

Operation and Modeling of Bench-Scale SBR for Simultaneous Removal of Nitrogen and Phosphorus Using Real Wastewater

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Abstract Experimental work was carried out on nitrogen and phosphorus removal from real wastewater using a bench-scale SBR process. The phosphorus removal was stable and the phosphorus concentration remaining in the reactor was maintained within 1.5 ppm, regardless of the addition of an external carbon source. In the case of nitrogen, an external carbon source was necessary for denitrification. The effect on denitrification with the addition of various carbon sources, such as glucose, methanol, acetate, and propionate, was also investigated. Acetate was found to be the most effective among those tested in this study. When 100 ppm (theoretical oxygen demand) of sodium acetate was added, the average rate of denitrification was $2.73 \text{ mg NO}_3^- \text{-N (g MLSS)}^{-1} \text{ h}^{-1}$, which was ca. 4 times higher than that with the addition of 200 ppm of methanol. The phosphorus and nitrogen concentrations were both maintained within 1.5 ppm by the addition of an appropriate amount of a carbon source during a long-term operation of the SBR. The mathematical modeling was performed using Monod kinetics, other microbial kinetics, mass balances, and stoichiometry. The modeling was found to be useful for predicting the SBR operation and optimizing the HRT.

Keywords: SBR, nitrogen removal, phosphorus removal, wastewater treatment, modeling

INTRODUCTION

Biological methods for the treatment of municipal and industrial wastewater have been in use for many years. Nitrogen and phosphorus are not toxic chemicals, however, they are limiting nutrients for algal growth. As a result, since the input of these elements to aquatic environments accelerates eutrophication, nitrogen and phosphorus must be removed from discharged wastewater effluents. Currently, numerous biological methods are popular for wastewater treatment, especially nutrient removal, because of their non-toxicity to the environment and low cost. Nitrogen can be removed biologically by the nitrification of ammonia under aerobic conditions and denitrification of nitrite and nitrate under anoxic conditions. Phosphorus removal is performed by phosphorus release instead of an organic substrate uptake in the anaerobic phase, and by an overplus uptake using the PHB stored during anaerobic phase in the aerobic and anoxic phase. Accordingly, alternating oxygen conditions are needed to remove nitrogen and phosphorus simultaneously. One technology that has been successfully used in treating liquid waste with excessive amounts of nitrogen and phosphorus involves the use of cyclically operated reactors known

as sequencing batch reactors (SBR). Due to its simplicity and low capital and operating costs, an SBR provides an alternative advanced wastewater treatment facility. A modified SBR system, that incorporates alternating aerobic and anoxic/anaerobic stages in the reaction period, not only allows for the effective removal of organic matter and suspended solids, but also achieves a satisfactory reduction of nitrogen by nitrification-denitrification processes and phosphorus by release and uptake processes. SBR development has progressed steadily over recent years. Proper process design and equipment selection can achieve capital and energy savings of up to 60% compared to conventional activated sludge designs. Enhanced phosphorus removal in activated sludge has been studied intensively since 1959 and conflicting data have been put forward supporting either the chemical precipitation of phosphorus [1], biological accumulation, and/or biologically mediated chemical precipitation of phosphorus [2]. However, until now none of these mechanisms has been clearly defined or fully understood. Notwithstanding, experimental evidence has been reported on the biological uptake of phosphorus using *Acinetobacter* as the responsible agent [3]. The historical development of biochemical models for biological excess phosphorus removal has included work by Nicolls and Osborn [3], Rensink *et al.* [4], and so on. Mathematical models for phosphorus removal in activated sludge systems have also been studied by Smolders *et al.* [5] and Wentzel *et al.* [6].

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Mathematical descriptions of the microbial reactions in wastewater treatment processes can be problematic due to the presence of a large number of different components that are involved in the metabolism. However, mathematical models are powerful tools whereby the designers of biological wastewater treatment systems can investigate the performance of a number of potential systems under a variety of conditions. Simulation models of activated sludge systems, such as the IAWPRC model [7] or SIMPRC are structured on the basis of dividing the wastewater into various fractions according to the physical state of the components and their biodegradability. The process and modeling of the simultaneous removal of nitrogen and phosphorus have been previously investigated by many engineers, such as Wentzel *et al.* [8]. The modeling of SBRs has been studied using total mass balances, and many researchers have also examined kinetic, stoichiometric, and metabolic models of nitrogen or phosphorus removal processes. However, bench-scale SBR systems for nutrient removal have not yet been completely simulated. Accordingly, this study developed a bench-scale SBR process for the simultaneous removal of nitrogen and phosphorus (N/P) from real wastewater. A mathematical model was also established using Monod kinetics, mass balances, and fundamental mechanisms of simultaneous N/P removal.

