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Simultaneous removal of phosphorus and nitrogen in sequencing batch reactor

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Abstract

In this research, investigations were made on material transfer mechanisms and optimum operation mode for sequencing batch reactor system removing phosphorus and nitrogen simultaneously. Phosphorus release characteristics were expressed in the Monod equation, in which the reaction rate was replaced with specific phosphorus release (SPR) rate. The rate of SPR was increased during the first 80 days, but increased sharply to reach 0.003 hr^{-1} afterwards. Phosphorus removal efficiencies were about 60% in the first 80 days, 75% after 80 days, and above 95% after 120 days. After 120 days, phosphorus concentration in effluent was below 0.5 mgl^{-1} when 8 mgl^{-1} was in the influent and the released phosphorus after 3-hour-anaerobic period was 60 mgl^{-1}. In the proposed optimum operation strategy (2-hour anaerobic react, 3-hour aerobic react, 4-hour anoxic react, and 3-hour settle and draw), phosphorus reappeared if the oxidized nitrogen was completely denitrified. In order to prevent this undesirable phosphorus release, anoxic period should be reduced to the extent of which the minimal concentration of the oxidized nitrogen existed. Phosphorus removal efficiency was stable under shock load as 5 times high as normal phosphorus concentration.

Abbreviations: dP/dt – Phosphorus release rate ($mgl^{-1}\,hr^{-1}$); K – Phosphorus release yield constant (mg P mg TOC^{-1}); dS/dt – Substrate utilization rate ($mgl^{-1}\,hr^{-1}$); X – Mixed liquor suspended solid (MLSS, mgl^{-1}); S – Soluble TOC (mgl^{-1}); k – $q_{max}\,(Y_{max})^{-1}$ – Maximum substrate utilization rate; Y – Yield coefficient (mg mg^{-1}); K_s – Saturation constant (mgl^{-1}); P_{max} – kK – Maximum phosphorus release rate (hr^{-1}); P_{rel} – Total released phosphorus (mgl^{-1}); P_o – Phosphorus in influent (mgl^{-1}); P_e – phosphorus in effluent (mgl^{-1}); t – Anaerobic period (hr)

Introduction

Srinath et al. (1959) first reported the phenomenon of phosphorus uptake in excess of normal metabolic requirements of activated sludge. After many years of research, biochemical model for excess biological phosphorus removal has been proposed (Marais et al. 1983; Comeau et al. 1986; Wentzel et al. 1985; Mino et al. 1988). Under anaerobic conditions (in the absence of both free oxygen and nitrates as terminal electron acceptors), carbon substrates – such as formate, acetate, butyrate and other low molecular weight fatty acids – are transported across the membrane by facilitated diffu-

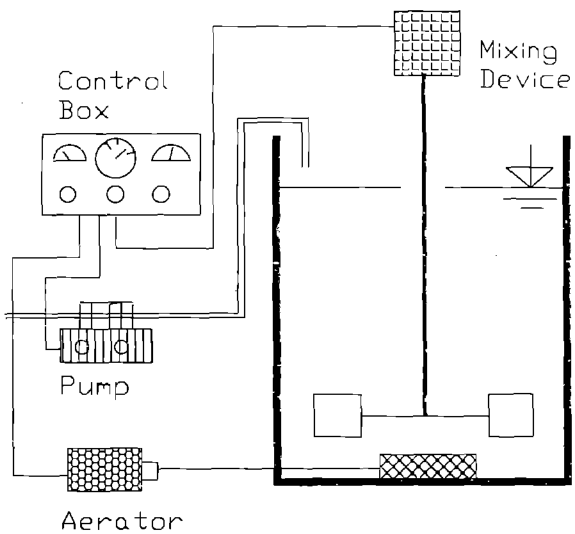

Fig. 1. Schematic diagram of the bentch-scale SBR.

sion and are stored as the insoluble lipid, poly-β-hydroxybutyrate (PHB). The energy for fatty acid transport comes from polyphosphate hydrolysis, which causes phosphate release into the surrounding medium. Upon aeration, the stored acetate in the form of PHB can be used for energy production to accumulate phosphorus and replenish polyphosphate stores.

Nitrogen removal in activated sludge wastewater treatment processes can be achieved by biomass synthesis, air stripping, and nitrification followed by denitrification. Biological nitrification alone does not increase the removal of total nitrogen from the waste stream over that achieved by conventional biological treatment. The principal effect of the nitrification treatment process is to transform ammonia nitrogen to nitrate in an aerobic environment. A subsequent anoxic condition is required for complete nitrogen removal from the wastewater by the mechanism of denitrification.

