of the pre-settled wastewater.

Keywords Backwash water; biofilter; denitrification; nitrification

Introduction

Nitrifying microorganisms are characterized by lower growth rate than heterotrophic bacteria present in systems aiming at organic matter removal (Henze *et al.*, 1995; EPA, 1993). The nitrification therefore requires higher sludge age to achieve complete ammonium-nitrogen conversion. The high load AS system is mostly capable for the removal of organic matter from municipal wastewater. The process is characterized by high organic material loads (sludge load e.g. 0.7–1.3 kgBOD$_5$ kgMLSS^{-1} d^{-1}). Typically the sludge age is below 2 days, the hydraulic retention time is usually less than 1.5 hours. Various authors advise several techniques for enhancing nitrification in the AS process. Among them adjustment of reactor arrangement to plug flow character, application of selectors, step feeding, pH control and upstream organic material removal enhancement are mentioned (Daigger and Parker, 1999). Another option is "seeding", that is, the addition of nitrifying microorganisms to the AS process, which provides nitrifying biomass to the bacterial system that grow at a higher rate than nitrifiers. Therefore seeding of non-nitrifying biomass with nitrifiers results in ammonium conversion in those systems, where nitrification was not been experienced previously. Seeding sources may include the parallel AS process or a separate process treating high ammonium concentration solids handling recycle streams.

The biofiltration process proved its feasibility in upgrading existing municipal wastewater treatment plants for nutrient removal (Pujol *et al.*, 1994a, 1994b; Sagberg *et al.*, 1992; Sagberg and Grundnes Berg, 2000; Rogalla *et al.*, 1994; Paffoni *et al.*, 1990). Examples exist for combined application of the AS and biofiltration processes, where

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biofilters are built downstream of the AS process, for nitrogen, phosphorus or further suspended solids removal. Biofor® type biofilters were implemented in some high load AS wastewater treatment plants (e.g. Achères WWTP, Paris). In these systems the biofiltration is a separate process running independently of the AS stage.

The main objective of the paper presented is to investigate conditions of nitrification and pre-denitrification occurring in the high load AS system by using results of the mass balances calculated for the plant. Analysis concerning the seeding effect of nitrifying biomass generated in the nitrifying biofilter and the denitrification potential in the anoxic zone of the AS basin was carried out.

The South-Budapest municipal wastewater treatment plant

The SBWWTP was upgraded into nutrient removal in 1998–1999. The plant hydraulic capacity was enlarged to 80,000 $m^3\ d^{-1}$, which can be increased to 120,000 $m^3\ d^{-1}$ in future. The plant serves a combined sewer system with a relatively small amount of industrial discharges. The effluent standard values for the plant were 50 mgCOD l^{-1}, 10 $mgBOD_5\ l^{-1}$, 10 mgTN l^{-1} and 1 mgTP l^{-1}. The plant before upgrading consisted of screens, grit removal, presettlers, AS basins, and final settlers (see Figure 1). The upgrade of the plant comprised implementation of Biofor® type nitrifying and denitrifying biofilters downstream of the AS stage. For post-denitrification in the denitrifying biofilter, methanol (as an external carbon source) was added. Phosphorus removal was obtained by chemical precipitation at five different dosing points for feeding ferric sulfate ($Fe_2(SO_4)_3$). The major part of the chemical was added into the AS basin, and about 10–20% of it was dosed into the nitrifying biofilter.

To reduce the amount of methanol dose in the denitrifying reactor, partial flow recirculation of the nitrified effluent was introduced to the AS basin, from the Biofor® NP filter (see Figure 1) effluent utilizing the easily biodegradable carbon of the raw (pre-settled) wastewater. According to the preliminary calculations for the denitrification and hydraulic capacity of the AS stage, 22,000–23,000 $m^3\ d^{-1}$ water flow (that is, about one-third of the raw water flow) including the backwash water of the nitrifying and denitrifying biofilters was adjusted. The recirculation into the AS stage however, increased the hydraulic load of the final settler. The simultaneous precipitation established in the AS basin however ensured good effluent suspended matter concentrations (<20 mg l^{-1}) through improving settling properties of the floc. The design of the AS tank enables the spatial separation of the reactor zones for different functions (see also Figure 5).

Reactor specific elements

Table 1 and Figure 2 show the influent water characteristics entering the AS basin. The relatively shallow (2.5 m in depth) AS basin ensured plug-flow character. The dissolved oxygen concentration, measured at the outlet point of the basin was between 4.5–7.0 mg l^{-1} on average.