MATERIALS AND METHODS

Experimental System

The SBR system consisted of a reactor, controller (time, solenoid valve, pH), pumps, ion selective electrodes (DO, pH, ORP), and tanks (Fig. 1). The reactor was made of an acrylic plastic cylinder with a 30 L volume. Solenoid valves adjusted the gas flow for each cycle according to a time sequence. The controller controlled the duration of each condition within one cycle. The pH, DO, and ORP electrodes were all located at the reactor side.

SBR Operation

During operation the volume of sludge and treated water was kept at 10 and 20 L, respectively. The reactor was operated at 26°C. The SBR had a solid retention time (SRT) of 20 days. The operational cycle for the SBR included 25 mins of fill, 3 hs of an anaerobic period with mix, 3 hs of aeration with mix, 2 hs of an anoxic period with mix, 40 min of settle followed by 25 min of decant, and 30 min of idle. The oxygen concentration required for an anaerobic phase was below 0.2 ppm, whereas that for an aerobic phase was kept above 4 ppm. Samples were taken every 1 h and analyzed after filtering with a glass fiber filter. In this study, the real wastewater was obtained from Taejon Wastewater Treatment Plant of Korea and the average influent BOD, COD, TN, TP, NH_4^+ , and PO_4^{3-} were 45, 60, 25, 2.8, 18, and 2.2 mg/L, respectively.

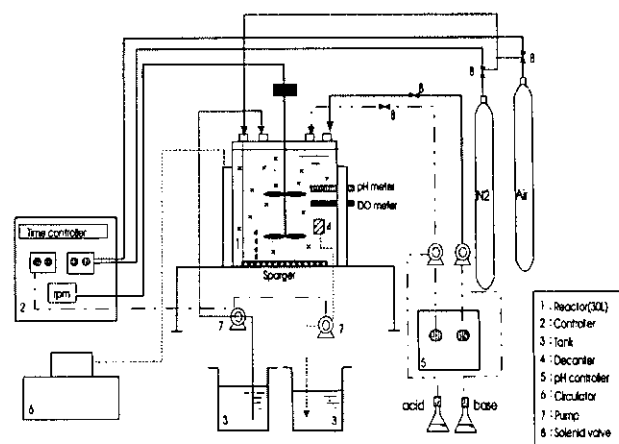


Fig. 1. Schematic diagram of SBR.

Analytical Methods

For the analysis of NO_3^- , NO_2^- , PO_4^{3-} , NH_4^+ , and BOD, the samples were immediately filtered through a glass fiber filter (Whatman GF/C). The concentrations of NO_3^- , NO_2^- , PO_4^{3-} , and NH_4^+ were determined using an Eutrophication meter (HC-1000, Central Kagaku Co. Ltd., Japan). The TN, TP, BOD, MLSS (mixed liquor suspended solid), and COD were measured according to Standard Methods [9]. The pH, ORP, and DO (Dissolved Oxygen) were measured using ion-selective electrodes (ORION).

Modeling

In order to perform an effective system operation, the mathematical modeling and simulation of the behavior of the microbes inside the SBR are essential. Usually, variations in the quality and quantity of the influent wastewater are significant in an SBR system. In this study, the model equations (Table 1-5) were set up using multiple substrates Monod kinetics, material balances, and the principles of nitrogen and phosphorus removal on the basis of previous literature [5-8]. The kinetic parameters were appropriately modified to match the SBR system used in the current study (Table 6). It has already been demonstrated that kinetics and stoichiometry can drastically vary in an SBR, in contrast to a continuous feeding reactor [10].

RESULTS AND DISCUSSION

System Performance Using Real Wastewater

Several operation strategies were attempted to evaluate the performance of the SBR using wastewater from the Taejon wastewater Treatment plant in Korea. The system operation was performed using a sequence of anaerobic (3 h) – aerobic (3 h) – anoxic (2 h) phases, which is the optimum operation condition for synthetic

Table 1. Model equations for anaerobic phase

$$\frac{dS_1}{dt} = -a(1) \frac{S_1}{a(2) + S_1} \frac{PolyP}{a(3) + PolyP} X_1 + a(4) \frac{dS_2}{dt}$$

$$\frac{dS_2}{dt} = -a(5) \frac{S_2}{a(6) + S_2} X_3$$

$$\frac{dP}{dt} = a(7) \frac{S_1}{a(8) + S_1} \frac{PolyP}{a(9) + PolyP} X_1$$

$$\frac{dPolyP}{dt} = -a(10) \frac{S_1}{a(8) + S_1} \frac{PolyP}{a(9) + PolyP} X_1$$

$$\frac{dPHB}{dt} = a(11) \frac{S_1}{a(2) + S_1} \frac{PolyP}{a(3) + PolyP} X_1$$

