Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25093

181 (2020) 197–203
March

Comparative analysis of the phosphorus removal characteristics between two-stage and single-stage SBR processes for phosphorus and nitrogen removal

Hongyan Li[a,b], Lei Bai[a,b], Beisheng Long[a,b,*], Hua Kang[a,b], Hongbo Liu[a,b], Shuping Wang[a,b], Xi Nie[a,b]

[a]*School of Water Conservancy and Environment Engineering, Changchun Institute of Technology, Changchun 130012, China, Tel. +86 13086842918; email: 345914799@QQ.com (B. Long), Tel. +86 15844056686; email: 563-li@163.com (H. Li), Tel. +86 18347635264; email: 248734150@QQ.com (L. Bai), Tel. +86 15948390385; email: 156252439@QQ.com (H. Kang), Tel. +86 13944801938; email: 61244588@QQ.com (H. Liu), Tel. +86 15526639671; email: 820036423@QQ.com (S. Wang), Tel. +86 13578909329; email: 793100379@QQ.com (X. Nie)*
[b]*Jilin Provincial Key Laboratory of Municipal Wastewater Treatment, Changchun institute of Technology, Changchun 130012, China*

Received 1 May 2019; Accepted 30 October 2019

ABSTRACT

Under normal temperature and sufficient carbon source conditions, with simulated sewage as the treatment object, the characteristics, and advantages of phosphorus removal in the two-stage sequencing batch reactor (SBR) dephosphorization and denitrification process were investigated through comparative analysis. The phosphorus removal characteristics of the single-stage enhanced biological phosphorus removal-sequencing batch reactor (EBPR-SBR) were also discussed. Results showed that the phosphorus removal grade SBR1 of the two-stage SBR phosphorus removal and denitrification system has similar anaerobic phosphorus release and aerobic phosphorus uptake processes to the single-stage SBR. However, the phosphorus removal efficiency of the SBR1 system with low sludge age and high organic load is higher than that of the single-stage SBR system. The rate of specific phosphorus release of the fast phosphorus-releasing segment (0–0.5 h) and the rate of specific phosphorus absorption of the fast phosphorus-absorbing segment (0–1 h) of the SBR1 system are 1.43 and 1.79 times higher than those of the single-stage SBR system, respectively. The effluent total phosphorus (TP) of the single-stage EBPR-SBR system can be no higher than 1.0 mg/L but not 0.5 mg/L. Phosphorus release occurs in polyphosphate-accumulating organisms at the beginning of EBPR-SBR system sedimentation, and the rate of phosphorus release increases over time. The rate of phosphorus release is constant after 40 min of sedimentation. The average rate of phosphorus release is 0.0138 mg P/L min. The final effluent TP of the two-stage SBR phosphorus removal and denitrification system may not be affected by the fluctuation of the effluent phosphorus concentration of the phosphorus removal grade SBR1. Thus, the TP can be easily and stably kept equal to or lower than 0.5 mg/L.

Keywords: Two-stage SBR; Single-stage SBR; Phosphorus-rich sludge; Phosphorus release; EBPR; Sedimentation time

1. Introduction

In light of the increasingly stringent sewage discharge standard, the principal contradiction concerning urban sewage treatment has shifted from the removal of organic pollutants to that of nitrogen and phosphorus pollutants. Biological phosphorus and nitrogen removal remains the most economical, effective, and widely applied sewage treatment technology at present. However, the corresponding biological phosphorus and nitrogen removal techniques extensively

* Corresponding author.

used in engineering practice are inherently problematic in such aspects as incompatible sludge ages between nitrifying bacteria and polyphosphate-accumulating organisms (PAOs), competition for carbon source in denitrification and phosphorous release, and effect of the nitrate component in the anaerobic zone on phosphorous removal, making it difficult for the system to remove phosphorus and nitrogen effectively at the same time [1–5]. Moreover, the effluent total phosphorus (TP) of the enhanced biological phosphorus removal (EBPR) system fails to meet the first-level A standard of the existing national standard (GB18918-2002; that is, TP ≤ 0.5 mg/L) because of the phosphorus release effect of phosphorus-rich sludge and inevitable existence of a small amount of phosphorus-rich sludge particles in the effluent [6]. After comprehensively analyzing the status quo of the phosphorus and nitrogen removal process and related problems at home and abroad, the present study considered the environmental protection requirements of biological phosphorus and nitrogen removal, as well as the flexible operating characteristics of the sequencing batch reactor (SBR) process, and proposed the serial and multistage phosphorus and nitrogen removal mode of a two-stage SBR, which was proven to be effective in processing PAOs and nitrifying bacteria in two separate reactors by controlling the sludge age. This analysis provides a solution to the contradiction between phosphorus and nitrogen removal. The procedures targeting phosphorus, organics, and nitrogen removal are optimized. To achieve better effluent quality, the phosphorus and nitrogen removal efficiency of the two-stage SBR process is increased by a factor compared with the traditional single-stage SBR. The effluent TP of the novel system can be stabilized at <0.5 mg/L. This study adopted comparative analysis to investigate the phosphorus removal characteristics and strengths of the two-stage SBR phosphorus and nitrogen removal process. The phosphorus removal characteristics of the single-stage enhanced biological phosphorus removal-sequencing batch reactor (EBPR-SBR) were also discussed.

