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RESEARCH ARTICLE

Pilot-scale verification of efficient nitrifier backseeding in a combined activated sludge-biofilm system

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Abstract

Purpose of the paper is to experimentally verify that a downstream nitrifying fixed-film reactor may effectively backseed an activated sludge (AS) system. The experiment was carried out at the Southpest Wastewater Treatment Plant in Budapest, Hungary, with two pilot-scale AS systems connected directly to the preclarified influent and to the stream recirculated from the nitrifying fixed-film reactor of the full-scale plant ensuring both the nitrate and the backwashed biomass recirculation. Effluent NH_4-N level dropped down to near zero in the experimental systems whereas no significant nitrification occurred in the full-scale plant being operated at lower aeration intensity. Simulation model developed for describing the combined system supported that backseeding was the cause of the high nitrification efficiency having been limited by inadequate oxygen supply in the full scale system.

Keywords

activated sludge · biofilm reactor · nitrification · backseeding · modeling

Acknowledgement

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Introduction and goals

Different technologies have been developed for the reduction of Solids Residence Time (SRT) required for efficient nitrification in activated sludge (AS) systems. The in-situ bioaugmentation technology described by Khrutková *et al.* [12], cultivates nitrifying organisms in a regeneration zone placed in the return sludge stream using reject water of digesters as basic NH_4-N source. In the Bio-Augmentation Batch Enhanced Technology process (BABE) (Salem *et al.* [17]), the activated sludge system is augmented by its natural nitrifier population enriched through nitrification of the sludge processing waste by part of the returned sludge. Head and Oleszkiewicz [7] investigated the effects of seeding Sequencing Batch Reactors (SBR) operating at low temperatures by nitrifiers cultivated at higher temperatures, in separate SBRs and observed that even at low temperatures (10 textdegree C) the required minimum SRT for nitrification could be considerably decreased through seeding.

Another approach of enhancing nitrification has been the application of nitrifying fixed-film units supplementing the activated sludge system. Hu *et al.* [8] described the External Nitrification Biological Nutrient Removal Activated Sludge system (ENBNRAS) which contained a side-stream nitrifying trickling filter for upgrading the treatment performance. Activated sludge systems following an upstream biofilm unit (Daigger *et al*. [3]; Parker and Richards [15]; Daigger and Parker [4]), or those receiving the excess sludge of a downstream fixed-film reactor are constantly seeded by the microorganisms having been cultivated in the biofilm. However, it is not obvious that microorganisms having grown in the fixed-film system may survive and efficiently grow also in the activated sludge unit. In cases when the wastewater is at least partly of industrial origin and contains potentially inhibitory chemicals, the likelihood of nitrifier survival is greater when it is introduced into the activated sludge system from an upstream biofilm reactor. Doubts can be raised, however, in cases when the activated sludge unit precedes the fixed-film unit being the source of the backseeded biomass. Namely, it can be assumed, that microorganisms in this case would grow at considerably lower concentrations of these inhibitory substances in the biofilm then in the activated sludge unit.

It is a common engineering practice to use fixed-film systems for nitrification of wastewater leaving a high-load activated sludge treatment stage (Chudoba and Pujol [2]). When the backwash water of these fixed-film reactors is introduced into the activated sludge basins, nitrifiers will be mixed with the suspended biomass. However, due to the well-known sensitivity to toxic organics, survival and efficient growth of these nitrifiers have not been considered as a reliable technological solution, although some inhibitors proved to be well tolerated by nitrifying organisms following an acclimation phase (Xiong *et al.* [19]).

The purpose of the paper is to experimentally verify the possibility of enhanced nitrification in an upstream activated sludge unit through backseeding by the excess biomass wasted from the nitrifying fixed film reactor by using adequately aerated, continuous-flow pilot-scale systems. The idea behind this is the assumption that although the concentration of dissolved organics may be relatively low in the downstream biofilm niche, the effluent toxic organic level of the high-load activated sludge system may still be considerably high. Thus, at least part of the possibly inhibiting compounds of the activated sludge influent may also be present in the biofilter influent, facilitating adaptation and consequent survival and growth of the sensitive nitrifiers also in the activated sludge system.

