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Transformation of phosphorus in intermittent aerated biofilter under aerobic continuous feeding with long backwashing intervals

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Abstract

A combined fixed-film system composed of anaerobic biofilter, aerobic biofilter, and intermittent aerated biofilter (IABF) is developed for enhanced biological phosphorus removal (EBPR) treating domestic wastewater. This work presents details on the performance of IABF under aerobic condition, where phosphorus-accumulating organisms are accumulated. Analysis on distribution of phosphorus in both the bulk and the biofilm indicates that the PAOs-rich biofilm is characterized by a high activity, a strong P capacity, and a good adaptability of fluctuations in aerobic continuous loading. An innovative means for P removal slows down accumulation of P in biofilm. As a result, removal of P-rich biomass is no longer a key limitation of EBPR performance in the biofilm system. Long backwashing interval is practicable in IABF under aerobic continuous feeding regime.

Keywords: Biological phosphorus removal; Intermittent aeration; Biofilm; Backwashing interval; Continuous flow

1. Introduction

Biofilm processes have proved to be reliable for organic C and N removal without some of the problems of activated sludge processes, such as problem in sludge settleability, secondary release of phosphate in the final clarifier. However, biofilm system is not common for enhanced biological phosphorus removal (EBPR). A few studies on SBR systems have been reported [1–6]. Some studies focused on continuous flow systems by alternating unaerated/aerated conditions in biofilm reactors in cycles and reversing the flow direction at the end of each cycle with the influent into the anaerobic reactor [7–11]. Most of these reports carried out on laboratory scale systems. Only a single semi-full-scale plant (17 m^3) was investigated [6].

One of the reasons for this is the complexity of the process [12]. To accumulate Phosphorus accumulating organisms (PAOs) in biofilm attached on carrier materials, the system should be subjected to alternating unaerated/aerated conditions in temporal sequence under continuous flow or discontinuous flow where substrate is available under anaerobic condition. In anaerobic condition, PAOs take up easily biodegradable substrate quickly from the bulk and store them in form of polyhydroxyalkanoates accompanied with degradation of polyphosphate and consequent release of phosphorus. In the subsequent aerobic condition, PAOs grow aerobically and take up phosphate from the bulk to recover intracellular polyphosphate level by using polyhydroxyalkanoates stored anaerobically as carbon and energy sources. For removal of phosphorus from biofilm system, backwashing of filters must take place at a time where the internal storage of phosphorus in bacteria is at its highest, which is the only means for removal of P-rich biomass [12,13]. It achieved limited net phosphorus removal due to the limited sludge wasting, and on the other hand, frequent sludge wasting may disrupt the performance of the system [9]. Diffusion limitation of phosphate possibly constitutes a serious problem regarding the use of a biofilm reactor for EBPR [14]. Regular and intensive backwashing is suggested for the efficient operation of EBPR in biofilm system [13].

A combined fixed-film system under continuous flow is developed for EBPR treating domestic wastewater. As an innovative method for removal of phosphorus established in intermittent aerated biofilter (IABF) in the system, it carries out long backwashing intervals. Our previous works demonstrated

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that the combined system is efficient for biological phosphorus removal in domestic wastewater treatment process, and an active biofilm is produced in IABF where PAO is accumulated under alternating anaerobic/aerobic condition.

The aim of the work is to investigate distribution of phosphorus in the column of IABF under aerobic condition, and to determine effects of long backwashing intervals on phosphorus transformation.

2. Materials and methods

2.1. IABF in the combined fixed-film system

The combined fixed-film system developed for EBPR consists of an anaerobic biofilter, two IABFs, and an aerobic biofilter (Fig. 1).

Anaerobic biofilter is used as a fermentation reactor and fed with domestic wastewater. The complex organic substances in influent is hydrolyzed and decomposed under anaerobic condition, as well as the organic components in particles in the wastewater that is hold up by filter bed in the reactor. Moreover, the content of readily biodegradable COD in the sewage, especially Volatile fatty acids (VFAs), is enhanced in this stage. Then the fermented sewage is introduced to IABF. The residual nutrient in the effluent of IABF is treated in aerobic biofilter.

Each IABF is operated in cycles by alternating unaerated/aerated condition. Cycle duration (CD) in IABF refers to the elapsed time of a unaerated/aerated cycle, including an anaerobic phase and an aerobic phase. An aerobic continuous feeding (ACF) regime applied in each IABF is detailed as following.

In anaerobic phase, IABF is fed with effluent of anaerobic reactor at the beginning, then recirculated and reacted; at the end of anaerobic phase, P-rich water is discharged and for further

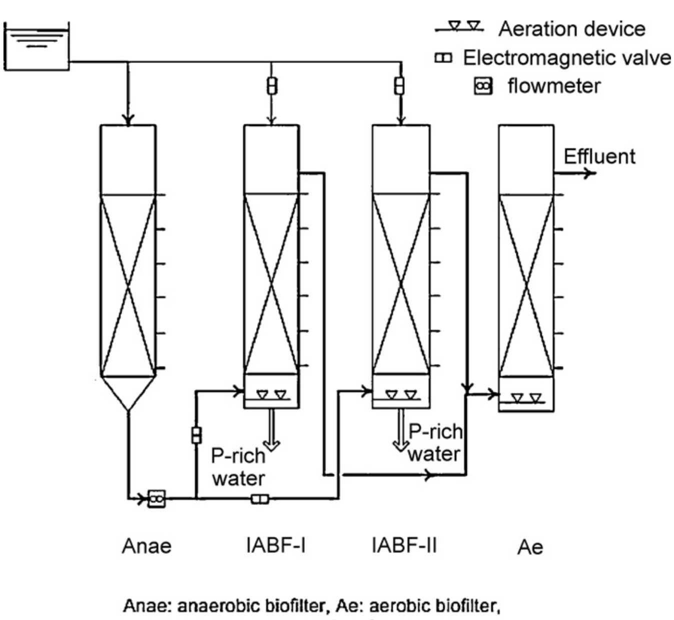

Fig. 1. Schematic of the combined fixed-film system. Anae: anaerobic biofilter, Ae: aerobic biofilter, IABF: intermittent aerated biofilter.

treatment by a chemical method separately. In the subsequent aerobic phase, to achieve a stable effluent, it divides into two steps. In the first hour, IABF is fed with raw wastewater at the beginning, and then aerated. After that, it steps into continuous flow operation where effluent of anaerobic reactor is introduced and an output is produced continuously with low concentration of phosphorus. At the end of aerobic phase, the reactor is emptied. The operation in a CD is finished. There are 0.07 h in anaerobic phase and 0.05 h in aerobic for filling, and 0.05 h for drawing in both phases in each CD.