$$\frac{dNH_4}{dt} = -a(12) \frac{S_2}{a(6) + S_2} X_3$$

$$\frac{dNO}{dt} = 0$$

$$\frac{dX_1}{dt} = a(17) \frac{S_1}{a(2) + S_1} X_1 - a(13) X_1$$

$$\frac{dX_2}{dt} = -a(14) X_2$$

$$\frac{dX_3}{dt} = a(15) \frac{S_2}{a(6) + S_2} X_3 - a(16) X_3$$

$$\frac{dV}{dt} = 0$$

Table 2. Model equations for aerobic phase ($S_1 > 0$)

$$\frac{dS_1}{dt} = -b(1) \frac{S_1}{b(2) + S_1} X_1 + b(3) \frac{dS_2}{dt}$$

$$\frac{dS_2}{dt} = -b(4) \frac{S_2}{b(5) + S_2} X_3$$

IF(PolyP $\geq X_1 \cdot 0.04$), then $\alpha = 0$, else $\alpha = 1$

$$\frac{dP}{dt} = -\alpha b(6) \frac{S_1}{b(7) + S_1} \frac{P}{b(26) + P} X_1$$

$$\frac{dPolyP}{dt} = \alpha b(8) \frac{S_1}{b(7) + S_1} \frac{P}{b(26) + P} X_1$$

$$\frac{dPHB}{dt} = b(9) \frac{S_1}{b(2) + S_1} X_1$$

$$\frac{dNH_4}{dt} = -b(11) \frac{NH_4}{b(12) + NH_4} X_2 - b(27) \frac{S_1}{b(2) + S_1} X_1$$

$$- b(28) \frac{S_2}{b(5) + S_2} X_3$$

IF(NH₄ ≥ 0.1), then $\alpha = 0$, else $\alpha = 1$

$$\frac{dNO}{dt} = b(13) \frac{NH_4}{b(12) + NH_4} X_2$$

$$\frac{dNO}{dt} = b(13) \frac{NH_4}{b(12) + NH_4} X_2$$

$$- \alpha (b(27) \frac{S_1}{b(2) + S_1} X_1 + b(28) \frac{S_2}{b(5) + S_2} X_3)$$

$$\frac{dX_1}{dt} = b(14) \frac{S_1}{b(2) + S_1} X_1 - b(15) X_1$$

$$\frac{dX_2}{dt} = b(16) \frac{NH_4}{b(12) + NH_4} X_2 - b(17) X_2$$

$$\frac{dX_3}{dt} = b(18) \frac{S_2}{b(5) + S_2} X_3 - b(19) X_3$$

$$\frac{dV}{dt} = 0$$

Table 3. Model equations for aerobic phase ($S_1 = 0$)

$$\frac{dS_1}{dt} = 0$$

$$\frac{dS_2}{dt} = -b(4) \frac{S_2}{b(5) + S_2} X_3$$

IF(PolyP $\geq X_1 \cdot 0.04$), then $\alpha = 0$, else $\alpha = 1$

$$\frac{dP}{dt} = -\alpha b(20) \frac{PHB}{b(21) + PHB} \frac{P}{b(26) + P} X_1$$

$$\frac{dPolyP}{dt} = \alpha b(22) \frac{PHB}{b(21) + PHB} \frac{P}{b(26) + P} X_1$$

$$\frac{dPHB}{dt} = -b(23) \frac{PHB}{b(24) + PHB} X_1$$

$$\frac{dNH_4}{dt} = -b(11) \frac{NH_4}{b(12) + NH_4} X_2 - b(27) \frac{S_1}{b(2) + S_1} X_1$$

$$- b(28) \frac{S_2}{b(5) + S_2} X_3$$

IF(NH₄ ≥ 0.1), then $\alpha = 0$, else $\alpha = 1$

$$\frac{dNO}{dt} = b(13) \frac{NH_4}{b(12) + NH_4} X_2$$

$$- \alpha (b(27) \frac{S_1}{b(2) + S_1} X_1 + b(28) \frac{S_2}{b(5) + S_2} X_3)$$

$$\frac{dX_1}{dt} = b(25) \frac{PHB}{b(22) + PHB} X_1 - b(15) X_1$$

$$\frac{dX_2}{dt} = b(16) \frac{NH_4}{b(12) + NH_4} X_2 - b(17) X_2$$

$$\frac{dX_3}{dt} = -b(19) X_3$$

$$\frac{dV}{dt} = 0$$

Table 4. Model equations for anoxic phase ($S_1 > 0$)

$$\frac{dS_1}{dt} = -c(1) \frac{S_1}{c(2) + S_1} \frac{NO}{c(12) + NO} X_1 - c(3) \frac{dS_2}{dt}$$