2. Materials and methods

2.1. Experimental device

The experiment involved two SBR systems, namely, single-stage and two-stage. Three identical SBRs made of a polymethyl methacrylate, which were shaped like a cylinder upper part and a circular truncated cone lower part. The total height of the reactor was 55 cm and the inner diameter of the cylinder was 19 cm. The effective volume of the reactors was 12 L. In addition to a small abrasive sandy head installed as a microporous aerator for aeration, the reactors were provided with small air pumps for oxygenation and blending, as well as temperature-controlling devices.

2.2. Experimental water and methods for water quality analysis

The experimental water was artificially synthesized sewage, with its alkalinity and pH adjusted by the addition of $NaHCO_3$ and its N and P contents adjusted by the addition of quantified NH_4Cl and KH_2PO_4. To determine how the concentration and biochemistry of organics in effluent affect them separately and optimally cultured heterotrophic PAOs and autotrophic nitrifying bacteria, two kinds of artificially synthesized sewage were selected. The conditions of the selected sewage are provided in Table 1.

In Table 1, "Sewage 1" has a chemical oxygen demand (COD) that is nearly equal to that of urban swage with a moderate to high concentration [7], in which soluble starch and peptone are macromolecular organics with a low biodegradation rate. In "Sewage 2", one of the major constituents is NaAc. "Sewage 2" is biochemically superior to "Sewage 1", and its COD is equal to that of urban sewage with a moderate to low concentration [7].

Methods for water quality analysis: Nitrate nitrogen was analyzed by the thymol crystal spectrophotometry method, COD was assessed by potassium dichromate compressed digestion method, and other indicators were examined by national standard methods [8].

2.3. System startup

During system startup, the sludge inoculated in the three SBRs of both single-stage and two-stage systems were a mixture of settled sludge in the aeration tank of Changchun FAW Sewage Treatment Plant and some anaerobic sediment mud from Nanhu Lake of Changchun. In the reactors, the water filling ratios were set as 0.5. The system temperature was kept at 23°C to 25°C.

For the single-stage SBR, "Sewage 1" in Table 1 was adopted as influent and introduced to undergo nitrogen and phosphorous removal. The practical operation involved the following procedures: short-term sewage influent/anaerobic stirring/aerobic aeration/hypoxic stirring with added methanol solution/short-term aeration/precipitation, sludge discharge, water discharge, and idleness. The sludge

Table 1
Test water quality

Item	Major components	COD/ (mg/L)	TN/ (mg/L)	NH_4^+–N/ (mg/L)	NO_3^-–N/ (mg/L)	TP/ (mg/L)	pH
Sewage 1	With soluble starch, peptone and beef extract as the major constituents (at a mass ratio of 3:1.25:1), added with a little nutritive salt	480~640	80~102	65~86	»0	6.5~11.9	7.3~8.0
Sewage 2	With NaAc and soluble starch as the major constituents (at a mass ratio of 1.34:1), added with a little beef extract and nutritive salt	330~430	26~113	25~110	»0	7.0~18.0	7.5~8.2

concentration (MLSS) was maintained at 4,200–4,400 mg/L and the sludge age was approximately 15 d in the system. Alkalinity and carbon source sufficiency were guaranteed in the nitration and denitrification sections, respectively. The time for anaerobic stirring, aerobic aeration, and hypoxic stirring was regulated in a real-time manner based on the tested experimental data. Aeration quantity was adjusted as necessary. One to two cycles were operated every day. As the number of acclimatization cycles increased, the nitrogen and phosphorus removal performance of the system was improved. When the system was stabilized, the color of the sludge in the reactors changed from ash black at the beginning of acclimatization to brownish-yellow.

The two-stage phosphorus and nitrogen removal system is composed of two SBRs (SBR1 and SBR2, or S1 and S2) connected in series. One operating cycle is illustrated in Fig. 1.

