

The feasibility study of the application of the AGS process for treating high-strength liquid anaerobic digestate

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(Received November 4, 2024, Revised November 29, 2024, Accepted December 12, 2024)

Abstract. This study aimed to evaluate organic matter and nitrogen removal by the aerobic granular sludge (AGS) process for high-strength liquid anaerobic digestate from an actual resource recovery facility. Specifically, the effect of different hydraulic retention time (HRT) on organic matter and nitrogen removal was investigated. The results revealed that the system operated with a HRT of 10.5 days, achieving an organic loading rate (OLR) of 0.54 kg-COD/m³/d and an organic matter removal rate of 64%. The organic matter removal efficiency of the AGS improved as the OLR increased. Finally, the organic matter removal efficiency achieved 73% at an OLR rate of 0.94 kg-COD/m³/d. However, the nitrification efficiency was maintained at 99.9% even though the nitrogen loading rate was increased. In the ozone reactor, organic matter removal efficiencies were relatively low due to the presence of refractory organic matter. The specific nitrification rate (SNR) value was calculated to be 0.121 kg NH₄⁺-N/kg MLVSS/day, while the specific denitrification rate (SDNR) value measured 0.228 kg NO₃⁻-N/kg MLVSS/day. This study demonstrates the applicability of the AGS process for the treatment of high-strength liquid anaerobic digestate and provides basic operating parameters for process design.

Keywords: aerobic granule sludge; denitrification; kinetics; liquid anaerobic digestate; nitrification; ozone

1. Introduction

Since the enforcement of the London Convention in 2012, the ocean disposal of organic waste—including livestock manure, sewage sludge, and food waste—has been prohibited. Consequently, there is growing interest in producing biogas through the anaerobic digestion of organic waste (Jo *et al.* 2019). Although facilities that recycle food waste to produce biogas are trending toward larger scales, managing the high-concentration effluent generated from digesters poses challenges to the environmental and economic viability of these facilities (Sinharoy *et al.* 2024).

The production of liquid anaerobic digestate in food waste recycling facilities generally contains high concentrations of organic matter, nutrients (such as nitrogen and phosphorus), and salinity, although these concentrations may vary depending on the characteristics of the inflow (Choi *et al.* 2020). When the effluent contains high levels of ammonia nitrogen, it can inhibit nitrifying microorganisms due to the presence of free ammonia (FA). Furthermore, a high amount of refractory organic matter and a low carbon-to-nitrogen (C/N) ratio led to low nitrogen removal efficiency (Anthonisen *et al.* 1976, Campos *et al.* 2002).

Conventional biological nutrient removal (BNR) processes used in advanced wastewater treatment—such as

biological nutrient reactors, membrane bioreactors, and A2O processes—present significant challenges for treating high-strength liquid anaerobic digestate (Jang *et al.* 2023, Yun *et al.* 2024). These challenges include high amount of waste sludge generation, extensive chemical use, operational difficulties, large installation areas, and the need for various mechanical equipment, all of which result in high operation and maintenance costs. Additionally, the activity of nitrifying microorganisms is temperature-sensitive, so when water temperatures drop below 10°C in winter, high ammonia concentrations in the effluent can lead to eutrophication and algae blooms (Jang *et al.* 2022). Furthermore, meeting effluent quality standards is difficult due to challenges in controlling the F/M ratio and the imbalance of the C/N ratio, often requiring the addition of external carbon sources like methanol.

Recently, aerobic granule sludge (AGS) has gained attention in wastewater treatment due to its compact structure, excellent settling properties, high salt tolerance, toxicity resistance, and capacity to handle high loads, making it highly promising for wastewater treatment applications (Anthonisen *et al.* 1976, He *et al.* 2017). AGS has a denser, more compact microbial structure compared to conventional activated sludge, allowing for a higher microbial concentration in the reactor and the ability to withstand high-load shocks. Additionally, when microorganisms are cultivated in granular form, the selective nitrification process bypasses the nitrification stage (oxidizing nitrite nitrogen to nitrate nitrogen), leading to the dominance of ammonia-oxidizing bacteria in the granules. This approach can reduce the oxygen required during the