Two IABFs are parallel and operated in turns. When IABF-I is undergoing the aerobic continuous flow operation, IABF-II is going through anaerobic phase and the subsequent first hour of aerobic phase. When IABF-I finished its operation in one CD, IABF-II starts to its aerobic continuous operation. Each IABF is operated in cycles, and cycles in a day depends on CD length.

The characteristic of IABF operated under the ACF regime is summarized as following: controlling P contents in biofilm is achieved by discharge of P-rich water at the end of anaerobic phase in each CD, instead of backwashing; and biofilm is exposed to the circumstance of co-existence of substrate and oxygen with continuous aerobic feeding.

Each reactor was 0.1 m in diameter and 1.0 m in height. Gravel, as a support, was used to charge gravel to a bed height of 0.06 m at the bottom of the column in each reactor. Then the filter media of enzyme-accelerated biological package material (inorganic, patented by Chongqing University), with effective diameter of 4–6 mm and specific surface of 796 $m^2\ m^{-3}$ approximately, was used to charge the filter to bed height of 0.5 m in each reactor. The total was 0.56 m in height of the column. Each reactor was equipped with washing devices, aeration devices in IABFs and aerobic reactor, in addition, recirculation in anaerobic phase in IABF. The total effective reactor volume of the system was 20.6l. All operations in IABFs were controlled by commercial timer switches and relays.

To determine effects of operating conditions on the performance of IABFs, two parallel sets were set up, named A system and B system. IABFs in the two systems are named A-IABF and B-IABF, and operating conditions are shown in Table 1. Biofilter is backwashed to prevent clogging. Backwashing carries out in each IABF in long intervals of 14–22 days in A-IABF and 13–27 days in B-IABF. The domestic wastewater used in this study came from the campus of Chongqing University in China. Its characteristics during the experimental period are shown in Table 1.

2.2. Analytic methods

COD and SCOD were measured according to a colorimetry method by HACH DR2010 spectrophotometer. Ammonium and total phosphorus (TP) were measured according to the standard methods [15]. *Ortho*-phosphate and dissolved *ortho*-phosphate were determined by flow injection analysis. VFAs were measured according to a potentiometric method [16]. The dissolved oxygen, pH, and temperature were also monitored.

Table 1
Operating parameters in A-IABF and B-IABF

	A-IABF					B-IABF			
	RUN1	RUN2	RUN3	RUN4	RUN5	RUN1	RUN2	RUN3	RUN4
RUN length (d)	17	15	11	10	18	17	15	21	18
T (°C)	21–24.9	22.5–24.1	23.9–27.9	27.2–28.9	28–32	21–24.9	22.5–24.1	23.9–28.9	28–32
CD (h)									
Total	8	8	8	6	6	8	8	8[c]	6
Anaerobic	3.0	3.0	3.0	2.0	2.0	3.0	3.0	3.0	2.0
Aerobic	5.0	5.0	5.0	4.0	4.0	5.0	5.0	5.0	4.0
HRT of IABF (h)	11.7	5.7	2.3	4.3	2.6	12.6	8.4	6.3	3.6
Organic loading[a] (kg m^{-3} d^{-1})	3.72 ± 0.54	4.15 ± 1.02	6.70 ± 0.79	4.14 ± 0.54	4.74 ± 1.21	1.54 ± 0.33	2.08 ± 0.61	1.74 ± 0.30	1.66 ± 0.47
P loading[a] (kg m^{-3} d^{-1})	0.0248 ± 0.005	0.034 ± 0.009	0.0511 ± 0.015	0.033 ± 0.003	0.032 ± 0.007	0.022 ± 0.007	0.030 ± 0.010	0.029 ± 0.003	0.025 ± 0.007
COD,inf[b] (mg l^{-1})	337 ± 100	351 ± 128	272 ± 64	232 ± 48	168 ± 37	337 ± 100	355 ± 100	252 ± 62	166 ± 38
COD,eff[b] (mg l^{-1})	75 ± 19	89 ± 24	79 ± 22	54 ± 10	50 ± 11	107 ± 18	86 ± 24	68 ± 26	46 ± 20
TP,inf[b] (mg l^{-1})	5.1 ± 1.3	5.6 ± 1.3	4.6 ± 1.1	4.1 ± 0.53	2.6 ± 0.45	5.9 ± 1.2	5.5 ± 2.0	3.9 ± 0.43	2.5 ± 0.54
TP,eff[b] (mg l^{-1})	0.32 ± 0.16	0.48 ± 0.25	0.72 ± 0.37	0.46 ± 0.08	0.63 ± 0.22	0.48 ± 0.19	0.33 ± 0.15	0.35 ± 0.18	0.32 ± 0.16
COD removal (%)	71.9	75.5	72.1	76.1	72.2	71.4	77.0	76.2	69.1
TP removal (%)	89.3	90.4	85.6	87.6	77.5	87.4	91.9	83.7	81.4

[a] Organic and P loading are real loadings of each IABF in per volume of filter bed in per day.
[b] Data are expressed as mean ± S.D. Calculations were made 14, 14, 12, 10, 18 data for RUN1–5 in A-IABF and 11, 9, 10, 10 data for RUN1–4 in B-IABF, respectively.
[c] CD was 6 h after 11 days.

The biofilm samples with the supported carriers were sampled at different depth in the column of IABFs, and frozen in refrigerator immediately. The detachment of biofilm from the carriers was according to a method described in Liu et al. [17]. Then the detached biofilm was dried in oven under 105 °C. Total solid (TS) and volatile solid (VS) of the separated biofilm were measured according to methods described in Liu et al. [17]. PHB in the dried biofilm was determined according to a colorimetry method [18]. Glycogen in the dried biofilm was determined according to an anthrone method [19]. Phosphorus in the dried biofilm was determined according to a colorimetric method [20]. Ash of the sample, a remainder in measurement of VS after treating at 550 °C, was used in the determination. The measurement of total phosphate content in ash was modified in this study. Ash was hydrolyzed with 4 ml nitric acid under 0.138–0.158 MPa. Then *ortho*-phosphate in the solution was determined by flow injection analysis after cooling to room temperature. Polyphosphate $Na_5P_3O_{10}$ was used as a standard during the procedure.

3. Results and discussions

3.1. Performance of P removal in IABFs

In A-IABF, HRT varied greatly from 11.7 to 2.3 h in RUN1–5 (Table 1). When the operation switched from RUN1 to RUN2 and from RUN2 to RUN3, the variation of HRT was over one time. As a result, a temporary increasing of concentration in effluent of IABF was observed. The system become stable after 1–2 days, and then the concentration of the effluent become low as usual. The samples were analyzed when the reactor was stable, and the average performance of A-IABF in RUNs is shown in Table 1.

