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PHOSPHORUS AND NITROGEN REMOVAL IN MOVING-BED SEQUENCING BATCH BIOFILM REACTORS

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ABSTRACT

A pilot moving-bed sequencing batch biofilm reactor (MBSBBR) fed with primary settled wastewater, was used in order to study organic carbon, phosphorus and nitrogen removal with and without external carbon sources. Patented KMT® polyethylene biofilm carriers were used. Organic carbon uptake and phosphorus release has been achieved in the anaerobic phase of the cycle, while nitrification, simultaneous denitrification (i.e., anoxic respiration of sequestered COD in the inner layer of the biofilm) and phosphorus uptake was observed in the aerobic phase. A stable biological phosphorus removal could be achieved only with an external carbon source. Since the process proved flexible and reliable, it is suitable for full scale application to municipal wastewater treatment plants (WWTPs), in order to meet EU total nitrogen and phosphorus limit values for discharge into sensitive receiving waters. © 1999 Published by Elsevier Science Ltd on behalf of the IAWQ. All rights reserved

KEYWORDS

Biological phosphorus removal; external carbon source; moving-bed sequencing batch biofilm reactor (MBSBBR); phosphorus accumulating organisms (PAOs); simultaneous nitrification-denitrification.

INTRODUCTION

Biological processes based upon suspended biomass (i.e., activated sludge processes) are effective for organic carbon and nutrient removal in municipal wastewater treatment plants. But there are some problems of sludge settleability and the need of large reactors and settling tanks and biomass recycling. Especially the first item could give rise to serious operating problems (increase of suspended solids and particulate nitrogen and phosphorus in the effluent, decrease of biomass in the system, etc.).

The use of the SBR-concept gives flexibility to the process, because of the related possibility of operating the plant according to a temporal sequence of events that take place in the same batch reactor and not according to a spatial sequence of continuous-flow stirred-tank reactors, where the different biological processes occur simultaneously.

Biofilm processes have proved to be reliable for organic carbon and nitrogen removal without some of the problems of activated sludge processes. Biological phosphorus removal in biofilm reactors is still in the

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research stage (González-Martínez and Wilderer, 1991; Gonçalves and Rogalla, 1992a, 1992b; Ruiz-Treviño *et al.*, 1992; Gonçalves *et al.*, 1994a, b; Kerm-Jespersen *et al.*, 1994; Garzón-Zúñiga and González-Martínez, 1996; Muñoz-Colunga and González-Martínez, 1996; Shanableh *et al.*, 1997; Morgenroth and Wilderer, 1998).

Moving-bed biofilm reactors (MBBRs) were chosen because, compared to the available fixed-bed biofilm reactors (biofilters), they are characterized by low head losses, no filter bed channeling (that is, a complete use of the bioreactor volume), no need of periodic backwashing and can be used to upgrade existing overloaded activated sludge plants without building new tanks.

Low-density polyethylene (density slightly less than 1.0 g cm^{-3}) KMT® biofilm carriers were used. They consist in small cylindrical elements (diameter 10 mm; height 8 mm) with an internal cross and small longitudinal fins on the outside surface. The filling ratio (volumetric filling in empty reactor) can be increased up to 70%, corresponding to a theoretical specific surface area of 500 m^2 m^{-3} and a void fraction of 95%. Since the biofilm growth mainly occurs in the protected internal faces of the carriers, it was assumed in the calculation an actual specific surface area of about 350 m^2 m^{-3}. These patented media have been already successfully used for nitrification (Ødegaard and Rusten, 1993; Hem *et al.*, 1994; Rusten *et al.*, 1994, 1995b; Pastorelli, 1995; Pastorelli *et al.*, 1996, 1997a, 1997b) and denitrification (Ødegaard and Rusten, 1993; Rusten *et al.*, 1994, 1995a; Pastorelli *et al.*, 1996, 1997b).

MATERIALS AND METHODS

Description of the pilot-plant

A flexible pilot-plant has been developed with the aim to evaluate (1) organic carbon and phosphorus removal in a moving-bed sequencing batch biofilm reactor (MBSBBR) and (2) simultaneous nitrification-denitrification during the aerobic phase of the SBR cycle.

A simplified flow-sheet of the pilot-plant is shown in Figure 1. Technical data of the pilot-plant are reported in Table 1. Further details can be found in Pastorelli (1995) and Pedrazzi (1997).