The removal mechanisms for phosphorus and nitrogen require similar environments of cyclic oxygenated and non-oxygenated biomass. Therefore, aerobic and anaerobic reactors in series are adopted for most phosphorus- and nitrogen-removal processes, such as the A/O, Bardenpho, and Rotanox processes (Yeoman et al. 1988).

Sequencing batch reactors (SBR) have become popular since the development of automatic electrical valves, timers, water level sensors, and microprocessors. Its advantages for phosphorus and nitrogen removal are derived from direct control of the operating strategy (anaerobic, anoxic and aerobic conditions) and the duration of each condition (Arora et al. 1985; Irvine et al. 1985).

In this research, the removal efficiencies of phosphorus and nitrogen were investigated in a bench-scale SBR for different operating strategies and in batch reactors under several conditions. The chronological changes of phosphorus and nitrogen were also investigated through one cycle in the SBR. With the results obtained in these experiments, an optimized operating strategy was determined for effective simultaneous phosphorus and nitrogen removal.

Materials and methods

A 15-1 SBR (Fig. 1) was operated for investigating the behavior and removal efficiency of phosphorus and nitrogen at room temperature (20–25° C) and for supplying sludge to batch experiments. Seed sludge was collected from a conventional municipal wastewater treatment plant.

As batch reactors, 125-ml flasks were used for evaluating various kinetic constants involved in phosphorus and nitrogen removal. Aerobic conditions were maintained on a rotary shaker operated at 2500–3000 rpm, while anaerobic conditions were created by capping the flask and flushing it with nitrogen gas.

Table 1. Operating strategy for the bench scale SBR.

Operation condition	Fill	React		Settle	Draw
	Anaerobic	Aerobic	Anoxic		
Time (h)*	3	6	1.5	1	0.5
Mechanism	Phosphate release	Phosphate uptake	Phosphate uptake	Solid separation	
	TOC uptake	Nitrification	Denitrification		

Volumetric COD load: 0.84 kg/m^3/day.

The bench-scale SBR was operated on the predetermined operating strategy shown in Table 1 until it showed excess phosphorus removal capability. Following this, several batch tests were performed to optimize the SBR system and investigate the characteristics of phosphorus release and uptake, as well as nitrification and denitrification. The synthetic wastewater fed within five minutes contained glucose and acetate as organic substrate whose concentrations were 300 and 330 mgl^{-1} as COD, respectively. The complete composition of the feed is given in Table 2.

Mixed liquor samples were taken every hour after the addition of substrate, while an effluent sample was taken 30 minutes after the settling started. TOC, phosphorus, ammonia, nitrite, nitrate, pH, DO, and MLSS were measured following Standard Methods (APHA 1985).

Results and discussions

Phosphorus Release

Figure 2 shows that soluble TOC was removed under anaerobic conditions, while soluble phosphorus increased drastically. The phosphorus release rate could be linearly related to the substrate (i.e., soluble TOC) uptake rate as shown in Fig. 3.

$$dP/dt = -K\,(dS/dt) \tag{1}$$

here

Table 2. Composition of the synthetic wastewater.

Components	Concentration (mgl^{-1})
Glucose	280 (300 as COD)
CH_3COONa	485 (330 as COD)
$(NH_4)_2SO_4$	140 (30 as N)
KH_2PO_4	44 (10 as P)
$MgSO_4$	50
$CaCl_2$	3.75
$FeCl_3$	0.25
$MnSO_4$	5.0
Na_2CO_3	66 (60 as $CaCO_3$)
$NaHCO_3$	105 (60 AS $CaCO_3$)

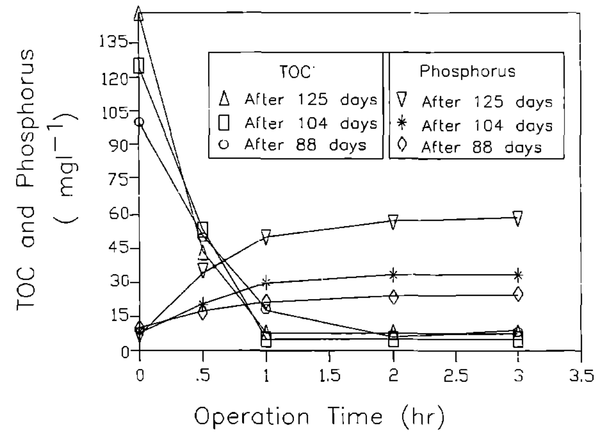

Fig. 2. TOC and phosphorus concentrations during the anaerobic condition following substrate feeding.

