The effect of temperature and sludge age on COD removal and nitrification in a moving bed sequencing batch biofilm reactor

H. Dulkadiroglu, E.U. Cokgor, N. Artan and D. Orhon

Environmental Engineering Department, Istanbul Technical University, ITU İnşaat Fakültesi, 34469 Maslak, Istanbul, Turkey

Abstract This study investigates the effect of temperature and the sludge age on the performance of a moving bed sequencing batch biofilm reactor (MBSBBR) for COD removal and nitrification. The experiments are conducted in a lab-scale MBSBBR operated at three different temperatures (20, 15 and 10 °C) with a synthetic feed simulating domestic sewage characteristics. Evaluation of the results revealed that removal of organic matter at high rates and with efficiencies over 90% was secured at all operation conditions applied. The nitrification rate was significantly influenced by changes in temperature but complete nitrification occurred at each temperature. The nitrification rates observed at 20 and 15 °C were very close (0.241 mg NO_X-N/m^2 d, 0.252 mg NO_X-N/m^2 d, respectively), but at 10 °C, it decreased to 0.178 mg NO_X-N/m^2 d. On the other hand, the biomass concentration and sludge age increased while the VSS/TSS ratios that can be accepted as an indicator of active biomass fraction decreased with time. It is considered that, increasing biofilm thickness and diffusion limitation affected the treatment efficiency, especially nitrification rate, negatively.

Keywords Moving bed; nitrification; SBR; sludge age; temperature effect

Water Science & Technology **Vol 51 No 11 pp 95–103** © IWA Publishing 2005

Introduction

Suspended growth and biofilm systems such as different activated sludge and biofilter configurations, although widely used as successful biological treatment schemes for domestic and industrial wastewater, have a number of inherent limitations. The operational difficulties experienced with these traditional systems motivated substantial research effort for the development of novel biological processes. In recent years, studies focusing on hybrid systems combining the advantages of suspended growth and biofilm systems have increased. In this context, *moving bed biofilm reactors* (MBBR), holding carrier elements freely moving in the reactor, have been developed as one of the most attractive hybrid systems (Ødegaard *et al.*, 1994). In the last 10 years, substantial research has been conducted on pilot and full-scale MBBR systems for the removal of organic matter and nutrients from domestic and industrial wastewaters (Rusten *et al.*, 1992; Pastorelli *et al.*, 1997; Broch-Due *et al.*, 1997; Johnson *et al.*, 2000). MBBR is promoted mainly because more biomass in the reactor can be sustained in the reactor and thus a higher and more stable treatment efficiency may be achieved, through the use of the carrier elements of various nature and type (Ødegaard *et al.*, 2000; Loukidou and Zouboulis, 2001).

Sequencing batch reactor (SBR), is another highly successful biological treatment alternative, widely studied in the last two decades (Wilderer *et al.*, 1997; Artan *et al.*, 2001, 2003). It is now extensively used based on a number of significant advantages its offers, such as, smaller volume since various processes can take place in a single reactor, ease in adjusting operational conditions, flexibility of operation, etc. Recently, it was suggested that MBBRs could be operated in a sequencing batch mode, in order to benefit from the advantages of both processes. An example is the work of Helness and Ødegaard (1999) where a phosphorus removal efficiency of 98% was reported operating a biological treatment system in the *moving bed sequencing batch biofilm reactor* (MBSBBR) mode. While such studies underline the benefit that can be derived from this combination, the MBSBBR certainly requires more research effort to establish itself as a reliable biological treatment alternative.

In this context, this study, undertaken with the objective of providing additional scientific insight in this area, specifically investigates the effect of temperature, sludge age and biomass concentration on organic matter removal and nitrification rate in a moving bed sequencing batch biofilm reactor.

