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Quantitative Analysis for the Behaviour of Phosphorus and TOC in Biological Wastewater Treatment

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생물학적 폐수처리에서 인과 TOC 거동의 정량적인 해석

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요 약

기존의 생물학적 인 제거 공정은 주로 경험적 인자를 고려하여 운전되었기 때문에 아직까지 폐수처리 시스템 전체를 파악할 수 있는 정량적인 연구가 미흡한 실정이다. 본 연구에서는 생물학적 인과 Total Organic Carbon(TOC)의 제거 공정을 모사하기 위하여 단일 균주인 *Staphylococcus auricularis*를 이용하였으며, 여기서 혐기와 호기 조건을 동시에 고려하는 모델 시스템을 제안하였다. 이 모델 시스템에서는 미생물 안의 인 농도를 고려한 인의 방출과 제거 특성을 나타내었으며, 인과 TOC가 제거되는 과정을 잘 모사하였다. 그리고 폐수 중 인의 농도 변화에 의한 인을 효과적으로 처리하기 위하여 각 농도별로 요구되는 싸이클 수를 예측할 수 있었다.

Keywords : 인, TOC, 모델 시스템, *Staphylococcus auricularis*, 싸이클 수

I. Introduction

Mathematical models are able to represent the behavior of a process on a simplified level. The principal aims of mathematical models are as follows.[1] First, models are built to allow prediction of the conversion or production of any system. Second, models are built to examine the nature and behavior of a system under the variety of operation conditions and to examine the regions where the model is valid, including how far from this region extrapolation is permitted. Third, models allow generalization to other situations within the boundaries of their validities. Fourth, models are mathematical formulas that can be manipulated to optimize processes. Fifth, models are used to identify unknown or previously disregarded process variables and parameters that may be significant variables. Sixth, as an indirect results, models may be also helpful in clarifying reaction mechanisms.

Many researches have been performed to establish models for the simulation of phosphorus removal by microorganisms.[2-6] Yeoun *et al.*[7] suggested the models describing removal of phosphorus and TOC by activated sludge under aerobic condition. They separated activated sludge into two parts; one was polyphosphorus accumulating bacteria and the other was non-polyphosphorus accumulating bacteria. They said that phosphorus, in the case of polyphosphorus accumulating bacteria, was removed by not only cell growth but phosphorus accumulation whereas only by cell growth in the case of non-polyphosphorus accumulating bacteria. They also reported that the driving force of phosphorus accumulation was the difference between the maximum possible phosphorus contents in cells and phosphorus contents. This approach was very helpful to analyze phosphorus removal by activated sludge. But the removal efficiency of phosphorus by activated sludge is low and unstable[8,9] thus another model for the novel phosphorus removal process is required.

Wentzel *et al.*[10] suggested the models for the simulation of phosphorus behavior under the only anaerobic condition. They considered release and removal of phosphorus simultaneously. That is, the release of phosphorus was due to polyphosphorus accumulating bacteria whereas the removal of phosphorus was due to non-polyphosphorus accumulating bacteria. There were another models describing the removal of phosphorus under the only anaerobic condition. They incorporated the concentrations of phosphorus and organics into a model.[2] Therefore the model could predict the effect of phosphorus and organics on the behavior of phosphorus simultaneously. But above two models described phosphorus behavior under the only anaerobic condition.

In the Sequencing Batch Reactor(SBR) system, aerobic and anaerobic conditions are changed repeatedly. Therefore, in this study, a model on the removal of phosphorus and TOC under anaerobic condition and that under aerobic condition were combined together. Microbial adaptation during repeated operations was considered by incorporating the term of phosphorus content in a cell.

II. Materials Methods

1. Microorganism and medium

Staphylococcus auricularis was used as a model microorganism to remove total organic carbon (TOC) and phosphorus in anaerobic and aerobic conditions. This strain was aerobically cultured at 25°C in a medium. The compositions of nutrients were presented in Table 1. The pH of synthetic medium was adjusted to 7.0 with 4% NaOH. Diluted or concentrated medium having the same ratios of components was used as synthetic wastewater for the experiments.

