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SIMULATION OF THE OPERATIONAL CONDITIONS OF THE FULL-SCALE MUNICIPAL WASTEWATER TREATMENT PLANT TO IMPROVE THE PERFORMANCE OF NUTRIENT REMOVAL

Naoyuki Funamizu, Shoichiro Yamamoto, Yoshio Kitagawa and Tetsuo Takakuwa

Department of Environmental Engineering, Hokkaido University

ABSTRACT

Simulation analysis based on a mathematical model is one of the powerful tools for determining the operational conditions for a full scale biological nutrient removal plant. The model that included the Activated Sludge Model No.2 was developed for simulating the performance of the plant in Sapporo City. The investigated plant has the biological reaction basin which consists of the four zones, anaerobic-aerobic-anoxic-aerobic phases with the step feed of the primary effluent to the anaerobic and anoxic zones. We performed three experiments to calibrate and verify our model: (i) Characterization of organic matters in the influent with the OUR test; (ii) Measurement of COD and nutrient concentration at the plant; (iii) Lab-scale batch experiments with the anaerobic-aerobic-anoxic-aerobic phases. The calibrating process showed that no modification of parameter values was required to evaluate the performance and population of the activated sludge. Simulated results showed that the choice of the sewage step feed ratio did not affect the nitrogen removal and that the denitrification rate in the anoxic zone was controlled by the hydrolysis rate of the slowly biodegradable organic matters. The results of the lab-scale experiment and simulation showed that the addition of the readily biodegradable organic matters like fermentation products of the primary settler sludge was effective to improve the performance of nitrogen removal.

INTRODUCTION

In upgrading the existing wastewater treatment plants which were designed originally only for carbon oxidation to treat nutrients, one of the most cost-effective solution is to create anaerobic, anoxic and aerobic zones within the existing reactor volumes, if the plants are not overloaded and have enough capacity to maintain nitrifying bacteria (Coen et. al., 1996). Setting the appropriate operating conditions is the key factor for the plant upgraded without the extension of reactor volumes. The Activated Sludge Models (Henze et al., 1987; 1995) have been frequently used to predict the performance of wastewater treatment plants, and simulation has become a powerful tool for operation and design of a wastewater treatment plant (Pedersen and Sinkjaer, 1992; Funamizu and Takakuwa, 1994). The objective of the study presented in this paper is to examine the appropriate operating conditions for the upgraded plant in Sapporo City by simulation analysis and lab-scale experiments.

METHODS

Description of the investigated plant
The plant investigated treats about 93500m³/day of wastewater during dry weather. This plant has two treatment trains . Each train has a primary settler, a biological reaction basin of the plug flow type with step feed line, and a final clarifier. One train is being operated as nutrient removal process and treats 51600m³/day of wastewater. The biological reaction basin has four zones as depicted in Fig.1. Since this plant had been designed as a conventional plug-flow type activated
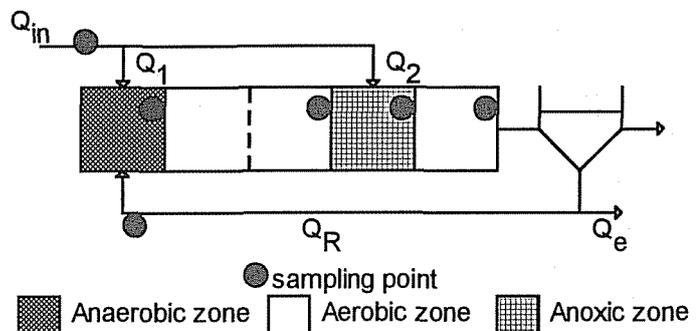

Fig. 1. Schematic description of the investigated plant

sludge system with step-feed lines, it was easy to change its operation scheme from a conventional to a nutrient removal process by reducing air supply in the zone 1 and 3.

Computer Simulation Model　　The biological reactions and the performance of the final clarifier were modeled in this study. The Activated Sludge Model No.2 was employed as the model for biological reactions. The flow scheme of the reaction basin was approximate with 10 complete mixing tanks in series. The clarification performance of the final clarifier was modeled by using the empirical formula by Chapman (1984). The regression analysis based on data from the plant yielded the following relationship:

$$X_{eff} = 8.12 + 0.0073\,L_P - 0.00048\,X_{f,in} \tag{1}$$

where X_{eff} and $X_{f,in}$ are solid concentrations (g/m^3) of effluent and influent, respectively, and L_p is the over flow rate (m/day). The solid concentration of the sludge from the final clarifier, X_u, was estimated by the flow volume and solid mass balance equations at the steady state.