$$\frac{dS_2}{dt} = -c(4) \frac{S_2}{c(5) + S_2} \frac{NO}{NO + c(27)} X_3$$

IF(PolyP $\geq X_1 \cdot 0.04$), then $\alpha = 0$, else $\alpha = 1$

$$\frac{dP}{dt} = -\alpha c(6) \frac{S_1}{c(7) + S_1} \frac{P}{c(24) + P} X_1$$

$$\frac{dPolyP}{dt} = \alpha c(8) \frac{S_1}{c(7) + S_1} \frac{P}{b(24) + P} X_1$$

$$\frac{dPHB}{dt} = c(9) \frac{S_1}{c(10) + S_1} X_1$$

$$\frac{dNH_4}{dt} = 0$$

$$\frac{dNO}{dt} = -c(11) \frac{NO}{c(27) + NO} \frac{S_2}{c(5) + S_2} X_3$$

$$-c(25) \frac{S_1}{c(2) + S_1} \frac{NO}{NO + c(12)} X_1$$

$$\frac{dN_2}{dt} = c(29) \frac{NO}{c(27) + NO} \frac{S_1}{c(2) + S_1} X_3$$

$$\frac{dX_1}{dt} = c(13) \frac{S_1}{c(2) + S_1} \frac{NO}{c(12) + NO} X_1 - c(14) X_1$$

$$\frac{dX_2}{dt} = -c(15) X_2$$

$$\frac{dX_3}{dt} = c(16) \frac{S_2}{c(5) + S_2} \frac{NO}{c(27) + NO} X_3 - c(15) X_3$$

$$\frac{dV}{dt} = 0$$

Table 5. Model equations for anoxic phase ($S_1 = 0$)

$$\frac{dS_1}{dt} = 0$$

$$\frac{dS_2}{dt} = -c(4) \frac{S_2}{c(5) + S_2} \frac{NO}{c(27) + NO} X_3$$

IF(PolyP $\geq X_1 \cdot 0.04$), then $\alpha = 0$, else $\alpha = 1$

$$\frac{dP}{dt} = -\alpha c(18) \frac{PHB}{c(19) + PHB} \frac{P}{c(24) + P} X_1$$

$$\frac{dPolyP}{dt} = \alpha c(20) \frac{PHB}{c(19) + PHB} \frac{P}{b(24) + P} X_1$$

$$\frac{dPHB}{dt} = -c(21) \frac{PHB}{c(19) + PHB} \frac{NO}{c(12) + NO} X_1$$

$$\frac{dNH_4}{dt} = 0$$

$$\frac{dNO}{dt} = -c(11) \frac{NO}{c(27) + NO} \frac{S_2}{c(5) + S_2} X_3$$

$$-c(25) \frac{PHB}{c(19) + PHB} \frac{NO}{NO + c(12)} X_1$$

$$\frac{dN_2}{dt} = 0$$

$$\frac{dX_1}{dt} = c(23) \frac{PHB}{c(19) + PHB} \frac{NO}{c(12) + NO} X_1 - c(14) X_1$$

