Pergamon

Wat. Sci. Tech. Vol. 34, No. 1–2, pp. 187–194, 1996.

0273–1223/96 $15·00 + 0·00

PII: S0273-1223(96)00509-4

PERFORMANCE OF A PARTLY AERATED BIOFILTER IN THE REMOVAL OF NITROGEN

P. C. Chui*, Y. Terashima**, J. H. Tay* and H. Ozaki**

* *School of Civil and Structural Engineering, Nanyang Technological University, Singapore*
** *Department of Environmental and Sanitary Engineering, Kyoto University, Japan*

ABSTRACT

The removal efficiency of nitrogen and organic matter in an anoxic/aerobic upflow fixed bed filter was studied. Tests were carried out on the effects of aeration, hydraulic loading rate, and COD/N ratio on nitrogen removal and carbon oxidation. A synthetic high nitrogen concentration wastewater was used as substrate feed in the study. At an influent concentration of 250 mg N/L, and for volumetric loadings of up to 1 kg N/m^3.day, between 41% and 86% of the nitrogen was removed. This was achieved without the recycling of effluent for denitrification. Nitrogen removal was possible when simultaneous denitrification took place inside the support media where oxygen was lacking. COD removal efficiency was consistently above 95% even at a high volumetric loading of 5 kg COD/m^3.day and a bulk liquid dissolved oxygen level as low as 1.1 mg/L. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Submerged filters; aeration; nitrification; denitrification; alkalinit; oxidation of organics.

INTRODUCTION

With increasingly stringent requirements in effluent quality, wastewater treatment facilities, both new and existing, are being pressurised into incorporating processes for nitrogen control. A number of municipal sewage treatment plants have already started to introduce biological nitrogen removal (Andersson & Rosen, 1990). Biological nitrification and denitrification process appears to be the most promising and attractive method for the removal of nitrogen from wastewater. The process involves oxidation of ammonia to nitrate by nitrifying organisms under aerobic conditions, and the subsequent reduction of the nitrate to nitrogen gas by denitrifying organisms under anoxic conditions. A common practice is to introduce the wastewater through an anoxic first stage for denitrification, and an aerobic second stage for nitrification and further degradation of organics not removed in the first stage. Part of the liquor in the second stage is then recycled to the first stage for nitrate removal (Sutton *et al.*, 1981).

Among the biological treatment processes, attached growth systems have the advantage of high biomass retention over suspended growth systems, thus greatly reducing the size required for the facilities. This is important if available land area in existing plants is limited. Examples of attached growth or fixed bed systems for nitrogen removal are the packed bed or submerged filters, rotating biological contactors and fluidised beds.

Nitrification and denitrification kinetics and process in submerged biofilters have been separately investigated (Haug & McCarty, 1972, Requa & Schroeder, 1973, and McHarness *et al.*, 1975). Subsequently, submerged filters arranged in series for combined carbon oxidation, nitrification, and denitrification have been proposed and studied (Inamori *et al.*, 1986, Jimenez *et al.*, 1987, and Goncalves *et al.*, 1994).

Single submerged biofilter systems for both carbon and nitrogen removal have also been investigated. Iida and Teranishi (1984) applied intermittent aeration and effluent recirculation to enhance nitrogen removal in an upflow filter packed with plastic media. Aeration was applied through the bottom of the filter and loading rate was about 0.2 kg N/m^3. day. At a hydraulic retention time of 7 hours, nitrogen removals were 55% when the filter was operated in the intermittent aeration mode, and 80% when the effluent was further recycled. Rogalla and Bourbigot (1990) proposed a biofilter system comprising an upper aerated zone for nitrification and a lower unaerated anoxic zone for denitrification. Effluent recycling was required to achieve high nitrogen removal efficiency of about 60%. More recently, the performance of an upflow aerated filter fixed with stainless steel meshes as support for biofilms was studied (Watanabe *et al.*, 1994). It was reported that while complete nitrification was achieved at a minimum retention time of 10 hr, TOC removal was 80%, and no denitrification occurred. It was only after the aeration point was raised and effluent recycled back into the bottom of the filter that overall nitrogen removal efficiency increased to 33%.

A few of the salient operating features, with regard to nitrogen removal in aerated submerged filters, were noted from these studies : a separate unaerated zone is desirable for carbon degradation as the nitrification process is sensitive to high organic loads; recycling of effluent to an anoxic zone where dissolved oxygen is lacking for denitrification; intermittent aeration to reduce dissolved oxygen in the bulk liquid; and that the type of packing materials used could influence denitrification.

