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ORIGINAL ARTICLE

Comparison of Bio-P module and the Modified Bio-P module in the step-feed biological nutrient removal process

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Abstract The Modified Bio-P module was evaluated in terms of the kinetic rate expression and engineering parameters, comparing the measured data of full-scale plant with simulated data. To simulate step-feed BNR (Biological Nutrient Removal), the ASM3 (Activated Sludge Model 3) with the EAWAG Bio-P Module (The Swiss Federal Institute for Environmental Science and Technology) and the ASM3+Modified Bio-P module were used. The RMSEs (root mean square error) of the T-N (total nitrogen) concentration of the effluent levels of measured and simulated examples were 2.29 for ASM3+Bio-P and 1.28 for ASM3+Modified Bio-P. In the case of T-P (total phosphorus), the RMSEs were 0.28 for ASM3+Bio-P and 0.25 for ASM3+Modified Bio-P. The annual removal rates for T-N were 0.77 for the measured, 0.69 for the Bio-P, and 0.74 for the Modified Bio-P samples, while the annual removal rates for T-P were 0.64 for the measured, 0.72 for the Bio-P, and 0.60 for the Modified Bio-P cases. With simulated data, the Modified Bio-P model was a better fit for the field data compared to Bio-P. The Modified Bio-P module reproduced the step-feed process more effectively than the Bio-P module.

Keywords Activated sludge model 3 (ASM3) · Modified Bio-P · Bio-P · Biological nutrient removal (BNR) · Modeling

List of symbols

$Y_{STO,O2}$	Aerobic yield of stored product per S_s
$Y_{STO,NO}$	Anoxic yield of stored product per S_s
$Y_{H,O2}$	Aerobic yield of heterotrophic biomass
$Y_{H,NO}$	Anoxic yield of heterotrophic biomass
$Y_{PAO,O2}$	Yield biomass/X_{PHA}
Y_{PO4}	Requirement of X_{PP} per X_{PHA} storage (PO_4 release)
μ_H	Heterotrophic maximum growth rate of X_H
$b_{H,O2}$	Aerobic endogenous respiration rate of X_H
K_{STO}	Saturation constant for X_{STO}
μ_A	Autotrophic maximum growth rate of X_A
q_{PHA}	Rate constant for storage of X_{PHA}
q_{PP}	Rate constant for storage of X_{PP}
$\mu_{max,PAO}$	Saturation Constant for S_s (X_{PAO})

Introduction

As a mathematical approach to remove biological organic substances and nutrients, ASM1 (Activated sludge model 1) was developed by the IWA (International Water Association) Task Group in 1987. ASM3 (Activated sludge model 3) was introduced in 1999 to overcome the inherent limits discovered in the application of the ASM1 model in

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the 10 years after its introduction (Gujer et al. 1999; Henze et al. 2000).

In ASM1, the microbial activities of the heterotrophs and autotrophs involved in decomposing C and N are mathematically described. However, ASM1 did not include PAOs (phosphate accumulating organisms), thus disregarding biological phosphorus removal (BPR). ASM1 consecutively evolved into the ASM2, ASM2d, and ASM3 models. ASM3 as well did not include BPR, only considering the microbial storing response that was disregarded by the previous ASM 1 and ASM 2 series of models.

Therefore, the Bio-P module for the removal of phosphorus using ASM3 was developed by EAWAG (Rieger et al. 2001). However, this model, termed the ASM3+Bio-P module, does not consider circumstances in which the storing response of PHA (polyhydroxyalkanotate) decreases in the presence of NO_x–N (Lee et al. 2006a). Therefore, an advanced model known as the ASM3+Modified Bio-P module, will include BNR (N and P) considerations that are as yet unconsidered in the existing model, such as the uptake of nitrate in the process of storing PHA and the discharging of PO_4–P (Lee et al. 2006b).

An analysis of the properties of the influent and the assumption of the sensitivity levels of the parameters were made prior to reproducing the existing BNR (Biological Nutrient Removal) process using the Modified Bio-P module (Rho and Gil 2007a). When using the modified model, appropriate modeling with an optimum operating factor would increase the efficiency of the nutrient treatment—when the influx fluctuates at various C/N ratios of biodegradable COD (chemical oxygen demand)/TKN (total kjeldahl nitrogen) ratios (Rho and Gil 2007b).

This study investigates the advanced performance of the ASM3+Modified Bio-P module by comparing the performance levels with the existing Bio-P module and the Modified Bio-P module. One-year field data including the BNR process were used for this comparison. In addition, for the measurement of the performance efficiency, reproduction of the data was done by manipulating the C/N ratios and the C/P ratios in the influent.