With "Sewage 1" in Table 1 also adopted as influent, S1 worked at high load but low sludge age. The slow-growing autotrophic nitrobacteria were inhibited and eliminated so that PAOs became the dominant bacteria in the system and constituted the phosphorus removal stage of the system. The actual practice includes the following procedures: short-term sewage influent/anaerobic stirring/aerobic aeration/precipitation, sludge discharge, water discharge, and idleness. The MLSS of the system was maintained at 3,100–3,500 mg/L and the sludge age was 5–7 d. The quality of both influent and effluent was inspected weekly. The anaerobic stirring time and aeration quantity and time in the aerobic section were adjusted as necessary. Two to three cycles were operated every day. As the number of acclimatization cycles increased, PO_4^{3-}–P in outlet water gradually decreased, but NO_x^-–N remained approximately zero. After the system was stabilized, the color of the sludge in the reactors changed from ash black at the beginning of acclimatization to brownish-yellow.

S2 treated the effluent from S1. The system operated at low load and high sludge age. Nitrobacteria and denitrifying bacteria were cultivated as the dominant bacterial flora that constituted the nitrogen removal stage. The system operation involved the following procedures: short-term influent and stirring/aerobic aeration/anaerobic stirring with added methanol solution/short-term aeration/precipitation, water discharge, and idleness. Alkalinity and carbon source sufficiency were guaranteed in the nitration and denitrification sections, respectively. During system operation, no sludge was discharged. Aerobic aeration and hypoxic stirring time were adjusted based on the tested experimental data, whereas aeration quantity was adjusted as necessary. Two to three cycles were operated every day. As the number of acclimatization cycles increased, the nitrification and denitrification rates of the system were slowly improved. After the system was stabilized, the MLSS in the reactor was 7,000–7,300 mg/L and the color of the sludge changed from ash black at the beginning of acclimatization to brownish-yellow. Computed as per the sludge quantity discharged from the system in everyday water samples, the sludge age of the system was >50 d.

The experimental results showed that, when "Sewage 1" and "Sewage 2" in Table 1 were selected for the experiment, the sludge age of the phosphorus removal stage (S1) was approximately 5–7 d, whereas that of the nitrogen removal stage (S2) was >50 d. In both stages, heterotrophic PAOs and autotrophic nitrobacteria were maintained in two reactors to ensure overwhelming growth to improve phosphorus removal and denitrification, respectively. The main difference between the two stages is that, when "Sewage 2" with better biochemical properties was adopted as the influent, S1 had a significantly higher phosphorus-removing load. Under the same operating conditions (water filling ratios >0.5 in both cases) and PO_4^{3-}–P removal rate >95%, the average influent load of phosphorus increased from 29.87 g P/m^3 d when "Sewage 1" was adopted as the influent to 52.51 g P/m^3 d. The phosphorus removal properties of the single-stage and two-stage systems were compared based on the typical periodic experimental results.

3. Results and discussion

3.1. Comparison and analysis of the phosphorus removal efficiency

The typical periodic test results of the phosphorus removal procedure in single-stage SBR and two-stage S1 with "Sewage 1" as the water inlet after the system operation became stable are provided in Tables 2 and 3. As shown in Table 2, for the periodic effluent, the COD is 510.1 mg/L, total nitrogen (TN) is 87.3 mg/L, NH_4^+–N is 60.6 mg/L, TP is 10.1 mg/L, initial value of MLSS in the reactor is 4,360 mg/L, and sludge age is approximately 15 d (no TN in the table). The periodic operation process is as follows: The short-term and centralized influent (for 2–3 min, including stirring and water sampling) is followed by the 180 min anaerobic period, 422 min aerobic period (with TP is being 0.42 mg/L when the aerobic period lasted 120 min; as nitrification was necessary, aeration was prolonged), and 150 min hypoxic stirring (no experimental data about the hypoxic process in the table). The COD load of the influent is 0.61 kg/m^3 d. The influence in Table 3 has nearly the same water quality as that in Table 2, with the COD being 540.0 mg/L, NH is being 86.0 mg/L