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Table 1 Effective thermal conductivity (k_e) and tortuosity (τ) models

Parameter	Average	Max.	Min.
COD (mg/L)	3,882	5,350	2,700
TN (mg/L)	2,254	2,880	1,920
NH ₄ ⁺ -N (mg/L)	1,946	2,210	1,700
Salinity (%)	1.1	1.2	1.0

Table 2 Operating conditions of SBR process

	Cycle (days)	Anoxic (hr)	Anaerobic (hr)	Settle (min)	Draw (min)
R-1	2	3	8.5	15	15
R-2	2	9.5	2	15	15



Fig. 1 Lab-scale AGS-ozone experimental equipment: R-1 (Left), Ozone (Middle), and R-2 (Right)

nitrification phase by approximately 25% and decrease the electron donors needed in the denitrification phase by about 40%.

Several studies have been conducted to evaluate the nitrification performance and microbial community dynamics of the AGS process for treating high-strength nitrogen wastewater. Chen *et al.* (2022) examined simultaneous partial nitrification and denitrification in the AGS process for municipal wastewater treatment. They reported high removal efficiencies of COD (92%) and NH₄⁺-N (95%) under different aeration modes in the AGS process. Sarvajith *et al.* (2020) investigated the effect of the COD/N ratio on the performance of the AGS process for high-strength ammonium wastewater treatment. Their findings indicated that the AGS system achieved the removal of 4000 mg/L NH₄⁺-N, and a low COD/N ratio was beneficial for maintaining the functional and structural stability of AGS. Kim and Ahn (2020) studied the impact of salt concentration on AGS performance for high-salinity wastewater treatment. The major results showed that removal efficiency gradually stabilized as the AGS adapted to saline conditions. While prior studies have focused on nitrification performance, sludge formation, microbial communities, and the settling characteristics of AGS, there remains a significant lack of research on optimizing AGS operating parameters and conducting efficiency confirmation tests using actual wastewater.

Therefore, this study aimed to evaluate organic matter and nitrogen removal by the AGS process for high-strength liquid anaerobic digestate from an actual recycling facility. Specifically, we investigated the effect of operating conditions such as hydraulic retention time (HRT) on the removal of organic matter and nitrification in the AGS

system. Additionally, we conducted kinetic studies on nitrification and denitrification. Finally, we analyzed changes in AGS morphology through optical analysis.

2. Materials and methods

2.1 Actual liquid anaerobic digestate

This study used the effluent discharged from the digesters of the 'G' resource recycling facility as the influent. The characteristics are shown in Table 1. During the 2 months of operational period, the concentrations of pollutants in the influent were as follows: COD: 2,700-5,350 mg/L, TN: 1,920-2,880 mg/L, NH₄⁺-N: 1,700-2,210 mg/L, and salinity: 1.0-1.2%.

2.2 System and experimental conditions

In this study, AGS larger than 0.2 mm, cultured at a pilot scale, was selected for use, with an MLVSS concentration of 4,000 mg/L. Fig. 1 shows the lab-scale setup of the combined aerobic granular sludge-ozone treatment system used in this study. The ozonation process was applied to biologically remove organic matter and nitrogen, as well as to eliminate organic materials that are difficult to biodegrade. R-1 and R-2 are of the sequencing batch reactor (SBR) type, with an ozone treatment system connected between them. R-1 uses a 20 L acrylic reactor, and R-2 uses a 10 L acrylic reactor. The ozone treatment system was designed as a 5 L reactor capable of generating ozone at a rate of 3 g O₃/hr. All of the experiments were conducted at controlled room temperature (25 °C).

The operation times for each stage of R-1 and R-2 were configured into the phases of fill, anoxic condition, aerobic condition, settling, and idle, with R-1 set to 3 hr, 8.5 hr, 15 min, and 15 min, and R-2 set to 9.5 hr, 2 hr, 15 min, and 15 min, as shown in Table 2.