When a sewage treatment plant has inflow with a low C/N ratio, external carbon should be added to the reactor and the adjustment of the step-feeding operation is required in order to induce successful denitrification and phosphorus release process. In this situation, the Modified Bio-P model is a tool for determining the amount of carbon required and the injection time via the simulated results.

Description of the process

Sewage data were obtained from the Ji-San sewage treatment plant, located in Daegu County, South Korea. Sewage sludge contains a large amount of water-soluble phosphorus, which is contributable to runoff when sewage sludge is used for land applications. Phosphorus loss from sewage sludge is an important issue for eutrophication (Liang et al. 2010). The Ji-San sewage treatment plant has adopted the BNR process as its advanced sewage treatment process. The sewage treatment plant in this study consists of a pre-denitrification tank, an anaerobic tank, the first anoxic tank, the second anoxic tank and an expiration tank. The step-feed process is applied in order to solve the problem of influx with a low C/N ratio and to use the carbon substances in the influent water efficiently.

A pre-denitrification tank was installed to prevent an obstruction response in the process of storing PHA potentially caused by NO_x–N remaining in the return sludge. $0.1Q$ was injected out of the total volume (Q) for effective denitrification. $0.6Q$ of influent volume was injected into the anaerobic tank for storing PHA, and $0.3Q$ of influent was injected into the second anoxic tank, where the denitrification process takes place. The produced sludge is transported to another treatment plant for solid handling. A simplified diagram of the processes used with the Bio-P module and the Modified Bio-P module is shown in Fig. 1.

ASM3+Bio-P/ASM3+Modified Bio-P

ASM1 when developed by IWA had a clear influence on the consumption of oxygen by subordinate nutritious microbes and on the denitrification process. In fact, the dynamic coefficients in this complex process are difficult to estimate, as the process is affected by various factors, such as the decomposition of microbes, hydrolysis, and the storage of the substrate. In addition, ASM1 did not consider the possibility that the endogenous respiration rates of nitrate microbes under aerobic and anoxic conditions could be different. ASM3 addresses the weaknesses of ASM1 (IWA, 2000). Therefore, EAWAG developed the Bio-P module as a sub-model to remove phosphorus in support of the ASM3 model.

The difference between the Bio-P module and the Modified Bio-P module is that the latter module considers the possibility of an obstruction of the response when the concentration of NO_x–N is larger than a specific value during the phosphorus discharge response and the storage of PHA as a result of PAOs (Phosphate Accumulating Organisms). The obstructing factor was added to the storing reaction equation of PHA to apply this circumstance to the newer model through the following dynamic equation:

$$q_{\mathrm{PHA}} \frac{S_{\mathrm{S}}}{K_{\mathrm{SS,PAO}} + S_{\mathrm{S}}} \frac{S_{\mathrm{HCO}}}{K_{\mathrm{HCO,PAO}} + S_{\mathrm{HCO}}} \frac{X_{\mathrm{PP}}/X_{\mathrm{PAO}}}{K_{\mathrm{PP,PAO}} + X_{\mathrm{PP}}/X_{\mathrm{PAO}}} \times \frac{K_{\mathrm{I,NO,PAO}}}{K_{\mathrm{I,NO,PAO}} + S_{\mathrm{NO}}} X_{\mathrm{PAO}}$$

where, $K_{\mathrm{I,NO,PAO}}$ is the parameter that expresses the obstructing effect of NO_x on the phosphorus discharging

