Water Science & Technology—WST | 61.9 | 2010

Intermittent feeding of wastewater in combination with alternating aeration for complete denitrification and control of filaments

Styliani Kantartzi, Paraschos Melidis and Alexander Aivasidis

ABSTRACT

In the present study, a laboratory scale system, consisting of a primary settling tank, a continuous stirred tank reactor and a clarifier were constructed and operated, using wastewater from the municipal wastewater treatment plant in Xanthi, Greece. The system operated under intermittent aeration in aerobic/anoxic conditions and feeding of the wastewater once in every cycle. The unit was inoculated with sludge, which originated from the recirculation stream of the local wastewater treatment plant. The wastewater was processed with hydraulic retention time (HRT) of 12 h, in which various experimental states were studied regarding the combination of aerobic and anoxic intervals. The wastewater was fed in limited time once in every cycle of aerobic/anoxic conditions at the beginning of the anoxic period. The two states that exhibited highest performance in nitrification and total nitrogen removal were, then, repeated with HRT of 10 h. The results show that, regarding the nitrification stage and the organic load removal, the intermittent system achieved optimum efficiency, with an overall removal of biological oxygen demand (BOD_5) and ammonium nitrogen in the range of 93–96% and 91–95% respectively. As far as the total nitrogen removal is concerned, and if the stage of the denitrification is taken into account, the performance of the intermittent system surpassed other methods, as it is shown by the total Kjeldahl nitrogen (TKN) removal efficiency of 85–87%. These operating conditions suppressed the growth of filamentous organisms, a fact reflected at the SVI values, which were lower than 150 ml/g.

Key words | denitrification, intermittent aeration, intermittent feeding, nitrification, wastewater treatment

Styliani Kantartzi (corresponding author)
Paraschos Melidis
Alexander Aivasidis
Department of Environmental Engineering,
Democritus University of Thrace,
Xanthi,
Greece
E-mail: *skantart@xan.duth.gr*;
pmelidis@env.duth.gr;
aaivazid@env.duth.gr

INTRODUCTION

Up until the 1970s, in Europe and more recently in Greece, many of the wastewater treatment plants (WWTPs) were not designed to incorporate the removal of nutrients, while still remaining deficient in design, with regards to the removal of the components responsible for eutrophication. The basic methods of activated sludge treatment can be improved by incorporating methods that enhance biological nutrient removal. The modified processes focus on complete nutrient removal, rather than simply oxidizing it. Based on high ammonia removal over partial oxidation to nitrite, or by the implementation of anaerobic conversion of nitrite and ammonium to nitrogen gas, the modified processes achieve enhanced nutrient removal (Hellinga *et al.* 1998, Kuai & Verstraete 1998).

The intermittent cycle process (Hamamoto *et al.* 1997; Zipper *et al.* 1998; Battistoni *et al.* 2003) is a modified conventional wastewater treatment process, which offers the advantage of alternating aerobic and anaerobic conditions periodically in a single reactor. The intermittent oxic/anoxic process with the automatic control may not

doi: 10.2166/wst.2010.136

only be viable, but also very effective and easy to implement in existing and new, from household to large scale, WWTPs (Battistoni *et al.* 2008). In systems that use combined nitrification/denitrification processes, the cost for aeration is abated, the sludge quality is improved and the organic load removal is higher. Improved quality of sludge leads to better separating conditions at the clarifier and effluent of a higher quality. Higher organic load removal can be obtained in comparison to the conventional aerobic systems. The denitrifying biomass shows scarcely phenomena of foaming. Biological nutrient removal (BNR) is effective regarding also the pH variations, by means of controlling the alkalinity production during the process. Using pH and oxidation reduction potential (ORP) as real time process control parameters, the dynamic characteristics of the system can be monitored and the end points of nitrification and denitrification can be detected (Tanwar *et al.* 2008). Higher nitrogen removal can be obtained in comparison to the conventional aerobic systems (Balku 2007).