Materials and methods

The experiments were carried out in a lab-scale, 10 L cylindrical Plexiglas MBSBBR of 10 L volume, placed into an incubator in order to operate at constant temperature (Figure 1). Wastewater was fed and discharged by peristaltic pumps controlled by timers. The experiments involved a cyclic reactor operation, each cycle including three phases: the reactor was filled during the initial *fill phase*, aerobic reaction was allowed to occur within the next *react phase* and the treated effluent was discharged in the following (*draw–discharge phase*). The react phase was selected as 420 min for the experiments involving a 8-hour cycle time and 300 min for 6-hour cycle time. Fill and draw-discharge phases were kept constant at 30 min each.

KMT® type K1 carrier elements, manufactured from polyethylene with a density of 0.95 g/cm^3 and cylindrical in shape with about 10 mm diameter and height, were used for biofilm growth. The walls inside the cylinder provided suitable and more surface area for biofilm growth. The reactor could be filled up to a maximum volumetric filling ratio of 70% depending on wastewater characteristics and organic loadings. Specific biofilm surface area at this filling ratio was 350 m^2/m^3. This value did not include outside surface area of carrier elements, because there was no biofilm growth due to shearing forces. In this study, carrier element filling ratio was applied as 70% at all runs to ensure maximum level of treatment capacity for the reactor (Ødegaard *et al.*, 1994).

MBSBBR was fed with a synthetic wastewater with COD concentration of 400 mg/L and ammonia nitrogen concentration of 40 mg NH_4-N/L, approximating domestic sewage

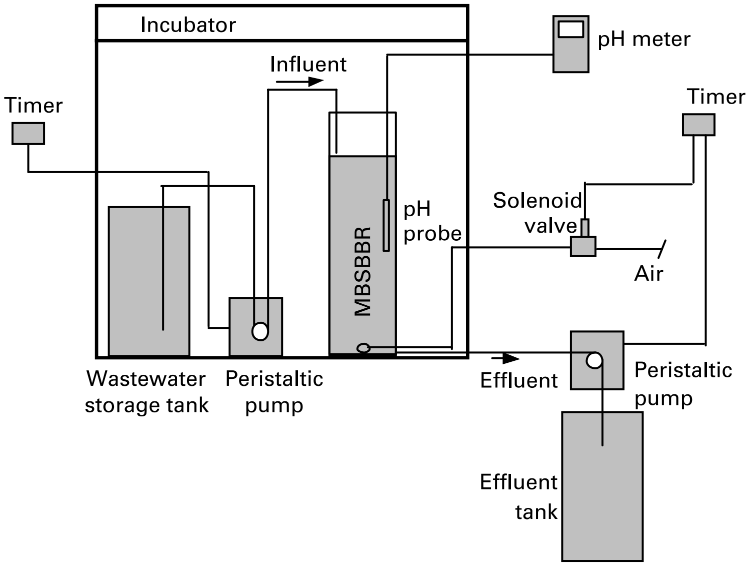


Figure 1 Schematic appearance of the experimental setup

characteristics. Macro and micro nutrients were added at necessary amounts. The composition of the synthetic wastewater with macro and micro nutrient stock solutions is given in Table 1.

Reactor performance was monitored by COD, NH_4-N and NO_X-N measurements. After an acclimation period of the biomass to loadings and temperatures, COD, NH_4-N and NO_X-N variations within a given cycle were determined for each set of experiments and these in-cycle measurements were repeated at different times to have a reliable assessment of the system performance at the selected operation condition.

COD was measured using the procedure defined by ISO 6060 (1986). For soluble COD (S_COD) determination, samples were subjected to vacuum filtration by means of Millipore membrane filters with a pore size of 0.45 μm. The Millipore AP40 glass fiber filters were used for total suspended solids (TSS) and volatile suspended solids (VSS) measurements. TSS, VSS, Total Kjeldahl nitrogen (TKN) and NH_4-N experiments were performed as defined in *Standard Methods* (1998). For attached biomass measurements, biofilm was detached from 30 carrier elements taken from the reactor into an aqueous medium of suitable volume. NO_X-N concentrations were determined using a *ChemLab* Autoanalyzer. pH was monitored by using a Hanna HI8711E pH controller.