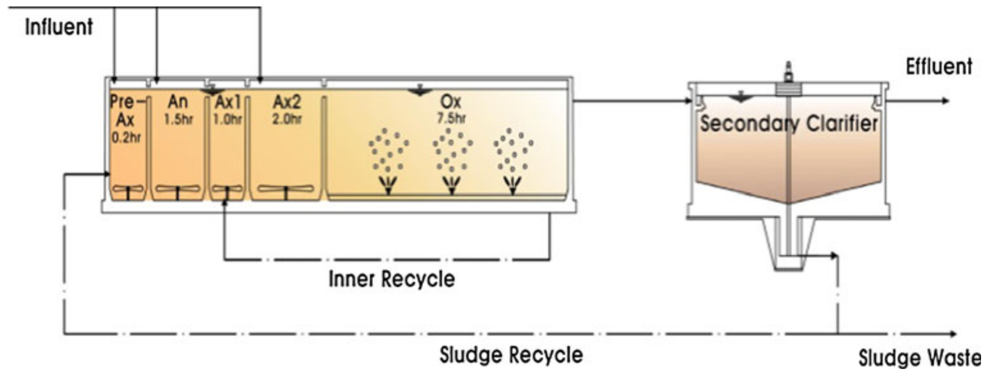

Fig. 1 Schematic diagram of the step-feed BNR process

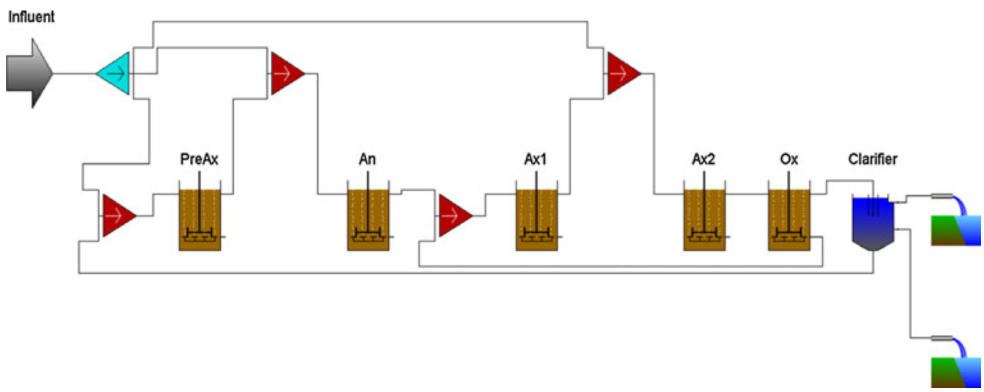

Fig. 2 GPS-X simulation layout for the modeling procedure

function of the PAOs. Its value is 0.05 mg/L (Lee et al. 2006c).

Modeling conditions and simulation procedures

The initial data of 100 days of operation out of 300 days at the Ji-San sewage treatment plant were used for the analysis of sensitivity levels of the parameters and their optimum values. The data of 200 days were used to reproduce the two models with an application of the optimized parameters. The operating conditions for this modeling procedure were an MLSS amount of 2,500 mg/L, an internal recycle ratio of 150%, a sludge recycle ratio of 85%, a SRT (Solid Retention Time) of 35 days, and an operating temperature of 13–28°C. The quantity and quality of the influent from the Ji-San sewage treatment plant were used for a dynamic simulation of the model.

The HRTs (Hydraulic Retention Times) for pre-denitrification, anaerobic, the first anoxic process, the second anoxic process, and for the expiration tanks were 0.2, 1.5, 1.0, 2.0, and 7.5 h, respectively. The average residence time in the final sedimentation basin was 7 h. The simulation layout was prepared using GPS-X (Hydromantis) for the optimization of the parameters, analysis of the influent and the dynamic simulation. This is shown in Fig. 2. In terms of software, ASM3 was included in GPS-X, but the EAWAG Bio-P module and the Modified Bio-P module were not installed. Therefore, GPS-X was used after data installation through the Model Developer software package. The simulation procedure is presented in the flow diagram in Fig. 3.

Simulation of two models using the optimized parameters

The two models were simulated using the optimized parameters of the ASM3+Bio-P module, which were also used for the ASM3+Modified Bio-P module. As a result, ten dynamic and disputable parameters were found. The optimized parameters for the ASM3+Modified Bio-P module are presented in Table 1. In addition, the differences in the values between the application of the default parameters to the two models and the application of the parameters with changes of the default parameters within 50–200% during the simulations were successfully identified through the WSSNE (weighted sum of squared normalized error) and the estimated sensitive parameters.