Loading rate of organic and P in RUNs change with HRT of IABF in RUNs apparently. Average COD concentration in effluent is not clearly affected by the fluctuations of hydraulic condition, but the fluctuation of influence concentration. While P content in effluent of IABF is 0.72 mg l^{-1} in RUN3 and 0.63 mg l^{-1} in RUN5 in average, respectively, which is higher than that in RUNs1, 2 and 4. The increasing flowrate enhance transportation between the bulk and the biofilm, as well as the erosion of biofilm resulting in the increasing fragments in effluent. After biofiltration by aerobic reactor, P content in effluent of system is 0.44 mg l^{-1} in RUN3 and 0.52 mg l^{-1} in RUN5, respectively. It is shown that the fluctuation of P content in IABF under different HRT is mainly caused by the increase of solid in the effluent under the rapidly increasing flowrate.

To achieve a stable loading condition, HRT of B-IABF was changed in RUNs according to the variation in concentration of influent with the change of season. Compared to A-IABF, B-IABF is subjected to lower organic and P loading with less fluctuation and P level in effluent in B-IABF is more stable than that in A-IABF. Not much difference in COD removal is observed in between A-IABF and B-IABF, except for RUN1 in B system with a slightly higher COD concentration in effluent.

Table 2
Operation parameters in biofilm systems for biological phosphorus removal in literatures

No.	CD (h)	Organic loading (g COD l^{-1} d^{-1})	P removal (%)	COD removal (%)	Backwashing Interval, (d)	Type of sewage	Characteristics of the system	Literature
1	4–6	1.06	29–41	76–82	≈7	Synthetic sewage	Two biofilter in series with alternating flow direction and aeration	[8]
2	6	0.3[a]	29	60		Synthetic sewage	Two biofilter in series with alternating flow direction and aeration	[7]
3	4–6		79.2–81.9	94.3–95.2	Daily	Synthetic sewage	A/O SBR	[21]
4	8	0.552–0.635	54.3–73.0	75.8–85.0		Synthetic sewage	A/O SBR	[2]
5	8	1	71	89	2–3	Municipal sewage	A/O SBR	[6]
6	6	0.9	50	90		Synthetic sewage	A/O SBR, moving bed	[22]
7	6–8	1.92–8.20[b], 1.68–8.39[a]	77.5–90.4	71.9–76.1	14–22	Domestic sewage	Alternating operated IABF continuous flow system	This study

[a] The number presents hydraulic loading (m^3 m^{-2} d^{-1}).
[b] The number presents organic loading of two alternating operated IABFs.

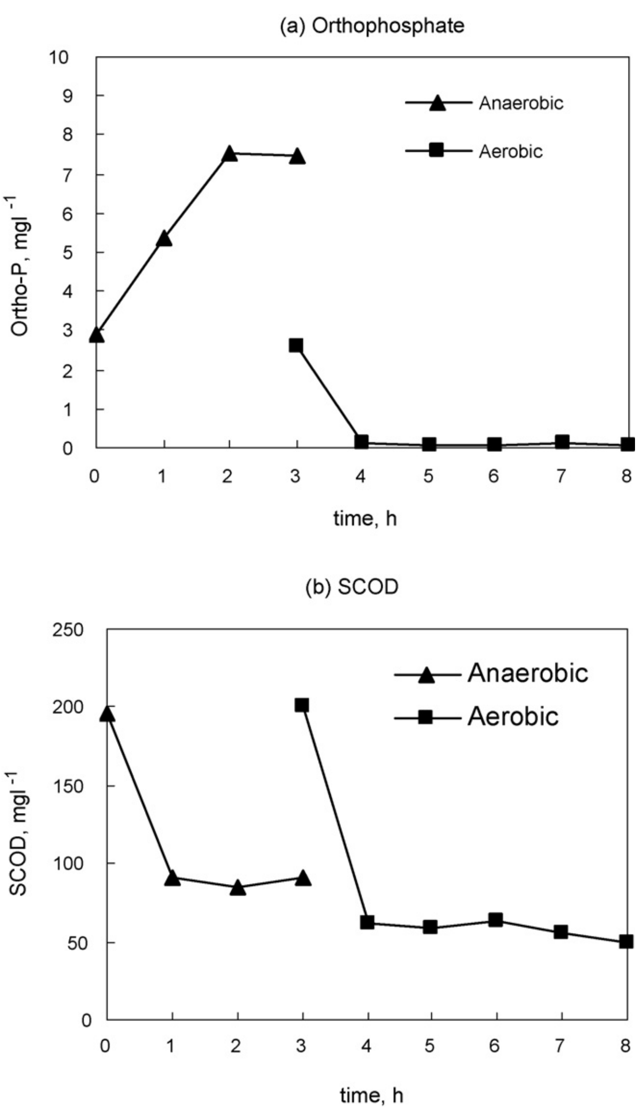

Fig. 2. Typical profiles of (a) P and (b) SCOD in CD.

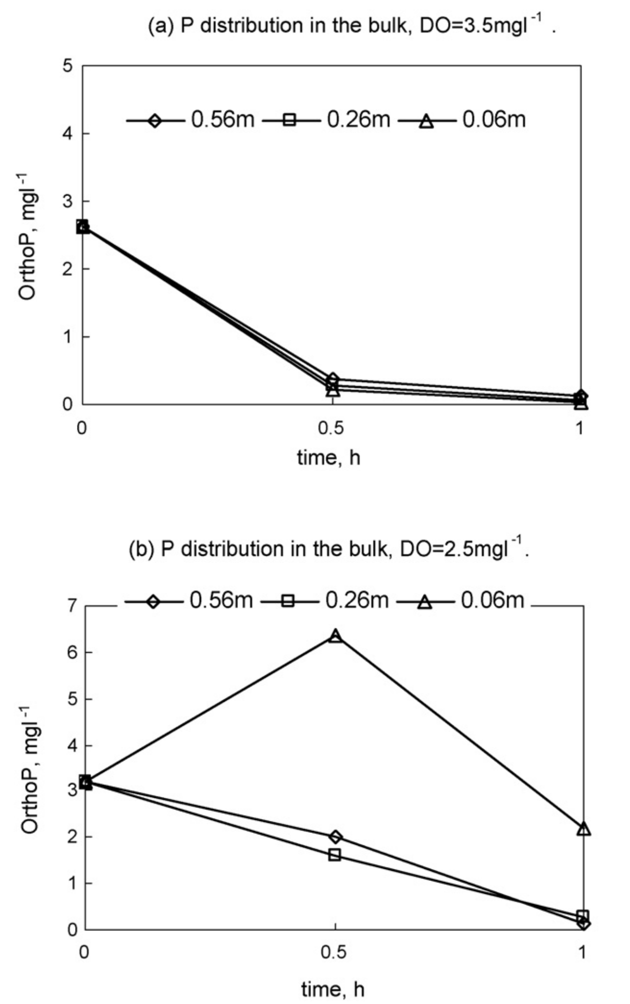

Fig. 3. Influence of DO at the beginning of aerobic phase. The profile is marked with a height in the column. (a) P distribution in the bulk, DO = 3.5 mg l^{-1}. (b) P distribution in the bulk, DO = 2.5 mg l^{-1}.