Enhanced biological nitrogen removal in the activated sludge unit of a combined activated sludge – downstream fixed-film system may decrease cost and energy requirements and improve process efficiency. Activated sludge denitrification with the carbon source of the influent wastewater may result in savings in the external carbon source required as well as in the oxygen demand and lower effluent COD and nitrate levels can be achievable (Jobbágy *et al.* [11]).

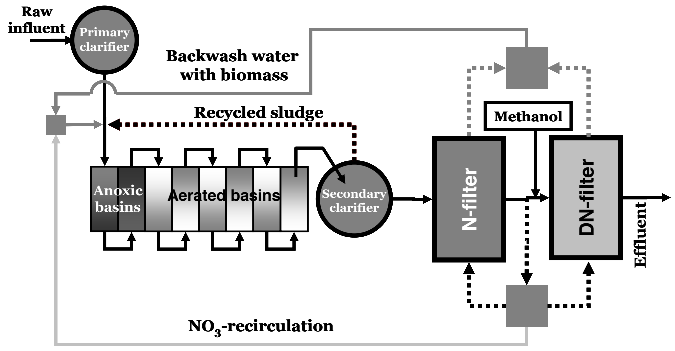

Fig. 1. Schematic of the Southpest Wastewater Treatment Plant

Configuration of the treatment plant and preliminaries

In order to meet the effluent criteria of the sensitive receiving water body, the high-load activated sludge system of the Southpest Wastewater Treatment Plant (WWTP) of Budapest, Hungary was supplemented by nitrifying and denitrifying fixed-film reactors (N-filter and DN-filter) in 1999 (Jobbágy *et al.* [9], Jobbágy *et al.* [10]). In this combined system the nitrate-rich effluent of the N-filter is recirculated to the first non-aerated basins of the activated sludge unit in order to decrease the methanol demand of the DN-filter (see Fig. 1.). The activated sludge reactors are divided into 8 equal volume basins connected in series. Four of the eight basins are equipped with both aeration devices and mixers. In general, the first 2 basins are operated in a non-aerated mode. Both kinds of the fixed-film reactors are backwashed by the nitrate-rich effluent of the N-filter and the excess biomass is wasted through the activated sludge units by feeding the backwash water into the recirculation line of the N-filter effluent.

Although nitrification in the activated sludge unit had not been a technological goal and had been rather unexpected due to the relatively short solids residence time (SRT) of 2-2.5 days, in some periods of the trial operation considerable ammonia removal was observed in this treatment stage. In order to adequately elucidate the role of a possible backseeding as well as to compare different technological options, an Activated Sludge Model No. 1 (ASM1) based mathematical model was developed for describing the interactions in the combined system (Jobbágy *et al.* [10]). At the start-up period of the Southpest WWTP also full-scale results showed that backseeding with the nitrifying biomass originating from the N-filters may enhance nitrification in the activated sludge unit (Tardy and Jobbágy [18]). Simulation studies with this model revealed that efficient backseeding may considerably improve performance by enhancing nitrification ability of the activated sludge unit, thereby facilitating considerable savings in both methanol and aeration costs. Full-scale results verified the applicability of the model, but long-term, efficient nitrification could not be achieved in the full-scale activated sludge unit although the enhanced activated sludge denitrification decreased the oxygen demand of carbon removal (Jobbágy *et al.* [11]). No direct investigation of possibly facilitating efficient backseeding through increased activated sludge aeration had been carried out. On the basis of the results, it could be assumed that insufficient aeration of the basins hindered the efficient backseeding, i.e. the unlimited growth of the backwashed nitrifiers in the activated sludge unit. However, it could not be unambiguously excluded that the backseeded nitrifiers had been unable to efficiently grow at the relatively higher level of possible toxicants, because this particular treatment plant receives not negligible part of wastewater of industrial origin.

Experimental

Basic considerations

At the time of the experiment there had been practically no nitrification in the activated sludge unit of the full-scale plant. It was assumed that the growth of nitrifiers had been basically hindered by the lack of oxygen and not by influent inhibiting pollutants in the AS unit.