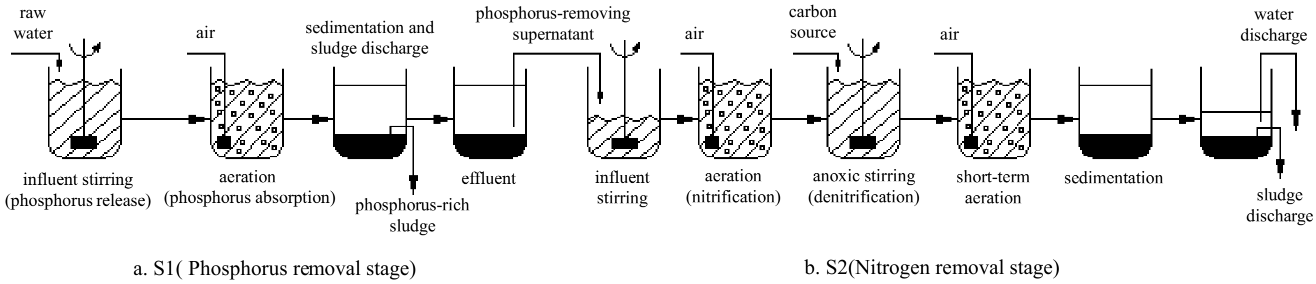

Fig. 1. Operation process of two-stage SBR in a cycle.

Table 2
Experimental results of single-stage SBR in a typical cycle

Indicator/ (mg/L)	Anaerobic stirring period/min							Aerobiotic aeration period/min										
	0	30	60	90	120	150	180	0	30	60	90	120	170	220	270	321	370	422
COD	218.2	92.1	80.3	73.0	62.4	57.1	53.9	53.9	43.5	35.9	33.5	32.5	31.5	31.2	30.7	30.5	30.5	30.4
TP	8.86	19.3	21	22.0	22.2	22.4	23.0	23.0	13.7	8.21	2.61	0.42	–	–	–	–	–	–
NH_4^+–N	33.5	34.8	34.3	35.0	36.1	36.0	35.0	35.0	34.8	34.2	33.2	30.7	27.7	22.5	17.3	12.3	8.84	4.78
NO_3^-–N	0.55	0.03	0.02	0.02	0.04	0.01	0.01	0.01	0.70	1.82	3.14	6.03	12.1	17.3	22.9	26.7	30.5	32.8
NO_2^-–N	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.14	0.16	0.15	0.15	0.16	0.02	0.17	0.09	0.04	0.02

Table 3
Experimental results of SBR1 for two-stage system in a typical cycle

Indicator/ (mg/L)	Anaerobic stirring period/min							Aerobiotic aeration period/min					
	0	30	60	90	120	150	180	0	15	30	45	60	90
COD	210.3	90.4	65.4	54.3	45.7	43.3	42.1	42.1	38.2	35.4	33.1	32.4	32.0
TP	8.42	19.9	22.4	24.1	24.5	25.0	25.0	25.0	19.4	13.2	8.89	4.56	0.11
NH_4^+–N	80.7	82.2	81.3	82.2	82.2	82.3	82.1	82.1	81.2	80.1	78.4	76.8	75.3
NO_3^-–N	0.45	0.23	0.21	0.12	0.10	0.03	0.02	0.02	0.13	0.23	0.24	0.31	0.34
NO_2^-–N	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.14	0.16	0.35	0.78	1.53

(with no peptone addition, TN in the water ≈ NH_4^+–N), and TP being 10.8 mg/L. The initial value of MLSS in the reactor is 3,360 mg/L, and the sludge age is approximately 6 d. For the operating cycle, the short-term and centralized influence is followed by the 180 min anaerobic period and 90 min aerobiotic period. The COD load of the influent is 1.44 kg/m^3 d.

When water is introduced, given that PAOs can significantly release phosphorus and absorb the organics, the TP concentration at 0 min of a cycle is higher than half of that in the influent in both Tables 2 and 3 when the water filling ratio is 0.5. However, the COD concentration in the mixed solution is lower than half of the COD concentration in the influent.

The ammonia–nitrogen concentration varies significantly in Tables 2 and 3 at 0 min because the single-stage SBR works as per synchronous removal of phosphorus and nitrogen, in which the ammonia–nitrogen concentration in the mixture obtained from the previous cycle is really low before water is introduced into the reactor and some of the organic nitrogen undergoes ammonification during short-term water supply. Therefore, in Table 2, after the dilution of the influent, the ammonia–nitrogen concentration (33.5 mg/L) at 0 min is slightly higher than half of that in the influent (60.6 mg/L). When targeting phosphorus removal, S1 nearly inhibits all of the nitrifying bacteria (with NO_x^-–N < 2 mg/L at the end of the aerobiotic period) by controlling the sludge age. During its operation, the ammonia–nitrogen concentration in the liquid mixture slightly decreases because of the assimilation and weak nitrification effects. This finding explains the insignificant difference in ammonia–nitrogen concentration at 0 min (80.7 mg/L) after the dilution of the influent in Table 3 and the influence of that cycle (86.0 mg/L).