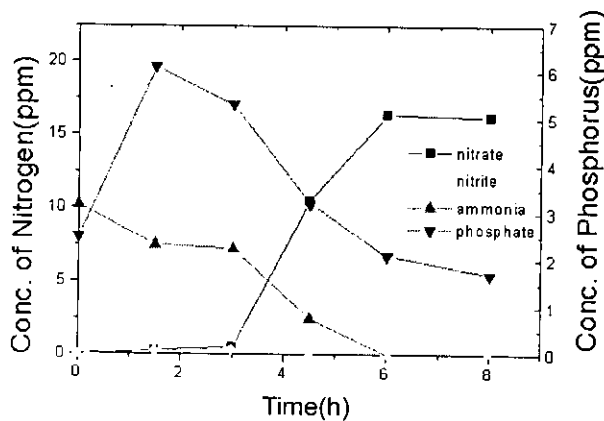
$$\frac{dX_2}{dt} = -c(15) X_2$$

$$\frac{dX_3}{dt} = -c(17) X_3$$

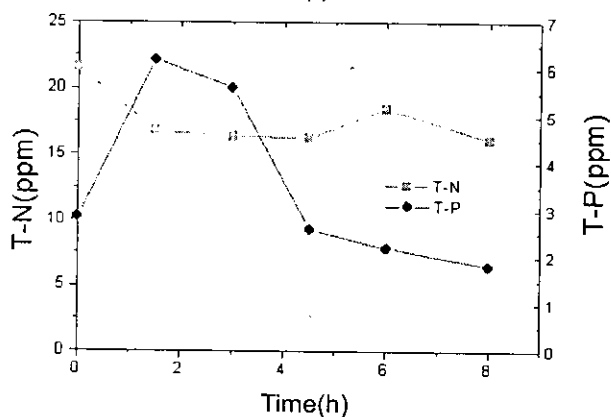
$$\frac{dV}{dt} = 0$$

Table 6. Parameters for model equations

Anaerobic	Aerobic	Anoxic
a(1) = 0.43	b(1) = 0.24	c(1) = 0.064
a(2) = 48.0	b(2) = 1.8	c(2) = 1.8
a(3) = 0.8	b(3) = 0.6	c(3) = 0.7
a(4) = 0.8	b(4) = 0.07	c(4) = 0.06
a(5) = 0.04	b(5) = 5.	c(5) = 5.0
a(6) = 5.0	b(6) = 0.011	c(6) = 0.004
a(7) = 0.014	b(7) = 4.	c(7) = 4.
a(8) = 9.0	b(8) = 0.018	c(8) = 0.023
a(9) = 10.0	b(9) = 0.007	c(9) = 0.011
a(10) = a(7)*1.8	b(10) = 2.	c(10) = 1.8
a(11) = 0.045	b(11) = 0.016	c(11) = 0.05
a(12) = 0.003	b(12) = 1.	c(12) = 2.7
a(13) = 0.0017	b(13) = 0.013	c(13) = 0.013
a(14) = 0.0021	b(14) = 0.03	c(14) = 0.0017
a(15) = 0.01	b(15) = 0.0017	c(15) = 0.0021
a(16) = 0.0024	b(16) = 0.009	c(16) = 0.04
a(17) = 0.02	b(17) = 0.0021	c(17) = 0.0024
	b(18) = 0.01	c(18) = 0.007
	b(19) = 0.0026	c(19) = 1.8
	b(20) = 0.010	c(20) = 0.03
	b(21) = 1.3	c(21) = 0.0026
	b(22) = 0.02	c(22) = 8.
	b(23) = 0.021	c(23) = 0.0185
	b(24) = 8.	c(24) = 3.0
	b(25) = 0.03	c(25) = 0.0040
	b(27) = 3.0	c(26) = 0.0034
	b(28) = 0.01	c(27) = 2.7
	b(29) = 0.01	c(28) = 0.009
		c(29) = 2.7

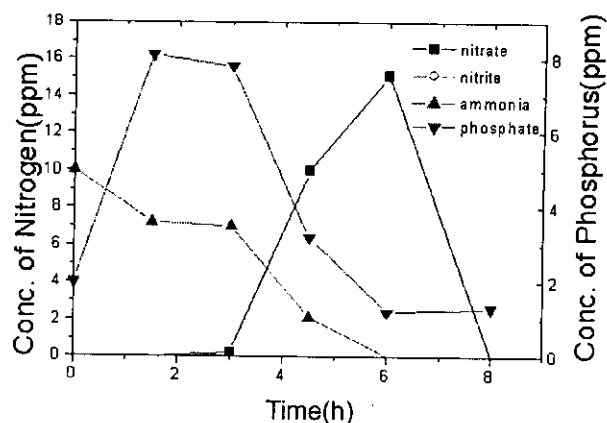


(a)

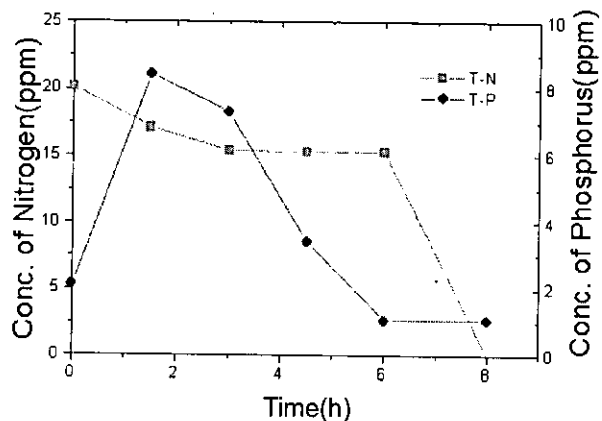


(b)

Fig. 2. SBR operation using real wastewater without addition of surplus carbon source for denitrification ((a) Profiles of nitrate, nitrite, ammonia, and phosphate; (b) Profiles of T-N and T-P).