In order to assure controlled operation, the experiments were carried out in pilot-scale systems, with sufficient air supply for nitrification. Nor reference system without backseeding was used in the experiment for the following reasons. Since the backwashed biomass of the fixed-film systems is introduced to the activated sludge reactors with the nitrate recirculation, in order to create a system without backseeding sterile filtration or at least efficient sedimentation of the recirculated biomass would have been necessary, which would have resulted in highly different SRT values in the two experimental systems, so the results of them would not have been comparable.

Therefore, the experimental results were rather compared to the full-scale performance and evaluated by the application of a mathematical model developed and successfully used in an earlier study (Jobbágy et al. [10]).

Configuration of the experimental systems

The pilot-scale systems were installed on site, while special care was taken for assuring the similarity of their biological niche to that of the full-scale system. The two experimental systems were divided into four reactors each, with volumes of 0.9 l, 0.9 l, 1.8 l, and 3.6 l, respectively (see Fig. 2). This compartmentalization aimed to adjust the concentration profiles of the occurring pollutants similar to those of the full-scale plant. The relative volumes of the first two reactors corresponded fully to those of the full-scale system. The third reactor represented the 3rd and 4th full-scale basins, whereas the fourth reactor represented the 5-8th basins of the full-scale system. In the experimental activated sludge systems only the first 2 reactors were operated under anoxic conditions.

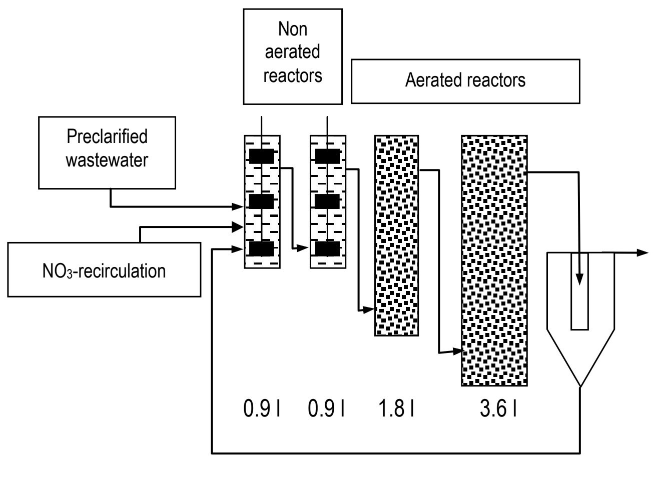

Fig. 2. Schematic of the experimental system

Both of the two experimental systems were directly fed by the preclarified influent of the full-scale plant, and were temperature controlled in accordance with the temperature values of the full-scale system. Both the hydraulic retention time of the wastewater (5.5 hrs) and the total SRT (~2 days) were set to the values characterizing the full-scale plant. In order to achieve the appropriate SRT value, the mixed liquor suspended solids (MLSS) concentration was also adjusted to that of the full-scale system. Excess sludge was wasted from the last reactors of the experimental AS systems.

In addition to the preclarified influent, the experimental systems were also directly connected to the combined, nitrate containing stream coming from the recycled effluent of the nitrifying fixed-film system including also the backwash water of the fixed-film reactors (N- and DN-filters). The experiment was started by filling up the reactors with the mixed liquor of the not nitrifying full-scale system, and then the effluent of the full-scale activated sludge unit was placed into the experimental clarifiers occupying one third of their volumes.

Controlled and measured parameters

Influent and effluent values as well as full profiles of COD, NH_4-N, NO_3-N, NO_2-N and dissolved oxygen (DO) concentrations were measured throughout the experiment using standard methods. Temperature and MLSS concentrations were measured daily in the last reactors. The pilot-scale experiment was