As shown in Tables 2 and 3, both cycles exhibit satisfactory phosphorus removal, and their actual effective phosphorus release periods are 180 and 150 min and actual effective phosphorus absorption periods are 120 and 90 min, respectively. The phosphorus release and absorption rates initially increase and subsequently decrease in both cycles. To facilitate the analysis, we define the first 0.5 h (0–30 min) of anaerobic stirring as the fast phosphorus-releasing period and the first 1 h (0–60 min) of aerobic aeration as the fast phosphorus-absorbing period.

After the calculation, the specific phosphorus release rates of the fast phosphorus-releasing period of the cycles shown in Tables 2 and 3 are 4.79 and 6.83 mg P/g MLSS h and the corresponding specific phosphorus absorption rates of the fast phosphorus-absorbing period are 3.39 and 6.08 mg P/g MLSS h, respectively. Apparently, with the same water filling ratio and nearly identical influent quality, although the S1 phosphorus removal system with low sludge age and single-stage SBR phosphorus and nitrogen removal system with high sludge age have similar anaerobic phosphorus release and aerobiotic phosphorus absorption processes and can well remove phosphorus, the S1 phosphorus removal system with low sludge age and high organic load has significantly better phosphorous removal efficiency than the single-stage SBR phosphorus and nitrogen removal system with high sludge age. Moreover, its specific phosphorus release and absorption rates in the fast phosphorus-releasing and phosphorus-absorbing periods are 1.43 and 1.79 times higher than those of the single-stage system with significantly reduced total effective phosphorus-releasing and phosphorus-absorbing times. This finding can be attributed to the high organic load (low sludge age) that inhibits the survival of nitrifying bacteria in S1 while providing a favorable growing environment for PAOs so that PAOs are significantly more active and denser in S1 than in the single-stage SBR system with higher sludge age.

3.2. Comparative analysis of the phosphorus removal effect

In engineering practice, sewage from the bioreaction tank usually undergoes plain sedimentation and is subsequently discharged in the form of a supernatant. For the stably working EBPR system, PO_4^{3-}–P in the supernatant is approximately 0 mg/L at the end of the aerobiotic period. By this time, the active sludge in the liquid mixture of the system is phosphorus-rich sludge, in which the phosphorus content can be 4% to 7% of its dry weight [9] or even >10% in several cases [10,11]. This finding indicates that, for the EBPR system, appropriate sedimentation after the aerobiotic period can effectively reduce the suspended solids (SS) concentration in the water and the TP concentration in the effluent at the same time. By contrast, as the sedimentation period is prolonged, PAOs may utilize the residual organics and internal carbon source in the reactor to release phosphorus and increase the TP concentration in the water [11–14]. Given such phenomena, reasonable sedimentation time before discharge constitutes an important factor affecting the final phosphorus removal effect of the EBPR system. In the present study, a comparative experiment on the phosphorus removal effect of the single-stage EBPR-SBR system (represented by S1 in the two-stage system) and two-stage SBR phosphorus and nitrogen removal system during the influent stage of "Sewage 2" in Table 1 was conducted.

3.2.1. Comparative analysis of varying P concentrations in predischarge liquid mixture with sedimentation time

Fig. 2 presents S1 of a typical cycle in the two-stage system (with PO_4^{3-}–P is being 64.91 mg/L at the end of the 2 h anaerobic stirring and COD being 31.5 mg/L and PO_4^{3-}–P is being 0.14 mg/L at the end of the 80 min aerobiotic period) and varying TP and PO_4^{3-}–P concentrations in the predischarge supernatant with sedimentation duration. PO_4^{3-}–P in the figure is detected from the water sample after filtering and sludge–water separation, whereas TP is measured directly from the liquid mixture after sampling is done.

Based on Fig. 2, under the present experimental conditions, the following conclusions can be drawn from the stably operating EBPR-SBR system:

- Effluent TP, which reaches its minimum value of 0.89 mg/L after 20 min of sedimentation, can be no higher than 1.0 mg/L but not 0.5 mg/L. This conclusion is consistent with the research summary of Qiu Shenchu et al. [6], which reported the inevitable results of the phosphorus-rich sludge particles in the effluent and the phosphorus release effect of phosphorus-rich sludge during sedimentation. If the phosphorus content in the phosphorus-rich sludge of the system is 6%, effluent PO_4^{3-}–P is 0.2 mg/L, and phosphorus-releasing effect of sludge during sedimentation is neglected, then SS in post-sedimentation effluent must be no higher than 5 mg/L so that the first-level A standard (or TP ≤ 0.5 mg/L) can be met. This standard is difficult to achieve in the system separating solid from liquid through sedimentation [6]. Furthermore, when the contribution of the phosphorus-releasing effect is considered, it is nearly impractical to control TP to be ≤0.5 mg/L in the effluent.
- PAOs release phosphorus right from the beginning of sedimentation and are at an increasingly high rate over time. After 40 min of sedimentation, the phosphorus-releasing rate tends to be a constant value, that is, 0.0138 mg P/L min. Gao Ming from Jinan University [14] conducted a static precipitation test by extracting phosphorus-rich sludge from three sewage plants at various locations in Shandong Province through the A²O, CAST, and oxidation ditch processes. Thus, the phosphorus-releasing effect of phosphorus-rich sludge during sedimentation is another important and non-negligible factor affecting the TP concentration in effluent of the Sewage Treatment Plant.
- The TP duration curve of the supernatant at 20 min of sedimentation exhibits an increasing trend, indicating that the TP-increasing effect of phosphorus release from the supernatant begins to outweigh the TP-decreasing effect of SS removal from sediment after 20 min of sedimentation. After 60 min of sedimentation, two synchronized increasing duration curves of PO_4^{3-}–P and TP tend to be parallel to each other (at which moment, the difference between the vertical coordinates of two lines is the contribution of SS to TP). Thus, at this time, the SS concentration in water becomes stable and further prolonging sedimentation is no longer meaningful for SS removal from the water.
- When sedimentation lasts for approximately 40 min, PO_4^{3-}–P in the supernatant begins to exceed 0.5 mg/L

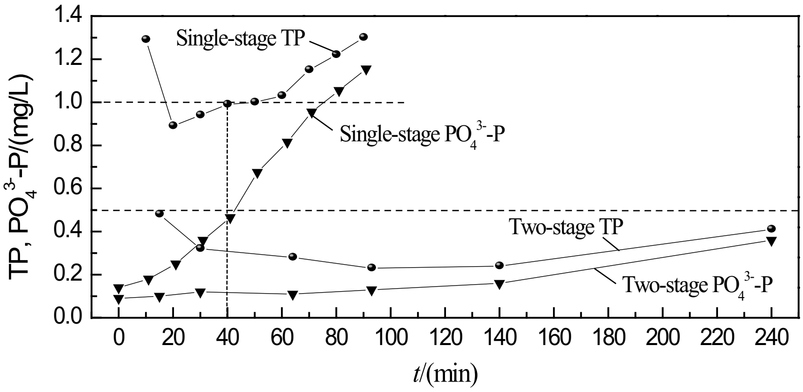

Fig. 2. Variation of supernatant TP and PO_4^{3-}–P with sedimentation time before drainage in single and two-stage SBR systems.

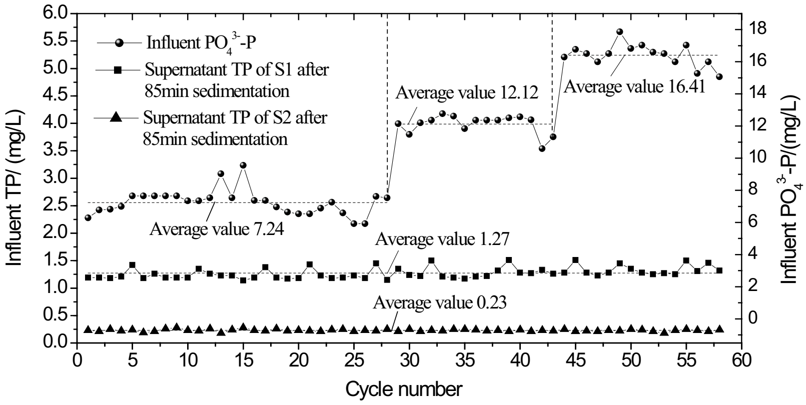

Fig. 3. Experimental results of phosphorus removal in the stable operation of the two-stage SBR system.

because it is detected after water sample filtering and sludge–water separation. This finding indicates that, under the present experimental conditions, if filtration alone is used to eliminate the effect of SS on effluent TP in the EBPR-SBR system, then the process must be completed within 40 min after sedimentation begins. However, TP cannot be ensured as being no higher than 0.5 mg/L because of the phosphorus-releasing effect.

As indicated by the previously presented conclusions, on the premise of meeting the sedimentation requirements, the EBPR-SBR system should shorten the sedimentation process as much as possible and discharge the water and sludge in time to weaken the phosphorus-releasing effect on effluent TP.