The intermittent aeration, in combination with the use of an anoxic/aerobic selector, reduces the sludge volume index (SVI) and suppresses the growth of filamentous microorganisms 0041, 0675 and 021 N caused by low F/M ratios (Nakhla & Lugowski 2003). Introducing a strong substrate gradient in the reactor, in such a way (pulse feed) that the fill time ratio is decreased (FTRox $\leq$ 4.2%) and the organic substrate is readily available to be absorbed near the maximum specific rate, leads to the formation of good settling quality sludge (SVI $<$ 100). These observations confirm that under conditions where a strong gradient of substrate is established in the process, the floc-forming microorganisms prevail and the filamentous bacteria are either washed out from the system, or, at least, become less abundant, or are even incorporated inside the floc (Martins *et al.* 2003). Optimizing the cycle length and the aerobic/anoxic phase fraction can lead to higher nutrient removal efficiency, flexible and reliable system operation for the treatment of variable flow and strength wastewater (Hong *et al.* 2008).

In the present study a continuous flow system operated under intermittent aeration by cyclic alternation of aerobic and anoxic conditions and feeding of the wastewater once at the beginning of every anoxic period. Various experimental states were studied in order to identify the optimal aerobic/anoxic intervals, during the operational cycle, for maximum organic and nitrogen removal and control of filamentous organisms.

MATERIALS AND METHODS

A lab-scale system consisting of a primary settling tank (PST), an intermittent continuous stirred tank reactor (i-CSTR) and a sedimentation tank (ST) was used in this study (Figure 1). During the anaerobic/anoxic and aerobic sequences, the content of the reactor was kept in

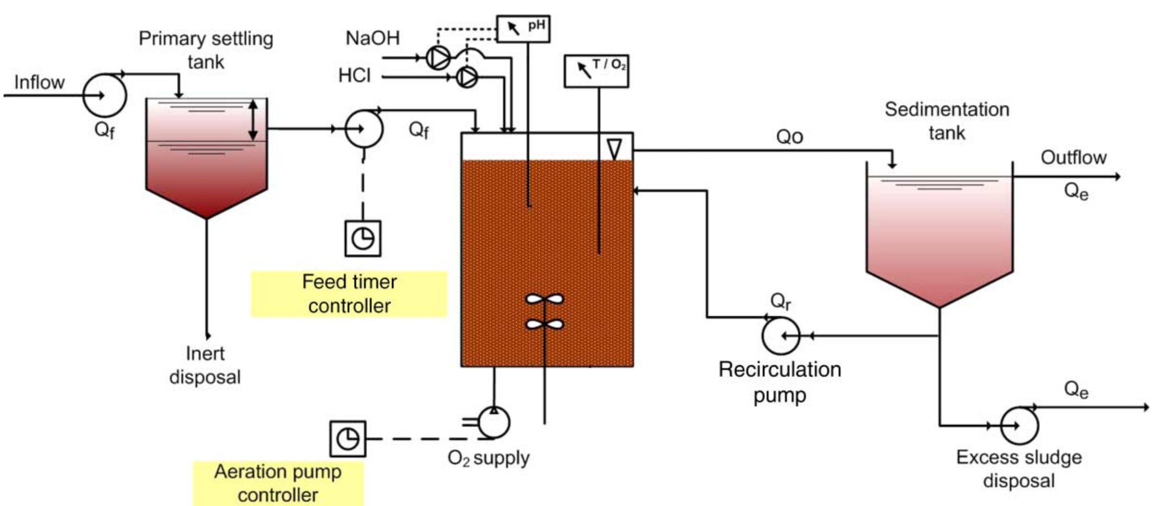

Figure 1 | Flow chart of the experimental unit.

suspension, by means of a low speed mixer fixed at the bottom of the reactor assembly.