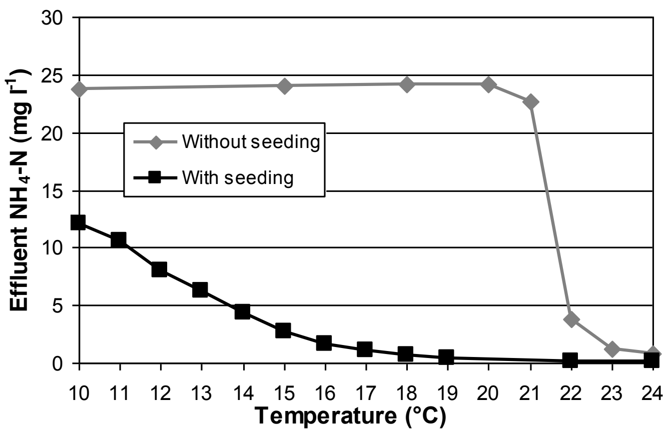

Fig. 3. Steady-state simulated effluent NH_4-N concentration values

carried out in a 30 days period, when AS nitrification could not have been detected for a long period of time despite some promising results of the trial operation (Jobbágy *et al*.[10]). This period was chosen on the basis of the results of simulation studies having predicted a significant difference between the performance of the efficiently seeded and unseeded activated sludge systems (Jobbágy *et al.* [10] and Fig. 3). At the beginning of the experiment flow rates of the influent and recirculated streams corresponded to the operation of the full-scale plant. In order to create different conditions for N-removal, rates of the recycled streams were modified according to the data of Table 1. In a previous study (Jobbágy *et al.* [10]) inadequate air supply had been suggested to be the reason of limited growth of the backwashed nitrifiers in the activated sludge system of Southpest Wastewater Treatment Plant. Therefore, care was taken that the pilot-scale systems were adequately aerated and the dissolved oxygen concentration was maintained at 4-6 mg l^{-1}. On November 11th, the air flow was decreased drastically in System 2.

Simulation studies

The Activated Sludge Model No.1 (ASM1) (Henze *et al.* [6]) was used as a basis for the simulation studies. The model was supplemented with the description of the quality of the unified

Tab. 1. Operational pattern of the experimental systems (l h^{-1})

	System 1					System 2				
Date	Preclar. influent	Sludge Rec.	N-rec	Unified influent	Air flow	Preclar. influent	Sludge Rec.	N-rec	Unified influent	Air flow
10.25	1.3	0.7	0.65	2.65	700	1.3	0.7	0.65	2.65	900
11.03	1.3	1.3	0.65	3.25	700	1.3	0.65	0.65	2.6	900
11.11	1.3	1.3	0.65	3.25	500	1.3	0.65	1.3	3.25	80
11.16	1.3	1.9	0.65	3.85	500	1.3	0.65	1.9	3.85	80

recirculated streams deriving from the nitrate-rich effluent of the N-filter combined with the backwash water of the N- and DN-filters. In the course of describing the processes occurring in the fixed-film reactors, the following assumptions were made (Jobbágy *et al.* [10]):

- Concentration of NO_3-N in the N-filter effluent was calculated on the basis of the difference between the influent and effluent NH_4-N concentrations, supplemented by the concentration of eventually occurring NO_3-N coming from the activated sludge unit. Incorporation of nitrogen into biomass was assumed to be negligible.
- It was assumed that practically all of the suspended solids leaving the secondary clarifier of the activated sludge unit are retained in the N-filter, which was consistent with the observations. Estimation of the total effluent suspended solids concentration of the secondary clarifiers was based on measured data, whereas the ratio of the different fractions was adjusted to the results of the ASM1 model applied.
- It was hypothesized that all of the suspended solids having left the secondary clarifiers or having been produced in the filters are fully backwashed and, therefore, end up together in the influent of the activated sludge unit.

Production of autotrophic bacteria (P_{aut}) in the N-filters was calculated using equation (1). In this equation Y_{NH4-N} [g nitrifying biomass COD g^{-1} NH_4-N removed] represents the growth yield, ΔNH_4N [g m^3] stands for the difference between the influent and effluent ammonia concentrations of the N-filters, whereas Q_N[m^3 d^{-1}] indicates the total flow rate through the N-filters. The value of Y_{NH4-N} was set to 0.32 g biomass COD g^{-1} NH_4-N removed (Jobbágy *et al.* [10]).

$$P_{aut} = Y_{NH4-N} \cdot \Delta NH_4 - N \cdot Q_N \quad [\text{g biomass COD d}^{-1}] \qquad (1)$$