Based on the results presented in Table 2, if the phosphorus content in phosphorus-rich sludge is 6%, then the SS concentration is 9.83mg/L in the supernatant at this time in accordance with the difference between TP and PO_4^{3-}–P (0.59 mg/L) after 30 min of sedimentation. This finding indicates that, under the present experimental conditions, to lower the effluent TP as much as possible (while ensuring that SS ≤ 10 mg/L), the ideal total time for sedimentation and water/sludge discharge in the EBPR-SBR system should be no longer than 30–40 min. Although the sedimentation performance of the practical EBPR-SBR system may be entirely consistent with the results shown in Fig. 2, it remains difficult to achieve complete sedimentation and water/sludge discharge within a short period. The reason is that an engineering-scale SBR usually takes approximately 2 h to achieve complete sedimentation and water discharge [15]. Moreover, a longer time is required when sludge discharge is further included.

Fig. 2 also shows that, under the present experimental conditions, for a two-stage SBR system in stable operation, after 93 min predischarge sedimentation at the final outlet S2, TP in the supernatant decreases from 0.48 mg/L to the lowest value of 0.25 mg/L after 15 min of sedimentation, whereas PO_4^{3-}–P increases only from 0.09 mg/L at the beginning of sedimentation to 0.13 mg/L. After 240 min of sedimentation, not only PO_4^{3-}–P increases to 0.36 mg/L but also the corresponding TP increases to 0.41 mg/L. This finding clearly shows that there are nearly no PAOs in the S2 system and the active sludge in the system is regular non-phosphorus-rich sludge. The phosphorus content in non-phosphorus-rich sludge was only 1.5%–2% [6,10]. Thus, the system effluent can be easily and stably kept no higher than 0.5 mg/L.

3.2.2. Stability of the phosphorus removal process in the two-stage SBR

With regard to the EBPR system, its phosphorus removal effect remains directly related to the influent quality, system operating conditions, and sedimentation duration [16,17]. In the present experiment, the TP concentration in S1 is also usually affected by the change in system operating conditions or fluctuation of influent phosphorus concentration, so that it is fluctuating in some sense. Nevertheless, given that phosphorus is an indispensable component for the growth of microorganisms, when the effluent from S1 undergoes nitrogen removal treatment in S2, the effluent TP can still be lower than or equal to 0.5 mg/L with satisfactory stability. Fig. 3 illustrates the changes in the influent PO_4^{3-}–P and supernatant TP concentrations of S1 and S2 after 85 min pre-effluent sedimentation in 58 cycles when the two-stage system keeps working stably. Moreover, the average PO_4^{3-}–P concentration is 7.24, 12.12, and 16.41 mg/L.

As shown in Fig. 3, in the influent experiment with three concentration gradients of PO_4^{3-}–P, after 85 min of sedimentation, although the TP concentration in the S1 supernatant fluctuates to some degree and is >1.0 mg/L, the average TP is 1.27 mg/L with a fluctuation interval of 1.14–1.51 mg/L and fluctuation margin of 0.37 mg/L. However, the supernatant TP concentration and stability in S2 are significantly superior to that in S1 because its average value is 0.23 mg/L with a fluctuation interval of 0.18–0.28 mg/L and a fluctuation margin of 0.1 mg/L only. The final effluent TP in the two-stage SBR system is free from the effect of fluctuating phosphorus concentration in the effluent of S1 and can easily and stably keep no higher than 0.5 mg/L. This requirement is unattainable for the existing regular EBPR systems that separate solid from liquid through sedimentation [6].

4. Conclusions

- Under ambient temperature and rich carbon source, the phosphorus removal grade SBR1 in the two-stage serially connected SBR phosphorus and nitrogen removal system and single-stage SBR system exhibit similar anaerobic phosphorus-releasing and aerobiotic phosphorus-absorbing processes, and both of them can achieve a satisfactory phosphorus removal effect. However, during its operation, the SBR1 system with a low sludge age and high organic load has a significantly higher phosphorous removal efficiency than the single-stage system. Moreover, the specific phosphorus release and absorption rates of the fast phosphorus-releasing segment (0–0.5 h) and phosphorus-absorbing segment (0–1 h) in the SBR1 system are 1.43 and 1.79 times higher than that in the single-stage system, respectively.

- The effluent TP of the single-stage EBPR-SBR system can be no higher than 1.0 mg/L but not 0.5 mg/L, which is an inevitable result of the phosphorus-rich sludge particles in the effluent and the phosphorus release effect of phosphorus-rich sludge during sedimentation.
- PAOs in EBPR-SBR begin releasing phosphorus right after sedimentation is started and at an increasingly high rate over time. The phosphorus-releasing rate becomes nearly constant after approximately 40 min of sedimentation, whereas the average rate at this time is 0.0138 mg P/L min.
- On the premise of meeting the sedimentation requirements, the sedimentation duration should be shortened as much as possible in the EBPR-SBR system and water and sludge should be discharged in time to alleviate the phosphorus-releasing effect on effluent TP.
- The final effluent TP of the two-stage SBR phosphorus and nitrogen removal system can be free from the effect of fluctuating effluent phosphorus concentration in S1 and keep no higher than 0.5 mg/L in an easy and stable manner. This is beyond the capacity of existing common EBPR systems that separate solid from liquid through sedimentation.