The total volume of the reactor was 5 L with a working volume of 4.5 L. The temperature was maintained at 20°C and a pH controller (Conducta PXRi2) was set to maintain pH value between 7.4 and 7.9. During the aerobic phase, air was inducted to the reactor through a fine bubble diffuser connected to a pneumatic compressor with an assembly of dissolved oxygen (DO) meter and probe. The concentration of BOD_5, chemical oxygen demand (COD), total solids (TS), mixed liquor suspended and volatile suspended solids (MLSS, MLVSS), TKN and the values of SVI, and alkalinity were analyzed according to standard methods (APHA 1998); the concentrations of NH_4^+-N, NO_3^--N, NO_2^--N were analysed using high pressure liquid chromatography (HPLC) with a Dionex conductivity detector. Grab samples for analysis were collected periodically from the influent and the effluent. The samples were placed in a refrigerator at − 18°C, until analysis could be performed. Each experimental state was studied provided that the system had reached a steady state. The identification of microorganisms found in the system was made according to the protocol of Eikelboom (Eikelboom 2000). The Gram and Neisser staining techniques and the Sulphur storage test were also applied.

Wastewater characteristics

For the start up of the system and until the desired activated sludge concentration was achieved, concentrated biomass was used from the recirculation stream of the local municipal WWTP in Xanthi, Greece, which operates under extended aeration activated sludge process. The system had been operating for three weeks before the experiments began and a week under the new conditions between the experimental state changes, to allow the biomass to acclimate to the operating conditions.

Urban wastewater was used for the experiments originating from the same WWTP. Adequate quantities were taken from the treatment plant every 48 h and were kept in refrigeration at 4°C, in order to prevent biodegradation of the organic content as much as possible. The COD reduction, which was observed during refrigeration, was less than 4% on a daily basis. The basic chemical parameters of the feed were checked regularly. The quality and the strength of the wastewater depended on the climate and seasonal changes. The average values of the main wastewater characteristics were: soluble COD (sCOD) 530 mg/L, BOD_5 238 mg/L, TKN 52.3 mg/L, NH_4^+-N 40.9 mg/L, NO_3^--N 0.8 mg/L, pH 7.55, and conductivity 983 μS/cm.

Table 1 | Intermittent system operating conditions

	Experimental state						
Parameter	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**
HRT, τ [h]	12	12	12	12	12	10	10
SRT [d]	10	10	10	10	10	10	10
COD [mg/L]*	492	686	594	555	424	399	490
F/M [g BOD/g MLVSS d]*	0.3	0.3	0.3	0.2	0.2	0.2	0.3
COD/BOD_5*	2.2	3.2	3.0	1.7	1.9	2.0	1.8
MLSS [g/L]*	1.90	1.65	1.65	2.46	2.39	2.14	2.06
TS eff [g/L]*	0.63	0.67	1.07	0.76	0.78	0.89	1.04
NH_4^+-N in [mg/L]*	32.7	46.4	34.6	33.0	55.5	38.8	42.4
NO_x^--N eff [mg/L]*	3.8	1.4	7.9	1.3	0.9	1.4	2.2
Aerobic conditions [min]	20	15	15	30	20	15	30
Anoxic conditions [min]	40	45	60	30	50	60	30
Cycle length [min]	60	60	75	60	70	75	60
Cycles/day	24	24	19.2	24	20.5	19.2	24

*Mean values.

Table 2 | Min, max and average values of organic load percent removal for all experimental states

	COD [% removal]			BOD [% removal]		
State	Min	Max	Ave	Min	Max	Ave
20/40 – 12 h	66.8	81.0	76.1	78.0	87.0	82.7
15/45 – 12 h	78.5	86.4	83.3	84.4	96.0	90.7
15/60 – 12 h	79.1	89.1	83.3	90.4	93.0	92.1
30/30 – 12 h	82.4	91.7	88.3	94.5	97.6	96.0
20/50 – 12 h	67.1	92.9	82.4	85.5	94.9	90.0
15/60 – 10 h	70.7	85.0	78.9	73.6	94.4	81.8
30/30 – 10 h	89.5	89.5	89.5	90.0	90.0	90.0

Experimental setup and reactor performing conditions

The substrate from the PST was fed to the bioreactor periodically, added quickly once at the beginning of the anoxic phase of every cycle, two minutes after the aeration was stopped. Moreover, the aeration in the CSTR was intermitted periodically. The process consisted of continuous alterations of aerobic/anoxic conditions.