Results and discussion

The experiments were carried out for a period of around two years. In the start-up period MBSBBR was initially seeded by activated sludge sustained in a fill-and-draw lab-scale reactor fed with the same synthetic wastewater. As outlined in Table 2, the experimental program included a sequence of five consecutive runs conducted by operating the system at three different temperatures (10, 15 and 20 °C) with two different cycle times (6 and 8 hours). The reactor was operated with an organic loading of 3.01 g COD/m^2 d and an ammonia loading of 0.30 g NH_4-N/m^2 d during runs with 3 cycles a day and 4.02 COD/m^2 d organic and 0.40 g NH_4-N/m^2 d ammonia loadings with 4 cycles a day.

Biomass accumulation

The biomass concentration of both biofilm and suspended biomass in the system was measured in each set of experiments as total suspended solids (TSS) and volatile suspended solids (VSS). Sludge ages were calculated by dividing the total biomass in the system by effluent biomass concentration. As can be seen from Table 3, the biomass

Table 1 Synthetic wastewater composition

Chemical	Concentration
Synthetic wastewater solution	*8.33 mL/L*
Acetic acid	20.00 mL/L
Propionic acid	6.20 mL/L
Ethanol	3.36 mL/L
Glutamic acid	7.24 g/L
Glucose	9.08 g/L
Macro-nutrient solution	*8.00 mL/L*
K_2HPO_4	160 g/L
KH_2PO_4	80 g/L
NH_4Cl	19 g/L
Micro-nutrient solution	*4.00 mL/L*
$MgSO_4.7H_2O$	15.0 g/L
$FeSO_4.7H_2O$	0.5 g/L
$ZnSO_4.7H_2O$	0.5 g/L
$MnSO_4.H_2O$	0.3 g/L
$CaCl_2$	2.0 g/L

Table 2 Experimental program

	Run I	Run II	Run III	Run IV	Run V
Temperature (°C)	20	15	10	20	15
Number of cycles (1/day)	3	3	3	4	4

Table 3 Variation of biomass and sludge age in the experiments

Run	Biofilm concentration		VSS/TSS	Suspended biomass conc. (mg/L)	Sludge age (day)	Net reactor volume (L)
	TSS, (mg/L)	VSS, (mg/L)				
I	1,735	1,590	0.92	800	4.4	8.54
II	3,415	2,825	0.83	620	6.7	8.32
III	8,505	6,020	0.71	500	15.9	7.70
IV	23,900	12,330	0.52	300	34.7	6.30
V	49,590	22,040	0.44	850	73.5	6.30

concentration exhibited a gradual increase throughout the experiments, from 1,700 mg/l in Run 1 to around 50,000 mg/l in Run 5. The great majority of the biomass is attached to carriers with only 300–800 mg/L of suspended biomass in the reactor depending on the specific operation setup. Biomass build-up on the carrier elements is visualized in Figure 2. A parallel increase was observed for the sludge age in the range of 4.4 to 73.5 days, mainly because the excess biofilm could not be removed and thus biomass accumulated in the system. On the other hand, the active biomass fraction decreasing as evidenced by the observed VSS/TSS ratios was usually accepted as an indicator of active biomass fraction. The decrease in the active biomass fraction may be attributed to diffusion limitation caused by steadily increasing biofilm depth. As indicated in Table 3, biomass accumulation negatively affected the net reactor volume.