In the DN-filters of the Southpest WWTP methanol is used as external carbon source. The production of the relevant heterotrophic bacteria can be described by equation (2).

$$P_{het} = Y_{X/MeOH} \cdot R_{MeOH/NO3-N} \cdot \Delta NO_3 - N \cdot Q_{DN} \quad [\text{g biomass COD d}^{-1}] \qquad (2)$$

where $Y_{X/MeOH}$is the heterotrophic yield on methanol as carbon source and was set to 0.4 g biomass COD g^{-1} COD MeOH on the basis of the data available in the literature (Koch *et al.* [13], Lemmer *et al.* [14], Aesoy *et al.* [1], Purtschert and Gujer [16]). $R_{MeOH/NO3-N}$ is the rate of methanol consumed for nitrate elimination. Considering that in the post denitrification filter nitrate serves both as nitrogen source and as electron acceptor, the value of 4.1 g methanol COD g^{-1} NO_3-N was used as $R_{MeOH/NO3-N}$ (Jobbágy *et al.* [10]). The eventual inactivity i.e. incapability for growth of the recirculated nitrifiers in the activated sludge unit caused by any unfavorable conditions, e.g. inhibiting compounds, oxygen deficiency, toxic pollutants, etc. was modelled through using a "viability factor" (f_v), representing the efficiently growing biomass ratio to the total amount backwashed from the N-filter.

BioWin 2.1 software (EnviroSim, [5]) was used for steady state and dynamic modeling of the activated-sludge systems. Composition of the mixed influent was calculated from the corresponding data of the preclarified influent and the calculated composition of the stream recirculated from the N-filter including also the backwashed biomass. Measured values of temperature, DO and flow-rates were used as input data of the simulation. Nitrification kinetic parameters of the activated sludge model were estimated on the basis of measured data and the evaluation of relevant values from the literature (Jobbágy *et al.* [10]), giving a maximum specific growth rate (μ_{Amax}) of 0.6 d^{-1} at 20 °C, applied together with the default temperature (T) dependence equation of the software, given in equation (3).

$$\mu_{\text{A}} = \mu_{\text{Amax}}\, e^{0.0695\,(T-20)} \qquad (3)$$

According to our simulation studies, to achieve full nitrification in a pilot scale system without seeding, the applied 0.6 d^{-1} value of μ_{Amax}in equation 3 should have been changed to higher than 0.9 d^{-1}. This would have been in contradiction with our former experiences in this particular treatment plant where the influent wastewater contains considerable industrial fraction.

Results and discussion

Steady-state simulation studies aimed to predict the impact of the nitrifiers seeded into the pilot scale activated sludge systems with N-recirculation at different temperatures. The calculations were carried out by using the average values of the operational and influent data measured preceeding the experiment (COD = 415 mg l^{-1}, TSS = 277 mg l^{-1}, TKN = 46.5 mg l^{-1}, NH_4-N = 35 mg l^{-1}, MLSS = 2.2 g l^{-1}). While simulating