Comparison with biofilm systems for biological phosphorus removal in literatures (Table 2), organic loading of alternating operated IABFs in this study is higher than that of those continuous systems where two biofilters operated in series, as well as the efficiency of P removal. SBR biofilm systems in literatures worked with a lower loading rate, and achieved higher P removal performance than that of continuous systems in literatures. Some of them were backwashed daily or every 2–3 days to control P content in biomass, resulting in a better performance of P removal. However, the efficiency of P removal in these SBR systems is also lower than that of the IABFs. It is shown that IABF can achieve an efficient P removal under the ACF regime with regular discharge of P-rich water in anaerobic phase, and the performance of P removal of IABF does not depend on backwashing intervals, in contrast to the classical biofilm system.

According to P balance and flow balance in the combined system, P input of the system as well as flow input of the system includes input in continuous flow, input in anaerobic phase in IABF, and input in first hour of aerobic phase in IABF. At a condition of HRT of IABF of 4.3 h and CD length of 6 h, 47.5% of P input of the system and 23.5% of flow input of the system can be stepped into further chemical treatment of P-rich water. After the chemical treatment, the residual nutrient in the treated liquor such as organic and ammonium could be removed by further aerobic treatment.

3.2. Characteristics of P and SCOD profiles in IABF

3.2.1. Typical profiles in CD

Under the ACF regime, typical profiles of phosphorus and organic in CD are quiet different from that of classical A/O sequencing batch biofilm system (Fig. 2).

There are three characteristics in the ACF regime. First, due to discharge of P-rich water at the end of anaerobic phase, P release and P uptake are two separated process in the ACF. Second, initial loading in aerobic phase under the ACF is dependent on characteristics of influent of the reactor, and independent of P release process. As a result, it is subjected to lower initial P and higher initial organic concentration. Third, P and organic concentration decrease quickly in the first hour, and maintain a stable and low level in effluent in the following continuous feeding.

3.2.2. Influent of DO at the beginning of aerobic phase

In classical A/O system, P release and uptake is based on the spatial or temporal separation between the electron donor (substrate) and the electron acceptor (oxygen). Early study showed that the extent of P uptake under the subsequent aerobic condition is dependent on the amount of externally available substrate [23]. A high substrate in aerobic phase results in a lower amount of P uptake. Recent studies focused on a PAO-rich system with the presence of both substrate and oxygen in

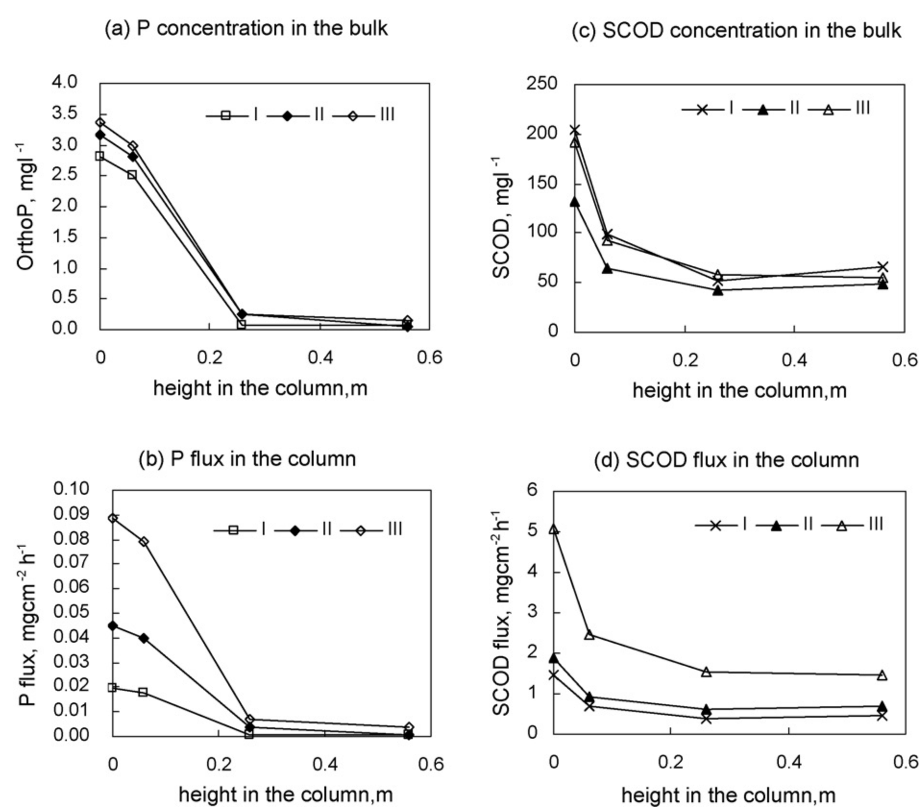

Fig. 4. Distribution of P and SCOD in the bulk under continuous feeding in aerobic phase. In (a–d), the profile marked with I, II, or III is a presentation of the15th day in RUN1, the 12th in RUN2 or the 11th in RUN3 in A-IABF, and the operating days since last backwashing in 7, 8, or 5, respectively. (a) P concentration in the bulk, (b) P flux in the column, (c) SCOD concentration in the bulk and (d) SCOD flux in the column.

aerobic phase where most of the studies were under an acetate-abundant condition [19,24,25]. It was shown that aerobic P release and PHB production was caused by the supplement of acetate.