2. Operation of bioreactor

SBR system were shown in Fig. 1. All experiments were also carried out in water bath at 25°C. In the SBR, working volume of the bioreactor was 1.5 *l* and equipped pump, air and nitrogen gas regulators were controlled by

Table 1. Nutrients concentration of the medium

Component	Concentration (g/L)
Glucose	0.5
Peptone	0.5
Yeast extract	0.5
Mono sodium glutamate	0.5
KH_2PO_4	0.44
$(NH_4)_2SO_4$	0.1
$MgSO_4 \cdot 7H_2O$	0.1

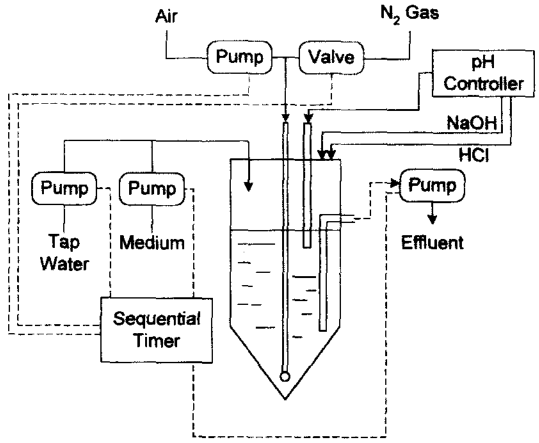

Fig. 1. Schematic diagram of a SBR for the removal of phosphorus and TOC.

sequence timer. The anaerobic and aerobic conditions were established by injection both 2 vvm of nitrogen and air. The pH was adjusted between 6.5 and 7.0 with 0.5 N-NaOH and 0.5 N-HCl.

3. Analytical methods

To measure TOC and phosphorus concentration, cells were removed from culture broth with 0.45 μm microfilter and supernatant was analyzed. TOC was assayed using standard method.[11] And to measure phosphorus concentration, the supernatant was mixed with ascorbic acid and the optical density of mixture was measured at 710 nm with a UV spectrophotometer (Uvicon 930, Kontron Co, U.S.A.). The concentration of cell was determined by measuring the optical density of cells at 660 nm with the UV spectrophotometer.

III. Results and Discussion

Generally, phosphorus and TOC concentrations were considered as main operation parameters in SBR system. And it was often reported that the phosphorus content in a cell was related to the release and removal rates of phosphorus.[12] Therefore, the effects of phosphorus, TOC and phosphorus content in a cell on the release and removal rates of phosphorus and TOC should be investigated to establish the mathematical models of SBR system.

First, the effect of TOC on the release rate of phosphorus under anaerobic condition was investigated. As shown in Fig. 2, as the initial concentration of TOC was increased from 500 mg/*l* to 2,000 mg/*l* at constant initial phosphorus concentration of 50 mg/*l*, the release rate of phosphorus was also increased. But the TOC concentration little influenced the removal rate of phosphorus under the aerobic condition as can be seen in Fig. 3.

And the effect of phosphorus on the removal rate of TOC was investigated. As shown in Fig. 4 and 5, the removal rate of TOC was independent of phosphorus concentration under both anaerobic and aerobic conditions. But it became higher with the increase of TOC concentration itself.

There was a report that the release rate of phosphorus in anaerobic condition was linearly proportional to the phosphorus content in a cell.[7] The same phenomenon was observed in this study as shown in Fig. 6(a) and the removal rate of phosphorus in aerobic condition was

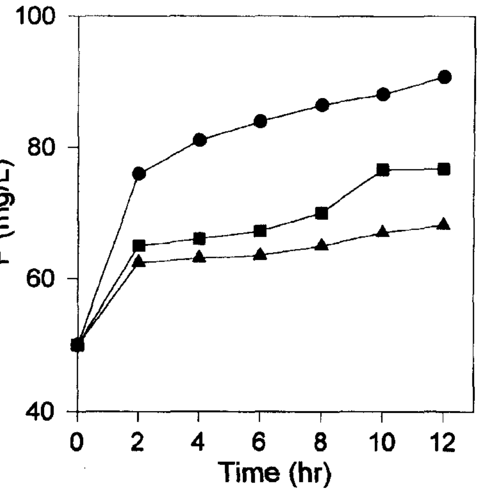

Fig. 2. Effect of TOC concentration on the release of phosphorus. (● : TOC = 2,000 mg/*l*, ■ : TOC = 1,000 mg/*l*, ▲ : TOC = 500 mg/*l*)

