Hybrid moving bed biofilm reactors: a pilot plant experiment

D. Di Trapani, G. Mannina, M. Torregrossa and G. Viviani

ABSTRACT

The growing increment of the urbanization and, on the other hand, the even more strict effluent limits imposed by the Water Framework Directive for the receiving water body quality state have led to the need for upgrading several existing WWTP. With this respect HMBBR systems are an innovative solution since they allow to upgrade existing high loaded WWTP without building new tanks. However, some uncertainties in their design, maintenance as well as performance have to be addressed due to their recent acquisition compared with well consolidated technologies such as activated sludge systems. In this light, a data gathering campaign on a HMBBR pilot plant has been performed. The aim was to detect the performance of such new technology as well as to survey the influencing effect of the carrier media filling ratio. Indeed, there may be problem of competitiveness between attached and suspended biomass that jointly operate in the same system for carbon and nitrogen removal. Such competitiveness may lead to a worsening of the system efficiency. The results are interesting and the gathered data in the experimental period show a slight difference in terms of performance behaviour, between the two systems (35 and 66%). Such result leads to address the filling ratio choice towards the 35%.

Key words | hybrid moving bed biofilm reactor, MBBR, model nitrification, organic carbon removal, pilot plant experiments

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INTRODUCTION

In the past decade, a number of biological nutrient removal processes have been developed which include the hybrid moving bed biofilm reactor (HMBBR) systems. In such systems the biomass is both suspended and attached as biofilm. More specifically, the latter grows attached on small carrier elements that are kept in constant motion throughout the entire volume of the reactor, resulting in uniform, highly effective treatment (Ødegaard *et al.* 1994; Rusten *et al.* 1995; Chen *et al.* 1997; Ødegaard 2006). Furthermore, the continuous carrier movement allows the biofilm death/ regeneration mechanisms and avoids the clogging risks. The HMBBR systems hence combine the moving bed biofilm reactor (MBBR) technology and activated sludge in the same tank and they are suitable for nitrogen removal due to the growing of different biomass species. Indeed, such systems are involved in a creation of multiple environments for enrichment of bacteria that specialise in different aspects of the treatment.

Interesting advantages of HMBBRs, especially looking at the traditional fixed bed biofilm reactor (biofilters), regard the low head losses, no filter channelling and no need of periodic backwashing (Pastorelli *et al.* 1999). However, it has to be stressed such new treatment technology is of quite recent acquisition and, as a consequence, their performance are not fully known. In particular, some uncertainties arise regarding the design as well as the filling ratio rate whose influence, up to date, is not clearly surveyed. Indeed, very few studies are reported from the technical literature with reference to HMBBR systems and this fact contributes to a not full knowledge

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about their behaviour (Gambaretto & Falletti 2005; Germain et al. 2006). Indeed, many doubts still arise regarding the kinetic parameters of hybrid reactors, specific to this kind of process, and that are probably quite different from pure MBBR and activated sludge ones, and where furthermore experimental surveys are lacking.

In this context, the main object of the paper is to present some results of a study carried out to evaluate the effect of the filling ratio on the performance of HMBBR systems. To achieve this goal a pilot plant, described in the following, was set up considering two lines with different filling ratios of 35 and 66%. Furthermore, respirometric analyses were carried out in order to detect the contribution of the different biomass species in the carbon and nitrogen removal.

MATERIALS AND METHODS

Description of the pilot plant

The pilot plant was built at the Palermo (IT) municipal WWTP (Acqua dei Corsari) and it is constituted by two lines with the same reactors but with different filling ratios (Figure 1) (Mannina et al. 2007). Each treatment line consisted of a 6.5 litres anoxic reactor, a 6.5 litres aerobic one and a 3.5 litres final settler.

The pilot plant has been in operation for a period of approximately three months whose first one was necessary for achieving good working conditions. The plant was continuously fed with a constant flow rate of 1 L/h of primary settled wastewater and an organic load up to 1.2 kg COD/m^{3}d. Return sludge was pumped from the clarifier to the anoxic tank considering a recycling flow rate equal to the influent one. Nitrate recycling was operated from the aeration tank outlet to the anoxic tank with a 4 L/h flow rate.

The aerobic reactors were characterised by two different filling ratios of 35% (line 1) and 66% (line 2), corresponding to a theoretical specific surface area of 190 m^2/m^3 and 330 m^2/m^3 respectively. Mixing was guaranteed in the anoxic tanks by mechanical stirrers, while in the aerobic ones by the aeration systems, coarse-bubble ones, installed at the bottom of each reactor. Special sieve arrangements, to retain the carriers within the aerobic reactors, have been adopted. The support material used was the Kaldnes Miljøteknology K1, whose characteristics are summarised in Table 1.

