Effects of influent COD/N ratio and internal recycle ratio on nitrogen removal efficiency in the KNR® process

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Abstract In this study, with the KNR® process that has many advantages, the nitrogen removal efficiency of KNR was experimentally investigated at various COD/N ratios of influent conditions. The optimal operating condition of internal recycle ratio was evaluated. The TN removal efficiencies were 59.1, 72.5 and 75.9% at the COD/N ratios of 3, 5 and 7, respectively. These high removal efficiencies resulted from high denitrification rate in UMBR with high microorganism concentration. Furthermore, specific endogenous denitrification at MLVSS of 10.3 g/L that is similar to MLVSS in UMBR was over two times higher than that at MLVSS of 2.06 g/L. This result suggests that endogenous denitrification rate in UMBR is so high that the requirement of an external carbon source can be saved. As the internal recycle ratio increased from 100 to 400%, the TN removal efficiency also improved from 69.5 to 82.9%, and the optimal internal recycle ratio was 300%.

Keywords COD/N ratio; internal recycle ratio; KNR® process; nitrogen removal; UMBR

Introduction

The general type of reactor used in the biological nutrient removal (BNR) system is a complete mixing stirred tank. An air diffuser and mechanical mixer are used for mixing an anoxic or anaerobic tank. The devices demand high operation/maintenance costs and high construction costs. The reactors for nutrient removal are multiple, such as an aerobic, anoxic and anaerobic tank for an A2O process, and for a Bardenpho process, UCT process and VIP etc. On the other hand, an up-flow bioreactor has been used as an anaerobic reactor to treat high organic strength wastewater since 1980. Advantages of an up-flow bioreactor include energy saving by self-mixing, plug-flow and high solid concentration.

The KNR® process was developed to remove nitrogen and phosphorus from municipal sewage with low C/N ratio. This process train was the same as the conventional activated sludge process, except that it adopted the UMBR instead of the primary settling tank. Since a primary settling tank in a conventional process can be easily retrofitted to the UMBR, the KNR® process could be a viable alternative to conventional BNR processes.

The UMBR, which plays the most important part in the KNR® process, is an upflow and plug-flow type reactor, while the other reactors in the BNR process are complete mixed stirred tanks. The mixed influent, along with return and internal recycle sludge, is distributed uniformly by rotating distributors at the lower part of the UMBR and upflow. This unaerated reactor is slightly stirred for uniform plug-flow. According to the height of the UMBR, different environmental conditions were observed. Below the distributors, sludge is thickened and the middle is in an anoxic condition due to the nitrate included in the internal recycle flow. Then, as the nitrate was denitrified completely in the middle,

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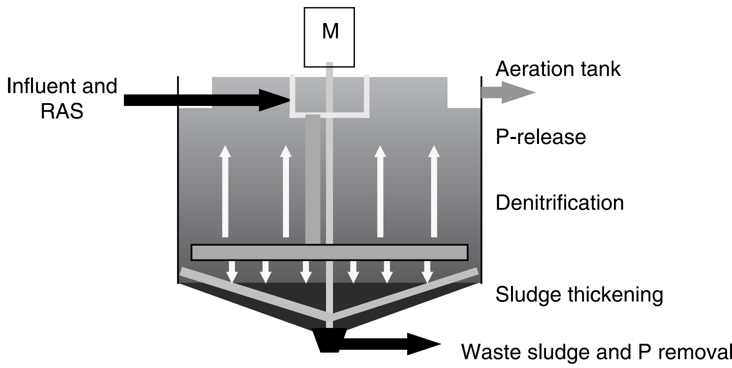

Figure 1 Schematic diagram of UMBR

the upper part became anaerobic. In summary, the UMBR could carry out the multiple functions of denitrification, anaerobic reaction and sludge thickening in one tank (see Figure 1). Moreover, high biomass concentration could be maintained since the UMBR was plug-flow, resulting in a high denitrification rate (Kwon *et al.*, 2002; Kwon *et al.*, 2003; Suh, 2003). According to the results of the operating pilot-scale plant (average 124.6 m^3/d of inflow rate), with approximately 3.9 of BOD/N ratio in influent, TN and TP removal efficiencies reached 68.6 and 87.0%, respectively.