Wastewater Characterization and Collecting of data at the investigated plant
COD and nutrient were measured at 6 sampling points as shown in Fig.1, and they were compared with the computed results from the steady state simulation. Since the content of readily biodegradable organic matter available as carbon source in the raw water is the limiting factor for the biological nutrient removal process (Barlindhaug and Ødegaard, 1996), fractions of organic matters in the primary effluent were measured. The Respiration test (Gujer and Kappeler, 1992), effluent COD analysis as well as total COD and volatile acids measurement were employed to classify organic matters into the readily biodegradable substrate S_F, volatile acid S_A, slowly biodegradable substrate X_S, heterotrophic biomass X_H, inert soluble organics S_I and inert particulate organics X_I. The biomass of phosphorus-accumulating bacteria and nitrifying organisms in the primary effluent were assumed to be negligible.

Lab-scale batch experiment　　In order to check the model with data from the unsteady state experiment, the lab-scale batch experiments were performed with 3L vessel at 20°C. The batch experiment consisted of four phases: (i)1.6h anaerobic phase. At the beginning of the anaerobic phase, V_r of the return sludge and V_1 of the primary effluent from the plant were mixed. N_2 gas was supplied through the diffusor. (ii) 3.2h aerobic phase. (iii) 1.6h anoxic phase. At the beginning of this phase, V_2 of the primary effluent was mixed again. This operation corresponded to the step feed of the

actual plant. (iv) 1.6h aerobic phase. We set the volume ratio V_2: (V_1+V_2) corresponding to the actual ratio of the step feed flow rate Q_2 : (Q_1+Q_2) in the plant. We call this ratio the step feed ratio in this paper. The ratio V_r : (V_1+V_2) was set corresponding to the actual sludge recycling ratio (= [return sludge flow rate] / [primary effluent flow rate]).
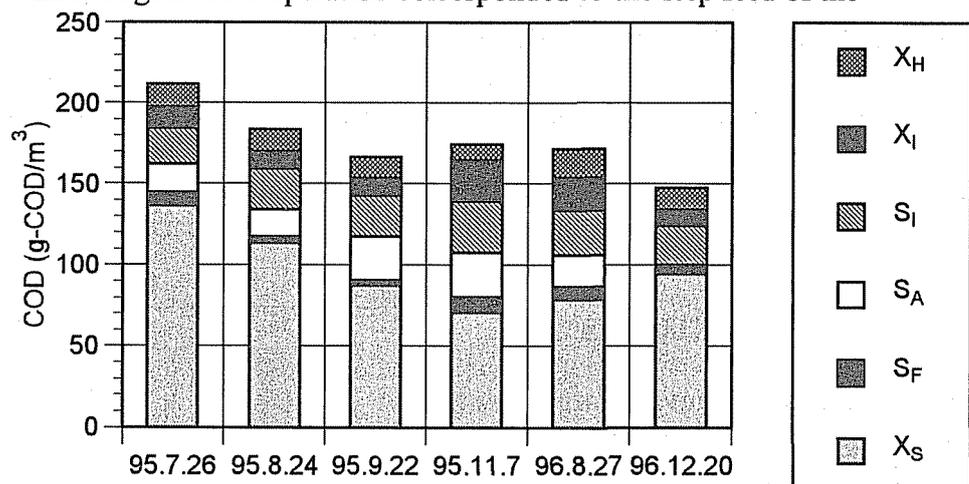

Fig.2. Fractions of organic matters in the primary effluent

Analytical methods　　All samples except for COD analysis were prefiltered with 0.45μm membrane filters. COD was analyzed according to Standard Methods (1989). NH_4-N, NO_3-N, PO_4-P, and volatile acids concentrations were determined using an ion chromatography.

