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SIMULTANEOUS ORGANIC AND NUTRIENT REMOVAL FROM MUNICIPAL WASTEWATER BY BSACNR PROCESS

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Abstract – Biological nutrient removal was investigated under a biological synthetic activated ceramic nutrient removal (BSACNR) process. Tests were made to establish whether organic compounds and nutrients (N, P) from municipal wastewater were eliminated effectively in a lab-scale BSACNR process by increasing the hydraulic retention time (HRT) from 4 hr to 10 hr. In the system, synthetic activated ceramic (SAC) media were packed in each reactor for attached growth of both nitrifying bacteria and denitrifying bacteria; the sludge of the clarifier was returned to the anaerobic reactor to release phosphate. In this configuration, nitrification, denitrification and phosphorus removal could be performed at their respective conditions. The influent was synthetic wastewater, and the mean concentration of COD, NH_4^+-N and T-P in the influent was about 200 mg/L, 20 mg/L and 8 mg/L, respectively. At a total HRT of the system of 4-10 hr, the system worked successfully obtaining the removal of COD, NH_4^+-N, T-N and T-P: 90.5-97.5 %, 72.9-94.4 %, 56.5-73.7 % and 36.0-61.1 %, respectively. The results of this research show that a biological synthetic activated ceramic nutrient removal (BSACNR) process packed with SAC media could be applicable for treatment of organic and nutrient from municipal wastewater.

Key words: Biological Synthetic Activated Ceramic Nutrient Removal (BSACNR) Process, Nutrient Removal, SAC Media, Nitrification, Denitrification, Phosphorus Removal

INTRODUCTION

Biological nutrient removal (BNR) from sewage and wastewater may be performed by adopting various process configurations [Munch et al., 1996]. It is well known that nitrogen removal can be accomplished by nitrification, followed by denitrification in the BNR process [Liu and Capdeville, 1996; Choi and Lee, 1996]. The mass balance of alkalinity at anoxic and aerobic conditions is shown as follows. Besides illustrating the stoichiometry between oxidized ammonia, oxygen consumption and biomass production, the following Eq. (1) indicates that a significant amount of alkalinity is destroyed during ammonia oxidation to nitrate [Randall et al., 1992].

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \rightarrow 0.21C_5H_7O_2N + 0.98NO_3^- + 1.04H_2O + 1.88H_2CO_3 \quad (1)$$

Approximately 7.14 mg of alkalinity (as $CaCO_3$) is consumed per mg NH_4^+-N oxidized on the assumption of full nitrification at aerobic conditions. On the other hand, in a heterotrophic denitrification reaction, one equivalent of alkalinity is produced per equivalent of nitrate reduced. This equates to 3.57 mg as $CaCO_3$ of alkalinity production per mg of nitrate reduced, or one-half the amount destroyed when ammonia is oxidized to nitrate. Therefore, it could be expected that the total amount of changed alkalinity is 3.57 times the concentration of removed NH_4^+-N at aerobic conditions [Randall et al., 1992].

Biological phosphorus removal can be achieved through a selection of bacteria capable of storing poly-phosphate. The selection of these phosphorus-accumulating bacteria can be made by exposing the bacteria to anaerobic conditions alternating with oxidizing conditions in a fixed-film reactor [Kerrn-Jespersen et al., 1994]. One process which has recently demonstrated significant potential for BNR is the biofilm process [Randall et al., 1992]. The biofilm process differs from the activated sludge process in that the latter operates with the activated biomass suspended in the system while it attaches to the carriers in the biofilm process, which means biomass grow and adhere to the surface of the carriers [Park et al., 1995; Park et al., 1996; Wang et al., 1991].