Initial organic loading in aerobic phase is dependent on the influent, where easily biodegradable organic substrate, such as VFAs, is limited and available in a dynamic manner in real wastewater treatment system. According to the observations in the experiments, initial P uptake is not disturbed by the variable organic. Furthermore, it is directly proportional to initial P loading (not shown). Only under a deficiency in DO, e.g., less than 2.5 mg l^{-1}, aerobic P release is possible to be observed (Fig. 3). At the beginning of aerobic phase, aeration system started to work after filling and DO is increasing. Occasionally, DO is not enough at the beginning for fluctuation of air supply. Ordinary heterotrophic organisms (OHOs) consume substrate as well as DO in the bulk at aerobic condition. When DO is deficient, it makes a shortage of oxygen supply in inner biofilm layer where PAOs release phosphorus under anaerobic condition. It is observed that the organic is depleted in half of an hour and then P concentration decrease quickly (Fig. 3), and P released in previous minutes is taken up by PAOs when oxygen supply is increased. When DO is lower than 2.5 mg l^{-1}, the phenomena may also take place at a situation where a thicker biofilm is formed after a long-term operation without wasting. In a normal situation with enough aeration, no aerobic P release is observed. Therefore, control of DO at the beginning of aerobic phase is to avoid P release in the system.

3.2.3. Distribution under aerobic continuous flow

Flux of P or SCOD is calculated according to the real P or SCOD loading in aerobic continuous feeding in IABF, expressed as amount of P or SCOD on cross-section of reactor in per hour. Concentration of *ortho*-phosphate and SCOD decreases along the flow direction in the column under different HRT, as well as flux of P and SCOD (Fig. 4).

Most of the decrease of P content is achieved in the deeper part, i.e., 0.06–0.26 m in height of the column, and a very low content is in the upper part under each operating condition (Fig. 4a). With the decrease of HRT, P flux at the entrance of IABF increased from 0.020 to 0.089 mg P cm^{-2} h^{-1}. More than 90% of the P flux is reduced in the deeper part, resulting in a little left in the rest of the column (Fig. 4b). Similar tendency is observed under different HRT with similar days in operating durations without wasting. P uptake in the deeper part grows with the increasing of the P flux. It indicates that the biofilm has a strong activity for P storage and a good adaptability of fluctuation in aerobic P loading.

Distributions of organic substance, in form of SCOD, are shown in Fig. 4c and d. It is different that most of SCOD decrease in the bottom of the column, i.e., 0–0.06 m height, which makes a low content and a low flux of the organic in the rest of the column.

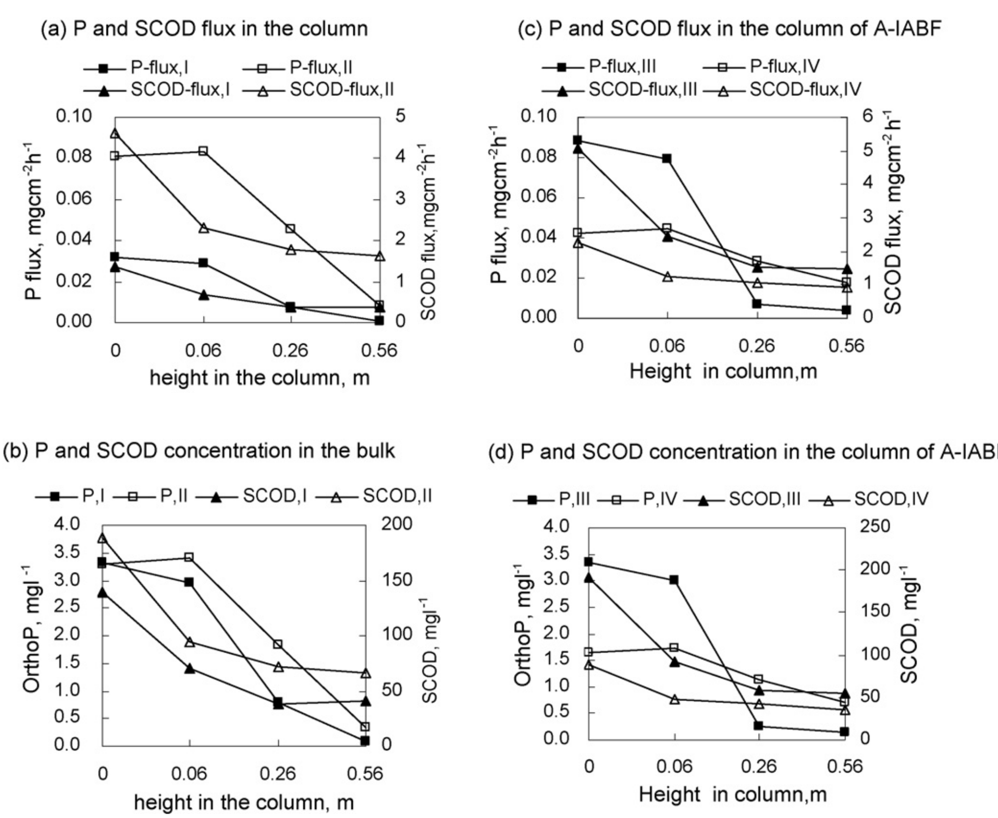

Fig. 5. Distribution of P and SCOD in the bulk under aerobic continuous flow during a backwashing interval. In (a and b), the profile marked with I or II is a presentation of the 8th or 22nd day in the backwashing interval of B-IABF, respectively. In (c and d), the profile marked with III or IV is a presentation of the fifth or 19th in the backwashing interval of A-IABF, respectively. (a) P and SCOD flux in the column of B-IABF, (b) P and SCOD concentration in the column of B-IABF, (c) P and SCOD flux in the column of A-IABF and (d) P and SCOD concentration in the column of A-IABF.

The results indicate that removal of flux of P and SCOD increases with loading of P and SCOD in aerobic continuous feeding in the early part of intervals, and most of flux of P and SCOD is removed in different part of the column.

3.3. P removal during a long backwashing interval

3.3.1. P and SCOD distribution in the bulk

During a long backwashing interval, P distribution in the bulk is illustrated in Fig. 5. Variations in flux and concentration are observed in the 8th and 22nd day in the long interval of B-IABF (Fig. 5a and b). Although P content in effluent of B-IABF increases from 0.08 to 0.35 mg l^{-1} with the increase of P loading, it still meets the most rigorous regulation for pollution control in China. Moreover, P reduction rate in 0.06–0.26 m height increases from 1.05 to 1.93 mg P l^{-1} h^{-1}, and that of in 0.26–0.56 m height grows from 0.226 to 1.22 mg P l^{-1} h^{-1}. P reduction rate grows with aerobic P loading after 22 days operation without wasting, which is shown that biofilm is still active in P storage after the long-term operation. Similar situation is also observed in other intervals in B-IABF as well as in A-IABF. Under the ACF regime, P available in aerobic phase depends on the input of influent of IABF, which is independent of P release in anaerobic phase. The result is shown that P uptake is dependent on P loading in aerobic phase in IABF under the ACF regime.