In this study, total nitrogen removal efficiency and effectiveness of KNR® process were investigated by changing the COD/N ratio of the influent and internal recycle ratio. The internal recycle ratio has been already studied as one along important operating condition for the BNR process. However, because the UMBR is a plug-flow reactor, this condition might affect the sludge concentration in the UMBR.

Materials and methods

Lab-scale KNR® process operation

The experiments were carried out in a laboratory scale KNR® process (Figure 2) with an operating volume of 9.2 L (UMBR: 2.5 L, aeration tank: 4.2 L, secondary settling tank: 2.5 L). The inflow was 14 mL/min, while the underflow from the secondary settling tank was recycled at the rate of 7 mL/min. Mixed liquor recirculated from the aeration tank was at the rate of 21 mL/min. All operating conditions are summarised in Table 1. The sludge age was controlled at approximately 50 days by withdrawing 50 mL

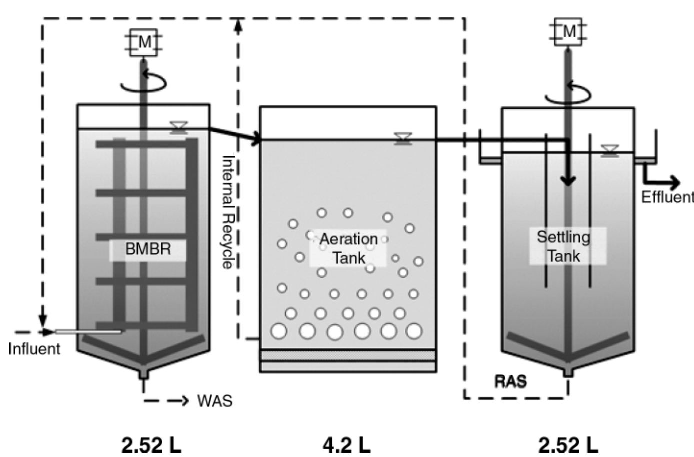

Figure 2 Schematic diagram of laboratory scale KNR® process

Table 1 Operating conditions of laboratory scale KNR® process

Condition	Unit	Value
Influent rate	mL/min	14
HRT	hr	UMBR 3
		Aeration tank 5
		Settling tank 3
Internal recycle flow rate	mL/min	21
Recycle sludge flow rate	mL/min	7
SRT	days	50 ± 10
Stirring speed in the UMBR	rpm	3
Temperature	°C	20 ± 5

of thickened sludge per day from the bottom of the UMBR. Seed sludge was taken from a Daejeon wastewater treatment plant in Korea.

Experimental procedure

COD/N ratio in synthetic wastewater. Generally, the COD/N ratio of sewage in Korea is around 5. Therefore, in this study 3, 5 and 7 of COD/N ratio were selected. For varying COD/N ratio of influent, COD was kept constant and only ammonia was changed. For the stable nitrification, alkalinity was increased as increasing ammonia. Table 2 shows the composition of synthetic wastewater.

Internal recycle ratio. During the investigation, the effect of the internal recycle ratio of the influent was the same as that of 5 of COD/N in Table 2 and was constant. The internal recycle ratio changed from 100 to 400% of influent flow rate. The operating period for each internal recycle ratio was 4 weeks.

Endogenous NUR test. For estimating the endogenous denitrification activity of the sludge in the UMBR, a NUR (nitrate utilisation rate) test was carried out with the sludge, which was taken from the UMBR when the COD/N ratio was 5 and the internal recycle ratio was 150% of influent. At the beginning of the NUR test, endogenous conditions were ensured by aerating the sludge over 2 h. After the endogenous respiration was reached, the anoxic condition was achieved by flushing the sludge with nitrogen gas until the DO became nil. Then, nitrate and some nutrients (ammonia and phosphorus) were added in pulse mode. After adding, the final concentration of nitrate, ammonia and phosphorus in the bottle were 15 mg NO_3-N/L, 10 NH_4-N/L and 5 mg PO_4-P/L, respectively. The working volume of the bottle was 800 mL.

Analytical methods

Suspended solids (SS), CODcr, and NH_4-N concentrations were measured according to *Standard Methods* (1998) after filtering through 1.2 μm GF/C filters. Concentrations of various ions in solution were analysed using ion chromatography (DX-120, Dionex, USA).

