Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.917992

54 (2015) 1098–1108
April

Taylor & Francis
Taylor & Francis Group

Nitrogen and phosphorus removal in a novel extra-loop fluidized bed bioreactor (EFBBR)

Yongsheng Lu[a,b], Christophe Dagot[b,*], Michel Baudu[c]

[a]*School of Environmental and Chemical Engineering, Shanghai University, Shanghai 200444, China, Tel. +86 21 66137748; email: luys7174@shu.edu.cn*
[b]*Groupement de Recherche Eau Sol Environnement, Université de Limoges, ESTER, 16 Rue Atlantis, F-87068 Limoges Cedex, France, Tel. +33 555 423697; email: dagot@ensil.unilim.fr (C. Dagot)*
[c]*Laboratoire des sciences de l'eau et de l'environnement, Université de Limoges, 123 Avenue Albert Thomas, 87000 Limoges, France, Tel. +33 555 457203; email: mbaudu@unilim.fr*

Received 26 January 2014; Accepted 12 April 2014

ABSTRACT

The performance of a novel extra-loop fluidized bed bioreactor (EFBBR) in sequencing batch reactor mode (total 12 h: anaerobic 1.5 h, aerobic 5 h, anoxic 4.5 h, settle 1 h, and idle 1 h) and employing a PVC tube as a carrier medium for the simultaneous carbon, nitrogen, and phosphorus removal from synthetic wastewater is discussed. The EFBBR was operated and the system commissioning and optimization lasted for about 300 d. During the operation, the EFBBR was able to achieve chemical oxygen demand (COD), ammonia nitrogen (NH_4-N), and phosphorus removal efficiencies of 90, 95, and 100%, respectively. The results presented that C/N was insignificant for COD removal. At C/P = 33.2, there were productions including NO_2-N and NO_3-N. However, at C/P = 10.4, nitrification was restrained with TKN/COD from 0.0805 to 0.139, and phosphorus was eliminated completely. The reactor operation can achieve nitrite accumulation successfully. Therefore, the EFBBR is a novel high-powered equipment for carbon and phosphorus removal simultaneously with a shortcut nitrification–denitrification process.

Keywords: Extra-loop fluidized bed bioreactor (EFBBR); SBR; Shortcut nitrification–denitrification process; Phosphorus removal

1. Introduction

Biological wastewater treatment processes are proving to be economical and efficient. Among these available different processes, the fluidized bed bioreactor (FBBR) seems to be the best one with many hydrodynamic and mass transfer advantages [1]. The FBBR outperforms other bioreactor configurations used in wastewater treatment such as:

(1) Very high biomass concentration up to 30–40 kg m^{-3} can be achieved due to immobilization of cells onto or into solid particles.

*Corresponding author.

Presented at the 6th International Conference on the "Challenges in Environmental Science and Engineering" (CESE-2013), 29 October–2 November 2013, Daegu, Korea

(2) The limit on the operating wastewater flow efficiencies imposed by the microbial maximum specific growth rate, as encountered in a continuous stirred-tank bioreactor (CSTR), is eliminated due to the decoupling of the residence time of the liquid phase and the microbial cell growth.
(3) Intimate contact between the liquid and solid phases is achieved.
(4) The use of supporting particles allows the partial replenishment of the fluidized bed without interrupting the operation in order to maintain high microbial activity [2].

The FBBR has attracted considerable interest as an alternative to the conventional wastewater treatment processes due to its high performance efficiency [3]. Some efforts show that the nutrient removals using the FBBR were excellent. The FBBR [4] with aerobic and anaerobic areas for municipal wastewater treatment obtained SCOD, BOD_5, N-TKN, and TN removal efficiencies of 80, 90, 80, and 70%, respectively. The FBBR [5] with sand as the biofilm carrier for the treatment of high-strength nitrate wastewater was used. It was observed that at a loading rate of 6.3 kg N $m^{-3}{}_{bed}$ d^{-1}, almost complete denitrification was achieved with a removal efficiency of 99.8%. Botrous et al. [6] utilized a laboratory-scale fluidized bed reactor with an external aeration loop for nitrification of high-strength ammonium wastewater (up to 500 mg L^{-1} NH_4-N) and demonstrated that the system was capable of handling ammonium removal efficiencies of up to 2.5 kg NH_4-N $m^{-3}d^{-1}$, while removal efficiencies were as high as 98%. Some studies [7] found that two anaerobic inverse fluidized bed reactors evaluated organic matter removal from brewery wastewater and observed COD removal efficiencies greater than 90%. Xing et al. [8] constructed a single continuous flow FBBR system consisting of porous carrier particles for retaining microbes to simultaneously remove carbonaceous and nitrogenous substances in wastewater under different C/N (mass ratio) values. TOC removal of up to 91% and maximum TN removal of 85% were achieved under a moderate C/N value. The model of petroleum-contaminated water in the laboratory FBBR was performed and the biodegradation process was almost completed [9]. The biological nutrient removal from wastewater using a circulating FBBR was innovated in recent years [10–12], and the same novel processes were successfully demonstrated to achieve close-to-effluent quality, as reflected by COD, NH_4-N, NO_3-N, and TP concentrations.

Simultaneous nitrification–denitrification was successfully demonstrated in the FBBR as well. The fluidized bed biofilm nitritation and denitritation reactors (FBBNR and FBBDR) were operated to eliminate the high concentrations of nitrogen by nitritation and denitritation processes [13]. The dissolved oxygen (DO) concentration was varied from 1.5 to 2.5 g m^{-3} at the top of the reactor throughout the experiment. NH_4-N conversion and NO_2-N accumulation in the nitritation reactor effluent were over 90 and 65%, respectively.

On one hand, in the above literature, simultaneous nitrogen and phosphorous removal in FBBR investigated feasibility as well. On the other hand, SBR as a mode for wastewater treatment has wide yields as well. The FBBR [14] working as a sequencing batch reactor (SBR) demonstrated that at the end of this cycle, COD uptake reached 87.1% and phosphorus removal was 50.2%. Other research [15] investigated a fluidized bed with sponge particles surrounded by stainless-steel wires as support particles for synthetic wastewater operating in batch mode, and obtained the kinetics of biological removal of COD and nitrogen. Li et al. [16] developed a biofilm reactor that was operated in an SBR mode employing fibrous carrier media treating artificial sewage at an HRT of 9 h with 90% phosphorous removal. The biodegradation of synthetic wastewater containing 2,4,6-trichlorophenol (TCP) in a sequencing batch-FBBR with waste coke particles as the biofilm carrier was applied [17]. COD removal was then more efficient and faster.