According to Figs. 4 and 5, P reduction is achieved at the height of 0.06–0.56 m in the column; contribution for the reduction in 0.06–0.26 m height is more than that in 0.26–0.56 m due to the gradient of P concentration and flux in the column. Moreover, SCOD flux is always reduced in large extent in 0–0.06 m height of the column under different operating conditions. As we know, biofilm is a complicated system where many kinds of microorganisms inhabit and compete for substrate and space. Biofilm is a typical system of coexistence of multispecies microorganisms. Many studies focused on the competition between fast growing OHOs and low growing groups,

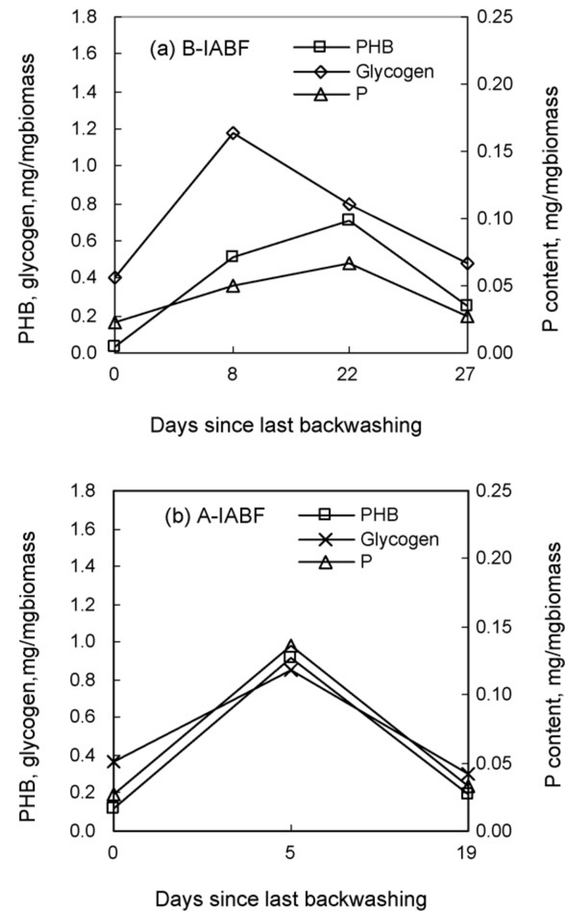

Fig. 6. Intracellular polymers in biofilm at the end of aerobic phase during a long backwashing interval. Biofilm samples are from the 0.56 m height in the column of IABF. '0' in abscissa presents the last day in last backwashing interval.

such as nitrifier, in the submerged biofilter [26–29]. It was shown that the competition of groups resulted in spatial distribution of species in biofilm that was dynamic with operating conditions. In aerobic phase, OHOs take up organic substrate to provide

Table 3
P and organic removal during a long backwashing interval in A-IABF and B-IABF

	B-IABF	A-IABF
Backwashing interval (d)	27	22
Temperature (°C)	23–28	28–30
COD,inf (mg l^{-1})	286(60)	207(36)
COD,eff (mg l^{-1})	84(25)	71(16)
TP,inf (mg l^{-1})	4.40(1.31)	3.39(0.77)
TP,eff (mg l^{-1})	0.32(0.13)	0.49(0.22)
Total organic loading (kg COD m^{-3} d^{-1})	1.76(0.30)	2.17(0.58)
Total P loading (kg P $m^{-3}d^{-1}$)	0.0324(0.0060)	0.0347(0.0080)
Aerobic organic loading (kg COD m^{-3} d^{-1})	1.23(0.29)	1.67(0.59)
Aerobic P loading (kg P m^{-3} d^{-1})	0.0227(0.0060)	0.0275(0.0080)
Aerobic organic removal rate (kg COD m^{-3} d^{-1})	0.95(0.20)	1.16(0.35)
Anaerobic organic removal rate (kg COD m^{-3} d^{-1})	0.248(0.091)	0.239(0.030)
Aerobic P uptake rate (kg P m^{-3} d^{-1})	0.0176(0.0051)	0.0250(0.0063)
P release rate (kg P m^{-3} d^{-1})	0.0097(0.0055)	0.0084(0.0042)
P content in wasting sludge (%TS)	2.5	3.5

a. Concentrations, loadings and rates in interval are expressed in form of average (S.D.), and data in A-IABF and B-IABF is 20 and 12, respectively.
b. Total P or organic loading is a sum of loadings in aerobic and anaerobic phase.
c. Each loading or rate is the real one in one IABF on per volume of filter bed in per day.
d. The interval in A-IABF is from the 7th day in RUN3 to the seventh in RUN5, and the one in B-IABF is from the fifth in RUN2 to the 16th in RUN3.

energy for growth, low growing PAOs utilize PHB stored anaerobically for growth and take up phosphorus from the bulk to recover intracellular polyphosphate pool. The observed phenomena implies that the reduction of P and SCOD in different part of the column possibly attributes to spacial distribution of OHOs and PAOs in IABF, where OHOs accumulate at the entrance of the reactor with high organic concentration and PAOs locate at the 0.26–0.56 m with abundant P source and lower organic.

The situation is a little difference in the longest backwashing interval in A-IABF where it is subjected to a higher organic and P loading (Table 3). In the later of the interval, COD concentration in influent is lower than 200 mg l^{-1}. Flux of P and SCOD in the 19th day is lower than that of the fifth in the interval due to the decrease of concentration of influent, even under the lower HRT (Fig. 5c and d). P reduction rate at 0.26–0.56 m height increases from 0.101 to 0.358 mg P l^{-1} h^{-1}, while that of 0.06–0.26 m decreases from 3.61 to 0.783 mg P l^{-1} h^{-1}. Amount of P removal is decreased and P content in effluent of A-IABF increase from 0.148 to 0.708 mg l^{-1}.

At the condition of low concentration in influent, substrate in anaerobic phase is available in limited manner, which results in lower P release rate and lower storage of carbon source. For long-term operation under low concentration, PHB storage in biological phosphorus removal system would decrease due to the shortage of substrate [30]. Under such condition, P uptake in aerobic phase is dependent on the PHB content [31]. In the deeper part of the column, limited P reduction is possibly due to the lower storage of PHB, and the increase in the upper part is due to growth in P available in the bulk.

Furthermore, average P release rate during the interval of A-IABF is lower than that of B-IABF, while average P uptake rate in A-IABF is higher than that of B-IABF (Table 3). Therefore, P accumulation in biofilm in A-IABF is more than that of B-IABF. That is another important reason for the decrease of P reduction at the later of the interval in A-IABF.