Table 2 Composition of synthetic wastewater

	COD/N = 3	COD/N = 5	COD/N = 7
Glucose (mg COD/L)	210		
Ammonium sulphate (mg N/L)	70	42	30
Potassium phosphate (mg P/L)	5		
Sodium hydrogen carbonate (mg $CaCO_3$/L)	450	250	200

Results and discussion

Effect of COD/N ratio (3, 5, 7)

Figure 3 shows the average TN removal efficiency with COD/N ratio in influent in 90 days. The standard deviations were 9.8, 9.1 and 5.8%, respectively. Though COD/N ratio was very low, TN removal efficiency was approximately 60%. Because high biomass concentration in the UMBR induced rapid denitrification and complete removal of organic matter, TN removal efficiency was high and stable complete nitrification could occur in the aeration tank. The average MLSS concentration in the UMBR was 11.9 g/L which is much higher than in a conventional activated sludge process. Plug-flow was the reason why the UMBR could maintain high concentration of biomass.

Figure 4 shows NO_x-N concentration in the UMBR, according to depths. NO_x-N was not detected in 5 and 7 of the COD/N ratio. Nitrate recirculated from the aeration tank was completely reduced with substrate in influent between the feed position and 16 cm of depth. This rapid denitrification activity could be because of the high biomass concentration in the UMBR. On the other hand, in the case of COD/N ratio 3, NO_x-N existed in the UMBR and complete removal of NO_x-N did not occur. Because of the high concentration of ammonia (70 mg NH_4-N/L) in influent, nitrate in internal recycle was almost as high as 26 mg NO_3-N/L. After rapid denitrification with substrate in influent in the lower part, Figure 4 shows the slow NO_x-N reducing by endogenous denitrification.

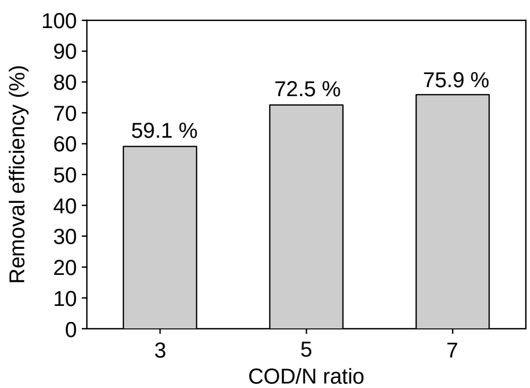

Figure 3 Effect of COD/N ratio in influent on TN removal efficiency

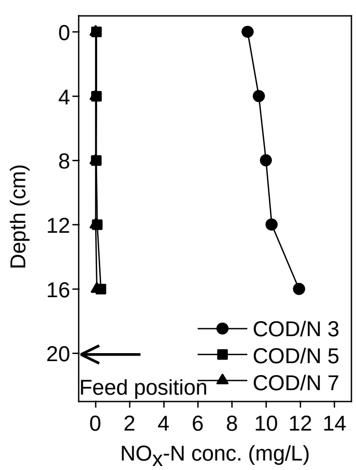

Figure 4 NO_x-N profile in the UMBR (feed position 20 cm)