1: anaerobic zone, 2 and 4: aerobic zone, 3: anoxic zone
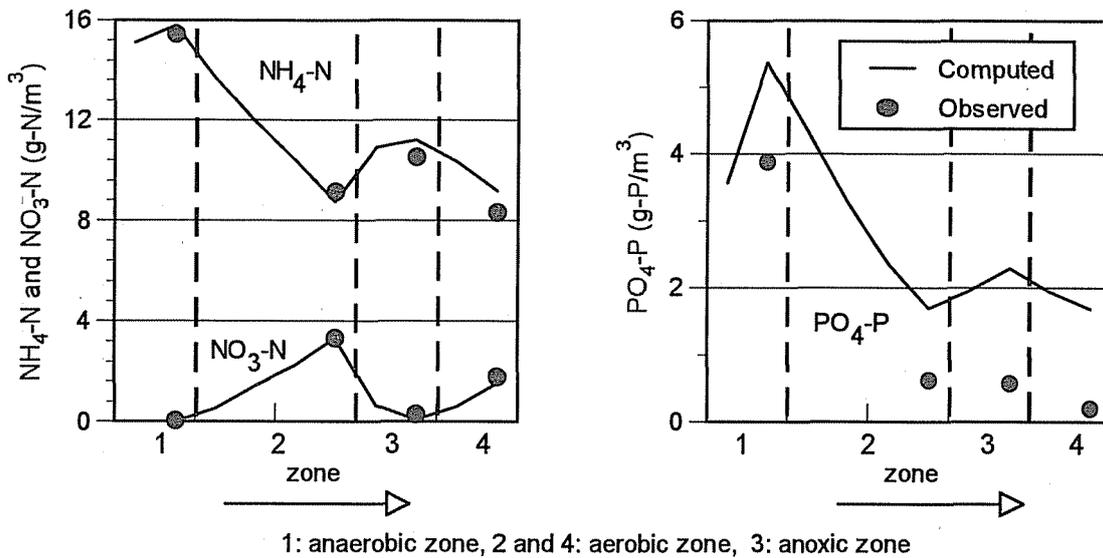
Fig. 3. Comparison of computed results with plant data

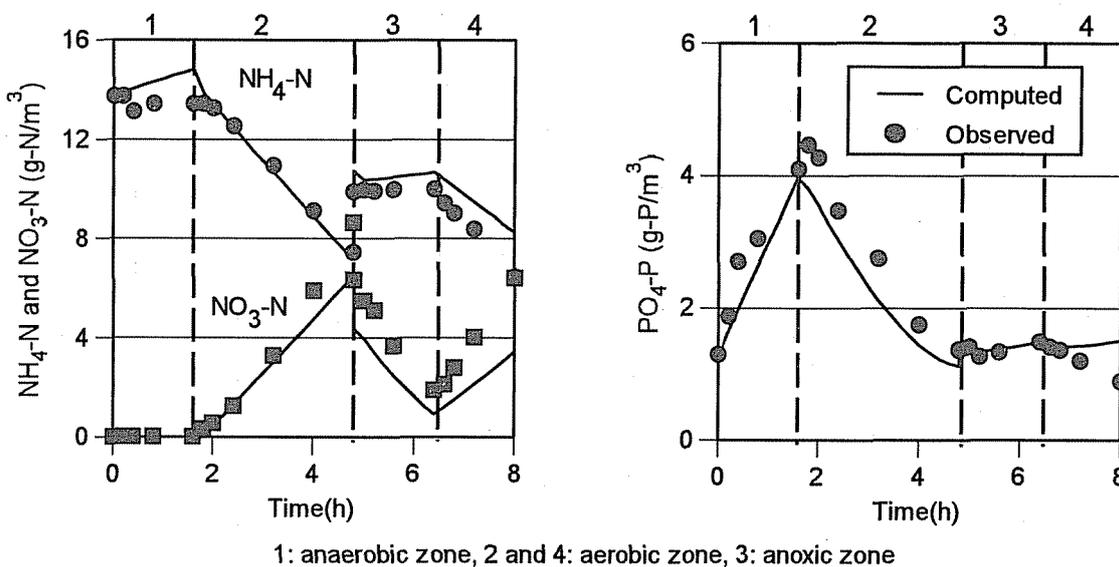1: anaerobic zone, 2 and 4: aerobic zone, 3: anoxic zone

Fig. 4. Comparison of computed results with data from batch experiments

RESULTS

Comparison of simulated results with measured data

The fractions of organic matters in the primary effluent. Figure 2 shows the fractions of organic matters in the primary effluent. The total COD concentration in the primary effluent ranged from 150 to 210 g/m^3 in the 6 samples. It contained 40-65% of X_S, 2-5% of S_F, 0-15% of S_A, 16-32% of S_I and X_I. The heterotrophic biomass occupied almost 6-10% of organic matters.