(a)



(b)

Fig. 3. SBR operation using real wastewater with addition of surplus carbon source (65 ppm ThOD of sodium acetate) for denitrification ((a) Profiles of nitrate, nitrite, ammonia, and phosphate; (b) Profiles of T-N and T-P).

wastewater. Figs. 2 and 3 show the N and P composition profiles with and without the addition of a carbon source for denitrification. Phosphorus was released during the anaerobic step and removed during the aerobic step. The phosphorus removal was stable and the phosphorus concentration remaining in the reactor was maintained within 1.5 ppm, regardless of the addition of an external carbon source. In the case of nitrogen, ammonia was completely oxidized into nitrate and no accumulation of nitrite was observed in the aerobic phase. The concentration of nitrate was higher than the initial concentration of ammonia due to the existence of organic nitrogen, such as amino acids and urea in the real wastewater, as shown in Figs. 2(a) and 3(a). When an external carbon source was added during the anoxic phase, nitrate was reduced to nitrogen gas which was then released (Fig. 3(a)). However, the denitrification did not occur without the addition of a carbon source and the removal rate was quite low because of the exhaust of organic components during the anaerobic stage. From these results, it is evident that an additional carbon source was necessary for a high removal efficiency

of nitrogen. The effect on the denitrification of the addition of various carbon sources, such as glucose, methanol, acetate, and propionate was investigated (Table 7). The amount of carbon source added was based on the theoretical oxygen demand (ThOD), which indicates the amount of oxygen needed for the carbon source to be completely converted into carbon dioxide and water. Acetate was the most effective carbon source among those investigated in this study, as shown in Table 7. When 100 ppm of sodium acetate was added, the average rate of denitrification was $2.73 \text{ mg NO}_3^- \text{-N (g MLSS)}^{-1} \text{ h}^{-1}$, which was ca. 4 times higher than that with the addition of 200 ppm of methanol. It has been previously reported that specific denitrification rates under anoxic conditions can occur at three different speeds, high, intermediate (occurring before the depletion of the substrate), and low (occurring after the depletion of the substrate) rates [11]. In this study, the average denitrification rate observed when sodium acetate was used as the carbon source was comparable to the intermediate rate. It has been reported that P can be released from bacterial cells during anoxic stages if a

Table 7. Comparison of carbon sources for denitrification

Carbon source ThOD (mg/L)	Glucose			Sodium acetate		Sodium propionate		Methanol		
	50	100	200	50	100	100	200	200	400	
Incoming oxidized Nitrogen (mg/L)	15.8	16.4	18.6	11.8	16.4	9.6	12	15.8	17.4	
Outgoing oxidized Nitrogen (mg/L)	Nitrate	8.35	4.6	1.2	4.4	0	3.4	1.0	7.5	0
	Nitrite	1.38	1.68	1.32	0	0	0.6	0.32	0.02	0.05
Time (h)	2	2	2	2	1.5	2	2	3	5.5	
Average rate of denitrification (mg N (g MLSS) ⁻¹ h ⁻¹)	0.76	1.27	2.01	0.93	2.73	0.7	1.34	0.69	0.79	

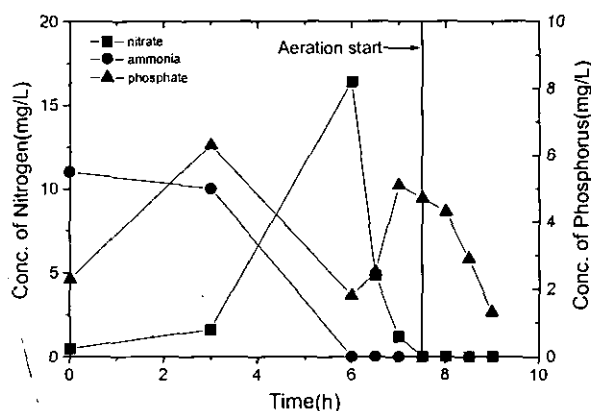


Fig. 4. Profiles of nitrogen and phosphorus when using acetate as carbon source for denitrification.

suitable carbon source, such as acetate, is added [12]. In the present work, when acetate or propionate was added as an external carbon source, which are both good substrates for phosphorus removal microorganisms, the phosphorus, that was taken up by the cells in the aerobic stage was re-released after the nitrate was some what consumed under the anoxic conditions. A short second aerobic period was necessary for the reuptake of phosphorus (Fig. 4). While the addition of external carbon should be sufficient for complete denitrification during the anoxic stage, an overloading of external carbon can also create other problems, such as incomplete COD removal and the secretion of phosphorus. Therefore, the carbon to nitrogen ratio (C/N ratio) for denitrification is an important factor for successful wastewater treatment [13]. Based on the above results, a long-term operation of the SBR system was carried out with the appropriate addition of acetate (C/N ratio: 3.5-4.0) during the anoxic phase, and the resulting TN and TP profiles for the long-term operation are shown in Fig. 5. The phosphorus and nitrogen concentrations were maintained within 1.5 ppm by the