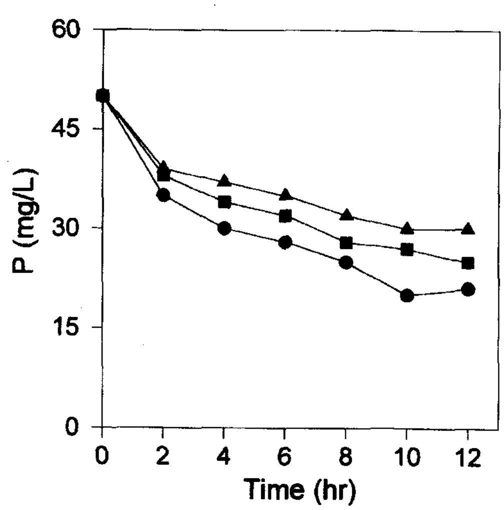

Fig. 3. Effect of TOC concentration on the removal of phosphorus. (● : TOC = 2,000 mg/*l*, ■ : TOC = 1,000 mg/*l*, ▲ : TOC = 500 mg/*l*)

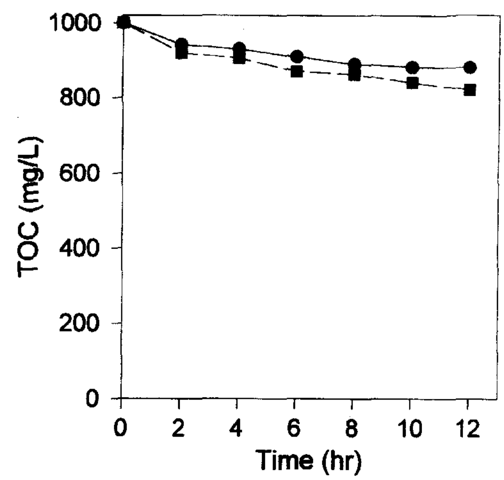

Fig. 4. Effect of phosphorus concentration on the removal of TOC under anaerobic condition. (● : 50 mg/*l* of phosphorous, ■ : 25 mg/*l* of phosphorous)

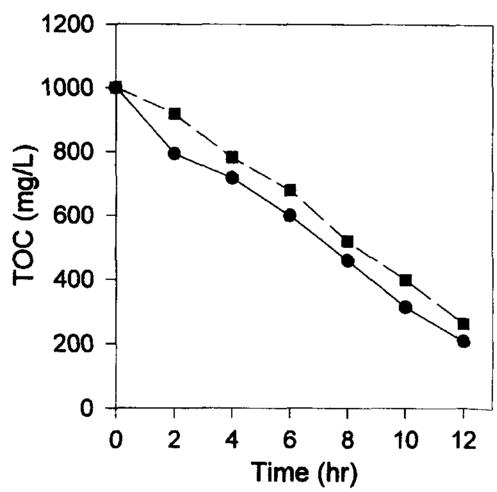

Fig. 5. Effect of phosphorus concentration on the removal of TOC under aerobic condition. (● : 50 mg/*l* of phosphorous, ■ : 25 mg/*l* of phosphorous)

decreased as phosphorus content in a cell became high as can be seen in Fig. 6(b). It was also found that most of the removed phosphorus was accumulated in a cell under aerobic condition. And the amount of released phosphorus from cell was found to be almost the same as that of increased phosphorus in broth. Therefore, it was assumed that the total amount of phosphorus was constant and the phosphorus content in a cell could be calculated by measuring phosphorus in broth and total phosphorus. The maximum phosphorus content was determined to be 18% from experiments. Therefore, one of the constraints in the models was that the phosphorus content in a cell could not exceed 18%.