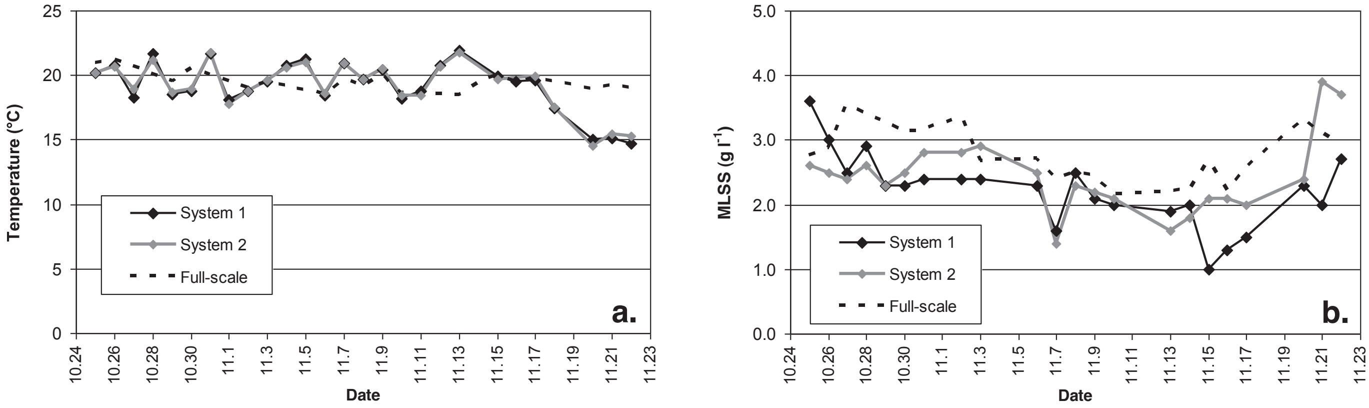

Fig. 4. Temperature (a) and MLSS (b) values in the experimental and in the full-scale systems

the efficient seeding, the autotrophic biomass having grown in the N-filter was assumed to be fully efficient also in the activated sludge unit, whereas in the case of simulating without seeding, the backseeded nitrifiers were considered to be inactive in the AS unit and regarded as suspended solids (f_v was set to 0). The large difference between the effluent NH_4-N values simulated with and without efficient seeding shown in Fig. 3., support the theory that backseeding may highly enhance nitrification in the given activated sludge system, especially in the temperature range of 18–20 °C.

On the basis of the steady-state simulation study, the pilot-scale experiment was carried out in autumn period (between 25th October and 23th November), when the temperature of the mixed liquor in the full scale activated sludge unit was in the range of 19–21 °C. Figs. 4 a. and b. show the values of temperature and MLSS concentration used as control parameters in the pilot scale systems, and adjusted to the full scale data. It can be observed that the temperatures of the pilot-scale reactors reflected the full-scale values very well. At the end of the experiment, the temperatures of the pilot-scale systems were decreased in order to investigate the performance at lower level. Fig. 4 b. shows that the MLSS concentrations of the pilot-scale reactors were in accordance with those of the full-scale system, and in fact, the values in the experimental systems proved to be rather lower. Influent and effluent NH_4-N concentrations measured in the full-scale system during the experiment have been depicted in Fig. 5. Calculated concentrations of the mixed influent of the activated sludge systems coming from the preclarified wastewater and from the N-recirculation including also the backwashed biomass, are also shown. It is obvious that no remarkable nitrification occurred in the full-scale plant in this period. On the contrary, following an “acclimation phase”, in which the appropriate part of the backseeded nitrifiers was able to grow up to the steady-state concentration, effluent NH_4-N concentrations dropped down to near zero in the pilot-scale systems, as had been suggested by the steady-state simulation studies (see Fig. 3.). After November 16th, just a slight increase was observed in the effluent NH_4-N concentration of System 1

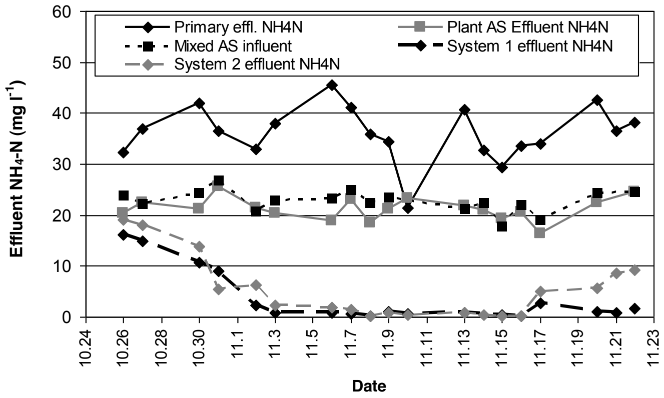

Fig. 5. Influent and effluent NH_4-N values in the full scale and pilot-scale systems

as a result of the decreased temperature (see Fig 4. a). In System 2, however, the effluent NH_4-N level increased significantly. The difference between the performance of the two experimental systems can be attributed to the drastically reduced aeration of System 2 (see Table 1).