Primary settled wastewater was fed to the pilot MBSBBR through a first completely mixed, non-aerated feed tank (FT) where fluctuations of the influent concentration were partly damped (HRT not less than 3 h). Soluble phosphorus was added in the feed tank (as a mixture 1:0.18 of K_2HPO_4 and KH_2PO_4) in order to increase P concentration up to 3-6 mgP l^{-1}. During the last 88 days a suitable carbon source (40-80 mgCOD l^{-1} as acetic acid) was also added in order to enhance biological phosphorus removal.

The MBSBBR was mechanically mixed in phases 1 and 2 and aerated in phases 3 and 4. Air flow rates could be adjusted adequately during aerated phases.

No settling tank was provided, but settleable solid tests in Imhoff cone were performed on the effluent of each MBBR. The pilot-plant was installed outdoors, inside a metallic prefabricated box without thermal insulation.

Description of the SBR cycle

The typical SBR cycle for P and N removal (Figure 2) is divided into two biological stages: (I) anaerobic stage (phases 1 and 2; readily biodegradable COD uptake and P release) and (II) aerobic stage (phases 3 and 4; COD oxidation, P uptake and simultaneous nitrification-denitrification). In phase 4, the effluent was discharged, without any settling phase. Unlike activated sludge SBRs, biofilm SBRs require neither a settling phase nor a residual liquid volume in the reactor at the end of the draw phase, because the biomass remains prevailingly attached to the carriers. As a consequence, both cycle time and reactor volume are reduced.

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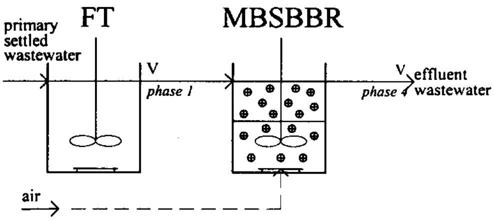

Figure 1. Flow-sheet of the pilot-plant.

Table 1. Technical data of the pilot-plant

Technical data		FT tank	MBSBBR reactor
Height	[m]	0.62	1.00
Diameter	[m]	0.51	0.75
Max volume	[m³]	0.110	0.400
Biofilm surface	[m²]	-	25
Mixing	-	yes	yes
Aeration	-	no	yes

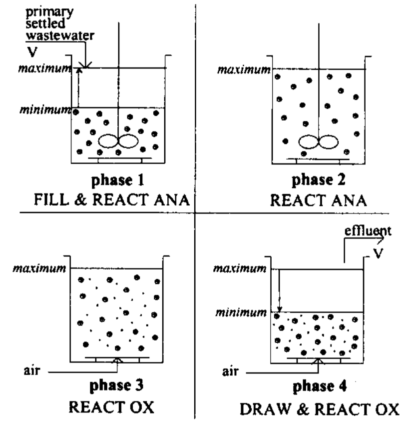

Figure. 2. Typical SBR cycle.

Table 2. Operating data of the pilot-plant

Run	days	cycles [-]	V_{in} [l $cycle^{-1}$]	t_{ANA} [min]	t_{OX} [min]	t_{cycle} [min]
III	126-194	285	75	180	180	360
IV	195-240	179	75	180→95	180→265	360
V	241-282	133	75	95	265	360

Operating data of the pilot-plant in the last three runs (RUN III, IV and V) are reported in Table 2. During each SBR cycle a given wastewater volume V_{in} (held constant and equal to 75 l) was treated. The process could also be managed by setting the number of cycles per day (n), the anaerobic stage length (t_{ANA}) and the aerobic stage length (t_{OX}). Typical number of cycles per day was 4, while anaerobic stage length and aerobic stage lengths were 95 min and 265 min respectively (inclusive of about 5-min fill & draw operations). The process was automatically controlled by a PC, using a software, written in LabVIEW® for Windows®, which controlled time phases by switching on and off pumps and valves according to time and/or water level input signals.

Wastewater characteristics

The pilot-plant was located at the Varedo wastewater treatment plant, near Milan, which is a WWTP (150,000 PE, 110,000 domestic and 40,000 industrial PE) fed with a combined sewer system. Characteristics of the primary settled wastewater fed to the pilot-plant (inclusive of phosphorus and organic carbon added, since they were dosed directly in the FT) are reported in Table 3. Table 3 clearly shows, there were large fluctuations of concentration of the contaminants, especially for those parameters related to the suspended fraction. Fluctuations of concentrations were due to the periodic change from dry to wet weather conditions and vice versa, but fluctuations of concentrations related to suspended matter were also due to the occasional overloading of the primary settling tank (discharge of night-soil tankers and surplus sludge recycling).