Comparison with data from the investigated plant. Figure 3 shows the comparison of the simulated results with the data from the plant on 95/7/26. It is seen from Fig.3 that the simulation model yielded thereasonable results. It should be noted that no modifications of parameter values were required in the calibration process of the full scale plant.

Comparison with data from the laboratory scale experiment. In simulation of the batch process, we utilized the computed bacteria population in the return sludge, that was calculated by the steady state simulation for the plant. The comparison in Fig. 4 shows that the model can simulate the nitrification process in the aerobic zone, the denitrification rate in the anoxic period as well as the phosphate release in the anaerobic phase.

The effect of step feed ratio on nutrient removal performance The operational parameters in the investigated plant were the sludge return flow rate, the excess sludge withdrawal rate and the step feed flow rate. Among them we chose the step feed flow rate as the operational variable. Figure 5 shows the computed results for the plant with the primary effluent 95/7/26, showing the influence of the step feed ratio on the total nitrogen removal performance. Simulated results shows that the choice of the step feed ratio can not improve the nitrogen removal. Nitrogen is removed as N_2 gas from the denitrification process as well as by the biomass in the excess sludge from the plant. Since the return sludge contained nitrate nitrogen, denitrification occurred both in the anaerobic zone and the anoxic zone of the investigated plant. It is seen from Figs.5 that the step feed ratio probably controls the N_2 gas production in the anaerobic and the anoxic zone, but the feed ratio can not affect the total N_2 gas production from the plant.

In an anaerobic-aerobic phosphorus removal and denitrification/nitrification system, the optimal phosphorus and nitrogen removal are obtained at about 7.4g COD/g-N in the influent according to Kuba (1996). On the other hand, in the primary effluent 95/7/26 that was used for the simulation in Figs.5, the concentration of the total biodegradable COD , i.e., $S_A + S_F + X_S$, was 162g COD/m^3, and T-N was 30.3 g-N/m^3. Hence the COD/N ratio was about 5.3. Thus this value showed that there was not enough organic matters in the primary effluent to remove all nitrogen. Furthermore, the COD/N ratio based on the readily biodegradable organic matters, $S_A + S_F$, was about 1.4. This implied the reaction rate was low in the denitrification process. The lab-scale batch test was performed to observe the nitrate nitrogen reduction rate in the anoxic phase. In the experiment, the return sludge, the primary effluent and 20 g-N/m^3 of nitrate nitrogen were mixed with N_2 gas, the time course of the nitrate

Fig 5. Effect of the step feed ratio on nitrogen removal. Sludge recycle ratio=0.4. Qe=750m^3/day.
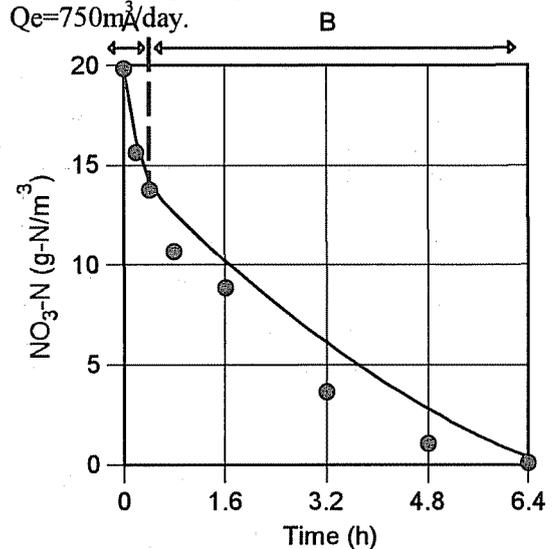
Fig.6. Time course of nitrate nitrogen in the anoxic zone

nitrogen was measured. The data and computed results in Fig. 6 show that there are two periods in the nitrogen reduction process: Period A has the high reaction rate because the readily biodegradable organic matters are utilized mainly for denitrification. Period B is the stage where the anoxic hydrolysis rate of the slowly biodegradable organic matters controls the rate of the overall denitrification process. Figure 7 gives the computed results for the investigated plant, showing the changes in the nitrogen removal performance with the retention time of the anoxic zone. Indeed the extension of the anoxic zone volume leads to improving the nitrogen removal. We confirm that the denitrification rate is the limiting factor to the nitrogen removal in the plant.