In this study, the extra-loop fluidized bed bioreactor (EFBBR) was utilized with anaerobic, aerobic, and anoxic processes. The sequencing batch operation was selected. The main objective of this study was to evaluate the simultaneous carbon, nitrogen, and phosphorus removal in the system.

2. Materials and methods

2.1. Reactor description

The pilot-scale EFBBR with a working volume of 38 L was established at the ENSIL, Limoges, France. Details of the reactor design and the hydrodynamic characteristics have been given elsewhere [18]. Fig. 1 shows the schematic diagram of the EFBBR. The PVC tubes with an average external diameter of 10.0 mm, internal diameter 8 mm, and density 1,200 mg m^{-3} were used as carrier for biomass attachment (Table 1).

2.2. Operational descriptions

The operating conditions of the pilot-scale EFBBR were controlled by maintaining the liquid recirculation, amount of solids in the columns, and the volume of air injected. The fluidization was realized by controlling the flow of the circulation pump. The Venturi aero-ejector

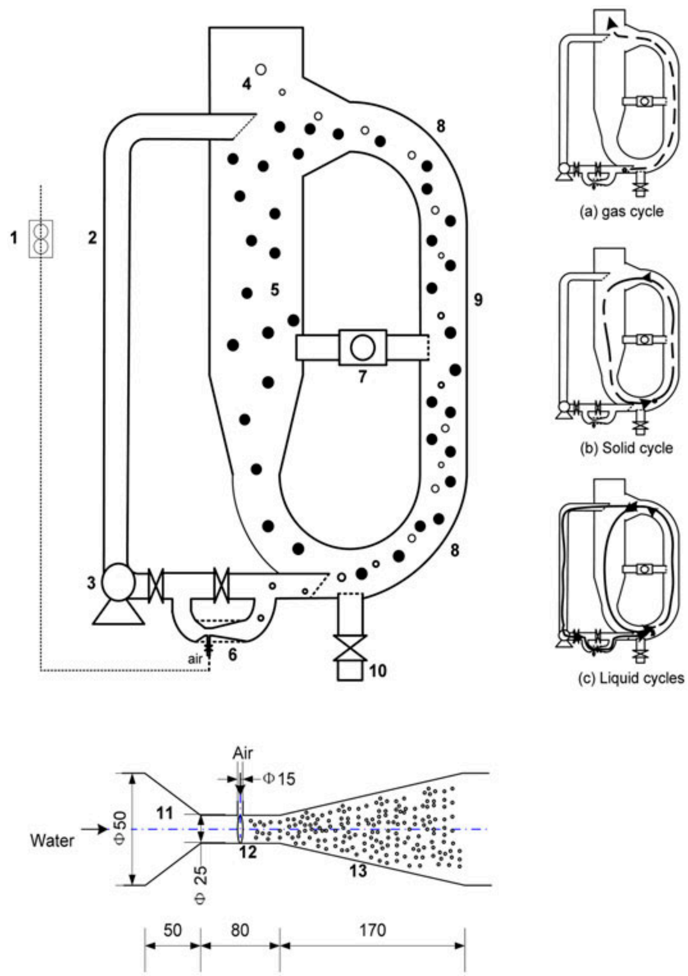

Fig. 1. Schematic diagram of the experimental apparatus.
Note: 1 air flowmeter, 2 circulation pipe, 3 circulation pump, 4 separation zone, 5 downcomer, 6 Venturi aero-ejector, 7 drainpipe, 8 connector, 9 riser, 10 sludge discharge, 11 reducing tube, 12 throat, 13 diffusion tube.

Table 1
Parameters of the EFBBR

Index	
Total height t of EFBBR (m)	2.2
Effective height of riser (m)	1.0
Inner diameters of riser (m)	0.1
Effective height of downcomer (m)	0.8
Inner diameter of downer (m)	0.2
Effective volume (L)	38
Replace the volume (L)	25

was the gas device whose flow was controlled by the circulation pump and the air flowmeter [18].

The system was able to be operated as two types of FBBRs by controlling the flow of the circulation pump and the Venturi aero-ejector. The anaerobic, aerobic, and anoxic processes were used in this work. At different craft stages, the originally systematic reactor had the function of a liquid–solid two-phase fluidized bed and gas–liquid–solid three-phase fluidized bed concurrently. Table 2 shows the operation conditions in detail.

2.3. Synthetic wastewater

The synthetic wastewater used in this study was prepared according to the domestic sewage with some modifications. The pilot-scale EFBBR was fed by a mixture of sugars (containing the powdered milk and glucose) and salts such as NH_4Cl and KH_2PO_4. The trace element concentrations are reported in Table 3. The experimental water temperature was 15–33℃.

2.4. Analysis method

All analyses were performed on grab samples taken from the reactors' influents and effluents, and

Table 2
Operational conditions applied to the process during the whole experiment

Stage	Anaerobic	Aerobic	Anoxic	Settle	Discharge	Idle
Circulation pump	On	On	On	Off	Off	Off
Verturi aero-ejector	Off	On	Off	Off	Off	Off
Cycle	Solid, liquid	Solid, liquid, gas	Solid, liquid	–	–	–
Type of fluidized bed	Two-phase	Three-phase	Two-phase	–		–

Table 3
Trace element concentration

Compounds	Concentration ($mg\ L^{-1}$) for COD = 400 $mg\ L^{-1}$
$CaCO_3$	350
$MgSO_4{\cdot}7H_2O$	21.5
$CaCl_2$	3.2
$FeCl_3{\cdot}6H_2O$	0.22
$MnSO_4{\cdot}H_2O$	1

completed in accordance with standard methods. Samples were withdrawn daily from the reactors and filtered using white filters of 0.45 μm, 47 mm radius. The NH_4-N, NO_3-N, NO_2-N, and PO_4-P were measured by ion chromatography (DIONEX DX-120) performed on 0.22-μm-filtered samples according to the standard method (AFNOR, 2008). And the supports of Dohrmann Phoenix 8000 were used for measuring the TOC concentrations. The COD, total nitrogen (TN), and total phosphorus (TP) were determined using the colorimetric methods (LCK 414, LCK114), LCK338 and LCK 348 with Hach DR2010, respectively. The DO was measured by DO meters (Sonde Orbisphere Modele 3600). The pH was monitored with WTW 320.