In view of the experience gained, an upflow partially aerated filter system was proposed. The filter, which was similar to that of Rogalla and Bourbigot (1990) but without recycling, consisted of an upper aerated zone for nitrification and denitrification, and a lower unaerated zone which functioned as an anaerobic reactor for organic matter elimination. A porous glass ring support medium, which allowed denitrifying organisms to thrive inside the voids of the media, was selected. The aim of this research was to study the performance of the partially aerated filter using a synthetic high nitrogen wastewater as substrate feed.

EXPERIMENTAL SET-UP AND PROCEDURES

The experimental set-up of the upflow fixed bed biofilter is shown in Figure 1. The filter was constructed out of a 2 m tall acrylic column having an inside diameter of 140 mm and with sampling ports located at 400 mm intervals along its height. The column was randomly packed with 15 mm and 25 mm diameter Siporax (manufactured by Schott Glaswerke, Germany) porous glass rings in separate layers to a depth of 1.8 m. These rings had pore sizes of between 60 and 300 mm; total pore area of 1 m^2/g; distributed weight of about 250 g/L; and a bulk density of approximately 0.7 g/cm^3. The porosity of the packing was 0.87 and the liquid volume in the filter was 26 L. The filter was aerated by compressed air pumped through an injection port about 600 mm from the base of the column. Two zones were thus created in the column : an aerated zone above the injection port, and an unaerated zone below it.

The filter was initially seeded with 2 L of activated sludge from a wastewater treatment plant. After three months of acclimation, tests were conducted using synthetic wastewater as substrate. The synthetic wastewater used in the study consisted of tap water and other chemical constituents as listed in Table 1. The concentrations of the constituents used in making up the wastewater had a COD and N of 1250 and 250 mg/L, respectively. Peptone and meat extract provided the organics and some of the essential nutrients. Ammonium chloride provided extra nitrogen and potassium phosphate contributed to the bulk of the phosphorus. Alkalinity was provided by sodium bicarbonate. Synthetic wastewater was prepared daily and stored in a refrigerator where it was fed through the base of the filter by means of a peristaltic pump. The biofilter was operated in a constant temperature room which was maintained at 35°C throughout the study.

The performance of the partially aerated filter was investigated through three series of test runs. The first run was carried out to determine the aeration and nitrogen removal efficiency under different air flow rates at a constant hydraulic retention time (HRT) and substrate loading. The second run was made to determine the effect of hydraulic loading rate on both organic matter and nitrogen removals. Finally, the influence of COD/N ratio was determined in the last run.

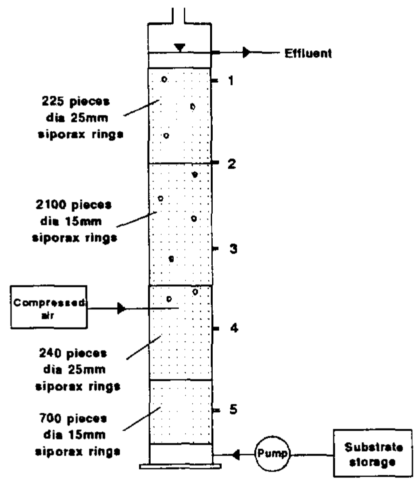

Figure 1. Schematic diagram of the filter system.

Effluent samples were collected daily and analysed for dissolved oxygen and ammonia-nitrogen concentration, and alkalinity. A full test was carried out once a week, and each test run took about two weeks to complete. In a full test, samples were tested for dissolved oxygen concentration (YSI model 58); pH (Horiba model F-8AT); alkalinity; COD; TOC (Shimadzu 5000 series); volatile suspended solids (VSS); total P; and all species of nitrogen. Samples for COD, TOC, TP and nitrogen were filtered through 0.45 mm membrane filters before testing. Ammonia, nitrite, and nitrate nitrogen were determined by the direct Nesslerisation, naphthylamine hydrochloride-sulphanilic acid, and brucine colorimetric methods, respectively. TKN samples were digested and distilled using a modified semi-micro Kjeldahl method and ammonia then determined by the direct Nesslerisation method. Details of the test methods are described in the "Standard Methods" (1992).