The system operated continuously at 10 d solids retention time (SRT) under different sets of operating conditions. The sludge age was kept constant at 10 d, gradually disposing 1/10 of the reactor content each day. The system performed 24, 19.2 and 20.5 cycles/day with a duration of 60 or 75 min/cycle. The reactor efficiency was assessed under a hydraulic retention time (HRT) of 12 and 10 h. The aerobic/anoxic phases varied between 20/40 min/min, 15/45, 15/60, 30/30, and 20/50, respectively, at 12 h HRT and the aerobic/anoxic phases varied between 15/60 min/min and 30/30, respectively, at 10 h HRT. During the anoxic reaction phase, mixing was provided without aeration, whereas during the aerated reaction phase, both mixing and aeration were provided. During the aerated reaction phase, DO concentration in the reactor was maintained at 2–2.5 mg/L. The processed wastewater was led to the settling tank through the overflow of the reactor. The operating conditions, according to the on/off aeration periods, are shown in Table 1.

RESULTS AND DISCUSSION

Organic matter removal

Results of organic load removal during the different experimental states, according to the on/off aeration periods, are shown in Table 2 and also in Figure 2.

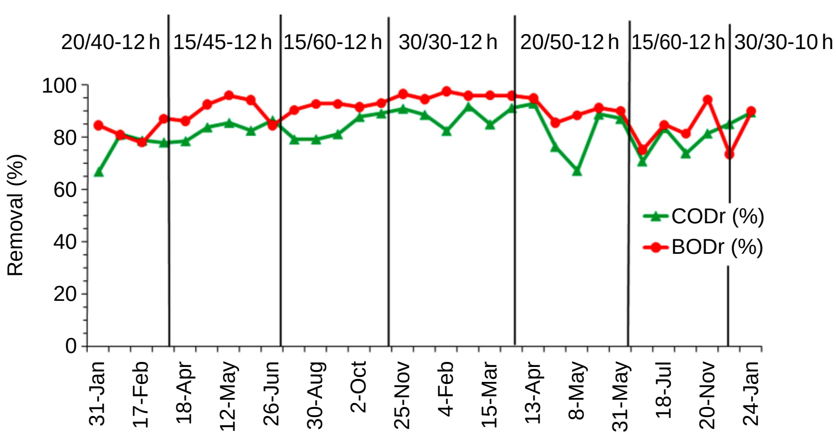

Figure 2 | BOD_5 and COD removal at all experimental states.