2.5. Domestication and biofilm formation

At the start up of the reactor, the pilot-scale EFBBR was seeded simultaneously with about 1,000 g of raw PVC tubes as carrier and the suspended nitrifying sludge (2,000–3,000 $mg\ L^{-1}$ MLVSS) from the wastewater treatment plant of Limoges. The synthetic wastewater was one-off fed into the reactor. The experimental operation was conducted with the constant aerated gas by Venturi aero-ejector. First start-up conditions include: normal temperature (about 20℃), aeration flow 120 L h^{-1}, influent TOC 90.75–233.95 $mg\ L^{-1}$, and operation period 12 h. During the 11 d of continuous operation, the sludge expanded and the effluent qualities were not satisfactory. Some of the sludge escaped following the effluent. The color of carrier surface did not change. By microscopic examination, it was found that the micro-organism was not immobilized on the carrier. Fig. 2 depicts the influent and effluent concentrations of TOC vs. the operation days. TOC removal efficiencies were up to 60%. Compared with the activated sludge process, the biofilm had no effect on nutrient removal. Because of the 12-h operation period, it was beneficial for the activated sludge growth and reproduction. Thereby, sludge captured the nutrients which should be fed to the micro-organisms of the carrier surface making the biofilm formation difficult. Moreover, the expanded sludge also restrained biofilm formation. Based on the activated sludge, which played a dominant function in the reactor, even a few micro-organisms could adhere above the carrier. Biofilm formation cannot be achieved using the weak nutrients.

When the operation period was shortened to 6 h, the start-up process was renewed. After seven days of continuous operation, the color of the carrier changed significantly and the adhesion phenomenon appeared on the carrier surface. By microscopic examination, it was found that the micro-organisms accumulated on the carrier surface, and the color of the biofilm was buff and clear. During the operation, the sludge was not expanded, and the concentration of the sludge

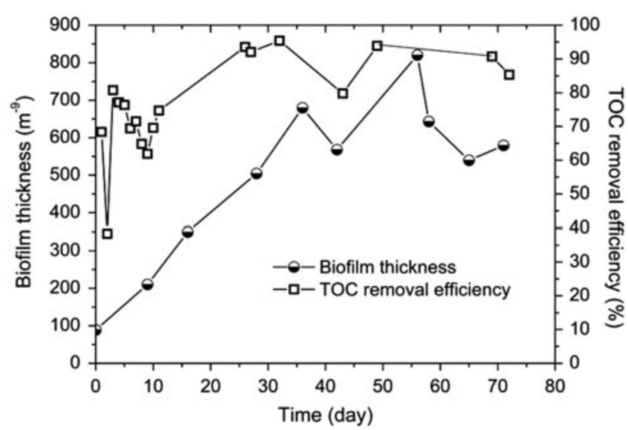

Fig. 2. TOC removal efficiencies and biofilm thicknesses vs. the operation days.

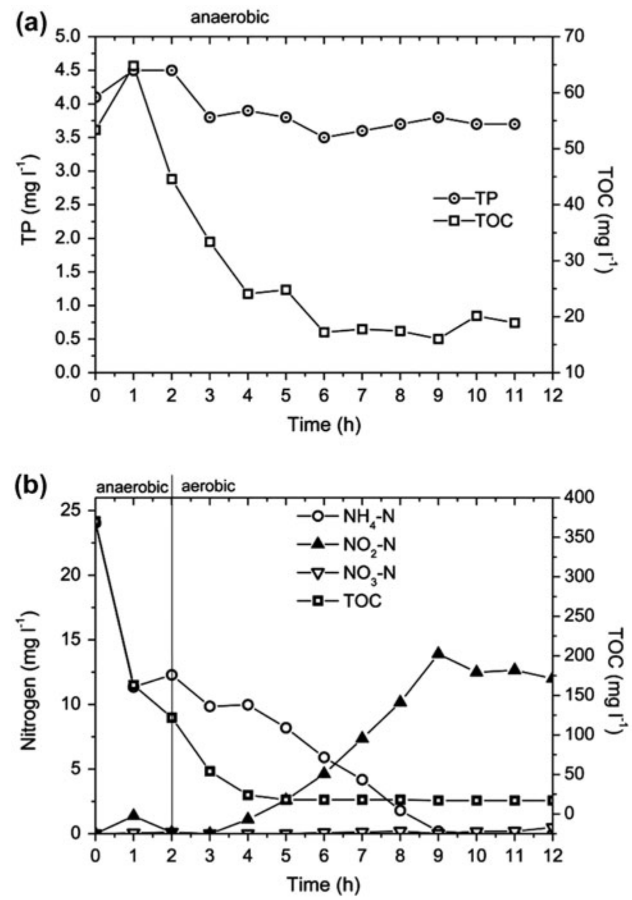

Fig. 3. (a) Phosphorus and (b) Nitrogen concentration changes during anaerobic and/or aerobic period.

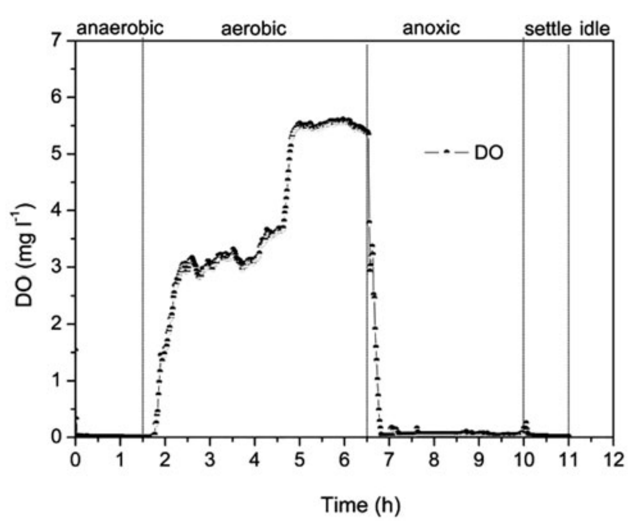

Fig. 4. Oxygen evolution during the SBR process using EF-BBR.

was steadily maintained. Fig. 2 shows biofilm formation versus the operation days.

Afterward, the biofilm formation was steady, and the thickness which adhered to the interior was above 300 μm. Because of the PVC tube structure, the biofilm in the interior was stronger than that in the exterior. When the biofilm formation was obtained, the operation period backed to 12 h, and the biofilm did not fall off. The initial bacterial adhesion was important for the biofilm formation; the exoteric infection was weak when the biofilm was achieved.