In order to investigate the causes of the efficient nitrification in the pilot-scale systems, simulation studies were carried out with the following options:

- *Simulated without seeding*: the backwashed nitrifying biomass was assumed to be fully inactive in the activated sludge system, regarded as suspended solids. Therefore, f_v was set to zero.
- *Simulated with seeding*: the backwashed nitrifying biomass was assumed to be able to efficiently grow in the activated sludge unit, f_v was regarded to be 1.
- *Simulated with seeding and acclimation phase*: in the first part of the experiment (October 25–November 2), an acclimation period was modeled in which value of f_v was gradually increased from 0 to 1. In the rest of the experiment f_v was set to 1.

Effluent NH_4-N and NO_3-N concentration values obtained by the dynamic simulation of the pilot-scale systems, together with

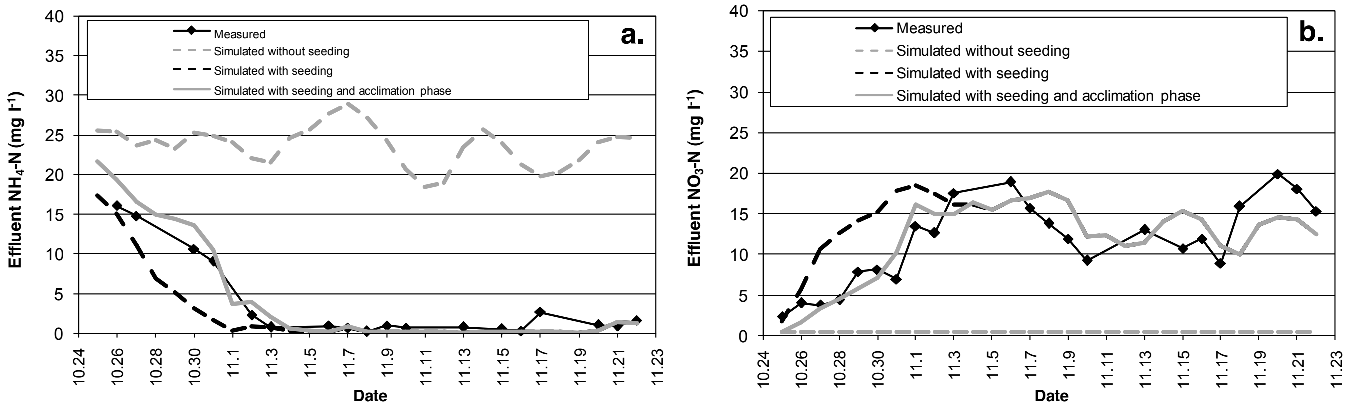

Fig. 6. Measured and simulated effluent (a) NH4-N (b) NO3-N values in System 1

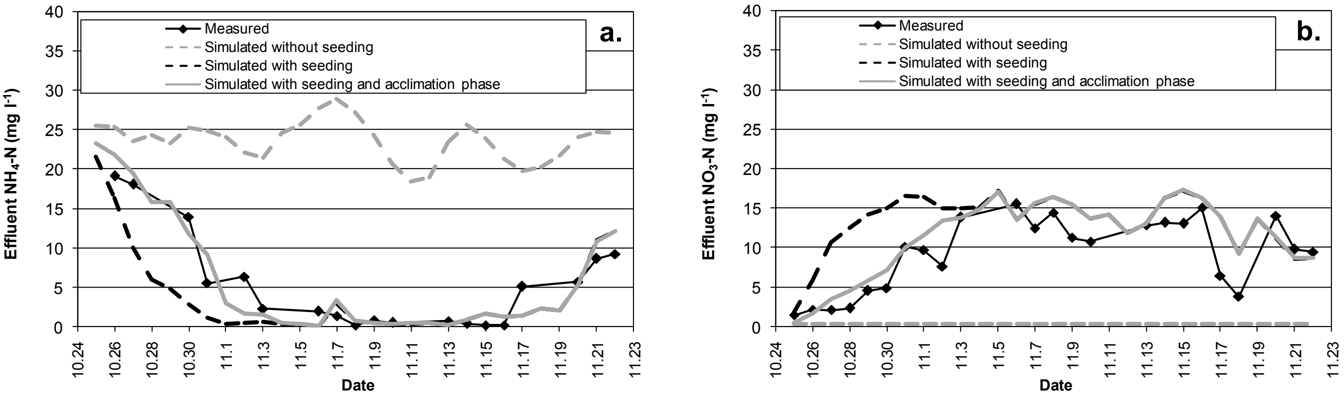

Fig. 7. Measured and simulated effluent (a) NH4-N (b) NO3-N values in System 2

the measured data are illustrated in Figs. 6. a,b and Figs. 7 a,b. The dymamic simulation followed the changes of temperature and also those of the operational parameters (air supply). The obvious difference between the measured data and the values simulated without seeding as well as the good fit of the curve with seeding verifies that efficient backseeding resulted in enhanced nitrification in both of the experimental systems. At the beginning of the experiment, the "*Simulated with seeding and acclimation phase*" option gave the best fit to the measured data, suggesting that a certain degree of acclimation of the backwashed biomass was required to reach its full activity in the activated sludge system. This result can be attributed to the difference of the microbial niche determined basically by the wastewater quality in the downstream fixed-film and in the activated sludge system. The options *"Simulated with seeding"* and *"Simulated with seeding and acclimation phase"* also resulted in values fitting very well to the last sections of the measured data of the pilot-scale systems. Thereby, the effects of decreased temperature as well as the additional impact of the reduced air supply in System 2 could be well described.