dP/dt = Phosphorus release rate (mg l^{-1} hr^{-1})
K = Phosphorus release yield constant (mg P mg TOC^{-1})
dS/dt = Substrate utilization rate (mgl^{-1} hr^{-1})
X = Mixed liquor suspended solid (MLSS, mgl^{-1})

As the specific substrate utilization rate can be expressed as a Monod function (Eq. (2)), Eq. (1) can be converted to a Monod form, Eq. (3).

$$\frac{dS/dt}{X} = \frac{k\,S}{K_s + S} \tag{2}$$

$$\frac{1}{X}\frac{dP}{dt} = \frac{P_{max}\,S}{K_s + S} \tag{3}$$

where
S = Soluble TOC (mgl^{-1})
Y = Yield coefficient ($mgmg^{-1}$)
k = Maximum substrate utilization rate ($mgmg^{-1}$ hr^{-1})
K_s = Saturation constant (mgl^{-1})
P_{max} = kK = Maximum phosphorus release rate (hr^{-1})

The left term of Eq. (3) is defined as the SPR (Specific Phosphorus Release rate, hr^{-1}), and P_{max} in this equation indicates the maximum specific phosphorus release rate for the given operating conditions.

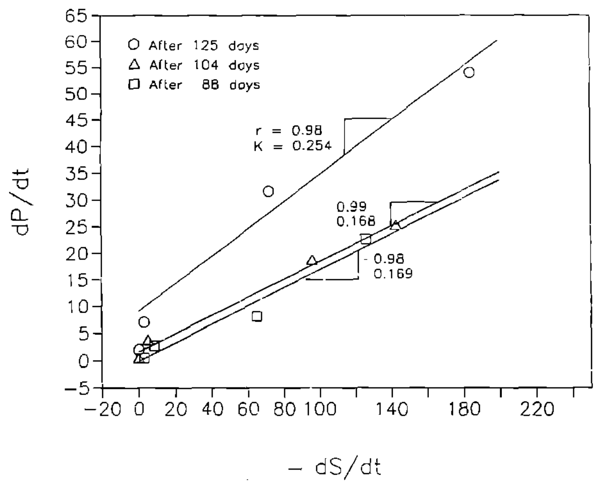

Fig. 3. Relationships between the phosphorus release rate and the substrate utilization rate during anaerobic conditions.

The data obtained from a batch test performed four months after the start-up of the experiment was calibrated according to Eq. (3). Figure 4 shows a good correspondance between the data and Eq. (3). Ks and P_{max} were 58.9 mgl^{-1} and 4.4×10^{-3} hr^{-1}, respectively.

Phosphorus uptake

Figure 5 shows the progress of phosphorus removal through an entire 12-hour cycle for different time

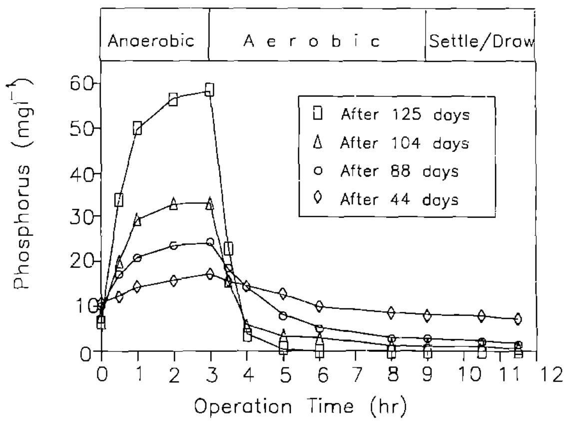

Fig. 5. Phosphorus concentrations through out 12-hour operation cycles.

after start-up. During the first 44 days of the experiment, the phosphorus removal efficiency was about 30%. During this time, significant phosphorus release and uptake did not occur. However, phosphorus released in the 3-hour-anaerobic period increased gradually for four months, eventually reaching six times the influent P concentration. Soluble phosphorus in effluent decreased as phosphorus release increased during the anaerobic period as shown in Fig. 6. The relationship between effluent P and released P is depicted in Fig. 7 and modeled by Eq. (4).