Table 1 Activated sludge reactor properties

	Average	Min.	Max.
Raw wastewater flow ($m^3\ d^{-1}$)	55,500	29,000	115,000
Backwash water flow ($m^3\ d^{-1}$)	6,600	2,100	10,000
Recycled water flow (incl. backwash water)	22,550	4,430	41,950
MLSS concentration (g l^{-1})	2.5	1.2	4.5
Sludge retention time – aerobic (d)	1,7	0.7	5.1
Specific organic matter load (kgCOD $kgMLSS^{-1}\ d^{-1}$)	1.1	0.2	2.4
Return sludge rate (%)	100		

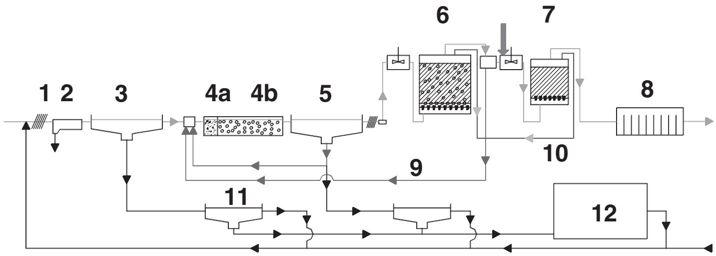

Figure 1 Schematic layout of the South Budapest Municipal Wastewater Treatment Plant (1. Screens, 2. Grit chamber, 3. Presettlers, 4a. Activated sludge tank – anoxic zone, 4b. Activated sludge tank – oxic zone 5. Final settlers, 6. Biofor® NP, 7. Biofor® DN, 8. Disinfection, 9. Recirculation of nitrified water and backwash water 10. Backwash water, 11. Sludge thickening, 12. Sludge treatment: digestion, dewatering)

Methods

The plant performance was monitored for 25 months starting at 1998 October. During the investigated period, samples from various points of the treatment process were analyzed. Daily samples were taken from the influent, the ”mixed” wastewater (mixture of influent, reject water, septic tank and sewer sludge), primary settled effluent, final settler effluent and the plant effluent. From the influent wastewater 24 hours flow proportional samples were taken. Mass balances for nitrogen (NH_4-N, NO_X-N, TN) were evaluated.

For monitoring the pre-denitrification, carbon removal and nitrification in the AS basin, flow proportional samples were analyzed. This measurement was carried out eight times. 24 points were selected for measuring dissolved oxygen concentration and eight points for the nitrogenous forms concentration in the AS basin.

Results

Wastewater characteristics

The wastewater from the sewer system is described in Table 1. Septic tank sewage, sewer sludge and reject water from the outdated and improperly operating sludge dewatering device contributed to the additional load of the wastewater to be treated in the plant during the investigated period. Therefore the pollutant concentration has increased by about 25% in the case of ammonium and by about 100% for organic nitrogen. The organic matter in the mixed sewage was also in higher concentration, the COD exceeded 750 mg l^{-1} on average. The presettlers showed high removal efficiency; about 55–60% of the organic matter (measured in COD) was removed.

Analysis of point samples from the raw sewage showed that filtered/non-filtered BOD_5 concentrations ratio was about 0.7 on average, indicating that dissolved organic matter was dominant. The raw wastewater flow was about 55,500 m^3 d^{-1} on average. On-line measurement gives information about the composition of the nitrified wastewater in the Biofor® NP effluent water, including NH_4-N, NO_3-N concentration. The characteristics of the backwash water convey uncertainties as it depends highly on the biomass activity and biofilm sloughing mechanisms in both the nitrifying and denitrifying biofilters. The backwash

Table 2 Raw water characteristics (mg l^{-1})

	pH	COD	TSS	TP	ortho-P	BOD_5	TKN	NH_4-N	orgN	NO_2-N	NO_3-N	TN
Average	7.8	540	273	8.1	3.5	273	38.6	28.0	10.6	0.2	0.5	39.1
Std. dev.	0.4	231	222	2.7	0.8	162	8.5	6.8	4.9	0.2	0.7	8.3
Max.	9.6	1777	2616	18.2	8.6	1000	84.7	70.3	34.1	1.9	10.5	84.9
Min.	6.6	97	50	1.8	0.5	60	12.0	6.3	0.5	0.0	0.0	13.8

intervals of the seven nitrifying and four denitrifying biofilter units were adjusted to 24 hours.