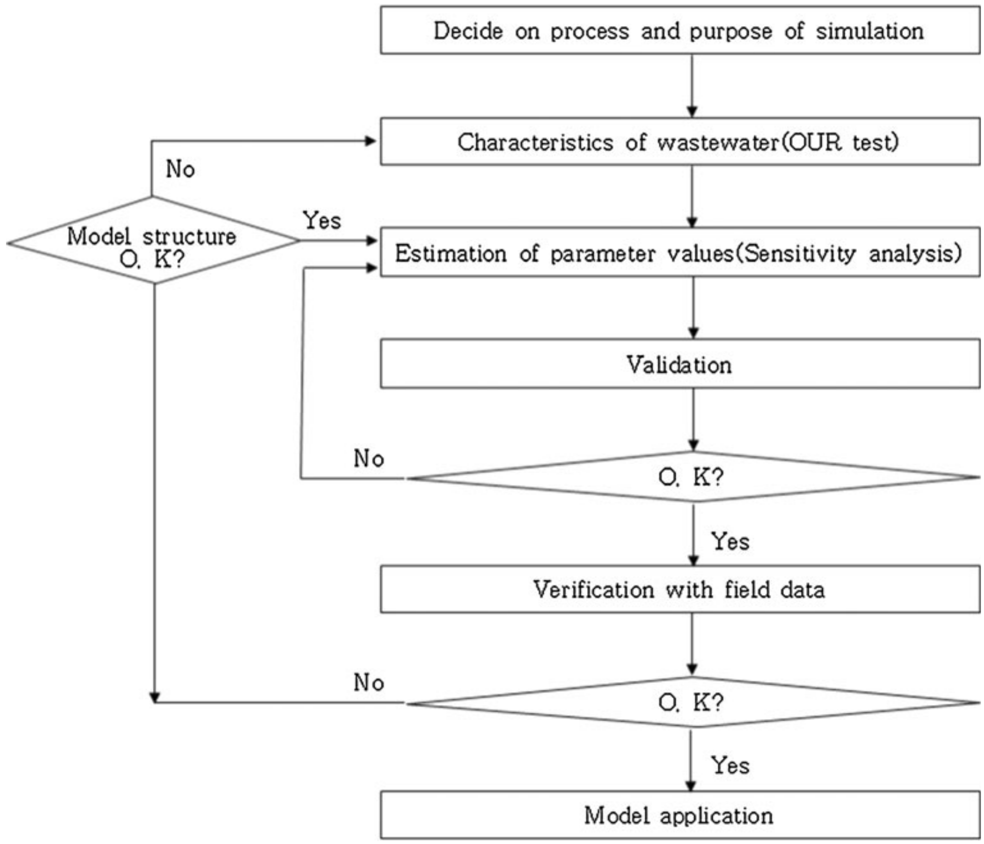

Fig. 3 Flow chart of the simulation procedure

Table 1 Estimated sensitive parameters of ASM3+Bio-P and ASM3+Modified Bio-P

ASM3+Bio-P			ASM3+Modified Bio-P		
Parameter	Default	Estimated	Parameter	Default	Estimated
$Y_{STO,NO}$	0.8	0.56	$Y_{STO,O2}$	0.85	0.7
$Y_{H,O2}$	0.63	0.57	$Y_{STO,NO}$	0.8	0.64
$Y_{H,NO}$	0.54	0.38	$Y_{H,O2}$	0.63	0.61
$Y_{PAO,O2}$	0.6	0.8	$Y_{H,NO}$	0.54	0.48
Y_{PO4}	0.35	0.25	Y_{PO4}	0.35	0.31
b_H	0.2	0.1	μ_H	2.0	3.9
μ_A	1.0	2.2	b_H	0.2	0.1
q_{PHA}	6.0	7.2	μ_A	1.0	1.35
q_{PP}	1.5	2.5	q_{PHA}	6.0	4.98
K_{STO}	5.0	7.4	q_{PP}	1.5	1.8
			$\mu_{max,PAO}$	1.0	0.59
WSSNE	984.3	423.5	WSSNE	881.5	264.4

$$\mathrm{WSSNE} = \mathrm{wf}_1 \times \mathrm{wf}_2 \sum_{j=1}^{m} \sum_{i=1}^{nj} \left[\frac{C_{i,t,\text{default parameters}} - C_{i,t,\text{changed parameters}}}{C_{i,t,\text{default parameters}}} \right]^2$$

In this equation, the variables are defined as follows:

$C_{i,t}$ is the concentration of i at time, t, in the effluent and in-process, i components (TSS, BOD, TN, TP, NH_4^+–N, NO_3^-–N, or PO_4^{3-}–P), wf_1 is the weighting factor; 5 for effluent and 1 for in-process, wf_2 is the weighting factor; 2 for TN, TP, NH_4^+–N, NO_3^-–N and PO_4^{3-}–P; 1 for TSS, BOD.