Measured and simulated effluent NH_4-N and NO_3-N data of the activated sludge unit of the full-scale plant are illustrated in Fig. 8. The high effluent NH_4-N and low (1-4 mg l^{-1}) NO_3-N concentration values could be well approximated through simulation with a highly decreased value of f_v (0.03). Since full nitrification could be achieved in both of the pilot-scale systems receiving the same influent, at the same SRT and temperature values, it can be excluded that wastewater characteristics or short SRT could be the cause of the restricted viability of the nitrifying biomass in full-scale. Considering also the fact that nitrification efficiency decreased in System 2 when oxygen supply was decreased suggest that in the full-scale system nitrification was basically limited by insufficient aeration. This has also been

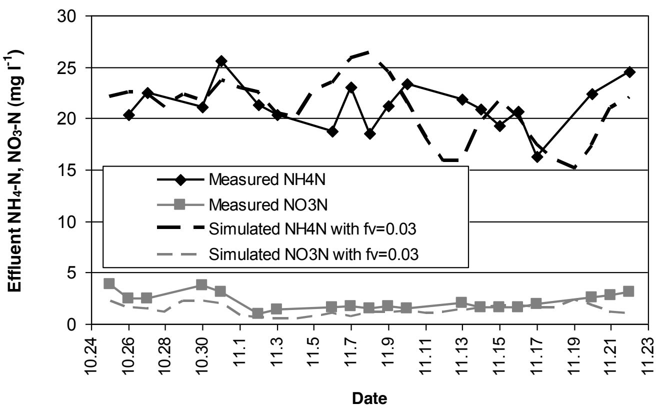

Fig. 8. Measured and simulated data of the activated sludge effluent of the full-scale plant

supported by full-scale experiments aiming increased denitrification efficiency at the Southpest WWTP (Jobbágy *et al.* [11]).

Conclusions

Two activated sludge pilot-scale systems were operated at the Southpest WWTP having a combined AS-biofilm treatment facility in Budapest, Hungary. The experimental systems were connected directly to the preclarified influent and to the stream, recirculated from the downstream nitrifying filter of the full-scale plant, carrying back the nitrate for denitrification as well as the backwashed excess biomass for wastage.

- It has been experimentally proven and supported by simulation studies that a nitrifying fixed-film reactor may efficiently backseed an upstream activated sludge unit treating domestic wastewater with industrial part, resulting in enhanced nitrification despite the industrial part of the influent.
- The ASM1-based mathematical model developed for describing the interactions in the combined activated sludge-biofilm system proved to be well applicable for the dynamic simulation of the performance.
- Simulation results fitted to the experimental data suggested that acclimation of the biomass backwashed from the fixed-film reactors may be required for sufficient activity in the activated sludge unit.
- On the basis of the pilot-scale results and simulation studies, nitrification proved to be limited by inadequate aeration in the full-scale system, since it had not been assumed that nitrification would occur at the short SRT values maintained in the AS unit.

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