For kinetic studies of electrode reactions Barnard [1974] adopted a single sludge system to remove both nitrogen and phosphorus without adding chemicals. Anaerobic, anoxic and aerobic conditions are typical of those used in nutrient removal processes. In recent years, many systems have been developed to rearrange the layout of anaerobic, anoxic and aerobic reactors. However, some conflicts arise when such a single sludge system is used to remove nitrogen and phosphorus simultaneously. First, the growth of nitrifiers is slower than that of heterotrophic bacteria; therefore, an operation using a long SRT should be adopted if improved nitrification is required. On the other hand, the system must be operated using a short SRT if phosphorus removal must be enhanced. Second, the carbon sources are generally not rich enough for denitrification since (a) the anoxic reactor is typically placed behind the anaerobic reactor, and (b) the short-chain fatty acids (SCFA) are utilized primarily for phosphate

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release in the anaerobic reactor. Biofilm has a long sludge age attached bacteria, a high biomass concentration and stability in operation. Biofilm can be used to resolve the above-mentioned conflicts, that is, addition of a fully submerged fixed-film process to provide attached media for bacteria [Lee et al., 1996; Su and Ouyang, 1996].

A new biological nutrient removal process, the biological synthetic activated ceramic nutrient removal (BSACNR) process, was developed in this study to remove nitrogen and phosphorus simultaneously from sewage and wastewater. It is expected that this new process can resolve the conflicts associated with the operation of a conventional nutrient removal process.

MATERIALS AND METHODS

1. Experimental Conditions and Setup

Laboratory scale reactors capable of performing continuous experiments for nutrient removal were used, including anaerobic/anoxic/aerobic reactors in series with one stage of anaerobic reactor and two stages of anoxic/aerobic reactors. A diagram of the BSACNR process is shown in Fig. 1. The net volumes of the anoxic and aerobic reactors were each 15.0 L, anaerobic reactor 7.5 L, and the total net volume of all reactors was 37.5 L. All of the reactors were filled with SAC (synthetic activated ceramic) media having a porosity of 66.5 %, a packing ratio of 15 % based on the volume of each reactor, and a specific surface area of 5.5 m^2/g. This medium was made of soil components at high-temperature conditions. Due to the large carrier surface in each reactor, thin biofilms are formed, so there are good merits related to bacterial adhesion. An agitator for mixing was installed in each of the anaerobic and anoxic reactors. Air was supplied through two fine-bubble bar-type diffusers at the bottom of the aerobic reactors by a blower with a capacity of 150 L/min. The air flow rate in the aerobic reactor was kept constant at 16 L/min (20 °C, 1 atm) over a wide range of HRT (hydraulic retention time). The temperature in the anaerobic reactor was controlled at 37±2 °C by a temperature controller.

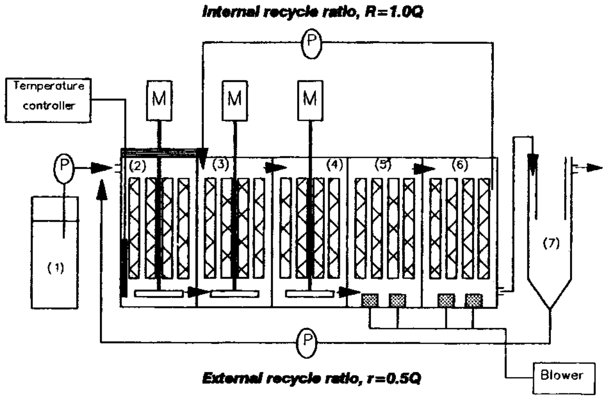

Fig. 1. Schematic configuration of fixed-film biological reactor with packed SAC media.