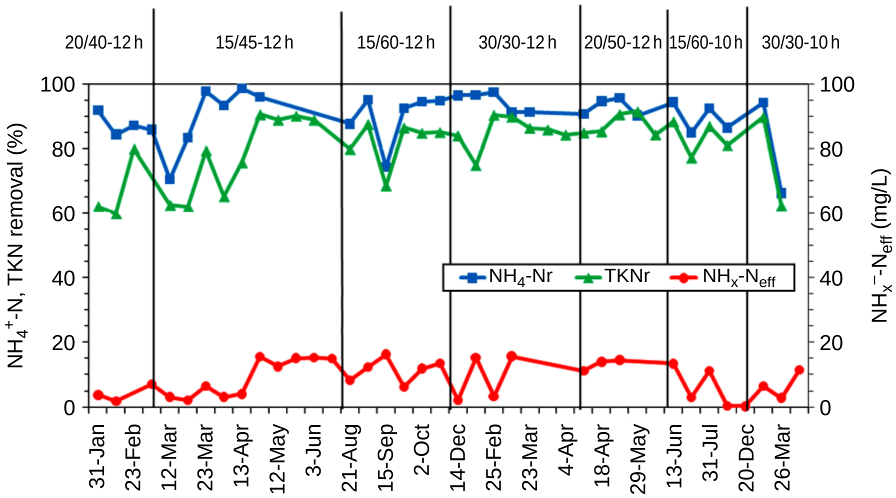

Figure 3 | TKN and NH_4^+-N removal and NO_x^--N effluent concentration for all experimental states.

The system achieved high efficiency regarding the COD removal. Particularly, at the experimental state 30/30–12 h the COD removal ranged from 82.4–91.7% with an average of 88.3%. The value 89.5%, which is shown as the highest removal efficiency at the state 30/30–10 h is not representative, as it is a single measurement. Correspondingly, the BOD_5 removal efficiency in the experimental states 15/45–12 h, 15/60–12 h, 30/30–12 h and 20/50–12 h exceeded 90% in all cases. The highest stability occurred at the experimental state 30/30–12 h where the BOD_5 removal efficiency ranged from 94.5–97.6 with an average of 96%. In this case the aeration period was longer and the organic carbon oxidation complete. In each case the system performed with efficiency higher than 80%.

Nitrogen removal

The nitrogen removal efficiency of the method, with regards to the NH_4^+-N and TKN, ranged between 80–100%. The measured results are shown in Figure 3. The TKN removal efficiency was at its highest point, at the experimental state 20/50–12 h ranging from 84.2–91.4 with an average of 87.3% and the second highest point was at 30/30–12 h, ranging from 74.7–90.3 with an average of 85.0% respectively. Correspondingly, the removal efficiency of NH_4^+-N reached at 98.6% at 15/45–12 h. However, the average ammonium removal efficiency is lower (89.3%) due to the operational instability of the system during the experiments (min 70.4% and max 98.6%). Thus, the best performing and most stable conditions were achieved at the 30/30–12 h

Table 3 | Min, max and average values of NH_4^+-N and TKN percent removal and NO_x^--N concentration in effluent for all experimental states

	NH_4^+-N [% removal]			TKN [% removal]			NO_x^--N [mg/L]		
State	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
20/40–12 h	84.3	91.8	87.8	59.8	79.9	67.2	1.7	3.7	2.7
15/45–12 h	70.4	98.6	89.3	61.9	90.5	78.0	2.0	15.6	9.0
15/60–12 h	74.3	95.1	89.8	68.4	86.4	82.0	6.1	16.3	11.4
30/30–12 h	91.1	97.4	94.6	74.7	90.3	85.0	2.1	15.7	9.1
20/50–12 h	90.2	95.7	92.8	84.2	91.4	87.3	11.1	14.5	13.2
15/60–10 h	84.9	94.3	89.5	77.1	88.3	83.3	0.2	13.4	5.6
30/30–10 h	66.2	94.2	80.2	62.2	89.7	75.9	2.8	11.5	6.9

state, in which the average ammonium removal efficiency ranged from 91.1–97.4% with an average of 94.6%. In the case of simultaneous nitrification/denitrification, the nitrification/denitrification rates depend on the reaction kinetics, floc size, density and structure, sCOD load and reactor DO concentration. With nitrate serving as the electron acceptor due to lack of oxygen, the rate of soluble substrate utilization is also controlled by the soluble substrate concentration. NO_x^--N is produced in the reactor during the aerobic period and the recirculation of the activated sludge flow from the secondary settling tank.

In the present experimental system the electron donor was provided by the wastewater feed, that was added 2 min after the interruption of the aeration, and the rate of denitrification was positively affected by the high sCOD concentration. Consequently, the NO_x^--N was quickly denitrified using the incoming fresh wastewater. During all the experimental states, the average effluent concentration of NO_x^--N was low, according to Table 3, and ranged between 2.7–13.2 mg/L.