Pre-denitrification

Pre-denitrification requires the availability of easily degradable organic matter in the sewage water (Henze, 1995; EPA, 1993). In general it can be stated, that the raw (settled) wastewater consists of readily degradable organic substrate for denitrification. Organic matter of the nitrified wastewater in the Biofor® NP had a dilution effect on the settled water. The average BOD_5 concentration of the incoming sewage was about 100–140 mg l^{-1}. An independent study reported similar conclusions on biodegradability and denitrification potential of the raw wastewater in the SBWWTP (Bute, 2000).

Mass balance analysis showed that about 30–40% of the total nitrogen is removed in the AS process by pre-denitrification resulting in methanol consumption reduction at post-denitrification.

Nitrification

The Biofor® NP biofilters arranged downstream of the AS process are to transform the ammonium-nitrogen in the wastewater. Upstream of the biofilters, a rapid mixing unit was established for the mixing of chemicals in order to achieve phosphorus precipitation of the settled wastewater. About 25–30% of the chemically treated and nitrified effluent wastewater is recirculated into the AS basin. The volume of the filter backwash water is about 3,800 and 2,700 $m^3\ d^{-1}$ of the nitrifying and denitrifying filters respectively. The amount of biomass (sloughing sludge from the biofilter media) can be estimated at about 660 kg d^{-1} in the nitrifying and 480 kg d^{-1} in the denitrifying filter (direct measurements concerning the volume and quality of the backwash water were not carried out).

The nitrogen forms of the AS inflow wastewater are shown in Figure 2. The COD concentration was between 80–260 mg l^{-1}. The nitrogen forms were as follows: 18 mgNH_4-N l^{-1}; 6.0 mgNorg l^{-1}; 4.2 mgNO_3-N l^{-1}; and 0.5 mgNO_2-N l^{-1}.

The nitrification rate in the AS basin has widely fluctuated in the investigated period. The bulk water temperature (average daily values) varied between 12 and 24.5°C (see Figure 3). Figure 3 shows, that with increasing temperature the ammonium load of the nitrifying biofilter decreases.

On the basis of the results it is stated that significant NH_4-N conversion occurred in the AS basin when the water temperature exceeded 20°C. The ammonium conversion rate was