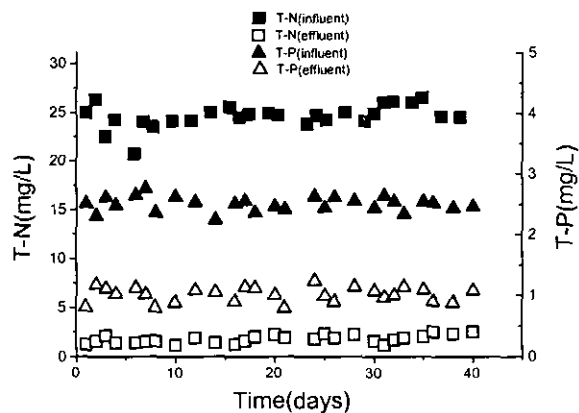


Fig. 5. Profiles of T-N and T-P during long-term operation of SBR using real wastewater.

addition of a suitable amount of a carbon source. From these results, it is evident that the stable elimination of phosphorus was achieved through a long-term acclimation of the sludge using real wastewater, while the nitrogen was eliminated by determining a suitable carbon source and only supplying enough to remove the oxidized nitrogen.

Simulation

A simulation study was carried out to evaluate and optimize the system performance using real wastewater. Furthermore, this study also examined the effectiveness with serious fluctuations in the quantity and quality of the influent wastewater. In order to verify the parameters selected from other references, the simulated results were then compared with experimental data, as shown in Fig. 6. The simulated results were found to be in good agreement with the experimental data, thus the parameters selected were determined as reasonable. The results of the simulation using real wastewater with the confirmed parameters are shown in Figs. 7, 8, and 9,

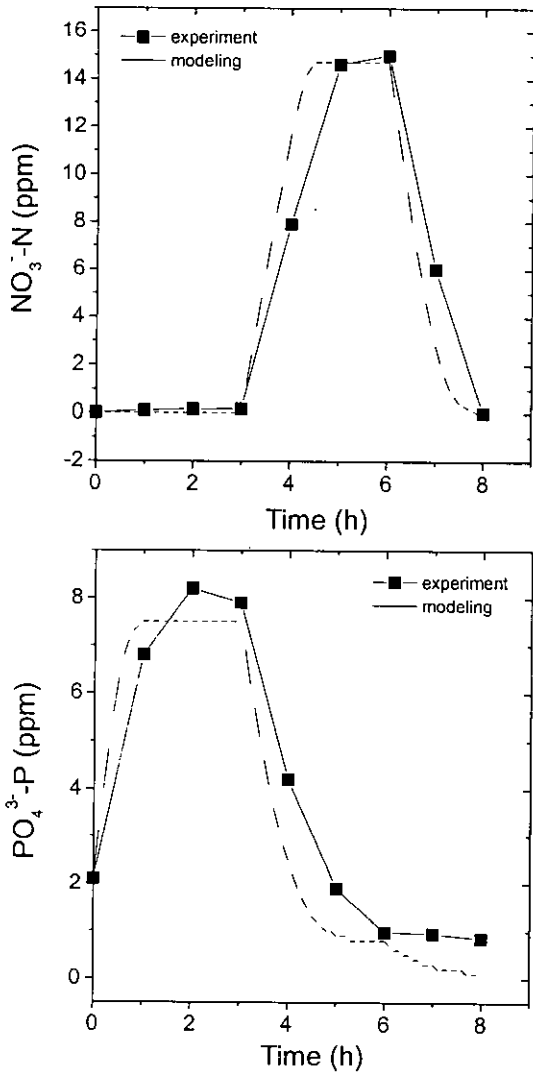


Fig. 6. Comparison of experimental data and simulated result.

respectively. The results in Figs. 7 and 8 indicate that the anaerobic phase continued even after the release of the maximum concentration of phosphorus, as shown in the experimental results. Thus, a shortened anaerobic phase can be expected from the simulation results. The phosphorus release which occurs in presence of volatile fatty acids (VFA) is called the primary release, whereas the release in the absence of VFA is called the secondary release [14]. The primary release of phosphorus is associated with the supply of energy for the basal energy requirement of the cells, and the energy required transferring VFA into the cells for storage in the form of poly-hydroxy-alkanoates (PHA). In contrast, since the secondary release of phosphorus is not associated with the storage of organic compounds, the phosphorus thus released is not removed by the P-removing bacteria in the subsequent aerobic stage. As a result, any secondary release of phosphorus is detrimental to the performance efficiency and should be prevented. A long hydraulic