System performance for COD and VSS removal

Average values representing regular observations of the effluent COD and VSS during five consecutive runs at different temperatures and organic loadings are plotted in Figures 3 and 4. After the initial start-up period, the effluent VSS level was observed to fluctuate between 70 and 170 mg/l. No observation was recorded below 50 mg/l. VSS retention efficiency of Runs IV and V was better with an effluent VSS level slightly fluctuating around 100 mg/l. These results reflect a lower VSS removal efficiency as compared to continuous flow activated sludge and conventional SBR systems, due to the facts that MBSBBR generated a substantial amount of suspended biomass flocks, in the range of 60–390 mg/l during the experiments. A fraction of the flocs disintegrate due to high

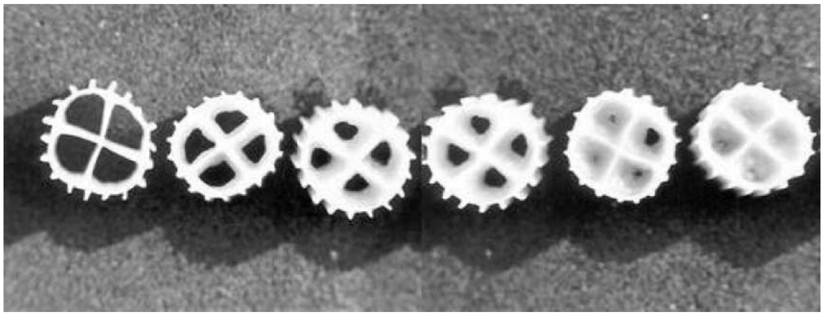


Figure 2 The evolution of biofilm growth on the carrier elements

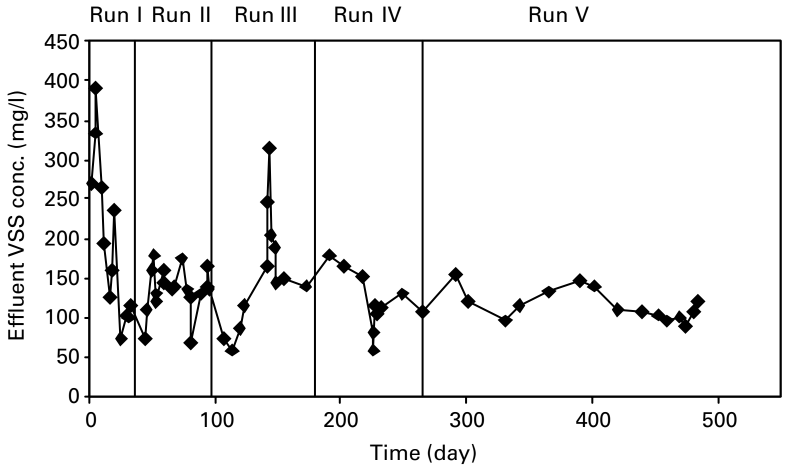


Figure 3 Average effluent VSS profile for consecutive experimental runs

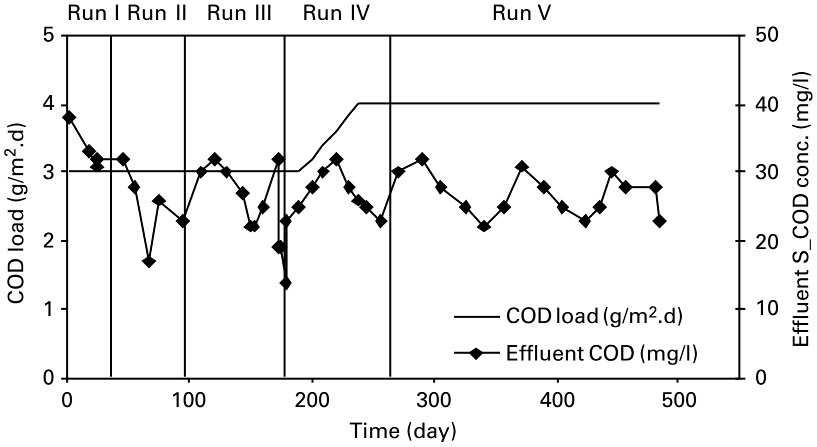
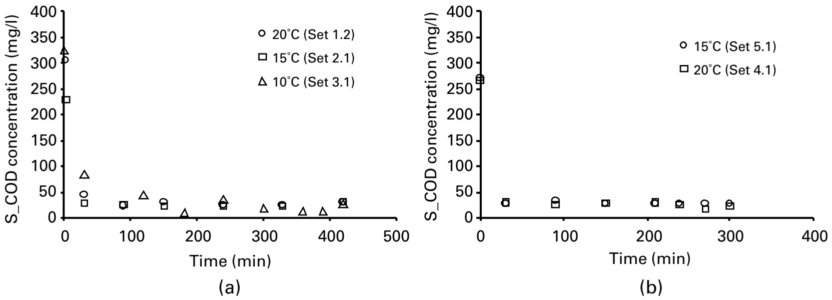