Addition of Acetic Acid to the anoxic zone Since the effective measures were desired without extending any existing reactor volume in this study, the effect of increasing the denitrification rate, that is, addition of acetic acid to the anoxic zone was examined by the batch experiment and
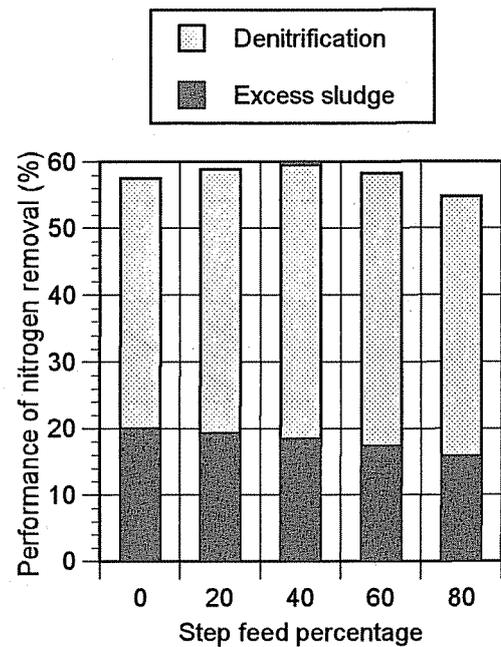
simulation analysis. Figure 8 gives the experimental and computed results from the batch test with the primary effluent, 96/12/20, showing that the addition of acetic acid increases the denitrification rate in the anoxic zone. Figure 9 shows the computed results from the full scale plant simulation with the primary effluent, 95/7/26. These results were yielded with the following operating condition; the feed of the acetic acid to the anoxic zone, but not step feed of the primary effluent. It is seen that the addition of acetic acid improves the performance of nitrogen removal. The 2000 kg/day of acetic acid addition corresponds to the 20 % of the total COD in the primary effluent. The simulated results also show that 9% of the additional excess sludge is likely to be produced by the 2000Kg/day dose of acetic acid.

In order to examine the possibility of supplying volatile acid from the sludge treatment system in the plant, the lab-scale batch thickening test was done for the primary sludge from the plant, and volatile acid concentrations in the supernatant were measured. Figure 10 shows that the major ingredients in the supernatant were acetic, propionic and butyric acid and that they occupied about 75% of total organic matters on the COD base. The amount of the volatile acid supplied from the sludge treatment system can be roughly estimated by the following calculation: [volatile acid production from unit mass of the primary sludge, $0.08g$-COD/g-sludge] x [concentration of the primary sludge, $26700g$-sludge/m^3] x [volume of the sludge per day, $3600m^3/day$]=$7700Kg$-COD/day. This value suggests that the primary sludge has the capacity to supply volatile acid to the anoxic zone. But the further study is required to realize this plan.