Table 1. Chemical composition of synthetic wastewater

Constituent	Concentration (mg/L)
Peptone	500
Glucose	225
Meat extract	350
Sodium bicarbonate	1500
Calcium chloride	24
Magnesium sulphate	27
Ammonium chloride	400
Ferrous sulphate	20
Potassium dihydrogen orthophosphate	100

RESULTS

Hydraulic characteristics of filter

Tracer studies were conducted during one of the test conditions to investigate the hydraulic characteristics of the filter. 50 mL of lithium chloride of 1000 mg Li/L concentration was injected into the base of the filter through the substrate feeding port. Lithium concentration in the effluent leaving the filter was determined using an emission spectrometer (Perkin Elmer ICP model P-400). The influent flow rate and air flow rate during the study were 49 mL/min and 6.5 L/min respectively. The theoretical hydraulic retention time, based on liquid volume and volumetric flow rate of the filter, was 9 hours. The residence time distribution in the filter is shown in Figure 2. The peak concentration was reached about 30 min after the injection and the actual mean residence time, computed based on the centroid of the curve, was 6.1 hours. The residence time distribution curve indicated that there was almost complete mixing in the filter. Levenspiel (1972) made use of a single dispersion number to represent the degree of dispersion in packed bed reactors. The dispersion number ranges from zero for an ideal plug flow system with no dispersion to infinity for the case of a completely mixed system. A dispersion number of 0.2 is considered to have a large amount of mixing. The dispersion number for the filter which was computed based on the mean residence time and the variance of the residence time distribution curve was 0.38, indicating substantial mixing in the filter. A complete mix condition would ensure rapid distribution of the influent in the filter and transfer of substrates and dissolved oxygen into the biofilm.

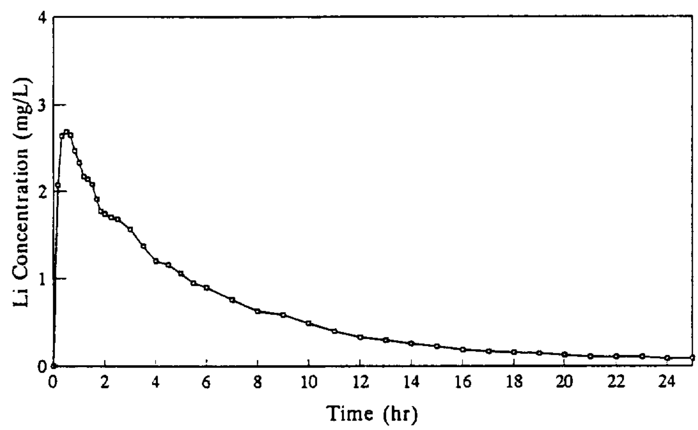

Figure 2. Residence time distribution in the filter.

Aeration characteristics

Five runs were carried out in the first test series, with air flow rates ranging from 1 to 5 L/min, to investigate the aeration characteristics of the filter. During the runs, the influent flow rate and substrate concentration were held constant. The influent flow rate was based on a retention time of 18 hours, while substrate concentrations of 1250, 250, and 25 mg/L for COD, N, and P, respectively, were used. The corresponding volumetric loading rates were 1.7 kg COD/m^3.day and 0.33 kg N/m^3.day. Bulk liquid temperature in the filter generally ranged between 29 and 31°C. The DO profiles along the height of the column for the various air flow rates are shown in Figure. 3. As shown, DO concentrations above the aeration point increased with air flow rate, and the highest concentration was achieved at the top of the filter. DO concentrations in the bulk liquid along the column depended not only on the air flow rate but also on the oxygen transfer efficiency and substrate loading rate, especially organic loading. The bottom unaerated zone was generally anaerobic with average oxidation reduction potentials at around -200mV compared to 200 to 300 mV in the aerated zone.

Nitrogen removal

The concentrations of different species of nitrogen in the effluent were also determined in the first test series. The results are given in Table 2. As may be seen from the table, the portion of ammonia being oxidised increased from 36.8 to 92.7% when DO concentration in the filter was increased from 1.1 to 3.8 mg/L, resulting from an increase in air flow rate from 1 L/min to 5 L/min. At low air flow rates, where average DO concentrations were below 3 mg/L, nitrification was inhibited and overall nitrogen elimination was affected. A sufficiently high bulk DO concentration was thus essential for maintaining the nitrifying biofilm. Generally, a DO concentration of between 2 and 4 mg/L was necessary to achieve nitrification (Sutton *et al.*, 1981).