During the field campaign Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS), referring to the fixed and suspended biomass, total COD (totCOD), soluble flocculated COD (solCOD), readily biodegradable COD (Ss), N-NH_4, N-NO_3, dissolved oxygen, temperature, pH and air flow rate were monitored. All the analyses were carried out according to the *Standard Methods* (APHA 1995), whereas COD was analysed according to Mamais et al. (1992). All the matter was classified into two

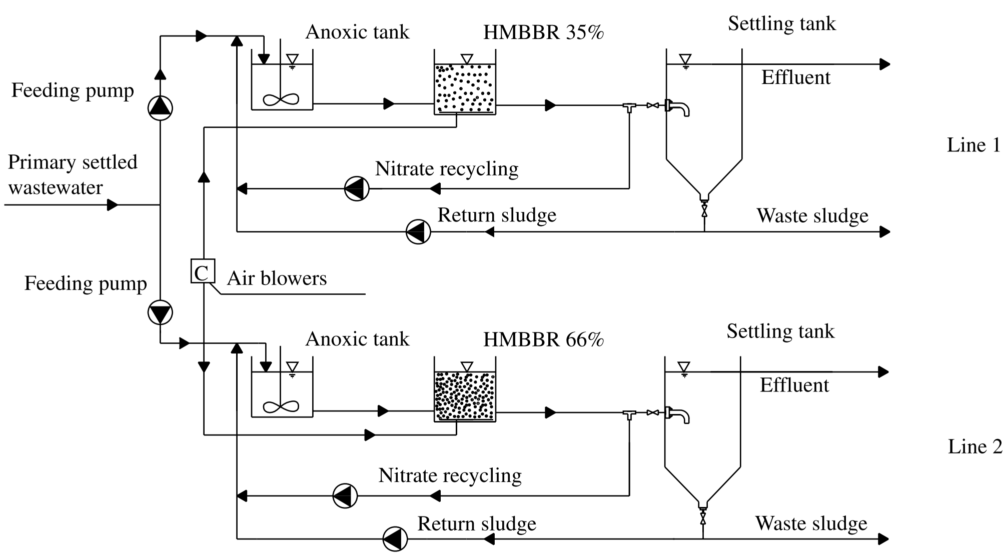

Figure 1 | Experimental pilot plant scheme.

Table 1 | Characteristics of media carriers

Diameter mm	Height mm	Density kg/m^3	Total surface m^2/m^3	Internal surface m^2/m^3
9.1	7.2	0.98	800	500

Table 2 | Average percentage of the organic matter fractions in the influent

S_S %	X_S %	$S_I + X_I$ %
15	75	10

S_S: readily biodegradable substrate; X_S particulate slowly biodegradable substrate; S_I: soluble inert substrate; X_I: particulate inert substrate.

groups: the soluble matter that can pass 0.45 μm GF/C filter and the particulate one that cannot pass (Gujer *et al.* 1999).

In Table 2 the different fractions of the influent organic matter evaluated using respirometric technology are reported. The measured percentages are in agreement with the common values reported in technical literature (Henze *et al.* 1987).

RESULTS AND DISCUSSION

Organic substrate removal

In Table 3 data on influent and effluent totCOD and solCOD concentrations are shown; despite inflow conditions varying considerably, the effluent organic concentrations of hybrid reactors, in terms of both total and soluble COD, were quite constant, suggesting that this kind of reactor is able to guarantee a very high process stability.

In Figures 2 and 3, totCOD and solCOD removals are related to the volume of the two hybrid reactors, and the bisector lines indicate 100% removal efficiency. Comparing the results obtained for the two systems, it can be observed

Table 3 | Influent and effluent COD concentrations

	Influent		Effluent HMBBR 35%		Effluent HMBBR 66%	
	totCOD mg/L	solCOD mg/L	totCOD mg/L	solCOD mg/L	totCOD mg/L	solCOD mg/L
Min	257	60	29	11	29	13
Max	632	211	60	32	72	26
Mean	437	133	37	21	38	20

that the experimental points, for both reactors, are very close to the bisectors, despite the variability of the organic load applied. As matter of the fact, average efficiency of 99% in terms of both totCOD and solCOD was recorded.