1. Influent reservoir	5. Aerobic reactor
2. Anaerobic reactor	6. Aerobic reactor
3. Anoxic reactor	7. Clarifier
4. Anoxic reactor	

Table 1. Composition of synthetic wastewater

Component	Concentration (mg/L)
Glucose	225
Na_2CO_3	212
KCl	17.5
NH_4Cl	59.4
$CaCl_2$	17.5
NaCl	37.5
$MgSO_4$	12.5
KH_2PO_4	35.1

Table 2. Sample analysis methods

Parameter	Method
DO	DO meter, model 58 (YSI Inc., USA)
pH	pH meter, HM-14P (TOA Electronics, Japan)
COD_{Cr}	Open reflex methods (Standard Method 19 th)
NH_4^+-N	Nesslerization method (Standard Method 19 th)
NO_x-N	HPLC (Waters, USA)
T-P	Stannous chloride method (Standard Method 19 th)
Alkalinity	Titration method (Standard Method 19 th)

Table 1 shows the characteristics of the synthetic municipal wastewater used in this study. The COD concentration of this synthetic municipal wastewater was 200 mg/L, NH_4^+-N, 20 mg/L and T-P, 8 mg/L. Sodium bicarbonate buffer was added to prevent a pH drop caused mostly by nitrification. Alkalinity in the synthetic municipal wastewater was maintained at 200 mg $CaCO_3$/L.

2. Acclimation and Operation

Seed sludge was obtained from a municipal wastewater treatment plant and acclimated to the synthetic municipal wastewater of 0.1 kg COD/m^3/day for about 15 days. At the start-up period, the air flow rate was controlled to detach easily the biofilm formed on the media surface. Once acclimated, HRTs were changed in the order of 10, 8, 6 and 4 hr to evaluate the performance of the BSACNR process on organic and nutrient removal. In a steady-state condition, reactors were operated for more than three weeks to collect data.

3. Analysis of Samples

Influent samples were collected twice a week and effluent samples every two days. Samples for the determination of soluble components were immediately filtered using 0.45 μm filter paper and cooled to prevent further reaction after sampling. All the samples, except NO_x-N which was measured by HPLC (Waters, USA), were performed according to Standard Methods (19 th). The methods of sampling analysis are given in Table 2.

RESULTS AND DISCUSSION

The performance characteristics of the control and BSACNR processes were compared in terms of organic carbon, nitrogen and phosphorus. For the operation period, pH fluctuations were rarely observed in the biofilm reactor, which reflected the constant variation of pH values in the synthetic

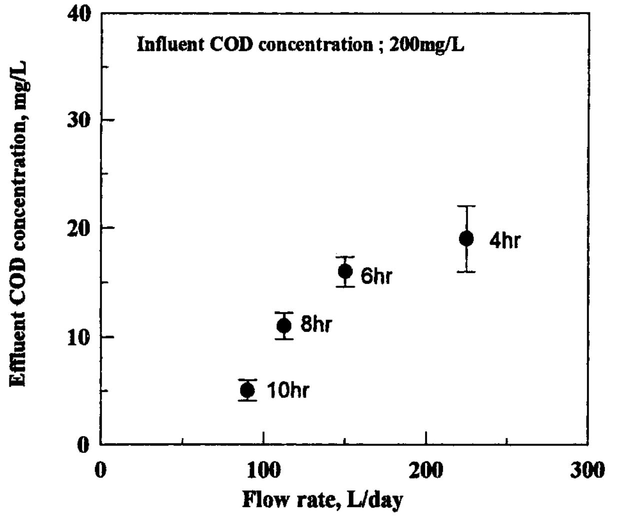

Fig. 2. Effluent COD concentration with flow rate in BSACNR process.

municipal wastewater. The pH was observed as 6.8-7.2 and 6.7-7.5 in the influent and effluent, respectively.

1. Removal of Organic Compounds

The COD concentration profiles in each reactor of the BSACNR process are shown in Fig. 2, which shows the results obtained from the BSACNR process with the different flow rates ranging from 90.0 to 225.0 L/day (organic loading rate; 0.48-1.20 kg COD/m^3/day) was applied using only one waste strength of 200 mg COD/L. The BSACNR process indicated that the effluent COD concentrations increased as the flow rates increased. As the organic loading rate increased, the variation of effluent COD increased. The difference in the effluent COD concentration was 3.0 mg/L in HRT 4hr, while in other HRT conditions (6-10 hr) it varied 0.9-1.1 mg/L. Despite organic loading, the rate of HRT 4 hr increased about three times over that of HRT 10 hr; only 14 mg/L of effluent COD concentration was increased. It was expected that effective removal of organic compounds could be achieved up to 1.20 kg COD/m^3/day in the BSACNR process. We found that COD removal efficiencies ranging between 90.5-97.5 % were similar to the 79.4-83.0 % obtained from the extended aeration at HRT 0.5-5.0 days [Wang et al., 1991] and the 89.7-91.3 % obtained from a combined process with activated sludge and fixed biofilm at HRT 8-12 hr [Su and Ouyang, 1996].