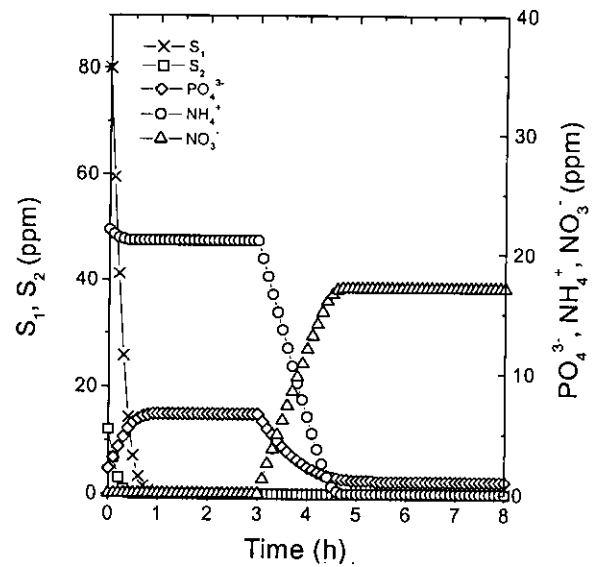


Fig. 7. Simulated result using real wastewater without addition of surplus carbon source for denitrification.

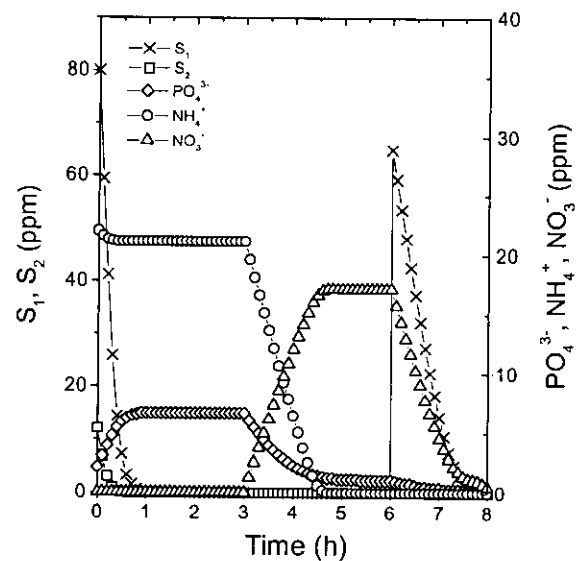


Fig. 8. Simulated result using real wastewater with addition of surplus carbon source for denitrification.

retention time during the anaerobic phase, an inadequate supply of organic compounds in the wastewater, and the insufficient activity of the fermentation bacteria in the anaerobic phase can all lead to the secondary release of phosphorus and an inefficient operation. Shahnaz and Oleszkiewicz [15] reported that a higher efficiency in phosphorus removal can be achieved by shortening the anaerobic period because a reduction in the anaerobic period prevents or minimizes the chance of the secondary release of phosphorus. Fig. 9 shows the simulated determination of the optimum HRT for the treatment of real wastewater with a surplus addition of a carbon source for denitrification. Based on this

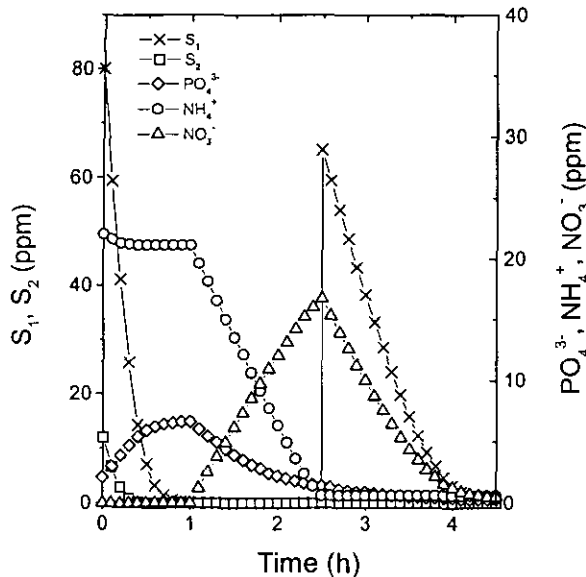


Fig. 9. Simulational determination of optimum HRT for treatment of real wastewater with addition of surplus carbon source for denitrification.

study, the optimum HRT that can achieve normal N and P removal from influents was obtained with a sequence of anaerobic (1 h) – aerobic (1.5 h) – anoxic (2 h) phases.

NOMENCLATURE

NH ₄	: Ammonium
NO	: Oxidized nitrogen
P	: Phosphorus
PHB	: Polyhydroxybutyrate
poly-P	: Polyphosphate
S ₁	: Readily biodegradable substrate
S ₂	: Slowly biodegradable substrate
t	: Time
TN	: Total Nitrogen
TP	: Total Phosphorus
V	: Reactor working volume
X ₁	: Phosphorus removing microorganisms
X ₂	: Nitrifying microorganisms
X ₃	: Denitrifying microorganisms

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