R-1 was designed for denitrification, organic matter removal, and a nitrification process, if the pH decreases below 7.3 due to nitrification, a 10% NaOH solution is automatically injected to maintain the pH at 7.6. The ozone treatment system, placed between R-1 and R-2, was used to degrade refractory organic matter and remove color from R-1 effluent, and it was operated as a continuous stirred-tank reactor (CSTR) type (HRT 1 day). R-2 functions as a post-denitrification process, where 33% methanol (CH₃OH) was injected at a ratio of 2.7 mg CH₃OH/mg NO₃⁻-N based on the maximum nitrogen concentration from samples taken at G city's resource recovery facility digesters, following a stabilization period of approximately 14 days. Residual methanol was removed through a post-aerator. A digital timer was installed to enable the automated operation of each device and the pH and DO were connected to an auto controller for real-time monitoring.

To evaluate the applicability of AGS in wastewater treatment, the HRT was progressively reduced from 10.5 days to 8.5 days and then to 8.0 days, as shown in Table 3 for each reactor.

During the first 28 days of operation, the HRTs for R-1, the ozone treatment system, and R-2 were maintained at

6.5, 1, and 3 days, respectively (Phase I). To increase the loading rates, HRTs were adjusted to 5.5, 1, and 2 days from days 29 to 48 (Phase II) and then to 5, 1, and 2 days from days 49 to 62 (Phase III). This approach aimed to evaluate the treatment efficiency of organic matter and nitrogen in filtrate using a combination of biological treatment with AGS and advanced oxidation.

2.3 Kinetics study of NH₄⁺-N removal

At the end of the operation, with an HRT of 8.0 days, 15 samples were collected during the reaction time to evaluate the kinetic parameters for the nitrification reaction in R-1 and the denitrification reaction in R-2. The results were applied to Eqs. (1) and (2) to derive the specific nitrification rate (SNR) and specific denitrification rate (SDNR), respectively.

$$SNR = \frac{(NH_4^+ - N)_{in} - (NH_4^+ - N)_{eff}}{X \times T_a} \times 24 \quad (1)$$

where,

- SNR = Nitrification rate (kg NH₄⁺-N/kg MLVSS/day)
- (NH₄⁺-N)_{in} = Influent ammonia concentration (mg/L)
- (NH₄⁺-N)_{eff} = Effluent ammonia concentration (mg/L)
- X = MLVSS concentration (mg/L)
- T_a = Aeration reaction time (hr)

$$SDNR = \frac{(NO_3^- - N)_{in} - (NO_3^- - N)_{eff}}{X \times T_b} \times 24 \quad (2)$$

where,

- SDNR = Denitrification rate (kg NO₃⁻-N/kg MLVSS/day)
- (NO₃⁻-N)_{in} = Influent nitrate concentration (mg/L)
- (NO₃⁻-N)_{eff} = Effluent nitrate concentration (mg/L)
- X = MLVSS concentration in the reactor (mg/L)
- T_b = Denitrification reaction time (hr)

2.4 Analytical methods

The chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH₄⁺-N), nitrite nitrogen (NO₂⁻-N), and nitrate nitrogen (NO₃⁻-N) of the influent and treated water were measured according to the Standard Methods for the Examination of Water and Wastewater. The structure of the AGS was observed at 40× magnification using an optical microscope (CX-31, Olympus) covered with a 0.17 mm-thick cover glass.

3. Results and discussion

3.1 Overall performance

Fig. 2 illustrates the changes in organic matter removal and nitrification of the R-1 reactor at different HRTs. During the first 28 days, the system was operated with an HRT of 10.5 days, achieving an average organic matter removal rate of 64% at an organic loading rate (OLR) of 0.54 kg-COD/m³/d (Phase I). Subsequently, when the OLR was increased to 0.67 kg-COD/m³/d from days 29 to 48,

Table 3 Experimental design of each SBRs

Phase	Period (days)	HRT (days)			
		I	0-28	6.5	1
I	0-28	6.5	1	3	10.5
II	29-48	5.5	1	2	8.5
III	49-62	5	1	2	8