Fig. 3 shows the concentrations of COD in each stage of the BSACNR process. The difference in COD concentration between influent and anaerobic effluent was 79.6-112.8 mg/L. The shorter HRT resulted in smaller differences. COD concentrations removed in the anaerobic unit of this process were caused by the dilution of external recycle and fermentation of anaerobic bacteria on the anaerobic reactor. COD reductions of 28.4-44.8 mg/L occurred in the anoxic reactor. COD of 58.8-75.6 mg/L were fed from the anoxic reactor to the aerobic reactor. These COD conditions are capable of helping phosphorus accumulating bacteria to uptake phosphorus in the aerobic reactor. Su and Ouyang [1996] reported that organic compound reduction was large in the order of anaerobic>anoxic>aerobic reactor, while in this study the order was anaerobic>aerobic>anoxic reactor. It is significant that the external recycle ratio (return sludge ratio) r, 0.5 Q and the internal recycle ratio R, 1.0 Q were applied in the BSACNR process, while it was r, 0.5 Q and R, 2.0 Q in the combined process with activated sludge and fixed biofilm [Su and Ouyang, 1996]. Increasing the recycle ratio may give rise to more COD reduction by dilution effects. It was expected that all effluent qualities could meet the water standard of effluents in Korea.

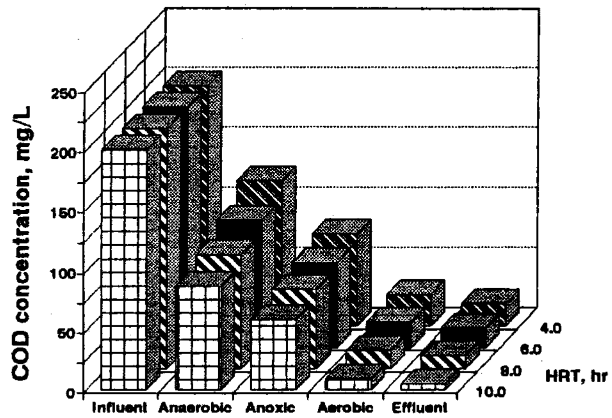

Fig. 3. Changes of COD concentration through various stages at different HRT in BSACNR process.

2. Nitrogen Removal : Nitrification and Denitrification

Fig. 4 shows ammonia removal rate versus ammonia loading rate in aerobic reactors of the BSACNR process. Fig. 4 indicates that as the ammonia loading rate increased from 48.0 to 120.0 g NH_4^+-N/m^3/day, ammonia removal rates increased. For over 60 g NH_4^+-N/m^3/day of ammonia loading rate, ammonia removal rates were fairly reduced in the BSACNR process, whereas ammonia removal rates of up to 60 g NH_4^+-N/m^3/day of ammonia loading rate were linearly pro-