3.3.2. Distribution of intracellular polymers during a long backwashing interval

Analysis on components in biofilm shows that accumulation of intracellular polymers in biofilm is variable in the long backwashing interval in B-IABF (Fig. 6a). The tendency of phosphorus accumulation is the same as that of P reduction in the bulk during the interval. After the long-term operation, backwashing results in detachment of the top layers of the thicker biofilm that offers the advantage of enhanced oxygen- and substrate-supply into the depth of the biofilm and maintains the activity in the biofilm with potential P storage capacity. With the increasing of loading in the interval, variable exposure to substrate promotes the storage of polymers inside of microorganisms, resulting in growing content of PHB and total phosphorus in the biofilm samples. In the later period, extra energy from the accumulated PHB is utilized for growth process. Therefore, content of polymer expressed in per unit of active biomass is reduced due to the growth of active biomass.

At the end of the interval, distribution of polymers in biofilm in the column of B-IABF is observed at the end of aerobic phase. Content of polymers in biofilm is variable with operating conditions in different backwashing interval. Compared with the last backwashing interval in B-IABF, the interval of 27 days is

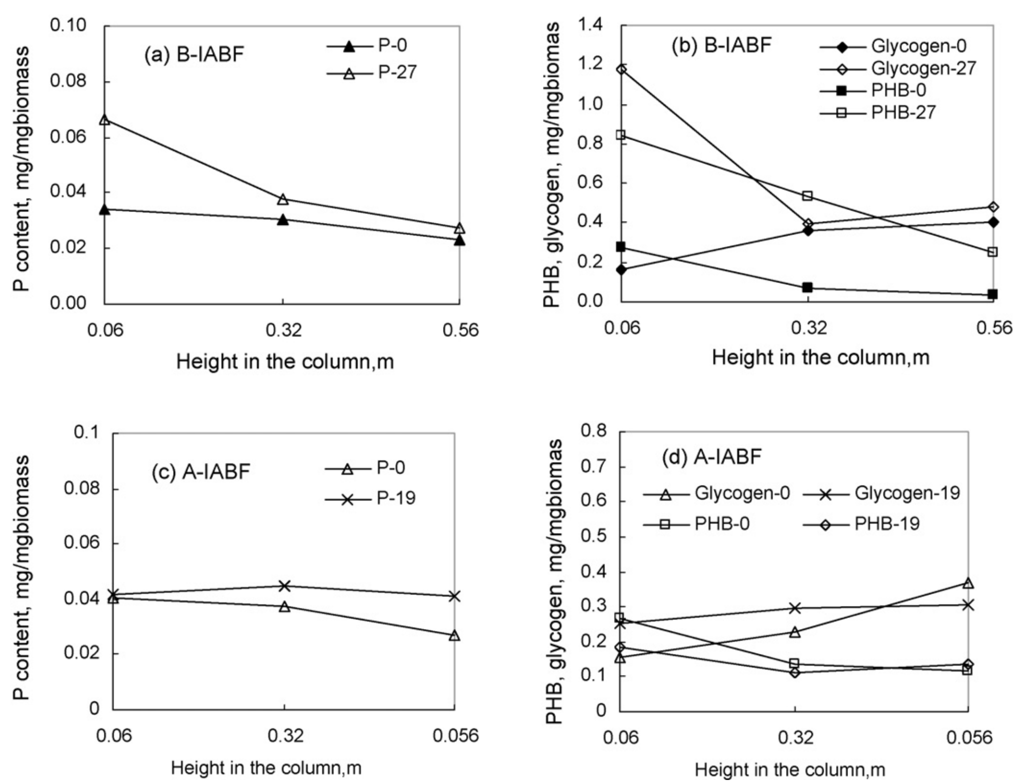

Fig. 7. Distribution of intracellular polymers in biofilm at the end of the backwashing interval. '0' in abscissa presents the last day in last backwashing interval.

operated under higher fluxes condition, and growth of aerobic P loading and P uptake rate is 28% and 22%, respectively. Long-term operation without wasting results in an accumulation of phosphorus in biofilm, especially in the deeper depth in the column where it is subjected to higher flux, as well as PHB and glycogen (Fig. 7a and b).

In A-IABF, contents of polymers in 0.56 m height of the column get down apparently in the 19th under low concentration of influent (Fig. 6b). With similar aerobic P loading and P uptake rate as that in the last backwashing interval, the19 days' continuous operation without wasting results in an accumulation of phosphorus at the middle and upper part of the column of A-IABF (Fig. 7c). Therefore, P reduction rate is decreased in the later of the interval.

Our study shows P accumulation in IABF is a slow process under the ACF regime, and in different extent at different part of the column under variable operating condition. The result indicates that the accumulation of P in biofilm is correlated to length of backwashing interval, loading rate during operating duration and influent condition. As long as P content in the effluent of IABF is under control, long backwashing interval is practicable in IABF under the ACF regime.

It is notable that higher glycogen content in biofilm is observed in B-IABF, in contrast to that of A-IABF at the same depth in the column (Fig. 7b and d). It implies the presence of GAOs in the system and a possible difference in fraction of this group in both reactors.

4. Conclusions

In the combined fixed-film system developed in the study, the ACF regime is applied in IABF, which includes the discharge of P-rich water at the end of anaerobic phase in each cycle as well as continuous feeding in the following aerobic phase. The results indicate that it is efficient for EBPR in the domestic wastewater treatment system. With fluctuations in loadings and hydraulic condition, efficiency of P removal in A-IABF is in a range of 73.3–90.4% in RUNs and 85.2% in average, P content in the effluent of IABF is in a range of 0.32–0.72 mg l^{-1} in RUNs and 0.59 mg l^{-1} in average.

Analysis on P distribution in both the bulk and the biofilm indicates that the PAOs-rich biofilm in IABF is characterized by a high activity, a strong P capacity, and a good adaptability of fluctuations in aerobic loading.

Under the ACF regime, removal of P from IABF carries out regularly in form of phosphate in the bulk, instead of P-rich compounds in solid that is a method in the classical biofilm system for biological phosphorus removal, which slows down accumulation of P in biofilm. As a result, removal of P-rich biomass is no longer a key limitation of the performance of biological phosphorus removal in IABF. It demonstrates that long backwashing interval is practicable in IABF under the ACF regime.

Low frequency of backwashing in IABF can economize energy resources in biofilm domestic wastewater treatment system, reduce energy consumption on backwashing, and minimize production of wasting biomass in backwashing process. The process presents a prospect of potential common application of biofilm system for biological phosphorus removal.