3. Results and discussion

3.1. SBR process design

As mentioned above, the aims of the pilot-scale EFBBR were to remove the nitrogen and phosphorus organic pollutants. Anaerobic period played the

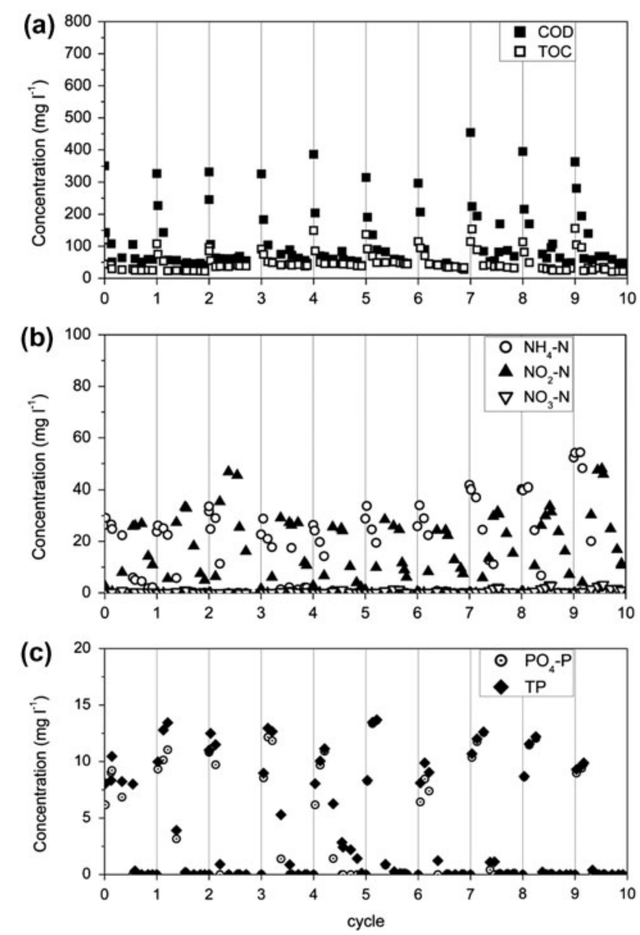

Fig. 5. Nutrient removal using the EFBBR (a) organic removal; (b) nitrogen removal; and (c) phosphorus removal.

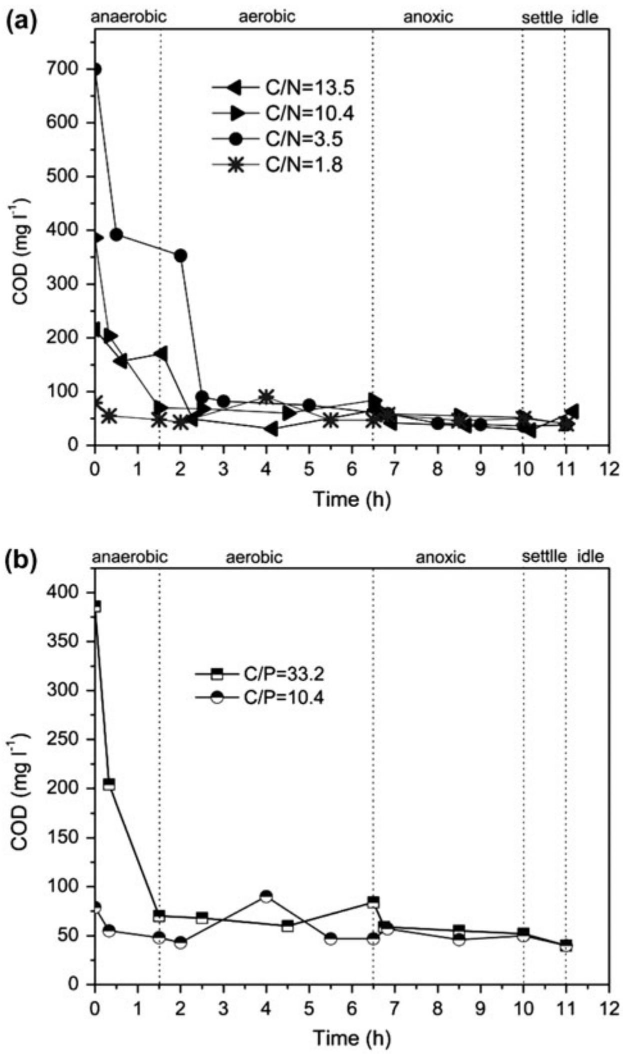

Fig. 6. Effect of different (a) C/N and (b) C/P values on COD removal.

important role in phosphorus removal. Phosphorus release under anaerobic conditions and phosphorus uptake under aerobic conditions were significant. This phenomenon was consistent with the conventional EBPR [19]. Attention must be paid to the phosphorus uptake time and the anaerobic period. During the anaerobic process, when the phosphorus concentration was steady and up to the maximum level, aeration would begin. According to Fig. 3(a), the phosphorus concentration increased at the beginning stage (about 1 h), and the phosphorus accumulated at the maximum level until 2 h. In the subsequent process, the phosphorus concentration decreased to some extent but was steadily maintained.

The nitrification can be obtained by several approaches in the mainstream aerobic reactor [20]. Fig. 3(b) shows the process with 2 h anaerobic and 9 h aerobic stages and describes the NH_4-N, NO_2-N, and NO_3-N concentration curves. NH_4-N decreased continually with a small quantity of NO_2-N and NO_3-N produced in the anaerobic stage. The ammonium oxidation occurred in the anaerobic stage. The main nitrification was obtained during the aerobic stage. NH_4-N was degraded continually until 9 h, NO_2-N accumulation achieved a maximum with 7 h aerobic stage, and the NO_3-N produced was weak nonetheless. Therefore, the short nitrification was accomplished. According to the removal efficiencies, 5-h aerobic stage was accepted for economic reasons.

The anoxic stage was designed for denitrification as well and the total process of nitrogen removal was completed. Thus, the pilot-scale EFBBR whose sequential operation selected had as a base the alternation of phases (1.5 h of anaerobic, 5 h of aerobic, 4.5 h of anoxic, 1 h of settling, and 1 h of idle). At the end of the settling stage, the excess sludge would be discharged for phosphorous removal. The whole process can ensure the treatment of carbon, nitrification, denitrification, and phosphorus removal. In fact, the technology of EFBBR was the biochemical wastewater treatment technology that combined the ordinary activated sludge method and the biofilm method. The flow of recirculation was 7 m^3 h^{-1} and ventilation was assured with a flow of about 2 L min^{-1} if necessary.