The Bio-P module and the Modified Bio-P module were compared in terms of the effluent quality. The densities of the effluent T-N (total nitrogen) and T-P (total phosphorus) from the simulations using field data from the Ji-san sewage treatment plant with each model were also compared to evaluate the accuracy of the assessed models, as shown in

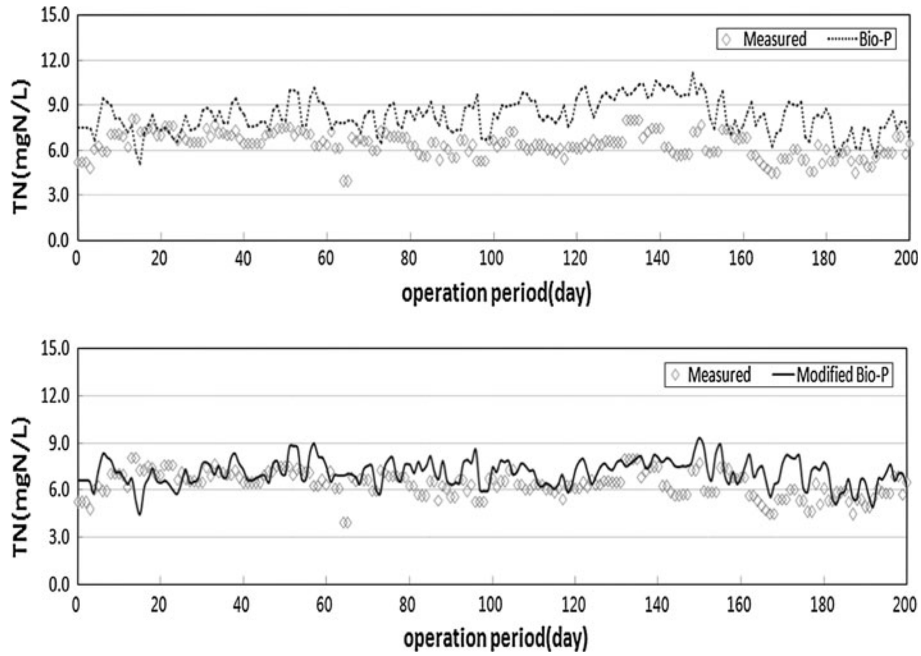

Fig. 4 Comparison of Bio-P and Modified Bio-P with measurements: T-N

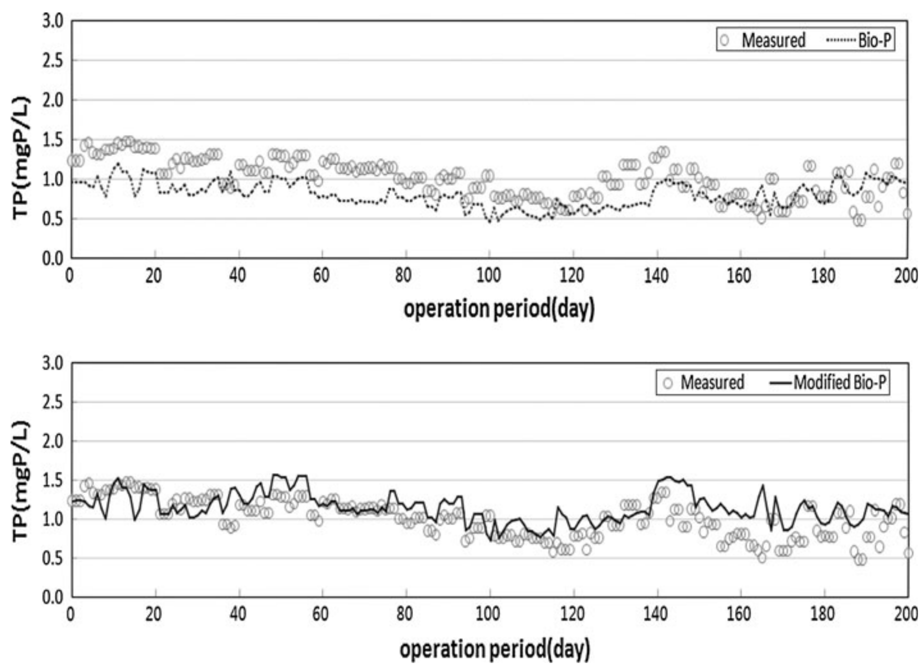

Fig. 5 Comparison of Bio-P and Modified Bio-P with measurements: T-P

Table 2 Root mean square error (RMSE) of the effluent concentration differences

Component	Bio-P	Modified Bio-P
T-N	2.289	1.279
T-P	0.298	0.251

Figs. 4 and 5. The following equations were used to calculate the RMSE (root mean square error), as described in Table 2, showing the mathematical deficiency between the field data and the simulated data.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(C_i - C_i^{'})^2}{N}}$$

where C_i is the measured data, $C_i^{'}$ is the simulation data, N is the number of data.