$$\ln(P_e) = 3.77 - 0.13\, P_{rel} \tag{4}$$

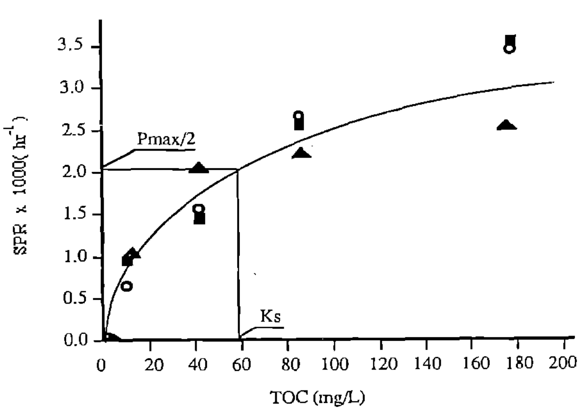

Fig. 4. Calibration of experimental data to Eq. (3) for a batch experiments performed 125 days after initiation of the experimentation.

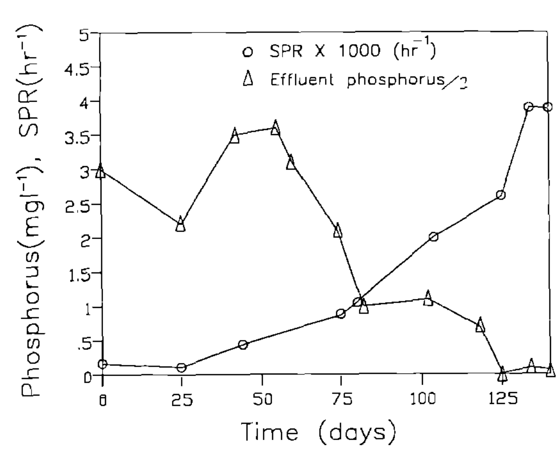

Fig. 6. SPR and effluent phosphorus.

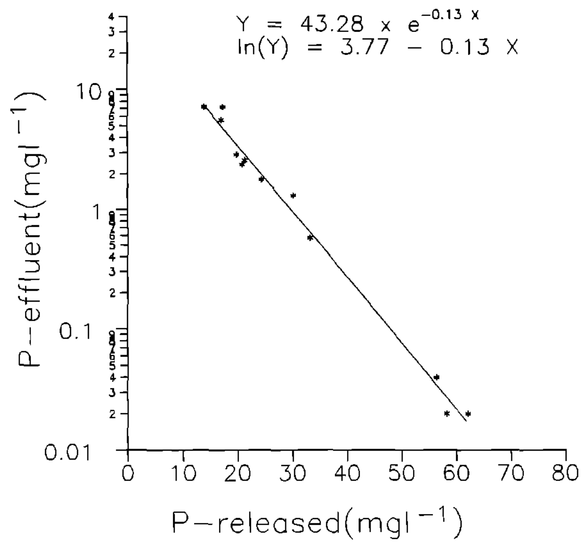

Fig. 7. Relationship between effluent phosphorus and phosphorus released during the 3-hour anaerobic period.

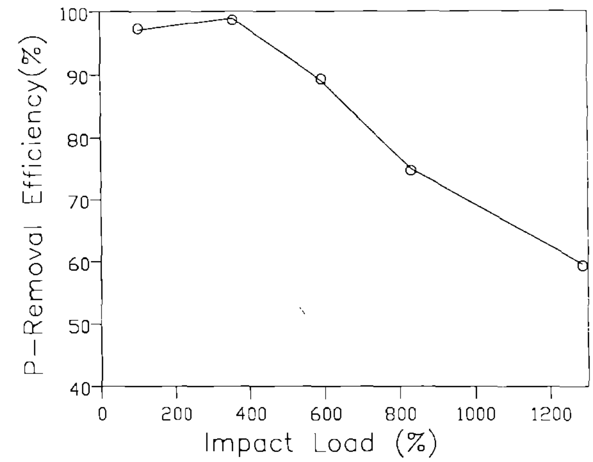

Fig. 8. Effect of shock P loads on the phosphorus removal efficiency.

where

P_{rel} = Phosphorus concentration after the anaerobic period (mgl^{-1})

P_e = Phosphorus in the effluent (mgl^{-1})

The equation demonstrates that the extent of phosphorus release correlates strongly to the removal efficiency for phosphorus in this reactor, which had constant P_0 and X. For example, Fig. 6 shows that phosphorus in effluent was 4.0 to 7.0 mgl^{-1} when SPR was about 0.0001 hr^{-1} before Day 88, while it became far below 1.0 mgl^{-1} when the SPR was above 0.0025 hr^{-1} after Day 125. However, it took 3 months to reach this condition, which could be explained as biomass adaptation or microbial selection under this anaerobic and aerobic condition.