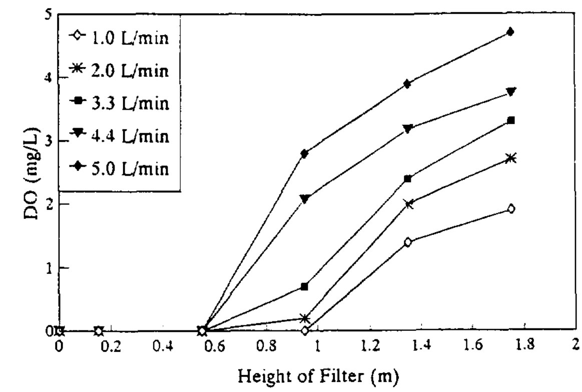

Figure 3. Effect of air flow rate on DO concentrations.

Table 2. Effect of aeration rate of N removal

Run No.	Air flow rate (L/min)	Max. DO (mg/L)	Ave. DO (mg/L)	TKN (mg/L)	NH3-N (mg/L)	NO2-N (mg/L)	NO3-N (mg/L)	Total-N (mg/L)	%N oxidised	%N removed
1	1	1.9	1.1	158	148	1.8	1.9	161.7	36.8	35.3
2	2	2.7	1.6	108.2	71	4.8	0.8	113.8	56.7	54.5
3	3.3	3.3	2	96.6	80	9	2.7	108.3	61.4	56.7
4	4.4	3.7	3	51.7	26	12	2	65.7	79.3	73.7
5	5	4.7	3.8	18.2	15.5	27	9	54.2	92.7	78.3

Nitrogen removal efficiencies of between 35 and 78% were attained for the various runs at an influent loading rate of 0.33 kg N/m^3.day. Denitrification could have occurred inside the hollow of the support materials where oxygen was lacking. The results also showed that denitrification was not inhibited by the presence of DO, as observed from the low nitrite and nitrate concentration in the effluent. Similar observations were also made by Smith *et al.* (1972) in their columnar denitrification study. There was, however, a slight nitrite build-up as DO level in the bulk liquid increased, indicating incomplete denitrification. This might also be caused by other inhibiting factors, such as deficiencies in carbon and alkalinity.

The effect of hydraulic loading rate on nitrogen removal was investigated in the second test series. Five runs were carried out at retention times of 6, 9, 12, 18 and 24 hours. Substrate COD and nitrogen concentrations were maintained at 1250 mg/L and 250 mg/L, respectively, during the tests. Nitrogen loading rates were between 0.25 and 1 kg N/m^3.day. Average DO level in the aerated zone was maintained around 3 mg/L.

Figure 4 shows the nitrogen profiles for the five retention times studied. As shown, there was an initial loss of about 20% nitrogen in the unaerated zone due to biomass assimilation. About 70% of the influent organic nitrogen was also converted to ammonia nitrogen by the heterotrophic bacteria in this zone. Nitrogen concentrations in the aerated zone were relatively constant as the filter was almost completely mixed. High nitrogen removals of more than 65% were achieved for retention times longer than 12 hours. Maximum nitrogen removal of 86% was achieved for a retention time of 24 hours. The highest nitrogen concentration in the effluent was 146 mg/L for the run at 6 hour retention time where 41% of the nitrogen was removed.

Figure 5 shows the effluent concentrations of the different nitrogen species for the four influent COD/N ratios investigated : 1, 2.5, 5, and 7.5. During the runs, the hydraulic retention time was maintained at 9 hours, air flow rate at 7 L/min, and substrate nitrogen concentration was kept constant at 250 mg/L. COD concentrations in the influent were varied from 250 to 1875 mg/L. From the results, the optimum influent COD/N ratio for nitrogen removal was around 5. As a substantial percentage of the organics was removed in the lower portion of the filter, a better expression would be the substrate consumption ratio (COD into aerated zone per unit of nitrogen removed there), which was about 6. At high influent COD/N ratios, nitrogen removal efficiency was limited by incomplete ammonia oxidation as nitrification was affected by the high organic load not removed in the unaerated zone. Although ammonia was completely oxidised for lower COD/N ratios, there was also a corresponding build-up in the nitrite and nitrate concentrations due to insufficient carbon for denitrification.

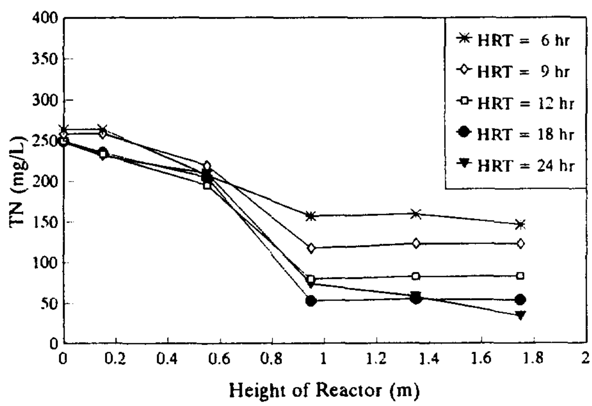

Figure 4. TN profiles for various HRT.