Changes in the C/N ratio

Wastewater treatment plants employing biological nitrogen removal frequently encounter problems arising from shock loads of organics or nitrogen materials. Shock load control is significant, because nitrifiers are very sensitive to these factors and because a deteriorated nitrification process cannot be easily recovered (Wei et al. 2010). To identify the change in the response speed of the PAOs and denitrifiers when there are sufficient or insufficient supplies of carbon sources in the response tank, artificial conditions for simulations were prepared that were identical to the operating conditions at the Ji-San sewage treatment plant, and simulations were performed regarding the application of the Bio-P and the Modified Bio-P modules while changing the C/N ratio from 2 to 7. Figures 6 and 7 show the results of a comparison between the T-N and T-P densities in the final effluent from the existing Bio-P module and after modeling the ASM3+Modified Bio-P module which considers the obstruction response of NO_x–N on the storage of PHA. The purpose of this modeling was to determine the influence of the response speed of PAOs and the denitrifiers on the removed nutrients and to determine if the response speeds of the PAOs and the denitrifiers are affected by the modeling process.

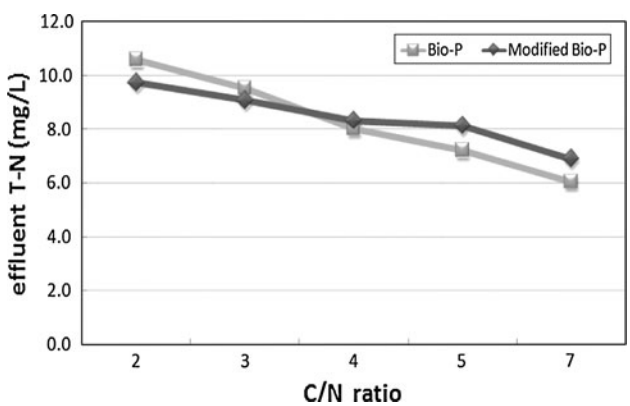

Fig. 6 Comparison of the simulated effluent T-N concentrations versus the C/N ratios

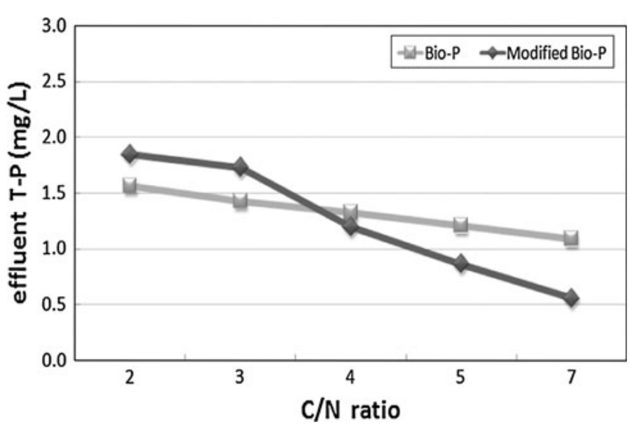

Fig. 7 Comparison of the simulated effluent T-P concentrations versus the C/N ratios

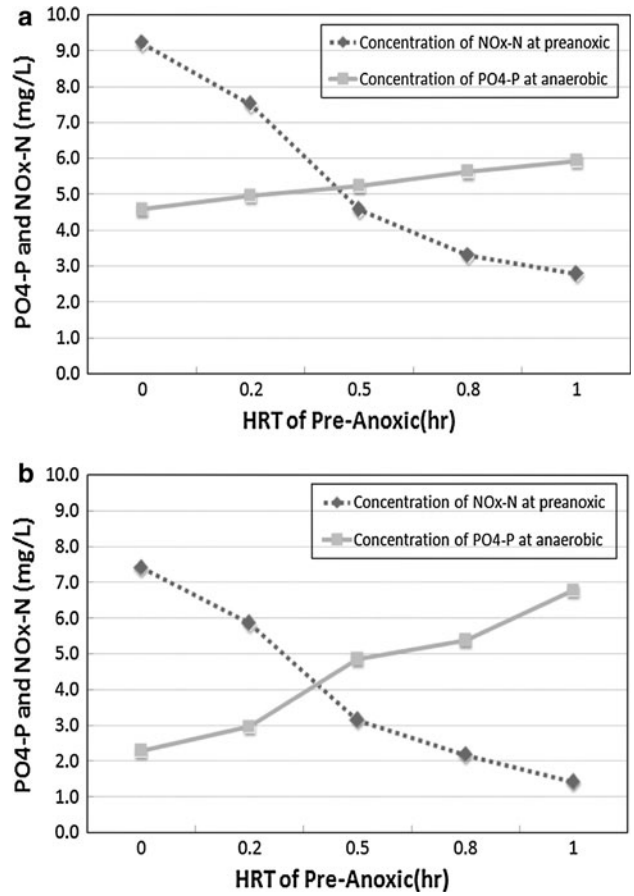

Fig. 8 PO_4–P and NO_x–N concentrations at each HRT of the Pre-Anoxic Tank: (**a**) Bio-P and (**b**) Modified Bio-P