Generally, the cell concentration did not change under anaerobic condition but it was increased as substrate was decreased under the aerobic condition. In this study, the initial cell concentration was as high as 3,600 mg/*l* and

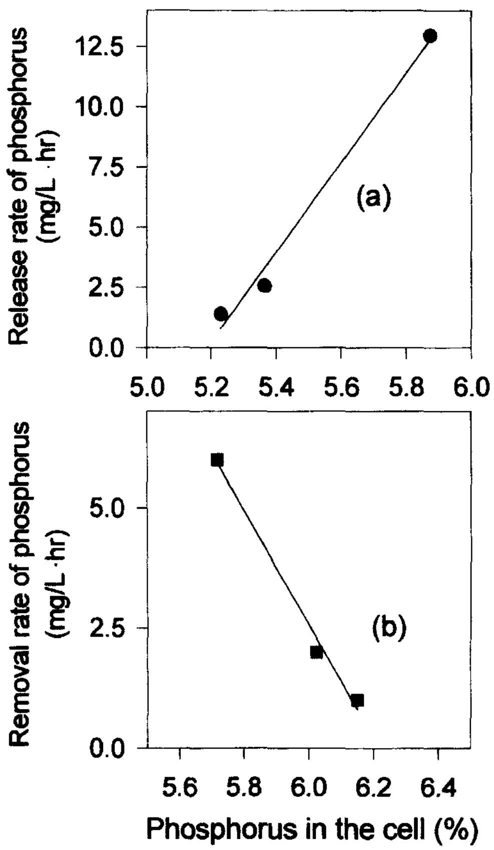

Fig. 6. Effect of phosphorus contents in a cell on the release and removal rate of phosphorus.

TOC was in the range from 100 to 2,000 mg/*l*. Since the cell yield on TOC was as low as 0.11, the amount of increased cells during aerobic operation was also very low. Therefore the cell mass was supposed to be constant during operation.

From the experimental results and related references,[13-15] the models describing the behavior of phosphorus and TOC in SBR system were suggested as follows.

(i) anaerobic condition

$$\frac{dC}{dt} = -\alpha_{\max,an}\left(\frac{C}{K_{C1,an}+C}\right)X \quad (1)$$

$$\frac{dP_b}{dt} = \nu_{\max,an}\left(\frac{C}{K_{C2,an}+C}\right)\left(\frac{P_c}{P_{\max}}\right)X \quad (2)$$

$$\frac{dP_c}{dt} = -\frac{1}{X}\left(\frac{dP_b}{dt}\right) = -\nu_{max,an}\left(\frac{C}{K_{C2,an}+C}\right)\left(\frac{P_c}{P_{\max}}\right) \quad (3)$$

(ii) aerobic condition

$$\frac{dC}{dt} = -\alpha_{\max,a}\left(\frac{C}{K_{C1,a}+C}\right)X \quad (4)$$

$$\frac{dP_b}{dt} = -\upsilon_{\max,a}\left(\frac{P_b}{K_{p,a}+P_b}\right)\left(1-\frac{P_c}{P_{\max}}\right)X \quad (5)$$

$$\frac{dP_c}{dt} = -\frac{1}{X}\left(\frac{dP_b}{dt}\right) = \upsilon_{\max,a}\left(\frac{P_b}{K_{p,a}+P_b}\right)\left(1-\frac{P_c}{P_{max}}\right) \quad (6)$$

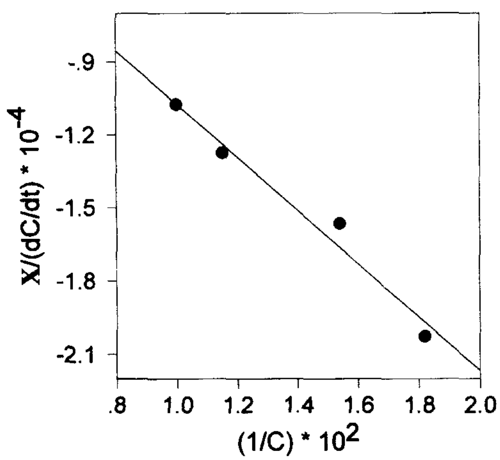

Fig. 7. Lineweaver-Burk plot of removal of TOC under the anaerobic condition.