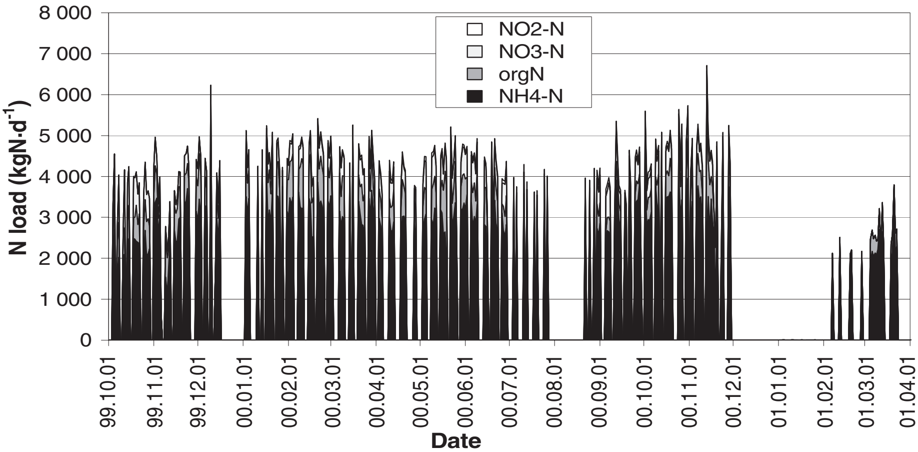

Figure 2 Nitrogen load of the activated sludge stage

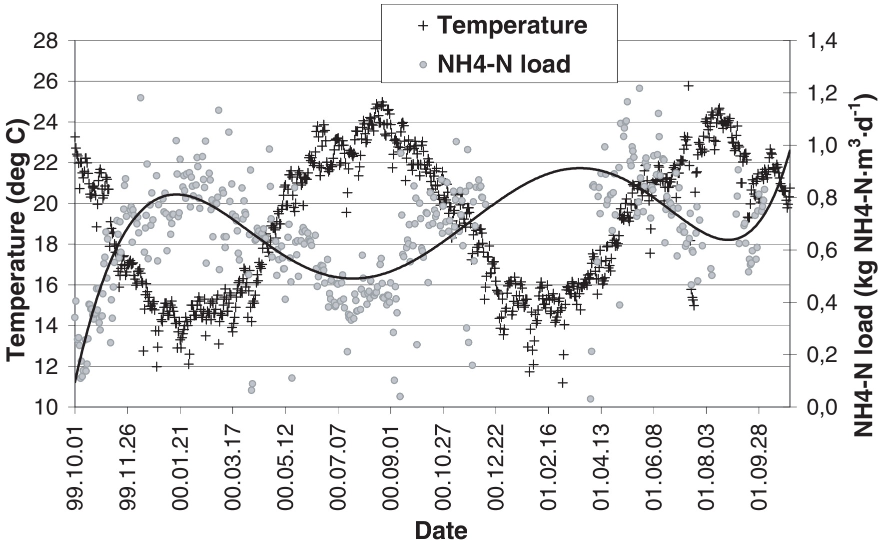

Figure 3 Water temperature in the AS basin and the specific ammonium-nitrogen load of the nitrifying biofilter

between 10–25% (based on entering NH_4-N). In colder wastewater (below 16°C) nitrification stopped completely. It should be mentioned, however, that the NH_4-N concentration has increased in the AS basin due to ammonification. The relationship between the water temperature and effluent water NH_4-N load is shown in Figure 4.

Table 3 Wastewater characteristics in the final settler effluent (mg l^{-1})

	pH	COD	TSS	TP	ortho-P	BOD_5	TKN	NH_4-N	orgN	NO_2-N	NO_3-N	TN
Average	7.9	58.3	19.4	1.9	1.4	12.4	19.5	17.0	2.7	0.7	2.8	22.6
Std. dev.	0.2	18	10.1	0.6	0.4	6.9	4.9	5.3	3.0	0.6	2.0	3.9
Max.	8.3	122	87.0	4.8	2.6	46.0	39.9	31.5	28.7	2.5	10.7	40.2
Min.	7.2	23	3.0	0.2	0.6	2.0	5.5	0.7	0.1	0.0	0.0	7.1

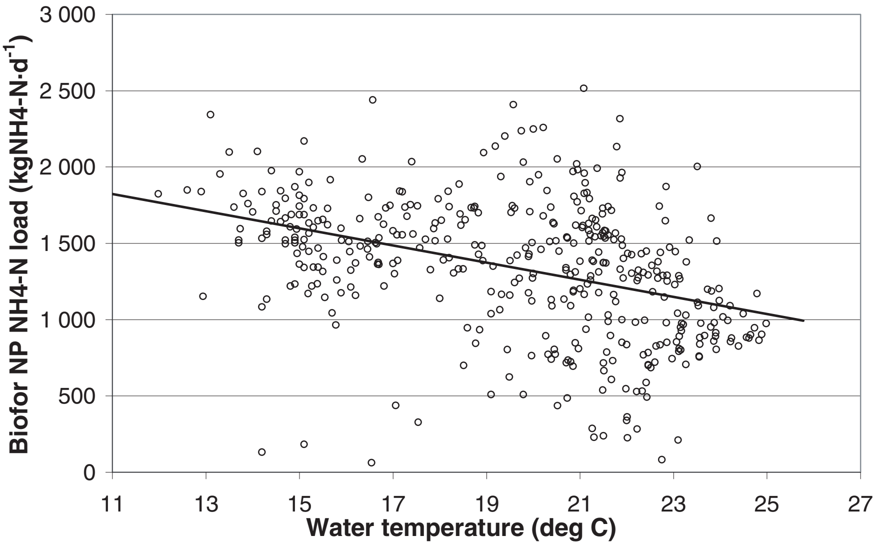

Figure 4 Water temperature and the specific ammonium-nitrogen load of the nitrifying biofilter