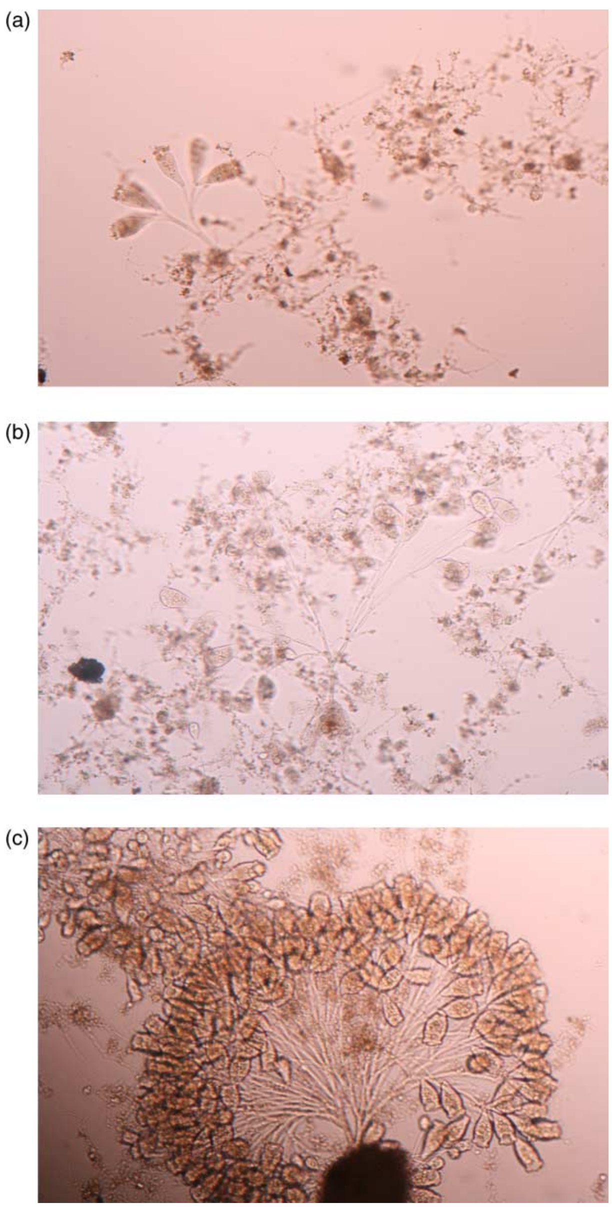

Figure 4 | The absence of filamentous microorganisms in biomass flocs.

Control of filamentous organisms

The abundance of several types of filamentous microorganisms often leads to problems of foaming and sludge bulking in activated sludge WWTPs. According to several researchers (Kappeler & Gujer 1992; Eikelboom *et al.* 1998; Madoni *et al.* 2000) the low F/M-ratio and the nitrogen and phosphorus deficiency (Jenkins *et al.* 1993) place the filamentous microorganism types 0041, 0675, and 021 N in the top three dominant species. Moreover, the wastewater characteristics, the plant design and the operating conditions, including DO concentration, lead to the proliferation of filamentous microorganisms. Types 0041 and 0675 are known to flourish on slowly metabolizable particulate substrates. The introduction of alternating aerobic/anoxic periods in combination with the feeding of the wastewater load once at the beginning of the anoxic period, enhance the reductive conditions in the reactor, thus enabling the hydrolysis of the particulate matter, and diminishing the advantages of the filamentous organisms over the floc-formers. During the microscopic investigation

Table 4 | Min, max and average SVI values for all experimental states

	SVI [ml/g]		
State	**Min**	**Max**	**Ave**
20/40–12 h	360	360	360
15/45–12 h	131	190	166
15/60–12 h	100	187	164
30/30–12 h	105	141	118
20/50–12 h	153	159	156
15/60–10 h	125	180	145
30/30–10 h	115	115	115