Figure 4 Average effluent COD profile for consecutive experimental runs



(a)

(b)

Figure 5 S_COD variations in a cycle at different temperatures and COD loadings: (a) 3.01 g/COD m^2 d; (b) 4.02 g COD/m^2 d

mixing forces introduced into the system to keep the carrier elements homogenously in suspension.

Figure 4 shows that COD removal efficiency over 90% was secured at all operation conditions applied. The effluent soluble COD level remained in the range of 20–30 mg/l, regardless of changes in organic loading and temperature. Taking into account that the

Table 4 Experimental results on nitrification

Set No	Temperature (°C)	Number of cycle (1/d)	Influent NH_4-N conc. (mg/L)	Effluent NH_4-N conc. (mg/L)	Effluent NO_X-N conc. (mg/L)	N_{sludge} (%)	Nitrification time, (min)
1.1	20	3	38.0	0	24.5	10.5	360
1.2	20	3	38.0	0	24.2	8.9	350
2.1	15	3	36.9	0	21.8	7.4	240
2.2	15	3	35.8	0	22.9	9.7	330
2.3	15	3	37.4	0	24.1	9.3	310
2.4	15	3	38.4	0	24.1	8.0	250
3.1	10	3	38.2	5.1	19.0	6.8	420
3.2	10	3	39.1	0.4	20.4	8.6	420
3.3	10	3	38.5	0	20.4	10.9	320
4.1	20	4	36.8	0	22.2	8.4	250
4.2	20	4	37.4	0.7	19.7	8.8	300
5.1	15	4	40.0	1.1	22.0	10.4	300
5.2	15	4	40.8	1.4	20.9	11.6	300

feed consists of a soluble and readily biodegradable substrate, the observed results should be interpreted as complete consumption and removal of all available substrate, with a clear indication of soluble residual microbial products generation at a rate of around 5 to 8% of the COD in the feed (Orhon *et al.*, 1999). The effluent total COD however inevitably included a sizeable particulate fraction due to corresponding VSS escape and could not be lowered below 150 mg/l under different operating schemes.

The pattern of COD removal was also observed through assessment of soluble COD profiles within a number of cycles at different conditions. Figure 5, illustrating results for five selected cycles representing a temperature range of 10–20 °C, confirms total soluble COD removal within the first hour of the cycle down to the residual level of 20–30 mg/l in the effluent.

Nitrification potential

Results of 13 different sets representing operation at different temperatures are summarized in Table 4. The obtained data indicate full nitrification independent of temperature, mostly with no NH_4-N concentration in the effluent. The time consumed to remove ammonia completely, was accepted as nitrification time. But in the cases in which ammonia could not be removed completely, cycle time was taken as nitrification time. The nitrification rate, however was significantly influenced by changes in temperature. As shown in Table 5, the nitrification rates observed at 20 and 15 °C were very close (0.241 mg NO_X-N/m^2 d, 0.252 mg NO_X-N/m^2 d, respectively), but significantly lower at 10 °C, decreasing to 0.178 mg NO_X-N/m^2 d. A similar trend was also observed for the ammonia removal rates, supporting the validity of the results obtained. At Runs 4 and 5 conducted with substantially higher biomass levels, lower nitrification and ammonia removal rates were calculated at the same temperature compared to previous runs, indicating the negative effect of excessive attached biomass depth on oxygen diffusion.