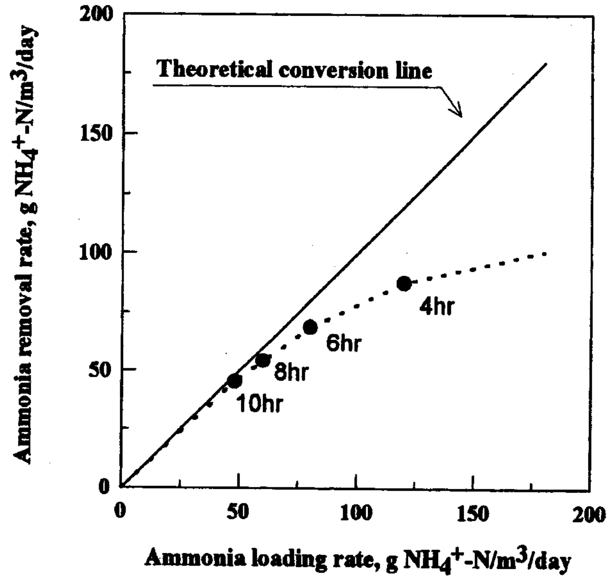

Fig. 4. Ammonia removal rate vs. ammonia loading rate in BSACNR process.

portional to ammonia loading rates. In this study, the ammonia removal efficiencies which ranged between 72.9-94.4 % were superior to the 56.7-92.0 % obtained from the extended aeration submerged biofilm process at HRT of 0.5-5.0 days [Wang et al., 1991]. Park et al. [1996] reported 90.0-96.6 % ammonia removal efficiencies could be achieved in a high strength ammonia concentration of 175-485 mg/L at HRT 32 hr.

Fig. 5 shows the concentrations of T-N, NH_4^+-N and NO_x-N in each stage of the BSACNR process. The notations A, B, C, D and E indicate the influent, anaerobic effluent, anoxic effluent, aerobic effluent and final effluent in the diagram shown in Fig. 5, respectively. The sum of NH_4^+-N and NO_x-N could be regarded as T-N, since there was no organic nitrogen in the influent of the synthetic municipal wastewater. The differences of NH_4^+-N concentration in the influent and anaerobic effluent were 5.14-6.88 mg/L. NH_4^+-N concentrations removed in the anaerobic reactor were caused by the dilution of external recycle and adsorption by anaerobic bacteria and SAC media on the anaerobic reactor [Lee et al., 1996]. It was assumed that NH_4^+-N reductions of 4.93-5.62 mg/L occurred in the anoxic reactor by the effects of dilution of internal recycle and of cell synthesis, partly. NH_4^+-N reductions of 3.30-6.56 mg/L occurred in the aerobic reactors. NH_4^+-N concentrations removed in the aerobic reactor were caused by nitrification of nitrifiers and assimilation by carboneous bacteria and nitrifiers in the aerobic reactor.

Also, Fig. 5 indicates that the HRT decreased from 10 hr to 4 hr, the NH_4^+-N concentration of aerobic effluent increased, and NO_x-N concentration of aerobic effluent decreased. It was found that 56.4-73.7 % of T-N removal efficiency in the BSACNR process is comparable with 59.0-74.4 % from the extended aeration submerged biofilm process at HRT 0.5 -5.0 days [Wang et al., 1991].

Fig. 6 illustrates the relationship between the concentration of nitrified ammonia and the consumed alkalinity in the aerobic reactor of the BSACNR process. The solid line indicates the theoretical alkalinity consumption, but measured values are not exactly consistent with the solid line. The proportional coefficient by the measured values, 6.82, is smaller than the theoretical proportional coefficient, 7.14. This difference indicates that a part of NH_4^+-N would be consumed to cell synthesis. Fig. 7 shows the relationship between the concentration of denitrified NO_x-N and the recovered alkalinity in the anoxic reactor of the BSACNR process. The measured values are consistent with the solid line of theoretical alkalinity recovered at anoxic conditions. The proportional coefficient by measured values is 3.55, similar to the theoretical proportional coefficient, 3.57. These results are comparable to the results from the simultaneous nitrification and denitrification reactor at HRT 15-17 hr [Moriyama et al., 1990].