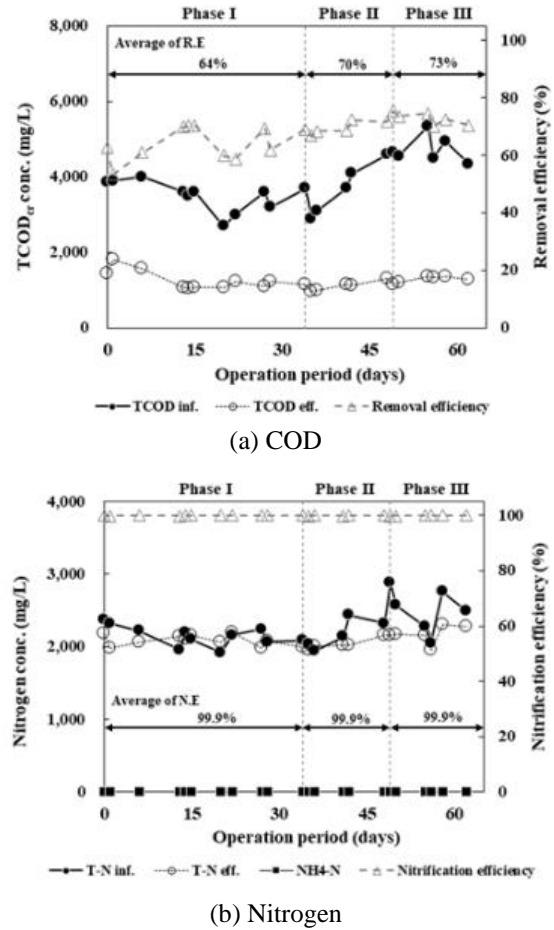


Fig. 2 Overall performance of R-1

the average removal rate increased to 70% (Phase II). Further increasing the OLR to 0.94 kg-COD/m³/d from days 49 to 62 resulted in an average removal rate of 73% (Phase III). The OLR has a significant influence on the formation and stability of AGS. Specifically, the increase in OLR led to the rapid formation and larger size of AGS granules (Tang *et al.* 2022). Therefore, the enhancement of formation and stability of AGS by increasing OLR could increase the COD removal efficiency with the increasing OLR in the AGS process.

Similar results were reported in studies by Wang *et al.* (2019) and Rosman *et al.* (2014), where AGS showed enhanced treatment efficiency and stability with higher organic loading rates. As illustrated in Fig. 2(b), the nitrogen loading rate (NLR) was gradually increased from 0.29 kg-NH₄⁺-N/m³/d to 0.42 kg-NH₄⁺-N/m³/d during the study, maintaining a nitrification efficiency of 99.9%. The growth of the autotrophic ammonia-oxidizing bacterial

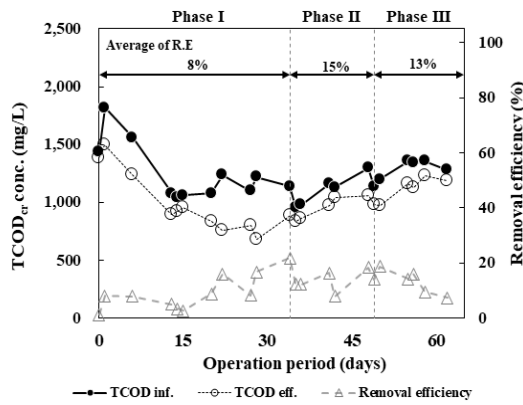
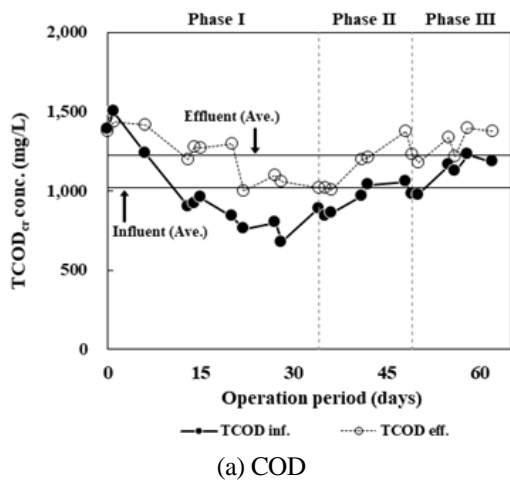
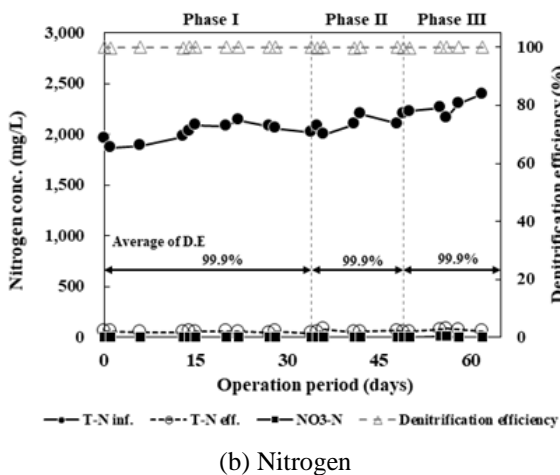