CONCLUSION

The mathematical model was developed for the simulation analysis of the municipal wastewater treatment plant having the anaerobic-aerobic-anoxic-aerobic biological reaction basin with the step feed. The validity of the model was confirmed with data from the plant investigated and the lab-scale batch experiment. The effect of step feed ratio was evaluated. Simulated results showed that the choice of the step feed ratio could not improve the nitrogen
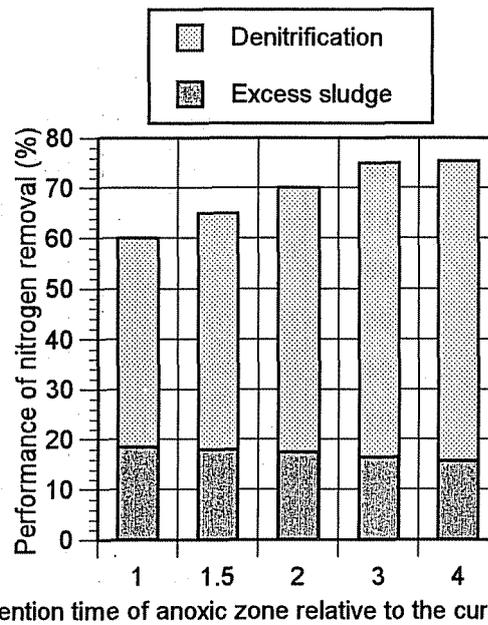
Fig.7. Effect of retention time of the anoxic zone on nitrogen removal
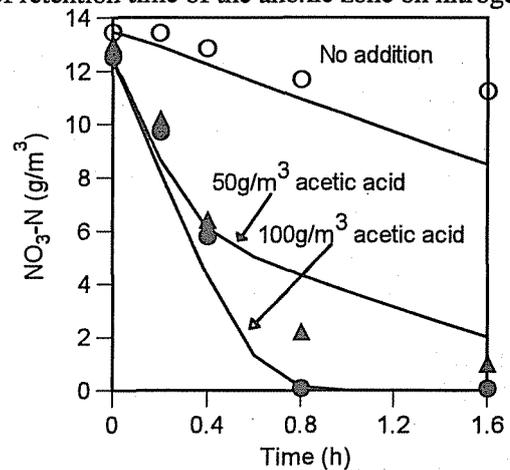
Fig.8. Effect of acetic acid addition on denitrification rate
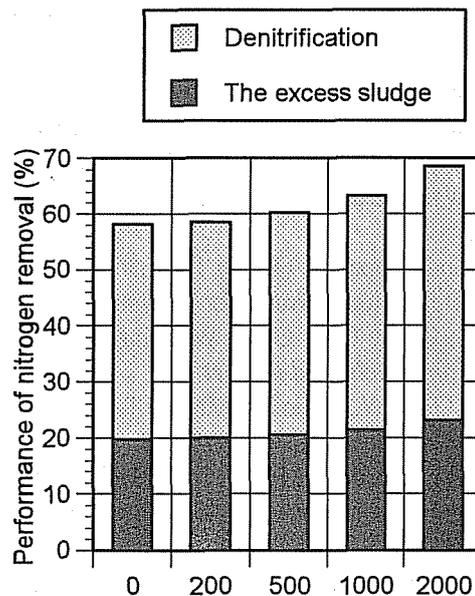
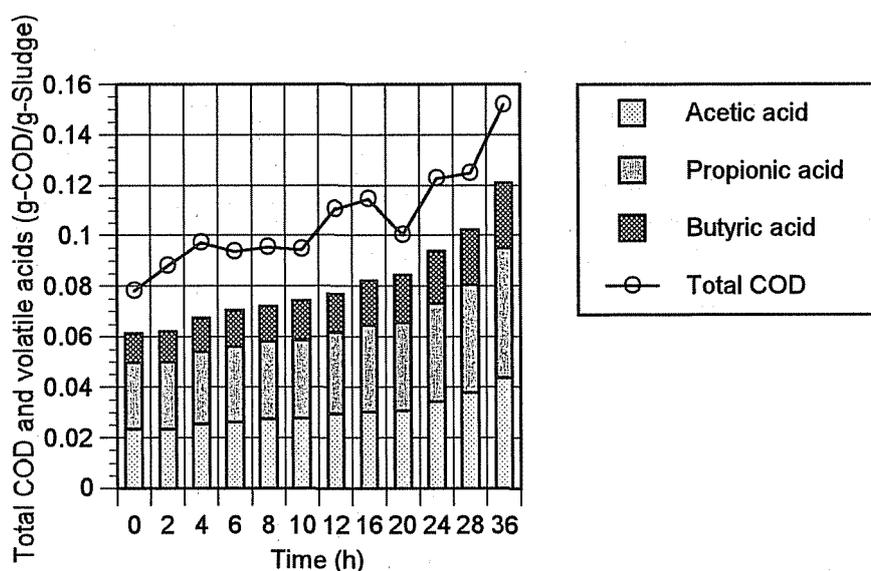Fig.9. Effect of acetic acid addition on nitrogen removal

Fig. 10. Composition of volatile acid in supernatant of the primary settler sludge thickening process.

removal performance, and also showed that the denitrification rate was low in the anoxic zone because of the low ratio of readily biodegradable COD to Nitrogen. The computed and lab-scale experimental results implied that the addition of readily biodegradable organic matters such as fermentation products of the primary settler sludge was effective to improve the performance of nitrogen removal.

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