Acknowledgments

This research was supported by the Open Project of Jiangsu Key Labs of Environmental Science and Engineering through grant Zd131203, Jilin Key Scientific and Technological Breakthrough Project through grant 20160204006SF, Open Project of State Key Laboratory of Urban Water Resource and Environment through grant QA201314, and Jilin Provincial Industrial Innovation Special Fund Project through grant 2016c093.

References

[1] S.H. Zhang, Z.Z. Huang, S.J. Lu, J. Zheng, X. Zheng, Nutrients removal and bacterial community structure for low C/N municipal wastewater using a modified anaerobic/anoxic/oxic (mA^2/O) process in North China, Bioresour. Technol., 243 (2017) 975–985.
[2] Q.L. He, Q. Song, S.L. Zhang, W. Zhang, H.Y. Wang, Simultaneous nitrification, denitrification and phosphorus removal in an aerobic granular sequencing batch reactor with mixed carbon sources: reactor performance, extracellular polymeric substances and microbial successions, Chem. Eng. J., 331 (2018) 841–849.
[3] Y. Ma, Y.Z. Peng, X.L. Wang, Improving nutrient removal of the AAO process by an influent bypass flow by denitrifying phosphorus removal, Desalination, 246 (2009) 534–544.
[4] C. Chan, A. Guisasola, J.A. Baeza, Enhanced biological phosphorus removal at low sludge retention time in view of its integration in A-stage systems, Water Res., 118 (2017) 217–226.
[5] G.J. Zhou, P.F. Zhou, R. Lei, L.J. Yuan, Y.E. Wang, Problems and optimal control strategies of the conventional A^2/O process for urban sewage treatment, Technol. Water Treat., 43 (2017) 11–17, 23.
[6] S.C. Qiu, T.T. Ding, Discussion on the achievement of total phosphorus in the biological treatment of urban sewage, China Water Wastewater, 18 (2002) 23–25.
[7] X.C. Zheng, Selection of biological nitrogen and phosphorus removal process for urban sewage, Water Wastewater Eng., 26 (2000) 1–4.
[8] The State Environmental Protection Administration, Water and Wastewater Monitoring and Analysis method, 4th ed., China Environmental Science Press (CESP), Beijing, 2002.
[9] J. Norbert, P.H. Johammes, Phosphate release of sludges from enhanced biological p-removal during digestion, Water Sci. Technol., 30 (1994) 281–292.
[10] Y.M. Lin, Y. Liu, J.H. Tay, Development and characteristics of phosphorus-accumulating microbial granules in sequencing batch reactors, Appl. Microbiol. Biotechnol., 62 (2003) 430–435.
[11] W.L. Chen, R.Y. Wang, Y.M. Li, Effect of acetate concentration on phosphate release during anaerobic fermentation of phosphorus-rich sludge, China Environ. Sci., 35 (2015) 1763–1770.
[12] L. Xu, G.T. Xu, G.H. Wang, X.J. Tan, H.Y. Liu, Factors influencing the re-release of anaerobic phosphorus in SBR sludge treatment, Acta Sci. Circumstantiae., 30 (2010) 789–794.
[13] D.S. Bi, X.P. Guo, D.H. Chen, Phosphorus release mechanisms during digestion of EBPR sludge under anaerobic, anoxic and aerobic conditions, Water Sci. Technol., 67 (2013) 1953–1959.
[14] M. Gao, Phoshorus Release and Phosphorus Recovery from Rich Phosphorus Sludge in EBPR, University of Jinan, 2016.
[15] Y.L. Shen, D. Zhao, Some countermeasures to enhance the effects of the SBR process on nitrogen and phosphorus removal, China Water Wastewater, 16 (2000) 23–25.
[16] X.X. Song, H.T. Fan, D. Huang, Z.J. Bing, H.C. Jiang, M.Y. Wang, W.L. Zhang, H.C. Wang, Research progress in the main influencing factors of enhanced biological phosphorus removal system, Environ. Prot. Sci., 44 (2018) 53–61.
[17] D. Li, M.Z. Cao, Y.Z. Guo, N. Mei, S. Li, J. Zhang, COD requirement for biological phosphorus removal granule system under different phosphorus concentrations, Environ. Sci., 39 (2018) 3247–3253.