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References

[1] M.A. Garzón-Zúñiga, S. González-Martínez, Biological phosphorus and nitrogen removal in a biofilm sequencing batch reactor, Water Sci. Technol. 34 (1–2) (1996) 293–301.
[2] A. Muñoz-Colunga, S. González-Martínez, Effects of population displacements on biological phosphorus removal in a biofilm SBR, Water Sci. Technol. 34 (1–2) (1996) 303–313.
[3] E. Morgenroth, P.A. Wilderer, Modeling of enhanced biological phosphorus removal in a sequencing batch biofilm reactor, Water Sci. Technol. 37 (4–5) (1998) 583–587.
[4] C. Falkentoft, P. Harremoës, H. Mosbæk, P. Wilderer, Stability of a lab-scale biofilm for simultaneous removal of phosphorus and nitrate, Water Sci. Technol. 43 (1) (2001) 335–342.
[5] A. Gieseke, P. Arnz, R. Amann, A. Schramm, Simultaneous P and N removal in a sequencing batch biofilm reactor: insights from reactor- and microscale investigations, Water Res. 36 (2002) 501–509.
[6] P. Arnz, E. Arnold, P.A. Wilderer, Enhanced biological phosphorus removal in a semi full-scale SBBR, Water Sci. Technol. 43 (3) (2001) 167–174.
[7] D.H. Abeysinghe, A. Shanableh, B. Rigden, Biofilters for water reuse in aquaculture, Water Sci. Technol. 34 (11) (1996) 253–260.
[8] A. Shanableh, D. Abeysinghe, A. Hijazi, Effect of cycle duration on phosphorus and nitrogen transformations in biofilters, Water Res. 31 (1997) 149–153.
[9] A. Shanableh, A. Hijazi, Treatment of simulated aquaculture water using biofilters subjected to aeration/non-aeration cycles, Water Sci. Technol. 38 (8–9) (1998) 223–231.
[10] D. Pak, W. Chang, Factors affecting phosphorus removal in two biofilter system treating wastewater from car-washing facility, Water Sci. Technol. 41 (4–5) (2000) 487–492.
[11] G.R. Franci, F. Rogalla, Biological phosphorus removal in fixed films reactors, Water Sci. Technol. 25 (12) (1992) 165–174.
[12] C.M. Falkentoft, P. Harremoës, H. MosbÆk, The significance of zonation in a denitrifying phosphorus removing biofilm, Water Res. 33 (1999) 3303–3310.
[13] E. Morgenroth, P.A. Wilderer, Controlled biomass removal—the key parameter to achieve enhanced biological phosphorus removal in biofilm systems, Water Sci. Technol. 39 (7) (1999) 33–40.
[14] C.M. Falkentoft, P. Arnz, M. Henze, H. Mosbæk, E. Müller, P.A. Wilderer, P. Harremoës, Possible complication regarding phosphorus removal with a continuous flow biofilm system: diffusion limitation, Biotechnol. Bioeng. 76 (2001) 77–85.
[15] F. Wei (Ed.), Standard Methods for Examination of Water and Wastewater, fourth ed., Chinese Environmental Science Publication, Beijing, 2002, pp. 243–249, 276–281.
[16] Y. He, Anaerobic Biotechnology for Wastewaters, China Light Industry Press, Beijing, 1998, pp. 519–521.
[17] Y. Liu, Q. Zhao, X. Zheng, Biofilm Technology for Wastewaters, China Architecture & Building Press, Beijing, 2000, pp. 99–100.
[18] J.H. Law, R.A. Slepecky, Assay of poly-β-hydroxybutyric acid, J. Bacteriol. 82 (1) (1961) 33–36.
[19] J. Ahn, T. Daidou, S. Tsuneda, A. Hirata, Transformation of phosphorus and relevant intracellular compounds by a phosphorus-accumulating enrichment culture in the presence of both the electron acceptor and electron donor, Biotechnol. Bioeng. 79 (2002) 83–93.
[20] L.O. Torres-Dorante, N. Claassen, B. Steingrobe, H. Olfs, Polyphosphate determination in calcium acetate-lactate (CAL) extracts by an

indirect colorimetric method, J. Plant Nutr. Soil Sci. 167 (2004) 701–703.
[21] R.J. Chiou, K.J.L. Ouyang, S.H. Chuang, The characteristics of phosphorus removal in an anaerobic/aerobic sequential batch biofilter reactor, Water Sci. Technol. 144 (1) (2001) 57–65.
[22] H. Helness, H. Ødegaard, Biological phosphorus removal in a sequencing batch moving bed biofilm reactor, Water Sci. Technol. 40 (4–5) (1999) 161–168.
[23] Z. Tonkovic, Energetics of enhanced biological phosphorus and nitrogen removal processes, Water Sci. Technol. 38 (1) (1998) 177–184.
[24] A. Guisasola, M. Pijuan, J.A. Baeza, J. Carrera, C. Casas, J. Lafuente, Aerobic phosphorus release linked to acetate uptake in bio-P sludge: process modeling using oxygen uptake rate, Biotechnol. Bioeng. 85 (2004) 722–733.
[25] M. Pijuan, A. Guisasola, J.A. Baeza, J. Carrera, C. Casas, J. Lafuente, Aerobic phosphorus release linked to acetate uptake: influence of PAO intracellular storage compounds, Biochem. Eng. J. 26 (2005) 184–190.
[26] S. Okabe, K. Hirata, Y. Watanabe, Dynamic changes in spatial microbial distribution in mixed-population biofilms: experimental results and model simulation, Water Sci. Technol. 32 (8) (1995) 67–74.
[27] F. Fdz-polanco, E. Méndez, M.A. Urueña, S. Villaverde, P.A. García, Spatial distribution of heterotrophs and nitrifiers in a submerged biofilter for nitrification, Water Res. 34 (16) (2000) 4081–4089.
[28] M. Boller, M. Tschui, W. Gujer, Effects of transient nutrient concentrations in tertiary biofilm reactors, Water Sci. Technol. 36 (1) (1997) 101–109.
[29] R. Nogueira, L.F. Melo, U. Purkhold, S. Wuertz, M. Wagner, Nitrifying and heterotrophic population dynamics in biofilm reactors: effects of hydraulic retention time and the presence of organic carbon, Water Res. 36 (2002) 469–481.
[30] C. Lopez, M.N. Pons, E. Morgenroth, Endogenous processes during long-term starvation in activated sludge performing enhanced biological phosphorus removal, Water Res. 40 (8) (2006) 1519–1530.
[31] B. Petersen, H. Temmink, M. Henze, S. Isaacs, Phosphate uptake kinetics in relation to PHB under aerobic conditions, Water Res. 32 (1) (1998) 91–100.