This aspect is also confirmed looking at Figure 3 where influent and effluent totCOD (a) and solCOD concentrations (b) are shown. The maximum influent totCOD concentration resulted 632 mg/L, while the average inflow concentration was of 437 mg COD/L and an average outflow totCOD of 37 and 38 mg COD/L for 35% and 66% filling ratio. The average efficiencies for totCOD removal were 90% and 89%, respectively, for the 35% and 66% filling ratios, underlying a very high removal efficiency for both reactors. The average removal efficiencies for soluble COD were 84.9% and 83.8% for 35% and 66% filling ratio respectively. These values are related to an average inflow concentration of 133 mg sol COD/L (that ranged from 60 to 211 mg sol COD/L).

Comparing the results obtained with the two parallel lines, it can be observed that 35% HMBBR had a higher COD removal efficiency than the 66% one. Such aspect is almost related to the different biomass species concentrations (Figure 4); in particular, in the 35% filling reactor, suspended growth concentration was higher than the 66% one, with average values of 3.9 and 3.4 kgTSS/m^3 respectively. Since suspended growth has a major ability for hydrolysis and bioflocculation, as addressed by other authors (Andreottola *et al.* 2000), the higher suspended growth concentration, the higher the enzymatic hydrolysis and bioflocculation, the higher the COD removal. This probably is the reason why the 35% HMBBR filling ratio showed a better behaviour in terms of COD removal. This is an important aspect connected with the suspended carriers filling ratio in a hybrid reactor and consequently with the competitiveness between attached and suspended biomass; in fact, while in a pure MBBR system (i.e. without sludge recycling from the final settler), the higher is the filling ratio, the higher are the performances of the system (Pastorelli *et al.* 1997; Andreottola *et al.* 2000; Wang *et al.* 2005), in a hybrid reactor there is probably an upper limit, beyond which the system performances decrease. Indeed, to confirm such a result, the comparison considering the same TSS concentrations in the reactors has to be carried out. Another aspect that suggests limiting the filling ratio is

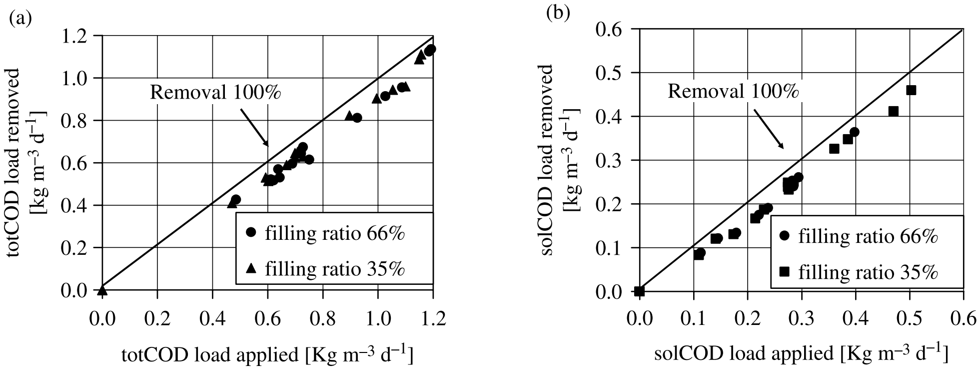

Figure 2 | TotCOD removal vs applied loads (a) and soluble COD removal vs applied loads (b).

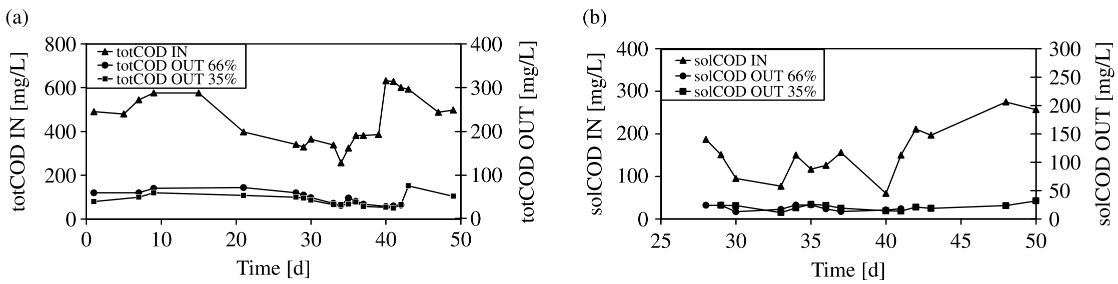

Figure 3 | TotCOD concentrations (a) and solCOD concentrations (b).

related to the carrier mixing in the reactor: in fact, the increment of the carrier concentration requires a higher air flux in order to maintain the carriers in suspension in the reactor. This aspect will consequently increase the operative cost of the biofilm/suspended growth process.