Monitoring, sampling and analyses

Monitoring. Temperature and dissolved oxygen were measured in each tank every workday, immediately before sampling. Air flow rates were monitored using flow meters.

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Sampling. Grab samples of the influent wastewater (in the FT) and the content of the MBSBBR at the end of phases 2 (anaerobic) and 4 (aerobic) were taken 3 days a week. All the samples referred to the same cycle in order to allow correct mass balances. The samples were analysed immediately after sampling for the parameters shown in Table 3.

Table 3. Characteristics of the primary settled wastewater fed to the pilot-plant

Parameter		N.	Minimum	Maximum	Average	Standard deviation	Coefficient of variation
TSS	[mgTSS l^{-1}]	73	44	1688	240	278	1.16
Total COD	[mgCOD l^{-1}]	44	95	4440	456	670	1.47
GF/C FCOD	[mgCOD l^{-1}]	24	76	338	155	53	0.34
0.45 FCOD	[mgCOD l^{-1}]	74	31	188	90	36	0.40
BFCOD	[mgCOD l^{-1}]	10	45	288	118	69	0.58
NH_4^+-N	[mgN l^{-1}]	27	15.9	51.5	32.7	7.3	0.22
NO_3^--N	[mgN l^{-1}]	6	0.0	0.2	0.1	0.1	1.55
Total P	[mgP l^{-1}]	54	7.7	30.0	12.7	4.0	0.31
PO_4^{+3}-P	[mgP l^{-1}]	76	3.1	15.6	8.1	2.6	0.32

GF/C FCOD, 0.45 FCOD and BFCOD explained below (Analytical Methods)

Analytical methods. Total suspended solids (TSS), COD, ammonia (NH_4^+-N), nitrate (NO_3^--N), soluble (PO_4^{+3}-P) and total phosphorus were measured according to the Standard Methods (1995). GF/C Whatman and 0.45-µm filters were used for filtration of samples.

Biodegradable filtered COD (BFCOD) was calculated as the difference between influent-GF/C filtered COD to the pilot-plant and effluent-0.45-µm filtered COD from the MBSBBR (assuming most of the effluent filtered COD as biologically inert). BFCOD represents the sum of the two components of the biodegradable COD: biodegradable soluble and hydrolysis products.

RESULTS AND DISCUSSION

Experimental results

The experimental programme aimed to study the behaviour of the MBSBBR for phosphorus removal with and without external carbon sources and also simultaneous nitrification and denitrification during the aerobic stage of the cycle.

The pilot-plant, fed with primary settled wastewater (with soluble phosphorus added), was operated for 282 days, 194 days without using external carbon sources and 88 days with an external carbon source added.

In this paper the results of the last three runs are summarised:

RUN III:	no external carbon source;
RUN IV:	external carbon source (about 40 mgCOD l^{-1} as acetic acid);
RUN V:	external carbon source (about 80 mgCOD l^{-1} as acetic acid).

The first two runs (not described in this paper) were used as start-up phase and to define the optimal operating parameters (cycle length and t_{ANA}/t_{OX} ratio). The last three runs were designed to study the effect of the readily biodegradable organic carbon source (acetic acid) on biological phosphorus removal in the MBSBBR.

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Table 4. Operating conditions, loading and removal rates of the anaerobic stage of the MBSBBR

Parameter	Run III			Run IV			Run V		
	n	loading rate [g m^{-2} d^{-1}]	removal rate [g m^{-2} d^{-1}]	n	loading rate [g m^{-2} d^{-1}]	removal rate [g m^{-2} d^{-1}]	n	loading rate [g m^{-2} d^{-1}]	removal rate [g m^{-2} d^{-1}]
0.45 FCOD (+)	14	4.01±0.94	0.21±1.00	22	6.72±2.06	0.70±1.62	5	9.23±2.03	4.15±1.14
PO_4^{+3}-P (*)	21	0.41±0.13	0.23±0.11	22	0.71±0.34	1.06±0.50	6	0.54±0.24	2.14±0.22
T	11	8.5-15.5		22	12.0-21.5		5	18.0-23.0	

(+) transfer = absorption.
(*) transfer = release.