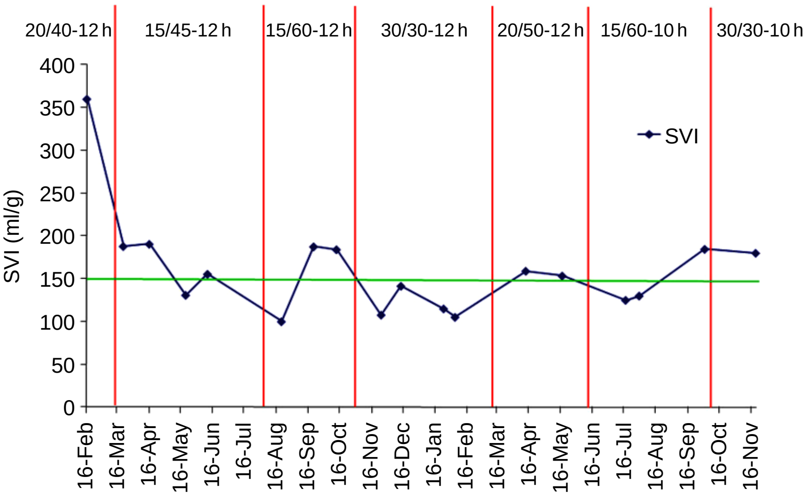

Figure 5 | Variation in SVI throughout the various experimental states.

of the grab samples the number of filaments was visually quantified and the filament index (FI) was determined. Over the whole experimental time the FI remained low, between FI0–FI1. This observation is attested in Figure 4(a–c).

In Table 4, the min, max and average SVI values for all states are shown. The values ranged from 115 to 360. Figure 5 depicts the variation in SVI throughout the various experimental states. The sludge settleability shows a marginal improvement and lower SVI values are achieved. In most of the experimental states the SVI was below the settlability threshold of 150 ml/g and especially during the states of aerobic/anoxic 30/30–12 h, 30/30–10 h and 15/60–10 h was approximately 100 ml/g. The complete denitrification and the high denitrification rate, which occurs on account of the high wastewater influent load at the beginning of the anoxic period, is the primary cause of the relative reduction observed at the SVI values (Figure 5).

CONCLUSIONS

The experimental process was designed to study the suitable conditions for carbon and nitrogen removal of sewage in a single tank. Intermittent aeration was used to accomplish both nitrification and denitrification in a single tank. During the aeration interruption, the reactor operated essentially as an anoxic reactor, as nitrate was used as the electron acceptor in lieu of oxygen for carbonaceous substrate utilization. At the beginning of the anoxic period influent wastewater was added at once to drive the denitrification. The SRT (10 d) and HRT (12 h) from this study system differs essentially from the conventional intermittent operation that operates at SRT 18–40 d and HRT greater than 16 h (Tchobanoglous *et al.* 2003).

The present control strategy can provide near optimum conditions for bacterial growth and performance, resulting in the optimization of wastewater treatment efficiency and capacity. Organic matter oxidation reached the highest point 88.3% and 96.0%, for COD and BOD_5 average removal efficiency respectively, at the experimental state 30/30–12 h. The removal efficiency of TKN reached an average of 87.3% at the experimental state 20/50–12 h and 85% at 30/30–12 h, respectively. The average removal efficiency of NH_4^+-N was approximately 94.6% at 30/30–12 h and 92.8% at 20/50–12 h, and presented a steady performance for most of the experimental states. During all experimental states, the effluent concentration of NO_x^--N was decreased and ranged in average values between 2.7–13.2 mg/L.

Feeding the wastewater at limited time once in every anoxic phase, followed by intermittent aeration, enabled the system to perform at high denitrification rate and achieve a high F/M-ratio. These conditions led to the extinction of the filamentous organisms, whereas they favoured the growth of the floc-formers. This fact was reflected at the SVI values which were lower than 150 ml/g, and the quality of the biomass which showed improved settleability in most of the experimental states.