Ammonium removal

With regards to the ammonium removal, the reactors' performance was really good, reaching average removal efficiency higher than 99% for both reactors. The average inflow concentration was 37 mg N-NH_4/L, while the average effluent concentrations were 0.28 and 0.33 mg N-NH_4/L for 66% and 35% filling ratio respectively. In Table 4 data on influent and effluent ammonium concentrations are shown, while the volumetric ammonium loads applied and removed in both systems are shown in Figure 5.

Comparing the results obtained from the two hybrid reactors, it can be pointed out that in the first part of the experimental period, the 66% MBBR filling ratio had a better behaviour than the 35% one, in terms of removal efficiency; this fact was a consequence of a higher concentration of attached biomass in such a reactor, due to a major number of suspended carriers in the reactor (Jianlong *et al.* 2000).

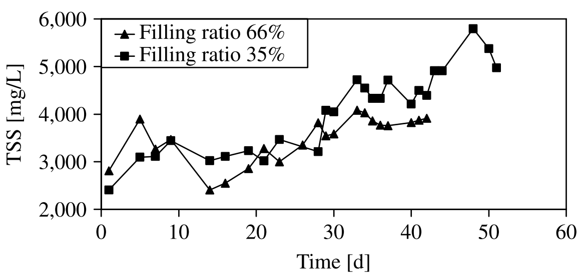

Figure 4 | MLSS concentrations in the reactors.

Table 4 | Influent and effluent ammonium concentrations

	Influent	Effluent	
		HMBBR 35%	HMBBR 66%
	N-NH_4 mg/L	N-NH_4 mg/L	N-NH_4 mg/L
Min	23	0.01	0.08
Max	54	1.80	1.30
Mean	37	0.33	0.28

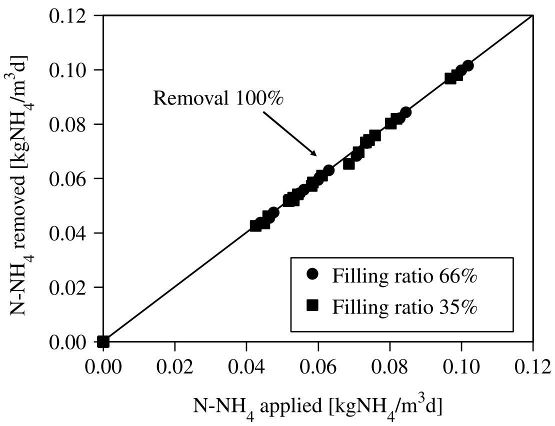

Figure 5 | N-NH$_4$ removal vs applied loads.

In fact, the higher sludge retention time of the biofilm, allowed by the suspended carriers, leads to a major growth of nitrifying bacteria, and consequently to an improved nitrifying activity in the reactor (Germain *et al.* 2006).

Figure 6(a) shows the influent and effluent ammonia concentrations, where can be outlined the excellent removal efficiencies of the systems, despite the external temperatures at the WWTP being not too high during the whole experimental period (ranging from 10 to 16°C).

However, during the 30th day of the experimental period, a biofilm detachment occurred, as outlined in Figure 6-b, and since this day the nitrifying activity in the 66% filling ratio decreased to the 35% filling ratio level, because of the loss of attached biomass. Indeed, as confirmed in literature (Rusten *et al.* 1995), it can be pointed out that the attached biomass showed a better specific nitrifying activity than the suspended one; so, this kind of reactor could be suitable in the upgrading of existing WWTP that are not able to nitrify, without the construction of new activated sludge tanks, which would require a high space availability.

The assessment of attached biomass was carried out considering the TSS on the support carriers. To evaluate the latter, a sample of 30 carrier elements was taken from each reactor, dried at 105°C for 24 hours and weighed. Then, this value was compared with an average "zero" weight determined at the beginning of the experimental period, thus obtaining the biomass weight in a single carrier element. So, as the number of carriers was known for each reactor, it was calculated the total attached biomass in the reactors and consequently, through the filling ratio, the grams of TSS per litre of reactor volume.