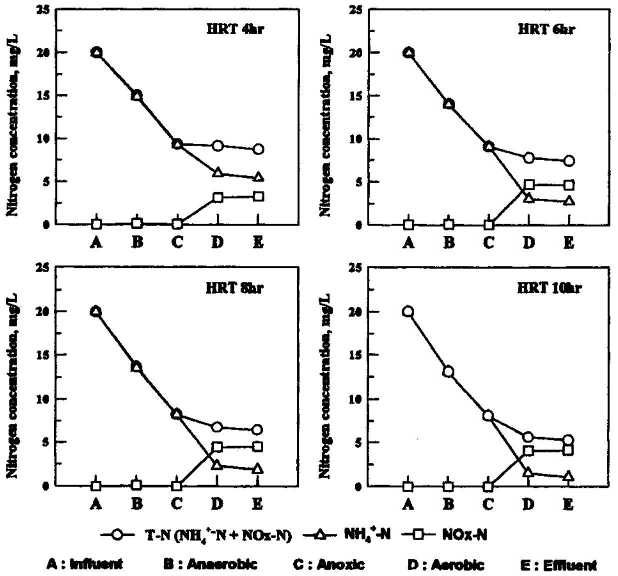

Fig. 5. Changes of nitrogen concentration in BSACNR process.

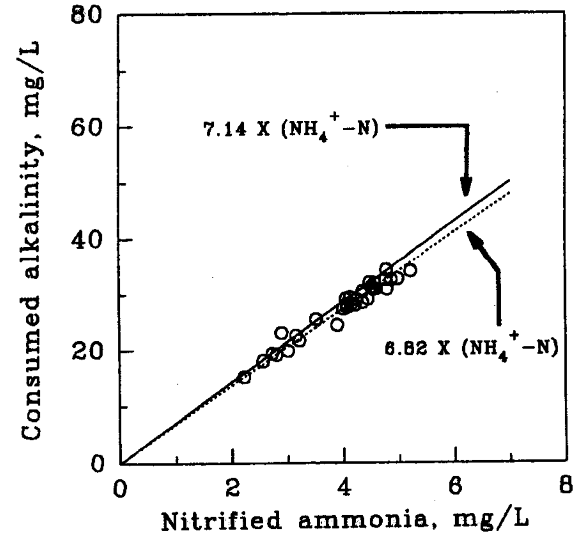

Fig. 6. Relationship between nitrified ammonia and consumed alkalinity in aerobic reactor of BSACNR process.

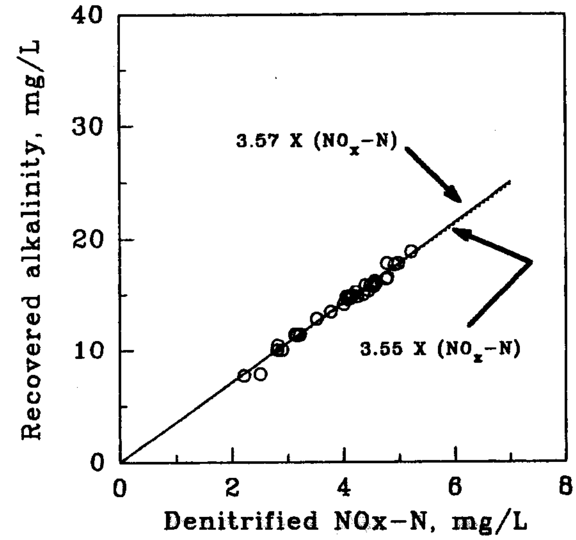

Fig. 7. Relationship between denitrified NO_x-N and recovered alkalinity in anoxic reactor of BSACNR process.