Table 4
Effect of different C/P values on denitrification (mg L^{-1})

	Time	Influent	Anaerobic effluent	Aerobic effluent	Anoxic effluent	Effluent
C/P = 33.2	NH_4-N	26.42	19.83	0.00	0.00	0.10
	NO_2-N	2.81	0.22	25.02	4.03	2.31
	NO_3-N	0.23	0.05	1.19	0.12	0.15
	TN	33	25	23	13	9
C/P = 10.4	NH_4-N	11.51	9.88	7.37	7.38	7.35
	NO_2-N	0.00	0.00	0.00	0.00	0.00
	NO_3-N	0.00	0.00	1.61	0.45	0.05
	TN	27.80	31.20	23	14	16.80

According to the hydrodynamic research, the mixing time of the pilot was too short; it belonged to a CSTR. The experimental results also presented the performance of the mass transfer [18]. The DO concentration in the downcomer was slightly less than the riser, but it was still in the range of the aerobic zone. Fig. 4 presents the oxygen evolution during the SBR process using EFBBR. In the anaerobic, anoxic, settle, discharge, and idled stages, the DO concentrations were about 0 mg L^{-1}. The DO concentration was increased by degrees in the whole aerobic stage. And at the end of the aerobic stage, DO can be up to 5.6 mg L^{-1}.

3.2. Nutrient removal

The system commissioning and optimization lasted for about 300 d. Under different initial COD concentrations, the removal results of COD in the influent and effluent are shown in Fig. 5(a). Based on the SBR characteristics of notable anti-impingement capabilities and the EFBBR's high-powered operation, the results showed that during the experimental period, the influence of the initial COD was light, and removal efficiencies of COD were up to 90%.

The performance of the EFBBR for nitrification and denitrification was excellent. Fig. 5(b) presents the temporal variation in influent ammonia and effluent ammonia, nitrates, and nitrites observed during the EFBBR operation. During all the periods, on average, the system achieved up to 95% ammonia removal efficiency, with influent NH_4-N concentrations of 13.8, 34.9, and 44.6 mg L^{-1}, respectively.

Fig. 5(c) depicts the concentrations of PO_4-P and TP in each stage, such as: influent, anaerobic, aerobic, anoxic, and final effluent during the EFBBR for the period of 10 cycles. The performance of EFBBR for phosphorus removal was satisfactory as well.

The wastewater COD and free ammonia (FA) were changed to obtain different C/N values. The results (Fig. 6(a)) demonstrate that different C/N values to wastewater COD removal efficiencies had almost not been influenced and removal efficiencies of COD all kept above 90%. The nitrogen quantity did not exert an obvious influence on the biodegradation of organic compounds. It could be owing to the SBR characteristics of notable anti-impingement capability and the EFBBR's high-powered operation as well.

Schule and Jenkins [21] considered that enhanced biological phosphorus removal (EBPR) in wastewater treatment involves at least two types of bacterial metabolisms: a polyphosphate-accumulating metabolism (PAM) and a glycogen-accumulating metabolism (GAM). Influent phosphorus/COD ratio can affect PAM and GAM on inner-cell energy competition. Punrattanasin [22] investigated the robust EBPR. Specific COD removal efficiencies were met up to 90% at the COD/TP ratios of 20, 30, 40, and 60. In this work, the results demonstrate that different C/P values influence the wastewater COD removal efficiencies

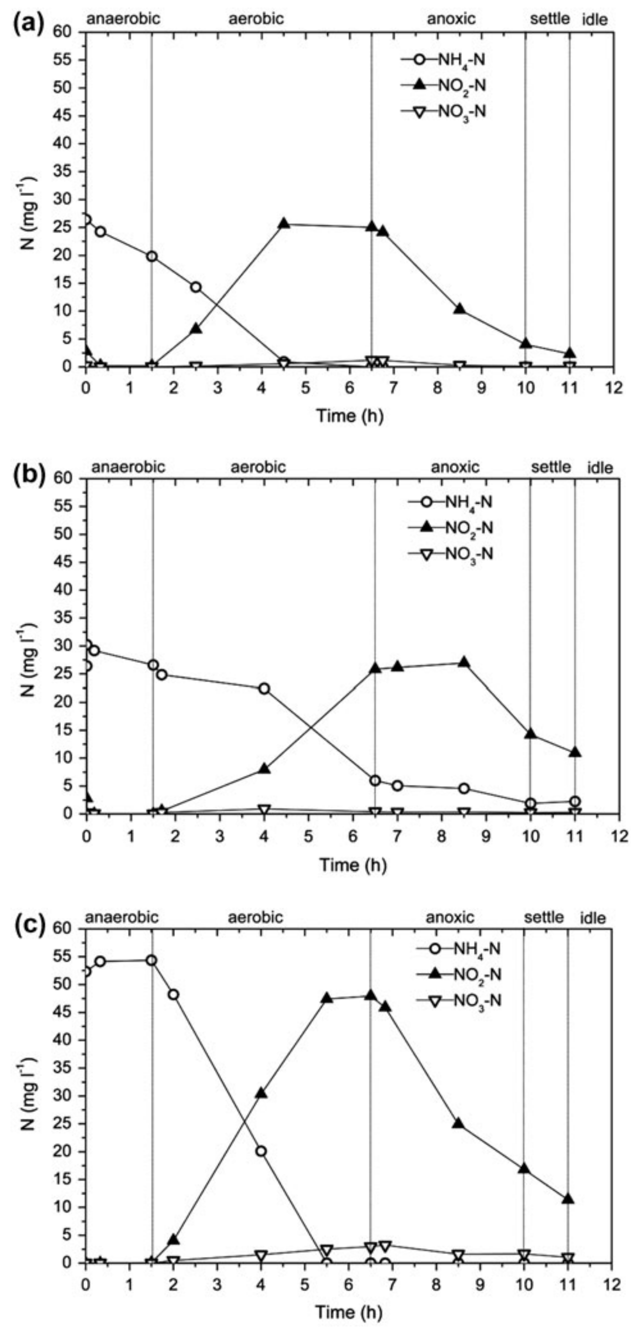

Fig. 7. Effect of the initial NH_4-N on the nitrogen removal rate: (a) pH=7.24, temperature from 19.1 to 27.1℃, max=30.1℃; (b) pH=7.35, temperature from 21.2 to 30.6℃, max=33.0℃; and (c) pH=7.34, temperature from 20.7 to 30.4 ℃, max=33.1℃.