NH_4-N and NO_X-N variations were also observed, parallel to COD profiles within selected cycles at different temperature, which verified as given in Figure 6, complete nitrification, although at different rates, before the end of the cycle. But the nitrification rates obtained in this study are lower than the values given in the literature. The nitrification rate is a parameter as usually expressed in terms of unit biomass in the reactor. The VSS measurements can only yield a crude index of biomass viability, consequently a wide range of values depending on specific operation conditions that affect the viability of the biomass in the reactor. In such studies, the nitrification rates found in the studies in MBBR's fed with municipal wastewater primary effluent were given as 1.1 g NH_4-N/m^2 d (Ødegaard *et al.*, 1994), 1.3 g NH_4-N/m^2 d (Hem *et al.*, 1994) and 1.07 g NH_4-N/m^2 d (Pastorelli *et al.*, 1997). Andreottola *et al.* (2000) reported a much lower observed nitrification rate in a rotating biological contactor (RBC) fed with municipal wastewater as 0.228 g NH_4-N/m^2 d. This value is very close to values reported in this study for the investigated MBSBBR system. The reason for the lower nitrification rates obtained in

Table 5 The effect of temperature on the nitrification rate

Run	Temperature (°C)	NH_4-N Removal rate		Nitrification rate	
		gNH_4-N/m^2 d	mgNH_4-N/mgVSS.d	gNO_X-N/m^2 d	mgNO_X-N/mgVSS.d
1	20	0.441	0.084	0.241	0.046
2	15	0.428	0.061	0.252	0.036
3	10	0.387	0.026	0.178	0.012
4	20	0.420	0.019	0.200	0.009
5	15	0.374	0.009	0.185	0.005

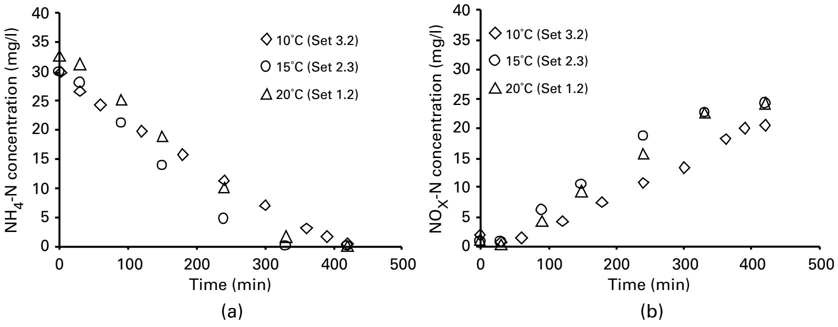


Figure 6 (a) NH_4-N; (b) NO_X-N variations in a cycle at different temperatures

this study can be attributed to the decrease in the biomass viability with increasing VSS accumulation in the reactor.

Conclusions

The basic advantage of the MBSBBR system is the high levels of biomass concentrations sustained in the reactor. In this study, a combined attached and suspended biomass of around 70,000 mg/l was observed after two years of system operation. However, the system exhibits continuous dynamic behavior, without any means to control the sludge age. The biomass accumulation appears to have a negative effect on the viability ratio.

The process achieved complete soluble COD removal and full nitrification under all operating conditions at different temperatures. The effluent soluble COD, in the range of 20–30 mg/l could be attributed to a constant level of residual microbial products generated as part of the biological activity in the reactor. Nitrification rate was significantly influenced by changes in temperature. Both nitrification and ammonia removal rates were reduced by higher biomass content at the same temperature.

The greatest feature of the activated sludge process today is the level of mechanistic understanding and interpretation of the process that allows full manipulation and control of the system, not so far achieved with biofilters, for effective organic carbon and nutrient removal. SBR configuration increased system flexibility in a much more simplified structure, combining biological reactor and settler in a single tank. Incorporation of a moving bed attached growth system into SBR operation, as tested in this study, while providing, means for holding larger amounts of biomass and significantly reducing the effective volume required, negatively affects the ability of system control associated with traditional, suspended growth SBRs. The weakness of the *moving bed sequencing batch biofilm reactor* is uncontrollable SS/VSS escape during treated effluent discharge, seriously affecting overall process efficiency. The remedial action would be to include a separate settler, which would totally remove the attraction of the SBR operation. Therefore, the MBSBBR system should best be used as an intermediate step in biological treatment, especially for nitrification.