Kinetic parameter estimation using respirometry

Respirometric analyses have been carried out in order to characterise the process behaviour and to detect about the different roles played by the biomass species in the carbon and nitrogen removal. Respirometric experiments were conducted using a "flow-gas/static-liquid" type as batch respirometer (Spanjers *et al.* 1996). The samples (1.5 litres) were taken from the aerated reactors, containing 35% carrier concentration, moved into a 2 litre beaker and finally aerated until endogenous condition was reached. The samples were maintained at a constant temperature of 20 ± 1°C with a thermostatic cryostat (JULABO). Agitation was provided by a magnetic stirrer (FALC), and the sample was aerated intermittently using an aeration pump. In order to evaluate the kinetics of the process, known amounts of sodium acetate and ammonium chloride were added to the samples during the analysis. The dissolved oxygen concentration was measured with an oxygen sensor (WTW mod. MULTI 340i), while the aeration control and data acquisition were provided by the OURsys software. The aeration intervals were set from 2 to 6 mgDO/L. The OURsys software

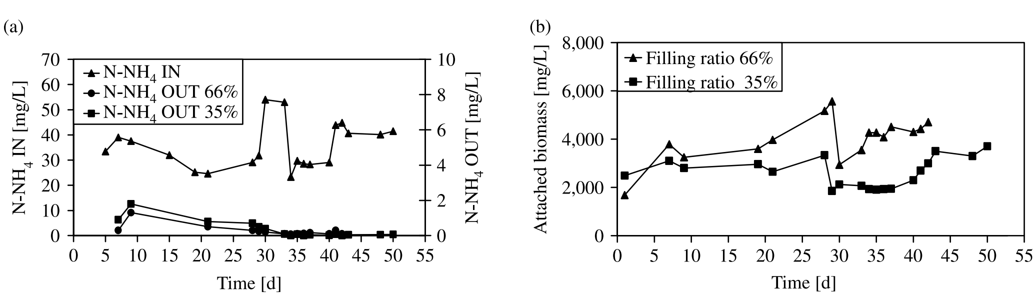

Figure 6 | Influent and effluent N-NH$_4$ concentrations (a) and attached biomass concentrations in the reactors (b).

Table 5 | Kinetic parameters obtained from respirometry

	Symbol	Parameter	Value	Unit
Suspended growth	$\widehat{\mu}_A$	Autotrophic max. growth rate	0.14	d^{-1}
	Y_A	Autotrophic yield coefficient	0.63	mg COD/mg NH_4
	K_{NH}	Saturation coefficient for ammonia	0.15	mg/L
Attached growth	$\widehat{\mu}_{Had}$	Heterotrophic max. growth rate	2.4	d^{-1}
	$\widehat{\mu}_{Aad}$	Autotrophic max. growth rate	0.4	d^{-1}
	Y_{Had}	Heterotrophic yield coefficient	0.85	mgSS/mg NH_4
	Y_{Aad}	Autotrophic yield coefficient	0.51	mgSS/mg NH_4

provided the generation of the respirograms, that feature the characteristic biomass endogenous and exogenous respiration phases. Starting from the OUR data, the estimation of the kinetic parameters was carried out. In Table 5 the kinetic parameters estimated using respirometric analysis have been reported. Indeed, during this first experimental period, there were some shortcomings related to the attrition between the carriers and the oxygen sensor, that didn't enable the evaluation of the remaining kinetic parameters. The kinetic values obtained ranged into the common intervals for biofilms reported in technical literature (Horn & Hempel 1997). The parameters using respirometric technique have been performed only for the system with a filling ratio of 35%; the same parameter values have been adopted for the other system (HMBBR 66%).

CONCLUSIONS

A pilot gathering campaign on a HMBBR was performed; the aim was to investigate the performance of this kind of system in terms of organic matter and ammonium removal and to evaluate the influence of the suspended carrier filling ratio. The experimental pilot plant was made up of two parallel hybrid MBBR systems with different filling ratios, 35% and 66% respectively.