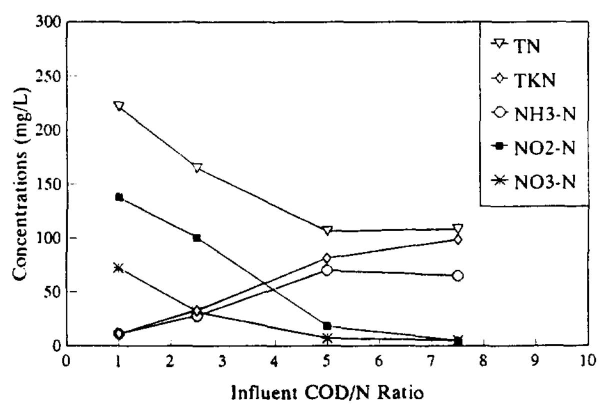

Figure 5. Nitrogen profiles at various influent COD/N ratios.

Alkalinity requirements

Alkalinity was provided in excess in the substrate for the nitrification process. Figure 6 shows the rate at which alkalinity (as $CaCO_3$) was destroyed as nitrogen was removed in the filter. The average alkalinity requirement was estimated at 4.3 mg of alkalinity as $CaCO_3$ per mg N removed. This was higher than the theoretical value of 3.57 mg, as denitrification could be incomplete.

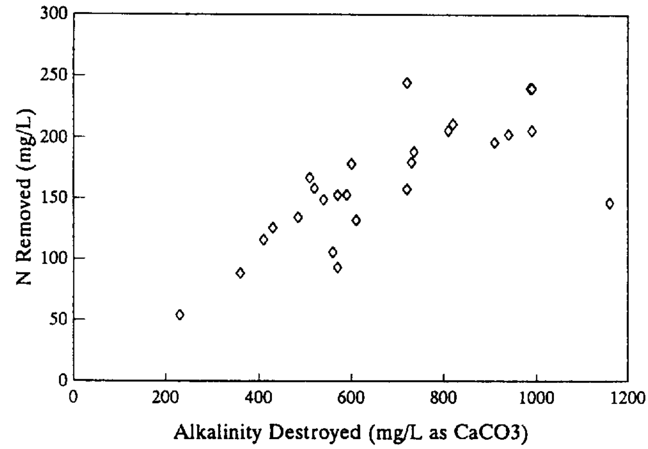

Figure 6. Alkalinity requirements.

Carbon removal

The COD profiles of the filter for the various hydraulic loading rates investigated are presented in Figure 7. Except for HRT of 6 hours, more than 70% of the organic matter in the other tests was eliminated at the lower portion of the filter. For the test run at 6-hour HRT, COD removal in the unaerated zone was about 60%. In all the tests, COD concentrations were fairly uniform in the aerated zone at around 50 mg/L, due to mixing caused by the rising bubbles. COD removal efficiency for the filter was consistently above 95% for loading up to 5 kg COD/m^3.day. pH in the lower zone was around 7 and that in the upper part was close to 8. Average suspended solids concentration in the effluent was around 300 mg/L. The inclusion of an anaerobic zone in the filter was able to eliminate a significant amount of the organic matter and this enhanced nitrification as competition for nitrifiers growth from heterotrophs was reduced. There were also little clogging problems as sludge production in the anaerobic zone was low, and compressed air bubbled directly into the aerated zone prevented solids build-up. Periodic backwashing, which is a requirement for filter systems using a denser packing material or systems treating a particulate substrate, was minimal during the study.

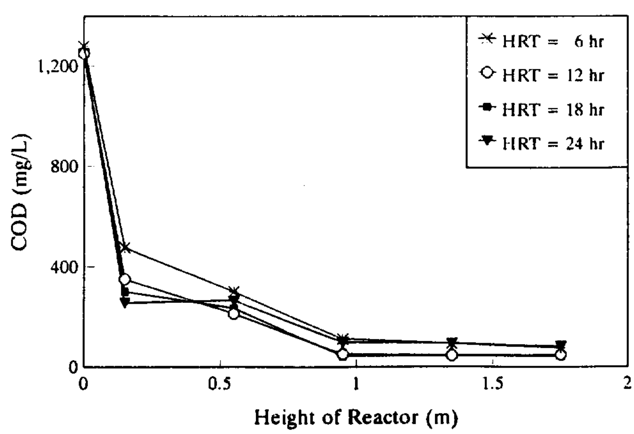

Figure 7. COD profiles for various HRT.