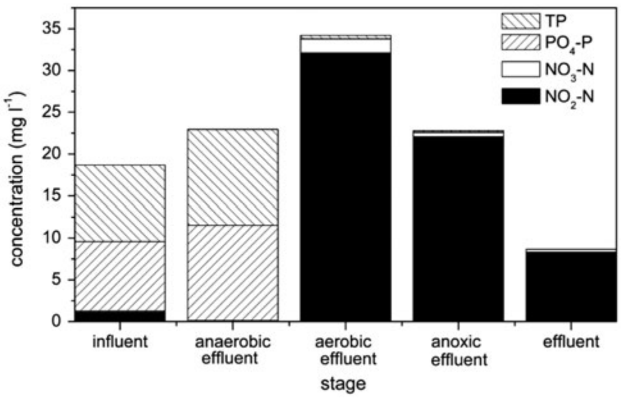

Fig. 8. Effect of NO_3-N, NO_2-N on the phosphorus removal rate.

and the denitrification rates (Fig. 6(b), Table 4). At C/P = 33.2, the COD could be treated quite completely and the removal efficiency was up to 90%. The conclusion was accorded with Punrattanasin's studies; there were the productions including NO_2^--N and NO_3-N. At C/P = 10.4, the COD removal efficiency was only about 32%, and NO_2-N and NO_3-N existed rarely. Therefore, the nitrogen quantity did exert an obvious influence on the denitrification, especially the type of productions.

3.3. Nitrification and denitrification

The removal changes of the NH_4-N were mainly based on the changes in the NH_4-N and COD volume loading. The total variation tendency was improvement in NH_4-N volume loading and a decrease in the removal rate of NH_4-N and TN.

The experimental results of the variations of the nitrogen oxidation components and their concentrations in EFBBR are shown in Fig. 7. The experimental temperature was not controlled and changed by the pump operation within 19.1–33.0℃.

During the anaerobic stage, different initial NH_4-N of influents began to be eliminated with lower NO_2-N and NO_3-N productions. Within the aerobic stage, NH_4-N was continuously eliminated, NO_2-N was produced quickly, but NO_3-N concentration still held on at a lower level. At the end of the aerobic stage, the NH_4-N was transformed to NO_2-N nearly completely. Their transformed efficiencies were above 85%. Similarly, the nitrite accumulation (NO_2-N/NO_x-N) was achieved to about 95%. The results showed that the different initial NH_4-N effects on the process of the products included the nitrosation and nitration. During the whole process, the NO_3-N concentration was weaker than NO_2-N. When the initial NH_4-N concentration was higher, the amount of nitrosation was greater. And the nitrite accumulation efficiency was higher during the aerobic step. The denitrification obviously occurred during the anoxic step, but the initial NH_4-N concentration was lower than that of the denitrification carried on slightly.

According to the traditional nitration theory, in the nitrification process, the efficiency of energy used by nitrite-oxidizing bacteria (NOB) was lower than the ammonia-oxidizing bacteria (AOB). Therefore, there should not be too much NO_2-N accumulation. The reason for nitrite accumulation is possibly that inhibitory action of FA on nitric acid fungus. Anthonisen et al. [23] discovered that FA has the inhibitory action for NOB and AOB, but NOB is more sensitive, and this function may realize at FA concentration only 0.1–1.0 mg L^{-1}. During the process, NH_4Cl was used for synthetic wastewater; the initial FA concentration was less than 0.6 mg L^{-1}.

The effect of the environment transforms on AOB and NOB. Some research discovers that from anaerobic stage to aerobic stage, AOB activity can restore very quickly under the anaerobic/anoxic condition, but NOB restoration of activity needs period of time to be able to be achieved gradually. Therefore, in the initial aerobic stage, nitration speed can lag in nitrosation speed and, the nitrite accumulation was obtained.

Previous research showed that FA can be used to enrich AOB and washout NOB [24,25]. And the most

Table 5
Phosphorus removal under the different TKN/COD

COD (mg L^{-1})	TKN (mgN L^{-1})	TKN/COD	TP (influent) (mg L^{-1})	TP (effluent) (mg L^{-1})
351	48.95	0.139	24.6	0
327	33.95	0.104	30.9	0
332	43	0.129	34.1	0
386	33	0.085	24.9	0
315	35	0.111	25.8	0
297	32.5	0.109	25.1	0

suitable environmental pH in which the AOB grows was 5.8–8.5, the NOB was 6.5–8.5 [26]. Guo et al. [27] found that AOB was the dominant bacterium and NOB could not be recovered with high DO. In this work, the initial FA concentration was less than 0.6 mg L^{-1}, pH was at the range from 7.24 to 7.35, and at the end of the aerobic stage, DO can be up to 5.6 mg L^{-1}. Results showed that AOB was the dominant bacterium. The SBR process followed the nitrite accumulation phenomenon.

The concept of shortcut nitrification–denitrification was presented by Voets et al. [28]. It was a new denitrogenation method developed by Delft University of Technology [29,30]. Based on the results of this work, it can be called shortcut nitrification–denitrification as well.

3.4. Phosphorus removal

Barnard [31] pointed out the necessity of an anaerobic area in the biological phosphorus removal system. The anaerobic habitat already indicates that it does need dissolvable oxygen in the anaerobic stage. Because oxygen is the easiest electronic receptor, if the oxygen exists, and concurrently anaerobic bacteria would not start fermenting and metabolizing and will not produce fatty acid, it will not induce the phosphorus release. On the contrary, in the presence of a small amount of oxygen, the phosphate release rate is inhibited. Generally, DO of in the anaerobic area should be smaller than 0.2 mg L^{-1}. According to Fig. 4(b), the anaerobic time of about 2 h for biological phosphorus accumulation was sufficient.

Similarly DO, NO_3-N, and NO_2-N in the anaerobic area will influence phosphorus removal in two paths: (1) The sour bacterium which produces the acid can use NO_3-N and NO_2-N as the electronic receptor oxidizes the organic ground substance, so the existence of NO_3-N and NO_2-N can inhibit from the ferment and fatty acids volatile. (2) The bacterium utilizes NO_3-N and NO_2-N as the denitrification and consumes the organic ground substance which exchanges biodegradation at the same time, thus competitiveness restrains the anaerobic phosphorus release by the bacterium.