Nicolls & Osborn (1979) found that *Acinetobacter spp.* were abundant in processes having excess phosphorus removal. But Lotter et al. (1985) suggested that *Acinetobacter spp.* are present in any wastewater and have the inherent characteristics of polyphosphate and PHB accumulation. The anaerobic followed by aerobic conditions applied to the system just helped the excess phosphorus-removing bacteria-Bio-P bacteria (Comeau et al. 1986) – to exhibit phosphorus release and uptake. She also indicated that the amount of phosphorus release and uptake increased slowly after the operating condition was changed to cyclic anaerobic and aerobic condition, as the species adapted to the changed environment.

The stability of the system against a shock P load was investigated once in batch experiments conducted after phosphorus release and uptake capacity were fully developed. The initial concentrations of phosphorus used in this experiment were 1.8, 3.25, 6.5, 9.7, and 13 times higher than that of the normal influent, and the experiment had a 2-hour anaerobic period, followed by a 5-hour aerobic condition. As shown in Fig. 8, phosphorus removal efficiencies were maintained over 90% up to 6 times higher than that of the normal influent P load, indicating an excellent capacity to handle shocks.

Excess phosphorus-removing bacteria, such as *Acinetobacter spp.*, could utilize oxidized nitrogen as an electron acceptor during anoxic period, which eventually promotes further phosphorus uptake and denitrification. Figure 9 shows phosphorus uptake using dissolved oxygen and nitrate as an electron acceptor after the 2-hour anaerobic period. In the reactor maintaining the anaerobic condition, phosphorus was only released. Thus simultaneous utilization of nitrate and uptake of phosphorus could be brought about phosphorus-removing bacteria.

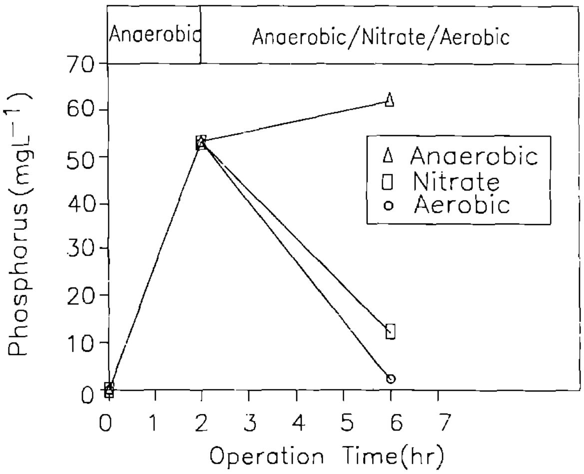

Fig. 9. Effect of electron acceptors on phosphorus uptake.

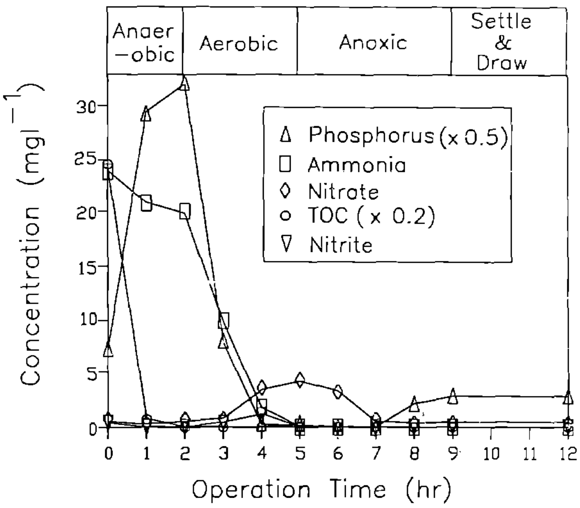

Fig. 10. Performance of SBR in terms of nitrogen species, phosphorus, and TOC on the optimized operation strategy.

Nitrogen removal

Dissolved nitrogen in wastewater can be removed by cell synthesis, air stripping, and nitrification/denitrification. However, while the amount of nitrogen removal by cell synthesis and volatilization usually is small compared to the influent load, removal by nitrification/denitrification can be large.