3. Phosphorus Removal : P Release and P Uptake

Fig. 8 shows the concentrations of T-P according to the

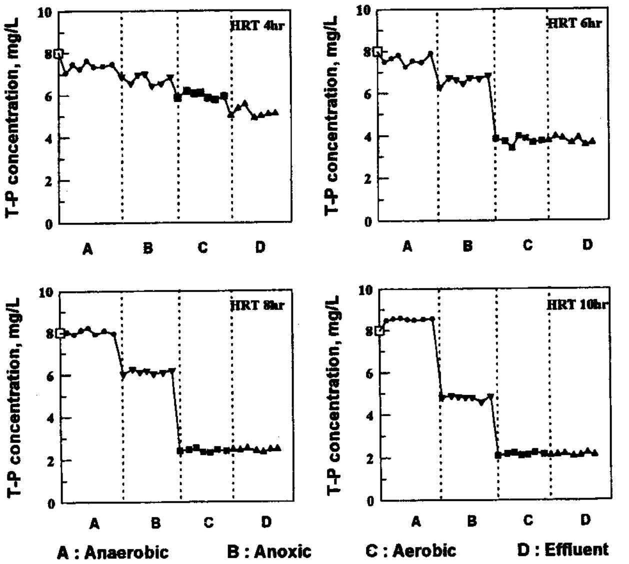

Fig. 8. Changes of T-P concentration in each reactor of BSACNR process.

variation of HRT 4-10 hr in the BSACNR process. The varying amounts of effluent T-P concentration in the anaerobic reactor were 8.53, 8.04, 7.53, and 7.38 mg/L at 10, 8, 6 and 4 hr of HRT. It was expected that T-P concentrations in the anaerobic effluent of HRT 4-10 hr would be similar to the T-P concentrations, 8 mg/L, in the influent, but the T-P concentrations in the anaerobic effluent of the BSACNR process were mostly higher than the T-P concentrations calculated theoretically by the dilution of the external recycle. This indicates that there was some phosphorus release by phosphorus-accumulating bacteria such as the *Acinetobactor ssp.* etc. [Kerm-Jespersen et al., 1994]. Nicholls and Osborn [1978] suggested that an anaerobic stage, free of nitrate, proposed by Barnard [1974] was necessary to allow the *Acinetobactor ssp.* to selectively take up acetates into the cells, using stored polyphosphates as the energy source and releasing phosphates to the liquid phase. T-P reductions of 0.49-3.69 mg/L occurred in the anoxic reactor of the BSACNR process, and 0.95-3.71 mg/L of T-P were reduced in the aerobic reactor of the BSACNR process. Phosphorus uptake can take place simultaneously at anoxic and aerobic conditions [Hoscoet and Florentz, 1985]. Kerm-Jespersen and Henze [1993] reported that the phosphorus uptake was slower under anoxic conditions than under aerobic conditions, because only part of the phosphorus-accumulating bacteria take up phosphate under anoxic conditions, whereas all the phosphorus-accumulating bacteria take up phosphate under aerobic conditions. In this study, the amount of phosphorus up-take in the aerobic reactor was similar to the amount of phosphorus up-take in the anoxic reactor. This indicates that there was not sufficient organic substance to produce new cells in the aerobic reactor. The T-P removal efficiency of HRT 4 hr was only 36.00 %, while theT-P removal efficiencies of HRT 6-10 hr were 52.86-61.11 %. As the HRT decreased from 10 hr to 4 hr, the T-P concentration varied more and more. Su and Ouyang [1996] reported 68.0-98.0 % at HRT 8-12 hr in a combined process with activated sludge and fixed biofilm. Further study is needed to improve the T-P removal efficiency in the BSACNR process.

CONCLUSIONS

The biological synthetic activated ceramic nutrient removal (BSACNR) process is feasible and useful for nutrient removal from municipal wastewater. It was tested in anaerobic/anoxic/aerobic reactors at HRT of 4, 6, 8, 10 hr.

The BSACNR process performed with COD_{Cr} removal efficiencies of 90.5-97.5 % at an organic loading rate of 0.48-1.20 kg COD_{Cr}/m^3/day. T-N removal efficiencies of 56.47-73.7 % were obtained in HRT 4-10 hr for the BSACNR process. T-P removal efficiencies of HRT 4-10 hr were 36.00-61.11 %. For further T-P removal, chemical or physical methods need to be applied after the biological phosphorus is removed. This BSACNR process is considered very suitable for the treatment of nutrient from municipal wastewater. Further study is needed for it to be applied in real municipal wastewater and pilot plant tests.

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