Fig. 3 COD removal in ozone reactor



(a) COD



(b) Nitrogen

Fig. 4 Overall performance of R-2

community can be enhanced by increasing the ammonia nitrogen concentration in the AGS-SBR system. (Zeng *et al.* 2023). Consequently, the nitrification efficiency enhanced with increasing NLR in the AGS process.

While studies by Cui *et al.* (2006) reported that salinity in wastewater inhibits the nitrification process, this study found no impact of salinity on nitrification efficiency.

The changes in organic matter removal by the ozone treatment system are illustrated in Fig. 3. During the operational period, the organic matter removal efficiencies

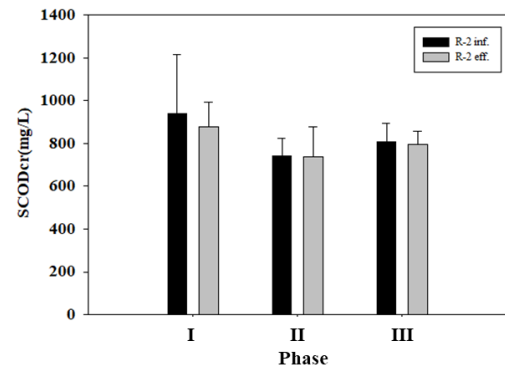


Fig. 5 Changes in the sCOD concentration at different HRT

in Phases I, II, and III were low, at 8%, 15%, and 13%, respectively, with the effluent organic matter concentration ranging from 680 to 1,500 mg/L. These results indicate the presence of refractory organic matter that is difficult to decompose using ozone. In a study by Lee *et al.* (2011) that investigated the removal of organic matter and color using advanced oxidation with ozone, four methods (O_3 , O_3/H_2O_2 , O_3/UV , and $O_3/UV/H_2O_2$) were tested, resulting in organic matter removal rates of 22%, 33%, 39%, and 56%, respectively. The color removal rates were reported to increase by approximately 5-10% with three of the methods compared to the results obtained with ozone alone, which aligns with the findings of this study using ozone as a standalone treatment.

Lim *et al.* (2022) also reported that certain non-reactive compounds, such as halogenated aliphatic compounds of saturated hydrocarbons, are difficult to fully oxidize with ozone alone. Processes combining hydrogen peroxide and UV light should be implemented to improve the treatment efficiency of refractory organic matter in wastewater.

The removal of organic matter and denitrification efficiency in the R-2 reactor after ozone treatment is shown in Fig. 4. During the operational period, the denitrification efficiency was maintained at 99.9%, with the nitrogen concentrations in the treated water measured at 57 mg/L, 58 mg/L, and 69 mg/L, respectively. Regarding organic matter, it was observed that the effluent had a higher concentration than the influent.

According to studies by Pribyl *et al.* (1997), extracellular polymeric substances (EPS) produced during microbial metabolism and soluble microbial products (SMPs) smaller than $0.45 \mu m$ contribute to poor sludge settling and an increase in organic matter concentration. This aligns with the increase in organic matter observed in the effluent of this study.

To confirm the amount of organic matter consumed as a carbon source for denitrification in the R-2 influent, the organic matter measurements of both the influent and effluent were filtered and are presented in Fig. 5.

The organic matter consumption rates were found to be 2.4%, 0.8%, and 0.9% for Phases I, II, and III, respectively. As previously mentioned, the low efficiency in converting refractory organic matter into more easily decomposable forms when treated solely with ozone likely accounts for these results.