REFERENCES

American Public Health Association 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edition, Washington, DC.

Balku, S. 2007 Comparison between alternating aerobic-anoxic and conventional activated sludge systems. *Water Res.* **41**(10), 2220–2228.

Battistoni, P., De Angelis, A., Boccadoro, R. & Bolzonella, D. 2003 An automatically controlled alternate oxic-anoxic process for small municipal wastewater treatment plants. *Ind. Eng. Chem. Res.* **42**(3), 509–515.

Battistoni, P., Fatone, F., Cola, E. & Pavan, P. 2008 Alternate cycles process for municipal WWTPs upgrading: ready for widespread application? *Ind. Eng. Chem. Res.* **47**, 4387–4393.

Eikelboom, D. H. 2000 *Process Control of Activated Sludge Plants by Microscopic Investigation*. ASIS, IWA Publishing, London, UK.

Eikelboom, D. H., Andreadakis, A. & Andreasen, K. 1998 Survey of filamentous populations in nutrient removal plants in four European countries. *Water Sci. Technol.* **37**(4), 281–289.

Hamamoto, Y., Tabata, S. & Okubo, Y. 1997 Development of the intermittent cyclic process for simultaneous N and P removal. *Water Sci. Technol.* **35**(1), 145–152.

Hellinga, C., Schellen, A. A. J. C., Mulder, J. W., Van Loosdrecht, M. C. M. & Heijnen, J. J. 1998 The sharon process: an innovative method for nitrogen removal from ammonium-rich waste water. *Water Sci. Technol.* **37**(9), 135–142.

Hong, K.-H., Chang, D., Kang, S.-W., Hur, J.-M., Han, S.-B. & Sunwoo, Y. 2008 Effect of cycle length and phase fraction on biological nutrients removal in temporal and spatial phase separated process. *J. Ind. Eng. Chem.* **14**(4), 520–525.

Jenkins, D., Richard, M. G. & Daigger, G. T. 1993 *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*, 2nd edition. Lewis Publishers, Boca Raton, FL, USA.

Kappeler, J. & Gujer, W. 1992 Bulking in activated sludge systems: a quantitative simulation model for Sphaerotilus natans, type 021 N, and type 0961. *Water Sci. Technol.* **26**(3–4), 473–482.

Kuai, L. & Verstraete, W. 1998 Ammonium removal by the oxygen-limited autotrophic nitrification-denitrification system. *Appl. Environ. Microbiol.* **64**, 4500–4506.

Madoni, P., Davoli, D. & Gibin, G. 2000 Survey of filamentous m/o from bulking & foaming activated sludge plants in Italy. *Water Sci. Technol.* **44**(6), 1767–1772.

Martins, A. M. P., Heijnen, J. J. & van Loosdrecht, M. C. M. 2003 Effect of feeding pattern and storage on the sludge settleability under aerobic conditions. *Water Res.* **37**, 2555–2570.

Nakhla, G. & Lugowski, A. 2003 Control of filamentous organisms in food-processing wastewater treatment by intermittent aeration and selectors. *J. Chem. Technol. Biotechnol.* **78**, 420–430.

Tanwar, P., Nandy, T., Ukey, P. & Manekar, P. 2008 Correlating on-line monitoring parameters, pH, DO and ORP with nutrient removal in an intermittent cyclic process bioreactor system. *Bioresour. Technol.* **99**, 7630–7635.

Tchobanoglous, G., Burton, F. L. & Stensel, H. D. 2003 *Wastewater Engineering: Treatment and Reuse*, 4th edition. McGraw-Hill, NY.

Zipper, T., Fleischmann, N. & Haberl, R. 1998 Development of a new system for control and optimization of small wastewater treatment plants using oxidation-reduction potential (ORP). *Water Sci. Technol.* **38**(3), 307–314.