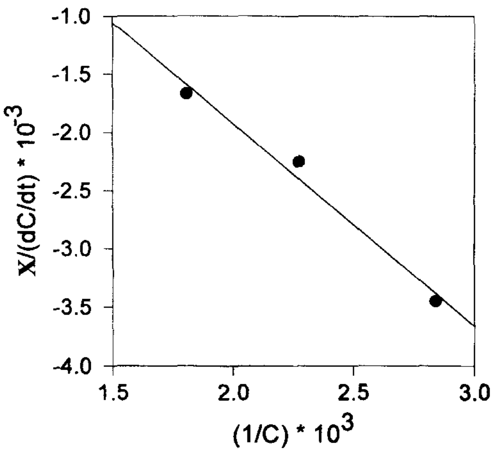

Fig. 8. Lineweaver-Burk plot of removal of TOC under the aerobic condition.

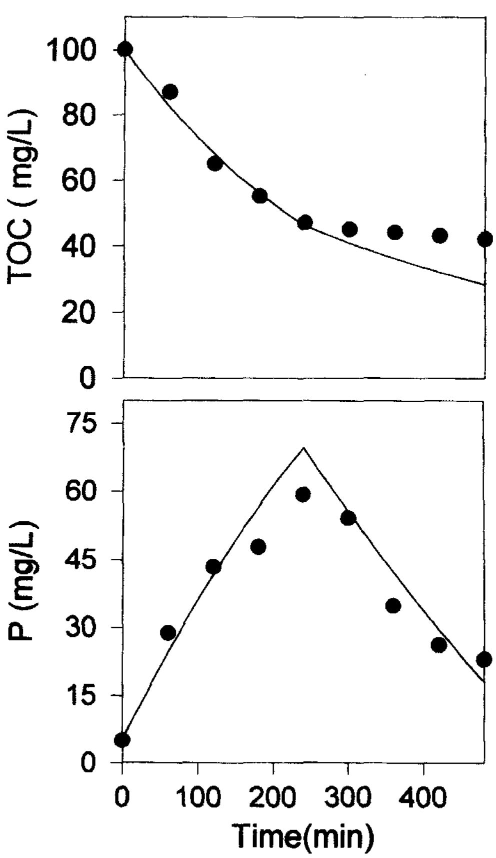

Fig. 9. Parameters estimation from curve fitting method.

Table 2. Parameter values for the simulation

Parameter	Value	Remark
$\alpha_{max,an}$	4.45×10^{-3} (1/min)	experimental
$K_{c1,an}$	4886 (mg/*l*)	experimental
$v_{max,an}$	3.50×10^{-4} (1/min)	estimated
P_{max}	0.18 (mg-P/mg-cell)	experimental
$K_{c2,an}$	12 (mg/*l*)	estimated
X	3600 (mg/*l*)	experimental
$\alpha_{max,a}$	6.48×10^{-4} (1/min)	experimental
$K_{c1,a}$	1124 (mg/*l*)	experimental
$\upsilon_{max,a}$	9.00×10^{-5} (1/min)	estimated
$K_{p,a}$	5.00 (mg/*l*)	estimated

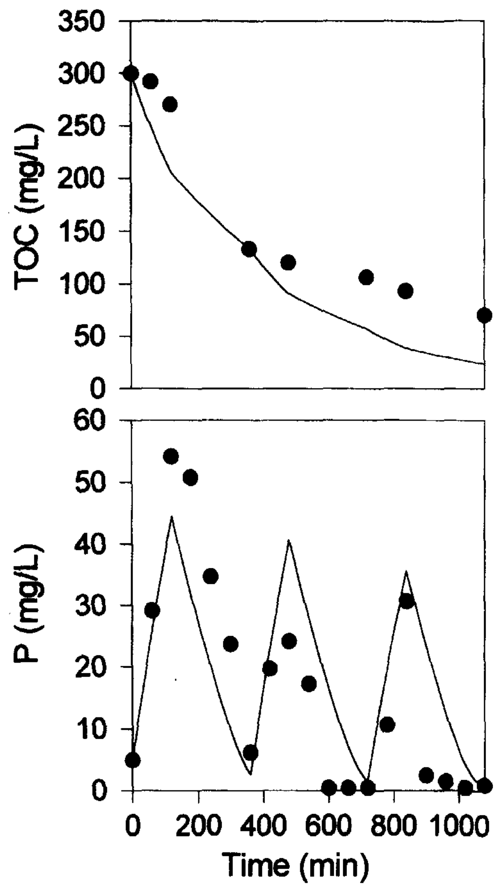

Fig. 10. Comparison of simulation results with experimental data under the cyclic operation of anaerobic and aerobic conditions. (initial conc. of phosphorus and TOC are 5 and 300 mg/*l*, respectively)