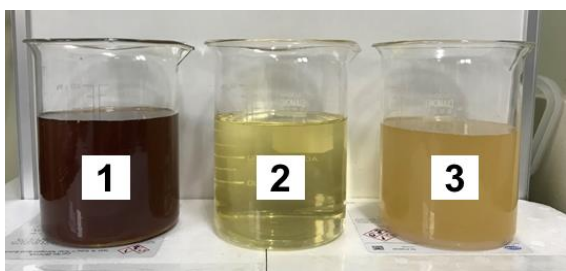


Fig. 6 Changes of effluent color in the different reactor: (1) R-1 (2) Ozone (3) R-2

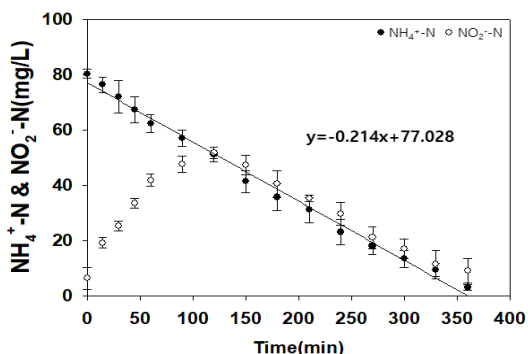


Fig. 7 Kinetics of $\text{NH}_4^+\text{-N}$ and $\text{NO}_2^-\text{-N}$ in R-1

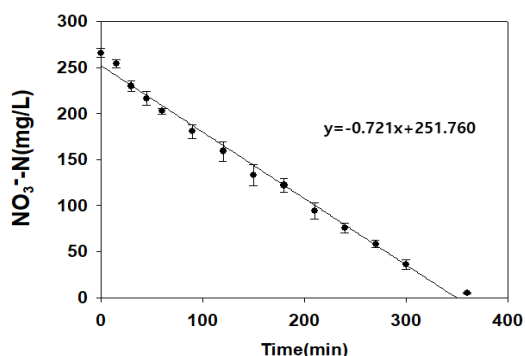


Fig. 8 Kinetics of $\text{NO}_3^-\text{-N}$ in R-2

Fig. 6 illustrates the changes in effluent color for each process, with R-1, the ozone treatment system, and R-2 showing values of 150 NTU, 67 NTU, and 212 NTU, respectively. Although there was no dramatic change in color in R-2, the presence of ultra-fine flocs resulting from the post-aerator for residual methanol removal likely contributed to the increased turbidity.

3.2 Kinetic evaluation of $\text{NH}_4^+\text{-N}$ removal

The nitrification behavior of ammonium nitrogen in R-1 and the denitrification behavior of nitrate nitrogen in R-2 were analyzed, as shown in Figs. 7 and 8, respectively. The SNR value derived using equations (1) and (2) in Section 2.3 averaged $0.121 \text{ kg NH}_4^+\text{-N/kg MLVSS/day}$, while the SDNR value averaged $0.228 \text{ kg NO}_3^-\text{-N/kg MLVSS/day}$.

Table 4 presents the SNR and SDNR values of the AGS applied in this study, which are similar to or slightly higher than those reported in previous studies. Chiu *et al.* (2007) reported SNR values of $0.01\text{-}0.05 \text{ kg NH}_4^+\text{-N/kg MLVSS/day}$

Table 4 Comparison of SNR, SDNR with previous SBR studies

Influent	SNR	SDNR	Salinity (%)	Reference
Liquid anaerobic digestate	0.11-0.12	0.22-0.23	1.0-1.2	This study
Synthetic wastewater	0.01-0.05	-	-	(Chiu <i>et al.</i> 2007)
Synthetic wastewater	0.07-0.16	0.07-0.20	-	(Yae <i>et al.</i> 2018)
Synthetic wastewater	0.04-0.14	0.07-0.11	0-5.0	(Kim & Ahn, 2020)
RO concentrate	0.04-0.07	0.10-0.29	-	(Kim & Joo, 2012)