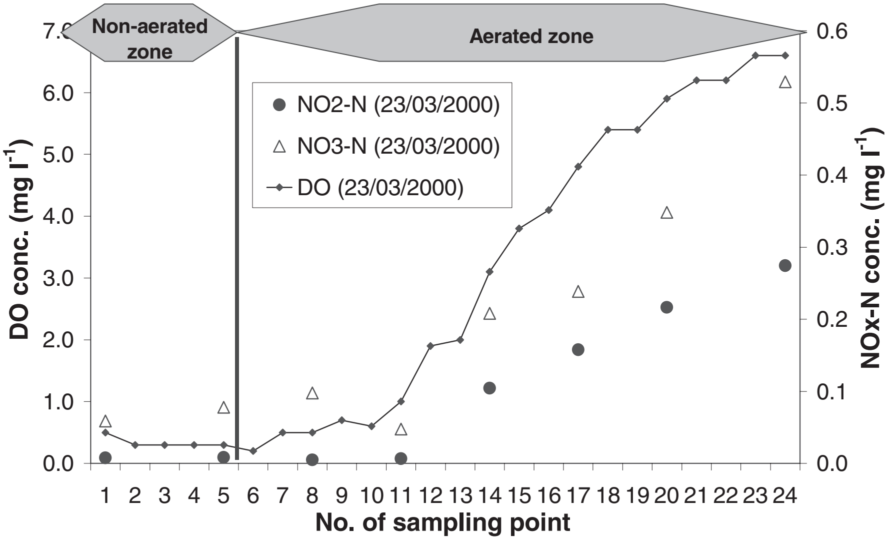

Figure 5 Typical oxygen and NO_X-N profile in the AS basin (23/03/2000)

Survey of nitrogen forms

During the survey of nitrogen forms in the AS basin the water temperature was between 15.4°C and 24.5°C. The influent wastewater contained 150–300 mgCOD l^{-1} (filtered), 17–24 mgNH_4-N l^{-1}, and 1.7–5.6 mgNO_X-N l^{-1}. The pH of the water was above 7.8 in all cases. One of the typical oxygen profiles measured in the basin (shown in Figure 5) demonstrates that in the aerobe zone oxygen concentration increases up to the saturation near the outlet. In the anoxic zone, 0.2–0.4 mg l^{-1} dissolved oxygen was ranged mostly due to oxygen rich recirculated nitrified wastewater. Figure 5 shows a "typical" increase of nitrite- and nitrate-nitrogen through the aeration tanks. Note, that sampling points No. 1–6 are located in the non-aerated zone.

Despite ammonification of organic nitrogen the bulk NH_4-N concentration decreased in all measurements. The nitrate and nitrite in the influent were eliminated at about 60–90% efficiency in the non-aerated anoxic zone i.e. the efficiency of pre-denitrification was relatively high (the oxygen in the anoxic zone has not hampered the NO_X-N reduction). However, increase of the NO_X-N concentrations was observed in the aerated zone. At higher temperatures (above 20°C) 4–17% of the incoming ammonium has converted to nitrite and nitrate. The highest nitrification rate – according to the expectations – was observed at temperatures above 24°C. At lower temperature, the conversion was very poor, about 1–4%.

Conclusion

Control of plant nutrients of municipal wastewater treatment in Hungary has been given priority by environmental authorities in the light of EU accession. The South-Budapest Municipal Wastewater Treatment Plant applies a high load AS process and biofiltration for the removal of carbon and nitrogen forms. Chemical precipitation is applied for phosphorus removal. 25 months of operation have showed, that nitrification occurs in the AS stage despite its low (1.5–2.0 days) aerobic sludge age. The nitrification is enhanced by the seeding of the nitrifying microorganisms derived from the nitrifying biofilter backwash water. On the basis of mass balances for nitrogen it was demonstrated, that about 20–25% of the influent ammonium can be converted to NO_X-N at temperatures above 20°C. At lower temperatures (<16°C) the nitrification reduced significantly in the AS stage.

Continuous feeding of the nitrifying biomass may contribute to better nitrification therefore it would be necessary to achieve optimized backwash water recycling by some operational modifications. The seven separate nitrifying biofilters in operation do not allow homogenous feeding of the sloughing nitrifying biomass into the AS basin (the backwash interval is 24 hours). Furthermore, microbiological research would be initiated for detailed evaluation of the composition of the recycled nitrifying and denitrifying biomass.

Recycling of the nitrified effluent of biofilters into the AS stage resulted in efficient pre-denitrification. The raw sewage contained sufficient readily biodegradable organic matter for denitrification in most of the cases. In the anoxic zone of the AS basin about 30–40% of the nitrogen was eliminated by pre-denitrification, complementing methanol consumption in the post denitrifying Biofor® DN filters.

Detailed evaluation of the nitrogen balances showed, that the particular buildup of the SBWWTP provided opportunities for future improvements in two aspects:

1. The use of backwash water for seeding AS tank to obtain nitrification in high load reactors.
2. To achieve pre-denitrification in the anoxic zone of AS tank by utilizing raw sewage to provide carbon sources for the process.

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