CONCLUSIONS

The performance study of a partially aerated filter demonstrated that high carbon oxidation and nitrogen removal efficiencies could be achieved without effluent recycling or intermittent aeration, thus reducing the operational requirements. The use of a packing material which could allow denitrifying organisms to thrive inside it is crucial for the filter performance.

The lower unaerated zone of the filter was very effective in the oxidation of soluble organic material and conversion of organic nitrogen to ammonia. More than 60% of the influent COD concentration of 1250 mg/L at retention times as low as 6 hours, was eliminated in this zone. Without which, nitrification in the aerated zone would be affected. It was also very stable, and produced little sludge which might have otherwise clogged up the filter.

Nitrogen removal efficiency was affected by the dissolved oxygen concentrations, hydraulic loading rates and COD/N ratios. A minimum DO concentration of above 3 mg/L in the bulk liquid was required to achieve a high nitrification rate. For an influent nitrogen concentration of 250 mg/L, removals of above 65% were achieved for retention times longer than 12 hours. Nitrogen removal was reduced to 41% when retention time was shortened to 6 hours. Overall COD removal was above 95% even at a relative high volumetric loading of 5 kg/m^3.day. The optimum influent COD/N ratio for nitrogen removal was around 5. The amount of alkalinity consumed per mg N removed was about 4.3 mg as $CaCO_3$, which was higher than the stoichiometric value of 3.57 mg.

REFERENCES

Andersson, B. and Rosen, B. (1990). Upgrading for biological nitrogen removal - some full-scale experiences from Sweden. *Wat. Sci. Tech.*, **22**(7/8), 93-104.

Goncalves, R. F, Nogueira, F. N., LeGrand, L. and Rogalla, F. (1994). Nitrogen and biological phosphorous removal in submerged filters. *Wat. Sci. Tech.*, **30**(11), 1-12.

Haug, R. T. and McCarty, P. L. (1972). Nitrification with submerged filters. *J. Water Pollut. Control Fed.*, **44**, 2086-2102.

Iida, Y. and Teranishi, A. (1984). Nitrogen removal from municipal wastewater by a single submerged filter. *J. Water Pollut. Control Fed.*, **56**, 251-258.

Inamori, Y., Sudo, R. and Goda, T. (1986). Domestic sewage treatment using an anaerobic biofilter with an aerobic biofilter. *Wat. Sci. Tech.*, **18**, 209-216.

Jimenez, B., Capdeville, B., Roques, H. and Faup, G. M. (1987). Design considerations for a nitrification-denitrification process using two fixed-bed reactors in series. *Wat. Sci. Tech.*, **19**(1-2), 139-150.

Levenspiel , O. (1972). Nonideal Flow, Chemical Reaction Engineering, John Wiley & Sons.

McHarness, D. D., Haug, R. T. and McCarty, P. L. (1975). Field studies of nitrification with submerged filters. *J. Water Pollut. Control Fed.*, **47**, 291-309.

Requa, D. A. and Schroeder, E. D. (1973). Kinetics of packed-bed denitrification. *J. Water Pollut. Control Fed.*, **45**, 1696-1707.

Rogalla, F. and Bourbigot, M. M. (1990). New developments in complete nitrogen removal with biological aerated filters. *Wat. Sci. Tech.*, **22**(1/2), 273-280.

Smith, J. M., Masse, A. N., Feige, W. A. and Kamphake, L. J. (1972). Nitrogen removal from municipal waste water by columnar denitrification. *Environ. Sci. Technol.*, **6**, 260-267.

Standard Methods for the Examination of Water and Wastewater. (1992). 18th ed. American Public Health Association, Washington DC.

Sutton, P. M., Bridle, T. R., Bedford, W. K. and Arnold, J. (1981). Nitrification and denitrification of an industrial wastewater. *J. Water Pollut. Control Fed.*, **53**, 176-184.

Watanabe, Y., Okabe, S., Arata, T. and Haruta, Y. (1994). Study on the performance of an up-flow aerated biofilter (UAB) in municipal wastewater treatments. *Wat. Sci. Tech.*, **30**(11), 25-33.