Changes of HRT in the pre-anoxic tank

To compare the obstruction response of the nitrates directly against the discharge of phosphorus from PAO, different HRTs were simulated in the pre-denitrification tank. If denitrification does not effectively occur, NO_x–N in the return sludge is moved into the anaerobic tank. In this situation, a uniform amount of influent containing carbon substances was allowed into the pre-denitrification tank after changes in the capacity of the tank and control of the response time of HRT from 0 to 1 h. Figure 8a, b shows the comparison between the densities of NO_x–N from the denitrification response of the denitrifiers in the pre-denitrification tank and those of PO_4–P from the discharge response of phosphorus from the anaerobic tank.

Results and discussion

Comparison of the models with the estimated parameters

The results of the simulation of the T-N concentration in the effluent, Fig. 4, showed that modeling by Modified

Bio-P produced lower results than that by Bio-P. In the case of Bio-P, no association was noted between the discharge responses of X_{PAO} and the denitrification response of X_{HD} regarding the carbon substances. Thus, with the same amount of carbon substances, the concentration of T-N in the effluent from Modified Bio-P was lower, as the concentration of NO_x affects the discharge response of phosphorus in X_{PAO}. Overall for T-N, the concentration in the effluent by Modified Bio-P was lower than that of Bio-P. As shown in Table 2, the error in the result between the simulated data and the field data of Modified Bio-P was 1.279, whereas it was 1.908 for Bio-P. Therefore, Modified Bio-P is shown to reproduce field data with greater accuracy.

However, the T-P concentration in the effluent of Modified Bio-P was higher than that of Bio-P. Regarding the results of the actual simulation, the T-P concentration in the effluent of Bio-P was lower, as shown in Fig. 5. With Modified Bio-P, the reproduced data showed an error result of 0.047, which is less than that noted with the field data. Modified Bio-P module data were a good fit for the field data for both nitrogen and phosphorus. The minor differences in the results imply that modeling while considering the competition between PAOs and denitrifiers is more accurate than modeling with Bio-P.

Comparison of reproduced results after changes in the C/N ratio

In the case of T-N in Fig. 6, when the C/N ratio was low, the T-N concentration in the effluent of Modified Bio-P was lower than the T-N concentration in the effluent of Bio-P. However, when the C/N ratio increased, the T-N concentration became higher for Modified Bio-P. On the other hand, in the case of T-P, the opposite results were shown, as in Fig. 7 when the C/N ratio was low, Bio-P resulted in better treatment efficiency than Modified Bio-P.

It appears that if a sufficient amount of carbon substance is not supplied, Modified Bio-P has better removal efficiency for nitrogen, as denitrification occurs in advance provided that NO_x exists. In contrast, Modified Bio-P results in lower removal efficiency for phosphorus compared to that of Bio-P, as the proper oxidation of phosphorus in an anaerobic tank does not occur. With a sufficient amount of carbon substance, the carbon substance in sewage flowing into a pre-anoxic tank and an anaerobic tank will be consumed for sufficient denitrification of denitrifiers and for the PHA storing of PAOs. Therefore, Modified Bio-P produces a better effluent quality of nitrogen than the result for Bio-P, but amount of carbon substances flowing into the second anoxic tank will decrease after the response. Thus, the amount of carbon substance in the second anoxic tank in the Modified Bio-P case is <that of Bio-P. It is very likely that the nitrogen concentration in the effluent of Modified Bio-P is lower than that of Bio-P.

Changes in the P-release rate due to changes in the pre-anoxic tank HRT

Figure 8 shows the results from the simulations of the concentration of PO_4–P in the effluent from the anaerobic tank and the concentration of NO_x in the effluent from the pre-denitrification tank with different HRTs. In Fig. 8, (a) is the result of the simulation with Bio-P and (b) is the result with Modified Bio-P. Bio-P shows relatively little change in the phosphorus discharged from the anaerobic tank when the concentration of NO_x in the effluent is decreased, but Modified Bio-P clearly increased the amount of phosphorus oxidized from the anaerobic tank when the concentration of NO_x in the effluent is decreased. This suggests NO_x in the effluent from the anaerobic has a negative effect in the case of Modified Bio-P, whereas for the case of Bio-P, there was no negative effect. Therefore, the equations applied to the Modified Bio-P model represent the obstruction responses quite accurately.