In this work, the nitrosation decreased rapidly during the anoxic step, and the preponderance in the denitrification production had a slight effect on the phosphorus removal. As the synthetic wastewater had no NO_3-N and NO_2-N import, the data were the leftovers of the last cycle with low concentration. The experiment suggested that the concentrations vary at different stages. At the end of the aerobic stage, NO_2-N and NO_3-N achieved accumulation values of 25.02–47.95 mg L^{-1} and 0.40–2.97 mg L^{-1} respectively. During the anoxic-stage operation, phosphorus concentration dropped to zero (Fig. 8). In a word, nitrification and denitrification did not affect phosphorus removal in EFBBR. The EFBBR proved to be novel

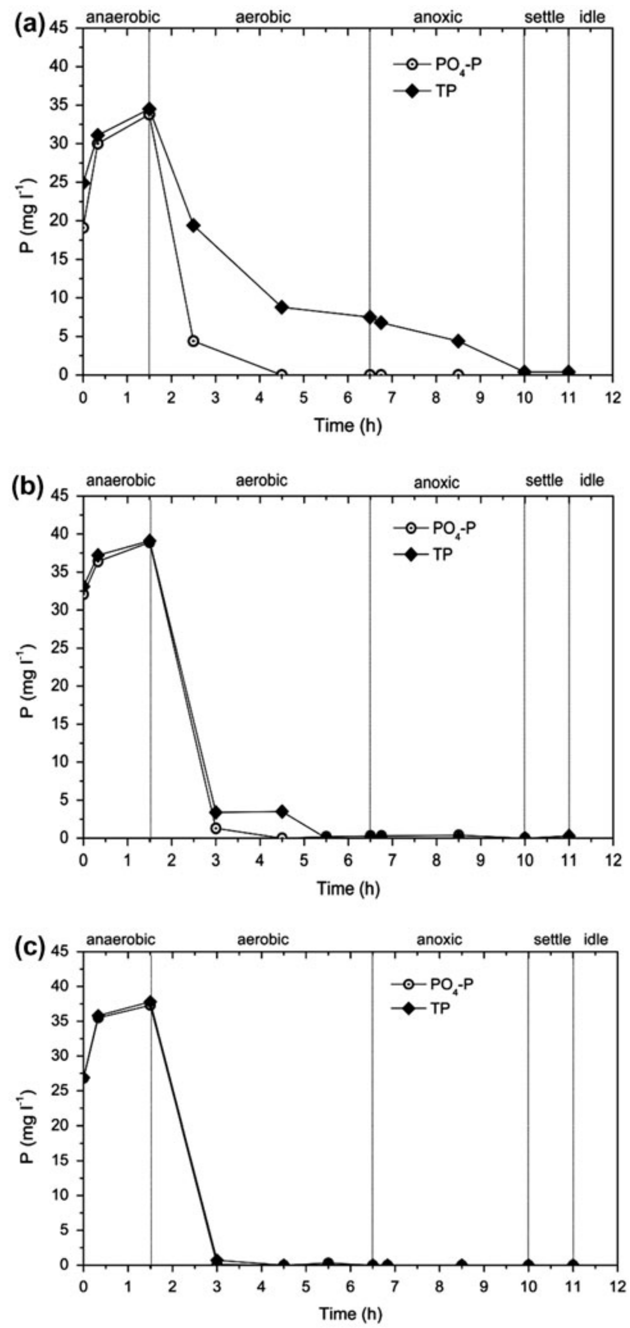

Fig. 9. Effect of temperature on the phosphorus removal (a) 19.1-28.4℃; (b) 20.4-23.6℃; and (c) 21.9-23.1℃.

high-powered equipment for simultaneous nitrification, denitrification, and phosphorus removal.

Another factor in phosphorus release was the influent organic compound density. We found (Table 5) that influent TKN/COD < 0.1 was helpful to biological phosphorus removal. At TKN/COD < 0.08 in Phoredox process, phosphorus was eliminated effectively; at 0.14, even if UCT process eliminated phosphorus, the result was not good. When TKN/COD = 0.14, the phosphorus removal efficiency was still better in external nitrification biological nutrient removal activated sludge (ENBNRAS) system [32]. In the work, TKN/COD from 0.0805 to 0.139, the phosphorus was eliminated completely.

Temperature has relatively light influence on the growth of phosphorus accumulating bacteria. Temperature influence on the phosphorus removal was to influence the sour production of the fermented fungus mainly. The data of Fig. 9 suggest that significant phosphorus release occurred across the anaerobic stage even though the actual increment in the PO4-P concentration was accumulated 15–77% unequally. In addition, in order to reach the denitrification at the same time, it was necessary to reduce the load and lengthen sludge age.

The similar liquid–solid circulating fluidized bed bioreactor (LSCFB) was used for nutrient removal from municipal wastewater [33]. Approximately, 85% phosphorous removal was observed without adding any chemicals. The LCSFB with a riser-anoxic zone and a downer-aerobic zone operated in continuous flow mode. Compared with the results, it could be found that in this study, the EFBBR with anaerobic, aerobic, and anoxic processes operated in SBR mode and phosphorous was eliminated completely. The SBR mode with the additional anaerobic stage could enhance the phosphorous removal efficiency.

4. Conclusions

A novel EFBBR employing the SBR mode (anaerobic 1.5 h, aerobic 5 h, anoxic 4.5 h, settle 1 h, and idle 1 h) was used to achieve close-to-excellent effluent quality, as reflected by COD, NH_4-N, PO_4-P, and TP removal efficiencies, respectively.

The performance of the EFBBR for simultaneous removal of carbon, nitrogen, and phosphorus was excellent. During the operation, the EFBBR was able to achieve COD, total NH_4-N, and P removal efficiencies of 90, 95, and 100%, respectively. Similarly, the nitrite accumulation was achieved to about 95%. The reactor operation can realize the nitrite accumulation successfully. The results showed that C/N was insignificant for COD removal. At C/P = 33.2, production included NO_2-N and NO_3-N. However, at C/P = 10.4, nitrification was restrained. When TKN/COD was from 0.0805 to 0.139, the phosphorus was purified completely.

Acknowledgments

This work was financially supported by the Foundation social européen, République Française. We also would like to express our gratitude to Groupement de Recherche Eau Sol Environnement (GRESE), France.

References

[1] J. Reese, E.M. Silva, S.T. Yang, L.S. Fan, Industrial applications of three phase fluidization systems, in: W.-C. Yang (Ed.), Fluidization, Solids Handling and Processing, William Andrew Publication, Westwood, NJ, 1999, pp. 583–682.

[2] T.L. Boumehdi, M. Fedailaine, K. Allia, Modelling three-phase fluidized bed bioreactor for wastewater treatment, Int. J. Chem. Reactor Eng. 6 (2008) 1–13. A11.

[3] A. Patel, J. Zhu, G. Nakhla, Simultaneous carbon, nitrogen and phosphorous removal from municipal wastewater in a circulating fluidized bed bioreactor, Chemosphere 65 (2006) 1103–1112.

[4] F. Fdez-Polanco, F.J. Real, P.A. Garcia, Behaviour of an anaerobic/aerobic pilot scale fluidized bed for the simultaneous removal of carbon and nitrogen, Water Sci. Technol. 29 (1994) 339–346.

[5] F.K. J. Rabah, M.F. Dahab, Nitrate removal characteristics of high performance fluidized-bed biofilm reactors, Water Res. 38 (2004) 3719–3728.