The parameters related to TOC removal were obtained through Lineweaver-Burk plot as shown in Fig. 7 and 8. The other parameters were estimated using the best fit to experimental data as shown in Fig. 9. And all parameters

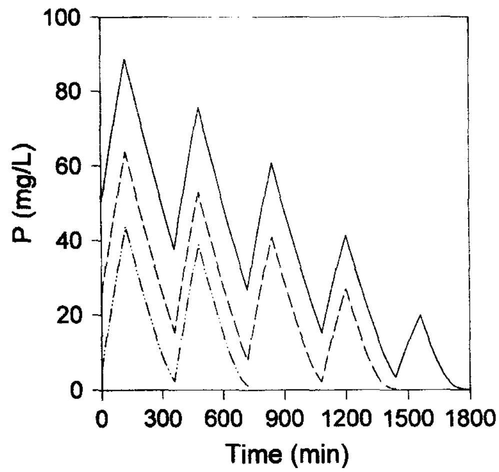

Fig. 11. Simulation for the effect of inital phosphorus concentration on phosphorus removal.
(———— : P ; 50 mg/*l*, TOC ; 2000 mg/*l*,
·················· : P ; 25 mg/*l*, TOC ;500 mg/*l*,
– – – – – – : P ; 5 mg/*l*, TOC ;300 mg/*l*)

were listed in Table 2. With these parameters, the simulation results well traced the behavior of phosphorus and TOC in a SBR system as shown in Fig. 10.

A simulation study for the effect of initial phosphorus concentration on phosphorus removal under the repeated anaerobic and aerobic conditions was conducted. And through experiments, it was found that 2 hours of of anaerobic and 4 hours of aerobic conditions were optimal one. As shown in Fig. 11, when the initial phosphorus concentration was 5 mg/*l*, two cycles of operation were required to remove phosphorus completely. And as the phosphorus concentration became higher, the more number of cycles was required to remove phosphorus. Therefore, if the concentration of phosphorus in wastewater is known, the required number of cycle operation can be estimated using these model equations.

IV. Conclusions

Quantitative analysis was conducted to investigate the effect of operation variables on the removal efficiency of phosphorus and TOC.

(1) The mathematical models on the removal of phosphorus and TOC under the repeated anaerobic and aerobic system were suggested. Microbial adaptation during repeated operations was considered by incorporating the term of phosphorus contents in a cell.

(2) The model well described the removal behavior of phosphorus and TOC and predicted the effect of operation variables on theremoval efficiency of TOC and phosphorus.

(3) when the initial phosphorus concentration was 5 mg/*l*, two cycles of operation were required to remove phosphorus completely, and as the phosphorus concentration became higher, the more number of cycles were required to remove phosphorus.

Nomenclature

P_b : phosphorus concentrations in broth (mg/*l*)
P_c : phosphorus content in cell (mg-phosphorus/mg-cell)
P_{max} : maximum phosphorus concentration that cell can accumulates (mg-phosphorus/mg-cell)
X : cell mass (mg/*l*)
C : TOC concentration (mg/*l*)
K_{C1} : half saturation constant TOC in the removal of TOC (mg/*l*)
K_{C2} : half saturation constant of TOC in the release of phosphorus(mg/*l*)
K_P :half saturation constant of phosphorus in the removal of phosphorus (mg/*l*)
t : time (min)

① Greeks
α : specific uptake rate of TOC (1/min)
υ : specific removal rate of phosphorus (1/min)
ν : specific release rate of phosphorus (1/min)
② Subscript
a : aerobic condition(–)
an : anaerobic condition (–)

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