Annual removal amounts of T-N and T-P

The annual amounts of T-N and T-P in the influent and effluent during the period when the model was applied to the Ji-san sewage treatment plant were 250,874.3 kg of influent and 58,997.0 kg of effluent for T-N and 26,110.6 kg of influent and 9,320.5 kg of effluent for T-P. The results of the simulations with ASM3+Bio-P and ASM3+Modified Bio-P are compared to the measured values in Table 3.

The actual annual removal rate of T-N was 76.5%. Modified Bio-P had a T-N removal rate of 74.2%, which was 2.3% <the actual value, while Bio-P had a removal rate of 69.5%, which was 7.0% <the actual value. This indicates that, under the same condition with a limited amount of carbon substance, the removal efficiency of nitrogen was better for Modified Bio-P, as its value was closer to the actual measured value. Bio-P had a T-P removal rate of 71.7% which was 7.4% better than the actual annual removal rate of 64.3%, while Modified Bio-P

Table 3 The Annual Influent Amounts and Effluent Mass of T-N and T-P (kg/year)

Component	Influent	Effluent		
		Bio-P	Measured	Modified Bio-P
T-N	250874	76427.1	58997.0	64848.8
T-P	26110.6	7390.70	9320.50	10579.2

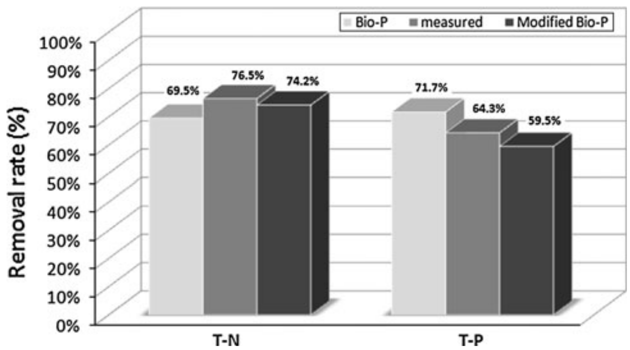

Fig. 9 Comparison between the measured and simulated (Bio-P and Modified Bio-P) values in terms of the annual removal rates of T-N and T-P

had a removal rate of 59.5%, which was 4.8% <the actual value. Modified Bio-P showed lower treatment efficiency of its phosphorus removal capability due to the adverse effect on NO_x–N given the storage of PHA. In Fig. 9, a comparison of the annual removal rates for T-N and T-P is presented.

Conclusion

A comparative study was made for a simulation of the Modified Bio-P module and a simulation of the existing Bio-P module. It measured the feasibility of the application of the Modified Bio-P module and evaluated the performances of the two models with simulated wastewater from a wastewater treatment plant. The following conclusions were drawn:

1. The Modified Bio-P module reproduced the step-feed process more effectively compared to the Bio-P module. NO_x acts as an inhibiting factor by storing PHA, and this consideration was applied to the model. Therefore, its reproduction accuracy is different from that of a model without an inhibiting factor.
2. In the case of a low C/N ratio, for T-N removal, Modified Bio-P resulted in a better water quality for treated water than that by Bio-P. For T-P, Bio-P had a lower concentration than Modified Bio-P. This is due to the relationship between the denitrifiers and the PAOs as a carbon substance applied to Modified Bio-p. The treatment efficiency of nitrogen removal with a limited amount of carbon substances has increased.
3. In the simulation result of T-P, a higher C/N ratio led to worse water quality for Modified Bio-P compared to Bio-P. The treatment efficiency of phosphorus was better for Bio-P, as a sufficient denitrification response in the pre-denitrification tank resulted in an anaerobic condition in the anaerobic tank. This is advantageous to PHA storage. However, the removal efficiency of nitrogen deteriorates due to the reduced amount of carbon substances flowing into the second denitrification tank.
4. By reproducing the two models with changes in the capacity of the pre-denitrification tank, in the case of the Bio-P module, the amount of oxidized phosphorus from the anaerobic condition was not affected by changes in the denitrification efficiency in the pre-denitrification tank. However, there were variations for the Modified Bio-P module due to the competition between the PAOs and the denitrifiers.

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