[6] A.E. Botrous, M.F. Dahab, P. Miháltz, Nitrification of high-strength ammonium wastewater by a fluidized-bed reactor, Water Sci. Technol. 49 (2004) 65–71.

[7] A. Alvarado-Lassman, E. Rustrián, M.A. García-Alvarado, G.C. Rodríguez-Jiménez, E. Houbron, Brewery wastewater treatment using anaerobic inverse fluidized bed reactors, Bioresour. Technol. 99 (2008) 3009–3015.

[8] X.H. Xing, B.H. Jun, M. Yanagida, Y. Tanji, H. Unno, Effect of C/N values on microbial simultaneous removal of carbonaceous and nitrogenous substances in wastewater by single continuous-flow fluidized-bed bioreactor containing porous carrier particles, Biochem. Eng. J. 5 (2000) 29–37.

[9] M.S. Kuyukina, I.B. Ivshina, M.K. Serebrennikova, A.B. Krivorutchko, E.A. Podorozhko, R.V. Ivanov, V.I. Lozinsky, Petroleum-contaminated water treatment in a fluidized-bed bioreactor with immobilized *Rhodococcus* cells, Int. Biodeterior. Biodegrad. 63 (2009) 427–432.

[10] A. Eldyasti, G. Nakhla, J. Zhu, Impact of calcium on biofilm morphology, structure, detachment and performance in denitrifying fluidized bed bioreactors (DFBBRs), Chem. Eng. J. 232 (2013) 183–195.

[11] A. Eldyasti, G. Nakhla, J. Zhu, Development of a calibration protocol and identification of the most sensitive parameters for the particulate biofilm models used in biological wastewater treatment, Bioresour. Technol. 111 (2012) 111–121.
[12] M. Li, G. Nakhla, J. Zhu, Impact of worm predation on pseudo-steady-state of the circulating fluidized bed biofilm reactor, Bioresour. Technol. 128 (2013) 281–289.
[13] S. Aslan, M. Dahab, Nitritation and denitritation of ammonium-rich wastewater using fluidized-bed biofilm reactors, J. Hazard. Mater. 156 (2008) 56–63.
[14] M. Rovatti, C. Nicolella, A. Converti, R. Ghigliazza, R. Di Felice, Phosphorus removal in fluidized bed biological reactor (FBBR), Water Res. 29 (1995) 2627–2634.
[15] F. Kargi, A. Uygur, H.S. Başkaya, Phosphate uptake and release rates with different carbon sources in biological nutrient removal using a SBR, J. Environ. Mange. 76 (2005) 71–75.
[16] J. Li, X.H. Xing, B.Z. Wang, Characteristics of phosphorus removal from wastewater by biofilm sequencing batch reactor (SBR), Biochem. Eng. J. 16 (2003) 279–285.
[17] F.M. Hu, H.H. Zhou, Z.F. Jin, Q. Sun, Z.Y. Pan, J. Zhu, Biodegradation of TCP in a sequencing batch-fluidized bed bioreactor with waste coke particles as the carrier, J. Environ. Eng. 139 (2013) 1222–1227.
[18] Y.S. Lu, C. Dagot, M. Baudu, J. Laurent, L.X. Hu, Hydrodynamics and oxygen transfer in a novel extra-loop fluidized bed bioreactor, J. Shanghai Univ. 14 (2010) 266–274.
[19] R.J. Chiou, Y.R. Yang, An evaluation of the phosphorus storage capacity of an anaerobic/aerobic sequential batch biofilm reactor, Bioresour. Technol. 99 (2008) 4408–4413.
[20] S. Salem, D.H.J.G. Berends, J.J. Heijnen, M.C.M. Van Loosdrecht, Bio-augmentation by nitrification with return sludge, Water Res. 37 (2003) 1794–1804.
[21] A.J. Schuler, D. Jenkins, Enhanced biological phosphorus removal from wastewater by biomass with different phosphorus contents, Part I: Experimental results and comparison with metabolic models, Water Environ. Res. 75 (2003) 485–498.
[22] W. Punrattanasin, Investigation of the Effects of COD/TP Ratio on the Performance of a Biological Nutrient Removal System: [dissertation], Virginia Polytechnic Institute and State University, Virginia, VA, 1997.
[23] A.C. Anthonisen, R.C. Loehr, T.B. Prakasam, E.G. Srinath, Inhibition of nitrification by ammonia and nitrous acid, J. Water Pollut. Control Fed. 48 (1976) 835–852.
[24] J.A. Torà, J. Lafuente, J.A. Baeza, J. Carrera, Combined effect of inorganic carbon limitation and inhibition by free ammonia and free nitrous acid on ammonia oxidizing bacteria, Bioresour. Technol. 101 (2010) 6051–6058.
[25] I. Jubany, J. Lafuente, J.A. Baeza, J. Carrera, Total and stable washout of nitrite oxidizing bacteria from a nitrifying continuous activated sludge system using automatic control based on oxygen uptake rate measurements, Water Res. 43 (2009) 2761–2772.
[26] U. Wiesmcmn, I.S. Choi, E.M. Dombrowski, Fundamentals of Biological Wastewater Treatment, Wiley-VCH, Weinheim, 2007.
[27] J.H. Guo, Y.Z. Peng, S.Y. Wang, Y.N. Zheng, H.J. Huang, Z.W. Wang, Long-term effect of dissolved oxygen on partial nitrification performance and microbial community structure, Bioresour. Technol. 100 (2009) 2796–2802.
[28] J.P. Voets, P. Meerschman, W. Verstraete, Soil microbiological and biochemical effects of long-term atrazine applications, Soil Biol. Biochem. 6 (1974) 149–152.
[29] M.S.M. Jeeten, S.J. Horn, M.C.M. van Loosdrecht, Towards a more sustainable municipal wastewater treatment system, Water Sci. Technol. 35 (1997) 178–180.
[30] W. Verstraete, S. Philips, Nitrification–denitrification processes and technologies in new contexts, Environ. Pollut. 102 (1998) 717–726.
[31] J.L. Barnard, A review of biological phosphorus removal in the activated sludge process, Water SA 2 (1976) 136–144.
[32] Z.R. Hu, S. Sötemann, R. Moodley, M.C. Wentzel, G.A. Ekama, Experimental investigation of the external nitrification biological nutrient removal activated sludge (ENBNRAS) system, Biotechnol. Bioeng. 83 (2003) 260–273.
[33] N. Chowdhury, J. Zhu, G. Nakhla, A. Patel, M. Islam, A novel liquid–solid circulating fluidized-bed bioreactor for biological nutrient removal from municipal wastewater, Chem. Eng. Technol. 32 (2009) 364–372.