Acknowledgement

This study was supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under Project Number YDABCAG-199Y112. This study was also conducted as part of the sponsored research activities of the *Environmental Biotechnology Centre* at ITU.

References

Andreottola, G., Foladori, P. and Ragazzi, M. (2000). Upgrading of a small wastewater treatment plant in a cold climate region using a moving bed biofilm reactor (MBBR) system. *Water Sci. Technol.*, **41**(1), 177–185.

Artan, N., Wilderer, P., Orhon, D., Morgenroth, E. and Özgür, N. (2001). The mechanism and design of sequencing batch reactor systems for nutrient removal – The state of the art. *Water Sci. Technol.*, **43**(3), 53–60.

Artan, N., Özgür-Yağcı, N., Artan, S.R. and Orhon, D. (2003). Design of sequencing batch reactors for biological nitrogen removal from high strength wastewaters. *J. Environ. Sci. Heal. A*, **38**(10), 2125–2134.

Broch-Due, A., Andersen, R. and Opheim, B. (1997). Treatment of integrated newsprint mill wastewater in moving bed biofilm reactors. *Water Sci. Technol.*, **35**(2–3), 173–180.

Helness, H. and Ødegaard, H. (1999). Biological phosphorus removal in a sequencing batch reactor moving bed biofilm reactor. *Water Sci. Technol.*, **40**(4–5), 161–168.

Hem, L.J., Rusten, B. and Ødegaard, H. (1994). Nitrification is a moving bed biofilm reactor. *Wat. Res.*, **28**(6), 1425–1433.

Johnson, C.H., Michael, W.P. and Blaha, L. (2000). Full scale moving bed biofilm reactor results from refinery and of slaughter house treatment facilities. *Water Sci. Technol.*, **41**(4–5), 401–408.

Loukidou, M.X. and Zouboulis, A.I. (2001). Comparison of two biological treatment processes using attached-growth biomass for sanitary landfill leachate treatment. *Environmental Pollution*, **111**, 273–281.

Orhon, D., Karahan, Ö. and Sözen, S. (1999). The effect of residual microbial products on the experimental assessment of the particulate inert COD in wastewaters. *Wat. Res.*, **33**(14), 3191–3203.

Ødegaard, H., Rusten, B. and Westrum, T. (1994). A new moving bed biofilm reactor – Applications and results. *Water Sci. Technol.*, **29**(10–11), 157–165.

Ødegaard, H., Gisvold, B. and Strickland, J. (2000). The influence of carrier size and shape in the moving bed biofilm process. *Water Sci. Technol.*, **41**(4–5), 383–391.

Pastorelli, G., Andreottola, G., Canziani, R., de Fraja Frangipane, E., de Pascalis, F., Gurrieri, G. and Rozzi, A. (1997). Pilot-plant experiments with moving-bed biofilm reactors. *Water Sci. Technol.*, **36**(6), 43–50.

Rusten, B., Ødegaard, H. and Lundar, A. (1992). Treatment of dairy wastewater in a novel moving bed biofilm reastor. *Water Sci. Technol.*, **24**(3–4), 703–711.

Standard Methods for the Examination of Water and Wastewater (1998). 20th edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Water Quality-Determination of the Chemical Oxygen Demand (1986). ISO, Ref. No. ISO 6060.

Wilderer, P.A., Irvine, R.L. and Doellerer, J (eds) (1997). Sequencing Batch Reactor Technology – Batch Application of Periodic Unsteady-state Processes – Selected Proceedings of the 1st IAWQ International Specialised Conference on Sequencing Batch Reactor Technology, held in Munich, Germany, 18–20 March 1996, *Water Sci. Technol.*, **35** (1) 278 pp.