Table 5. Operating conditions, loading and removal rates of the aerobic stage of the MBSBBR

Parameter	Run III			Run IV			Run V		
	N	loading rate [g m^{-2} d^{-1}]	removal rate [g m^{-2} d^{-1}]	n	loading rate [g m^{-2} d^{-1}]	removal rate [g m^{-2} d^{-1}]	n	loading rate [g m^{-2} d^{-1}]	removal rate [g m^{-2} d^{-1}]
0.45 FCOD (+)	14	4.07±0.96	0.34±1.18	22	2.75±1.01	0.88±0.62	5	1.85±0.63	0.73±0.40
PO_4^{+3}-P (*)	21	0.69±0.21	0.30±0.11	22	0.75±0.28	0.49±0.18	6	0.98±0.10	0.85±0.09
NH_4^+-N	-	-	-	-	-	-	7	0.93±0.41	0.39±0.16
NO_3^--N	-	-	-	-	-	-	7	0.39±0.16	0.36±0.16
T	11	8.5-17.5		22	12.5-21.5		5	18.0-23.0	
DO	4	2.2-7.4		6	2.2-4.7		4	1.8-2.3	

(+) transfer = uptake.
(*) transfer = oxidation in the bulk liquid.

During RUN III biological phosphorus removal without external carbon sources has been tested. A t_{ANA}/t_{OX} ratio equal to 1.00 has been used in order to give sufficient time for hydrolysis of particulate COD in the anaerobic stage, due to low readily biodegradable COD in the feed.

During RUN IV and RUN V biological phosphorus removal with external carbon sources has been tested. The t_{ANA}/t_{OX} ratio has been gradually decreased to 0.36 during RUN IV and fixed to 0.36 during RUN V because most of the organic carbon useful for biological phosphorus removal was provided as readily biodegradable COD and a long aerobic stage could improve phosphorus uptake. During RUN V, the long aerobic stage and the higher organic load (that is, higher COD uptake in the anaerobic stage) has allowed us also to evaluate the occurrence of simultaneous nitrification-denitrification.

The operating conditions, loading rates and removal rates of the anaerobic and aerobic stage of the MBSBBR are reported in Tables 4 and 5 respectively. The wide range of operating temperature in the three different operating periods was due to the absence of thermal insulation. The concentrations of the different contaminants in each sampling point are summarised in Table 6.

Phosphorus removal

Phosphorus release rates during anaerobic stage vs. BFCOD loading rates are shown in Figure 3. Phosphorus release rates appear to be very high, particularly in RUN V. This can be easily explained by observing that the organic loading rates were increased twofold from RUN III to RUN V, while at the same

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Table 6. Concentrations of the different contaminants at each sampling point during Run III, IV and V

Parameter	Run III			Run IV			Run V		
	FT tank	ANA stage	OX stage	FT tank	ANA stage	OX stage	FT tank	ANA stage	OX stage
TSS	267±97	-	151±34	120±38	-	135±40	139±49	-	173±62
0.45 FCOD	76±13	55±13	42±13	100±29	54±23	34±9	159±34	38±13	23±7
Total P	13.1±2.4	13.4±1.8	10.2±1.8	13.3±5.5	21.9±6.8	11.5±4.0	10.2±1.9	26.1±1.7	12.7±3.0
PO_4^{+3}-P	7.1±1.8	9.4±2.0	5.4±2.1	8.0±2.5	14.3±5.2	4.8±3.3	6.9±1.6	19.9±2.1	2.6±2.4
NH_4^+-N	-	-	-	-	-	-	25.2±6.6	18.8±8.3	10.9±6.6
NO_3^--N	-	-	-	-	-	-	0.0±0.0	0.0±0.0	0.6±0.6

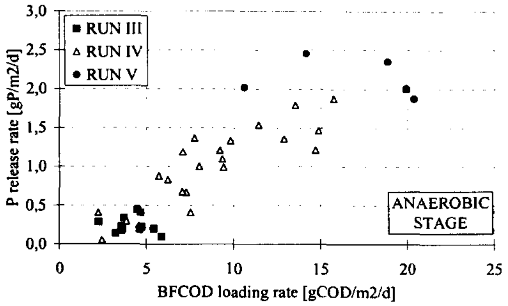

Figure 3. P release rate vs. BFCOD loading rate during anaerobic stage.

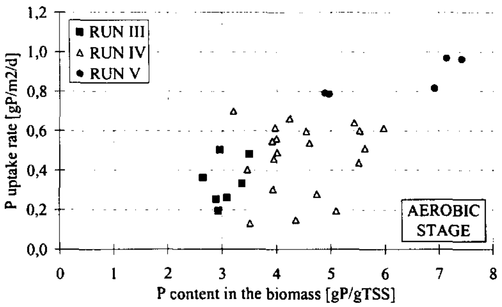

Figure 4. P release rate vs. P content in the biomass during aerobic stage.

time t_{ANA} halved decreasing from 180 to 95 minutes. The effect of the external organic source can be observed considering that phosphorus release rates increased more than two times.