The reactors showed a very high efficiency, both concerning the organic matter and the ammonium removal. In particular, referring to the organic matter removal, the 35% filling ratio hybrid reactor showed a better performance than the 66% filling ratio one. This behaviour is probably related to the competitiveness between suspended and attached biomass and to the fact that in the 35% filling ratio there was a higher suspended growth concentration which has a major ability in hydrolysis and bioflocculation. Indeed, to confirm this result, the comparison considering the same TSS concentrations in the reactors has to be carried out. Regarding the nitrification ability, both reactors showed excellent removal efficiencies, up to 99%, with a little advantage for the 66% filling ratio hybrid reactor, probably due to a major concentration of attached biomass, which leads to a higher concentration of slow growth species such as the nitrifying bacteria. Indeed, the results obtained in this first experimental period have suggested that in a hybrid reactor, probably due to the competitiveness between suspended and attached growth, there is a maximum value of the filling ratio that provides the best removal performance, and beyond which the process efficiency starts to decrease. The respirometric analyses seemed to be a very useful device to characterise the process behaviour, but further experimental campaigns are needed to overcome some shortcomings due to the attrition of the suspended carriers with the oxygen sensor, that sometimes leads to a mistake in the raw data.

Further development of the research will regard the evaluation of the hybrid process performance for a longer period, compared with a traditional activated sludge one, considering a prosecution of the data gathering campaign that is still in progress.

REFERENCES

Andreottola, G., Foladori, P., Ragazzi, M. & Tatàno, F. 2000 Experimental comparison between MBBR and activated sludge system for the treatment of municipal wastewater. *Water Sci. Technol.* **41**(4–5), 375–382.

APHA 1995 *Standard Methods for the Examination of Water and Wastewater*. APHA, AWWA and WPCF, Washington DC, USA.

Chen, G. H., Huang, J. C. & Lo, I. M. C. 1997 Removal of rate limiting organic substances in a hybrid biological reactor. *Water Sci. Technol.* **35**(6), 81–89.

Gambaretto, G. & Falletti, L. 2005 Impianto pilota a letto mobile ibrido per la rimozione biologica degli azotati (in Italian). *Ingegneria Ambientale* **XXXIV**(7/8), 382–388.

Germain, E., Bancroft, L., Dawson, A., Hinrichs, C., Fricker, L. & Pearce, P. 2006 Evaluation of hybrid processes for nitrification by comparing MBBR/AS and IFAS configurations. VI Biofilm Systems IWA Conference, Amsterdam/The Netherlands, 24–27 September 2006.

Gujer, W., Henze, M., Mino, T., Matsuo, T. & Van Loosdrecht, M. 1999 Activated sludge model No. 3. *Water Sci. Technol.* **39**(1), 183–193.

Henze, M., Grady, C., Gujer, W., Marais, G. & Matsuo, T. 1987 *Activated Sludge Model No.1*. IAWPRC Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment. IAWPRC Scientific and Technical Reports No1.

Horn, H. & Hempel, D. C. 1997 Growth and Decay in an auto-/heterotrophic biofilm. *Water Res.* **31**(9), 2243–2252.

Jianlong, W., Hanchang, S. & Yi, Q. 2000 Wastewater treatment in a hybrid biological reactor (HBR): effect of organic loading rates. *Process Biochem.* **36**, 297–303.

Mamais, D., Jenkins, D. & Pitt, P. 1992 A rapid physical-chemical method for determination of readily biodegradable soluble COD in municipal wastewater. *Water Res.* **27**(1), 195–197.

Mannina, G., Di Trapani, D., Torregrossa, M. & Viviani, G. 2007 Modelling of hybrid moving bed biofilm reactors: a pilot plant experiment. *Water Sci. Technol.* **55**(8–9), 237–246.

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

Ødegaard, H. 2006 Innovations in wastewater treatment: the moving bed biofilm process. *Water Sci. Technol.* **53**(9), 17–33.

Pastorelli, G., Andreottola, G., Canziani, R., Darriulat, C., de Fraja frangipane, E. & Rozzi, A. 1997 Organic carbon and nitrogen removal in moving-bed biofilm reactor. *Water Sci. Technol.* **35**(6), 91–99.

Pastorelli, G., Canziani, R., Pedrazzi, L. & Rozzi, A. 1999 Phosphorus and nitrogen removal in moving-bed sequencing batch biofilm reactors. *Water Sci. Technol.* **40**(4–5), 169–176.

Rusten, B, Hem, L. J. & Ødegaard, H. 1995 Nitrification of municipal wastewater in moving-bed biofilm reactors. *Water Environ. Res.* **67**(1), 75–86.

Spanjers, H., Vanrolleghem, P., Olsson, G. & Dold, P. 1996 Respirometry in control of the activated sludge process. *Water Sci. Technol.* **34**(3–4), 117–126.

Wang, R.-C., Wen, X.-H. & Yi, Q. 2005 Influence of carrier concentration on the performance and microbial characteristics of a suspended carrier biofilm reactor. *Process Biochem.* **40**, 2992–3001.