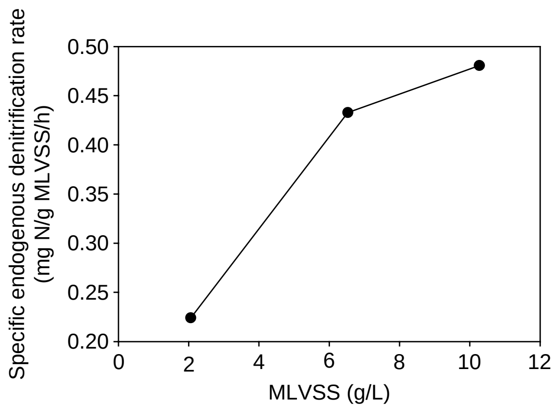

Figure 5 Specific endogenous denitrification rates as increasing MLVSS

For verifying the advantage of endogenous denitrification in high biomass concentration, an endogenous NUR test was carried out with the sludge of various MLVSS. The used concentrations of MLVSS were 10.3, 8.03 and 2.52 g/L. As shown in Figure 5, the specific endogenous denitrification rate was in proportion to MLVSS. Generally, the specific biological reaction rate, which is divided by the concentration of biomass, is regarded as constant. Beer *et al.* (1977) suggested that specific endogenous denitrification was not related to MLSS in the range between 2.5 and 4.0 g/L. However, in 10.3 g/L of MLVSS, endogenous denitrification rates were more than double, compared with that in 2.52 g/L. This relationship was confirmed by an other endogenous NUR test. Therefore, it can be concluded that the UMBR has the advantage of endogenous denitrification if an external carbon source is also used for denitrification, the UMBR can reduce the dosage.

The concentrations of COD in effluent from the UMBR and from the settling tank were similar due to complete removal of organic matters to denitrification. This led to high nitrification efficiency in the aeration tank. Average COD removal efficiency in all COD/N ratios was 94.3% and ammonia removal efficiency was 100%.

Effect of internal recycle ratio (100–400%)

Figure 6 shows average MLSS and TN removal efficiency as increasing internal recycle ratio from 100 to 400%. As expected, as the internal recycle ratio increased, MLSS in the UMBR was reduced due to the increase of the upflow velocity, and TN removal efficiency was achieved to 82.9%. However, TN removal efficiency increased slightly

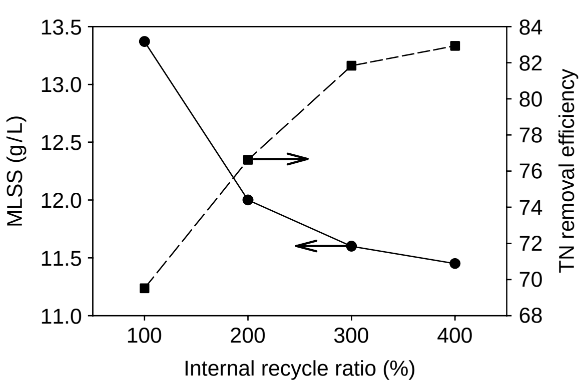

Figure 6 Average MLSS and TN removal efficiency as increasing internal recycle ratio

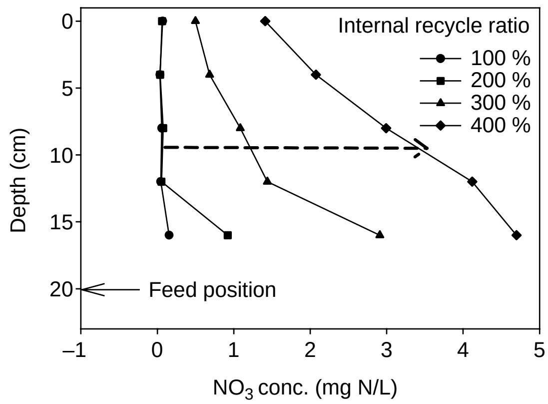

Figure 7 NO_3-N profile in the UMBR as increasing internal recycle ratio

between 300 and 400%. The nitrate profile according to depth of the UMBR is shown in Figure 7. At up to 200% of the internal recycle ratio, the nitrate in effluent from the UMBR was almost nil. From 300%, a little nitrate began to flow out from the UMBR, implying that the UMBR could not denitrify completely. Therefore, 300% of internal recycle ratio was suggested as the optimal recycle ratio.

Conclusion

This study shows the performance of a lab-scale KNR® process at various COD/N ratios in influent and internal recycle rations. Results show that the KNR® process has high potential to remove nitrogen in low COD/N ratio. Average TN removal efficiencies in 3, 5 and 7 of COD/N ratio were 59.1, 72.5 and 75.9%, respectively. This high TN removal efficiency was due to the high biomass concentration in the UMBR. The COD removal efficiency was maintained over 94% and nitrification occurred completely. From endogenous NUR tests, the advantage of the UMBR for endogenous denitrification was confirmed. Therefore, the KNR® process can save the costs of an extra carbon source. Internal recycle flow affected the concentration of MLSS in the UMBR as well as TN removal efficiency. The optimal internal recycle ratio was 300%.

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