Phosphorus uptake rates during aerobic stage vs. phosphorus content in the biomass are shown in Figure 4. Active phosphorus accumulating organisms (PAOs) built up phosphorus up to 7.5% (as gP $(gTSS)^{-1}$) or 9.0% (as gP $(gVSS)^{-1}$), but only when the external organic source was added. Biomass has shown only a slight increase in the period where the external organic source was added (from 18-19 to 22-23 gTSS m^{-2}) indicating that good performances depend more on biomass quality than biomass quantity. An increase in volatile fraction was observed (from 65-70% to 75-85%), due to higher organic loads.

Phosphorus uptake during aerobic stage vs. phosphorus release during anaerobic stage is shown in Figure 5. A direct proportionality between P uptake and P release was measured with a proportionality coefficient of 1.055 gP removed $(gP\ released)^{-1}$. This result is similar to that found by Gonçalves and Rogalla (1992b) but the proportionality coefficient is lower, probably because of the lower organic loads of the tests presented here.

Simultaneous nitrification-denitrification

Despite an anaerobic phase lasting 95 minutes per cycle, an active autotrophic biomass colonised the biofilm during RUN V, because of better COD removal in the anaerobic stage. As a matter of fact, from RUN III to RUN V an increase of organic loading and removal rate in the anaerobic stage and a corresponding decrease of organic loading rate in the aerobic stage could be observed. Ammonia removal rates up to 0.7 gNH_4^+-N $m^{-2}\ d^{-1}$ (with only about 2 $mgO_2\ l^{-1}$ dissolved oxygen in the MBSBBR) were measured without nitrate production (therefore with simultaneous denitrification) (Figure 6). This can be explained considering that most of the BFCOD was sequestered during the anaerobic stage, favouring nitrifiers growth in the outer

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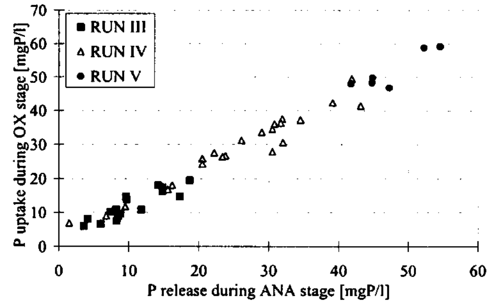

Figure 5. P uptake during aerobic stage vs. P release during anaerobic stage.

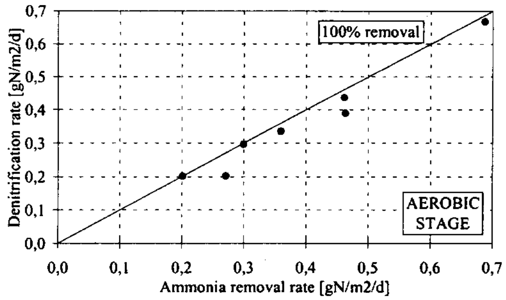

Figure 6. Ammonia removal rate vs. denitrification rate during aerobic stage.

layer of the biofilm and anoxic respiration of equestered COD in the inner layer. It can be assumed that PAOs were mostly denitrifiers.

CONCLUSIONS

A pilot MBSBBR was used in order to study (1) organic carbon and phosphorus removal in a moving-bed sequencing batch biofilm reactor (MBSBBR) and (2) simultaneous nitrification-denitrification during the aerobic phase of the SBR cycle. The process was studied in view of its application to full scale WWTPs. It proved flexible, reliable and easy-to-operate (no clogging problems, little suspended solids in the reactors and easy to settle or filter out, simple and rapid start-up, etc) and could meet EU total nitrogen and phosphorus limit values for discharge into sensitive receiving waters with only two stage (anaerobic/aerobic without a separate anoxic stage) using acetic acid as organic carbon source. A stable biological phosphorus removal could be achieved only with an external carbon source. Acetic acid addition allowed the growth of denitrifying PAOs living in the inner layer of the biofilm. They use nitrate produced in the outer layer by the autotrophic biomass to oxidise organic carbon sequestered in the cell during the anaerobic stage. Simultaneous nitrification-denitrification during the aerobic stage made it possible to remove part of the biodegradable COD stored as PHB reserves without using oxygen, therefore with energy savings.

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