Figure 10 indicates that ammonia was almost constant during the anaerobic period, although the small decrease may have been caused by the small degree of aerations occurring at the liquid surface. Most ammonia nitrogen was removed in aeration period when the DO concentration increased gradually from zero to 5.6 mgl^{-1}. However, only a small fraction of the incoming ammonia nitrogen was the nitrified to nitrate and nitrite. The long sludge age of 20 days and the neutral pH suggest that little of the observed nitrogen removal was by cell synthesis or volatilization. Thus, simultaneous nitrification and denitrification appeared to occur during the aerobic react period.

While phosphorus concentration profiles changed drastically as the operation time passed, nitrogen concentration profiles, especially ammonia nitrogen, did not change much throughout the experiments. These results suggest that nitrifying bacteria (e.g. *Nitrosomonas* and *Nitrobactor*) and denitrifying heterotrophes were present initially at significant amounts and adapted to the new environment. The longer adaptation time required for the phosphorus-removing bacteria, suggests that they were present initially in any small numbers and/or had a slow adaptation.

Simultaneous removal of phosphorus and nitrogen

Since phosphorus and nitrogen were removed in similar conditions, simultaneous removal could be made on the controlled operating condition. Operating results on the initial operating condition showed that 3-hour aerobic period was enough for complete removal of ammonia and phosphorus and 1.5-hour anoxic period should be extended for achieving a complete denitrification. However, ni-

Table 3. Performance of SBR on the modified operating strategy (SRT: 20 days, Temp: 25° C, MLSS: 6900 mgl^{-1}, pH: 8.6).

Components	Influent (mgl^{-1})	Effluent (mgl^{-1})	Removal efficiency (%)
TOC	230	5	97.5
Phosphorus	8.44	0.19	97.8
NH_4^+-N	33.6	0.0	
NO_x-N	0.0	0.5	98.4

F/M ratio: 0.116 kg-COD/kg-MLSS/day; HRT (hr): Anaerobic/Aerobic/Anoxic/Settle & Draw = 2.0/3.0/2.0/5.0.

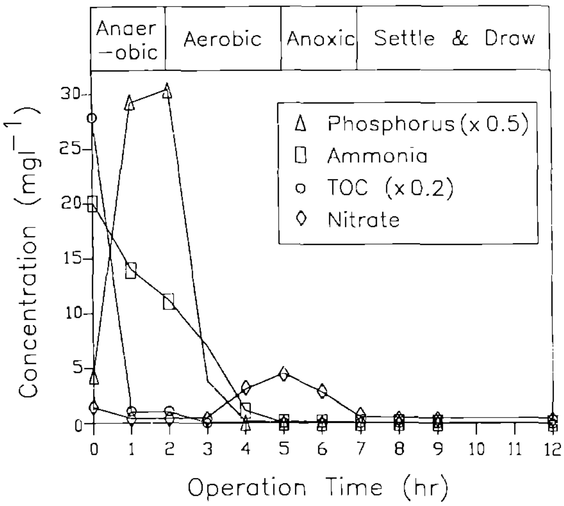

Fig. 11. Performance of the SBR on the modified operation strategy to prevent phosphorus release in the anoxic period.

trate and nitrite were completely denitrified in 2-hour anoxic period which was extended to 4 hours. Denitrifiers seem to use the sorbed or stored organic materials caused probably by the reduction of aerobic period. Phosphorus, however, was rereleased gradually in the anaerobic condition when the nitrate was completely denitrified. Hence, it appeared essential to maintain anoxic condition for the simultaneous removal of phosphorus and nitrogen.

The operating strategy was modified for preventing phosphorus release by decreasing the anoxic react by 2 hours. Improved phosphorus removal efficiency is shown in Fig. 11. Table 3 indicated that the removal efficiency of phosphorus, nitrogen, and organic substrate were well above 97%.

Conclusions

From this experimental research on simultaneous removal of phosphorus and nitrogen in SBR, the following conclusions can be made.

1. SPR (Specific Phosphorus Release) rate could be expressed by a Monod type function of the TOC concentration.
2. Phosphorus in effluent was an exponential function of phosphorus released during anaerobic react period.
3. Nitrogen was completely removed in the aerobic period and following the 2-hour anoxic period.
4. In order to prevent rerelease of P, it is necessary to prevent anaerobic condition in the anoxic period due to complete consumption of nitrate.
5. Under this experimental condition and the anaerobic/aerobic/anoxic react of 2/3/2 hours, the removal efficiencies of phosphorus, nitrogen, and TOC were about 98%.

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