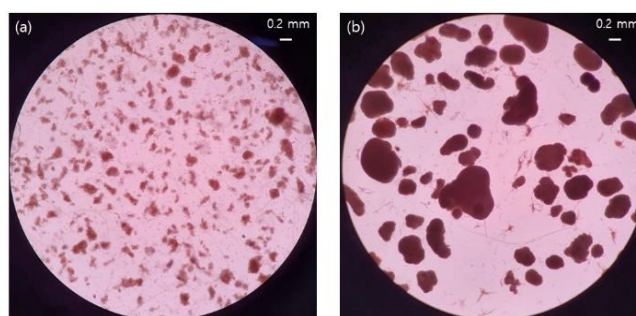


Fig. 9 Morphology of AGS in R-1 and R-2: (L) R-1, (R) R-2 ($\times 40$ magnification)

in SBR processes using synthetic wastewater. Yae *et al.* (2018) found SNR values of $0.07\text{-}0.16 \text{ kg NH}_4^+\text{-N/kg MLVSS/day}$ and SDNR values of $0.07\text{-}0.20 \text{ kg NO}_3^-\text{-N/kg MLVSS/day}$ in their study on the applicability of AGS in SBR processes using synthetic wastewater.

Kim and Ahn (2020) reported SNR values of $0.04\text{-}0.14 \text{ kg NH}_4^+\text{-N/kg MLVSS/day}$ and SDNR values of $0.07\text{-}0.11 \text{ kg NO}_3^-\text{-N/kg MLVSS/day}$ in SBR processes using synthetic wastewater with salinity levels of 0-5%. They observed that the SNR values decreased as salinity increased, attributing this phenomenon to the reduced microbial activity caused by salinity. However, in this study, the impact of salinity on microbial activity appears to be minimal.

Kim and Joo (2012) reported SNR values of $0.04\text{-}0.07 \text{ kg NH}_4^+\text{-N/kg MLVSS/day}$ and SDNR values of $0.10\text{-}0.29 \text{ kg NO}_3^-\text{-N/kg MLVSS/day}$ in SBR processes using RO concentrate. In their study, the use of methanol as an external carbon source resulted in somewhat higher SDNR values, which appear to be similar to the results obtained in this study.

3.3 Analysis of AGS

Fig. 9 shows the morphology of AGS in R-1 and R-2 when treated with liquid anaerobic digestate containing 1.0–1.2% salinity. The results revealed no disintegration of microbial flocs during the operation. While changes in floc size in R-1 were not distinctly noticeable, the size of the microbial flocs in R-2 increased from an initial 0.2 mm to 0.8–1.0 mm. This increase in floc size could be attributed to methanol injection, an easily degradable organic substance involved in the denitrification process. Additionally, studies by Li *et al.* (2017)

and Ou *et al.* (2018) have identified salinity as a key factor influencing microbial granulation. They reported that high salinity levels in wastewater enhance the formation of microbial EPS, which in turn accelerates microbial granulation and improves stability. The findings of this study, using digestate with high salinity, appear to support these conclusions.

4. Conclusions

In this study, the overall performance of AGS in treating high-strength liquid anaerobic digestate was investigated under varying HRT conditions. The following conclusions were drawn from the study:

- The average organic matter removal rate of 64 % was achieved with an HRT of 10.5 days and an OLR of 0.54 kg-COD/m³/d. As the HRT decreased, the organic matter removal rate of AGS increased, with average removal efficiencies of 73 % for R-1 and 25-46 % for R-2, respectively, due to enhancement of formation and stability of AGS granule.
- The nitrification efficiency reached 99 % with a 10.5-day HRT and a NLR of 0.29 kg-NH₄⁺-N/m³/d in the AGS process. Despite the decrease in HRT, nitrification efficiency was maintained, primarily due to the growth of the ammonia-oxidizing bacterial community with the increasing NLR in the AGS process.
- The SNR in this study ranged from 0.105 to 0.113 kg NH₄⁺-N/kg MLVSS/day, and the SDNR ranged from 0.378 to 0.422 kg NO₃⁻-N/kg MLVSS/day.
- The floc size in R-1 was not distinctly noticeable, while the size of the microbial flocs in R-2 increased from 0.2 mm to 0.8-1.0 mm. This increase in floc size could be attributed to the methanol injection for denitrification in R-2.

Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. RS-2021-KP002604).

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