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The effectiveness of step feeding strategies in sequencing batch reactor for a single-stage deammonification of high strength ammonia wastewater

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Abstract. A single-stage deammonification with a sequencing batch reactor (SBR) that simultaneous nitritation, anaerobic ammonia oxidation (anammox), and denitrification (SNAD) occur in one reactor has been widely applied for sidestream of wastewater treatment plant. For the stable and well-balanced SNAD, a feeding strategy of influent wastewater is one of the most important operating factors in the single-stage deammonification SBR. In this study, single-stage deammonification SBR (working volume 30L) was operated to treat a high-strength ammonium wastewater (1200 mg NH_4^+-N/L) with different feeding strategies (single feeding and nine-step feeding) under the condition without COD. Each cycle of the step feeding involved 6 sub-cycles consisted of aerobic and anoxic periods for partial nitritation (PN) and anammox, respectively. Contrary to unstable performance in the single feeding, the step feeding showed better deammonification performance (0.565 kg-N/m^3/day). Under the condition with COD, however, the nitrogen removal rate (NRR) decreased to 0.403 kg-N/m^3/day when the Nine-step feeding strategies had an additional denitrification period before sub-cycles for PN and anammox. The NRR was recovered to 0.518 kg-N/m^3/day by introducing an enhanced multiple-step feeding strategy. The strategy had 50 cycles consisted of feed, denitrification, PN, and anammox, instead of repeated sub-cycles for PN and anammox. The multiple-step feeding strategy without sub-cycle showed the most stable and excellent deammonification performance: high nitrogen removal efficiency (98.6%), COD removal rate (0.131 kg-COD/m^3/day), and COD removal efficiency (78.8%). This seemed to be caused by that the elimination of the sub-cycles might reduce COD oxidation during aerobic condition but increase the COD utilization for denitrification period. In addition, among various sensor values, the ORP pattern appeared to be applicable to monitor and control each reaction step for deammonification in the multiple-step feeding strategy without sub-cycle. Further study to optimize the number of multiple-step feeding is still needed but these results show that the multiple-step feeding strategy can contribute to a well-balanced SNAD for deammonification when treating high-strength ammonium wastewater with COD in the single-stage deammonification SBR.

Keywords: deammonification; sequencing batch reactor; single feeding; step feeding; sub-cycle; multiple, ORP

1. Introduction

Conventional domestic wastewater treatment process consists of the mainstream for treatment of the influent sewage and the sidestream for treatment of the reject wastewater generated from the sludge treatment process. The reject wastewater containing high organic and nitrogen compounds are usually returned to the mainstream. This may increase the nitrogen load of the mainstream by 10-20%, thereby reducing the nitrogen removal efficiency of wastewater treatment plant (WWTP) (Lackner *et al*. 2008). Therefore, it is needed to remove the high concentration of nitrogen compounds in sidestream so that the nitrogen load of the mainstream can be properly maintained as low enough to be treated. However, it is difficult to apply the conventional nitrification-denitrification process due to the low alkalinity and COD/N ratio of the reject wastewater (Bowden *et al*. 2015, Kataoka *et al*. 2002).

Deammonification consisting of partial nitritation, anaerobic ammonium oxidation (anammox), and heterotrophic denitrification can oxidize ammonia to nitrogen gas (Strous *et al.* 1999). The deammonification process can reduce aeration costs by about 60% compared to traditional nitrification-denitrification processes and does not require the addition of an external carbon source. In addition, biomass generation is only 10% of the conventional process, making it an economical nitrogen removal process (Lackner *et al.* 2014, Van Loosdrecht and Salem 2006).

In recent years, a single-stage deammonification sequencing batch reactor (SBR) that simultaneous nitritation, anammox, and denitrification (SNAD) occur in one reactor has been applied in several WWTP (Chen *et al.* 2011; Guo *et al.* 2007; Lackner *et al.* 2014; Zhang *et al.* 2019). In general, various factors such as nitrogen compound concentration, organic matter, suspended solids, temperature, salinity, pH, dissolved oxygen (DO), sludge retention time, and feeding strategy are known to affect single-stage deammonification in SBR (Park *et al.* 2018).

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Especially, in order to maintain an efficient and stable single-stage deammonification SBR, it is necessary to derive feeding strategies that can harmonize three biological reactions, SNAD. In general, there are various feeding strategies from step feeding including continuous and interval feedings to single feeding (Lackner *et al.* 2014). Although the single feeding strategy that supplies the influent once at the start of the cycle can operate the process more simply than a step feeding strategy, a step-feed strategy has been widely adopted in different wastewater treatment (Zhang *et al.* 2019). However, SBR has an obvious drawback of discontinuous operation, requiring highly complicated system control (Gu *et al.* 2019). In addition, not all SBRs for treating reject wastewater have adopted the same feeding strategy (Lackner *et al.* 2014). The number of sub-cycles from eleven to one was regulated based on the ammonium concentration introduced in a single-stage deammonification SBR (Choi *et al.* 2018). Thus, further study is still required to find a better feeding strategy to achieve more stable and high nitrogen removal performance.

Therefore, in this study, a single-stage deammonification SBR was operated with different feeding strategies (single and step feedings) to compare their effectiveness on the removal of high strength ammonia. Additionally, the study evaluated the effect of COD on different step feeding strategies. During the operation of the single-stage deammonification SBR, various operating parameters such as pH, DO, electric conductivity (EC), and oxidation-reduction potential (ORP) were monitored in real-time. The reactor performance was compared with ammonia removal efficiency (ARE), nitrogen removal efficiency (NRE), nitrogen removal rate (NRR), COD removal efficiency (CRE), and COD removal rate (CRR).

2. Materials and methods

2.1 SBR set up and inoculum

An SBR (30 L of working volume) with a control panel was constructed (Fig 1). The panel was equipped with four online sensors and data collectors: dissolved oxygen concentration with OPTEX (DOS-20) as a data collector (AER-102-DO), pH (JK-96 PI4) with a collector (SOTA-PT100-5M), ORP (JK-96) with a collector (SOTA-ORP-5M), and EC (AER-102-ECH) with a collector (KF-SENSOR).

Two different inocula were employed; one was activated sludge obtained from an aeration tank (Suyoung WWTP, Busan, South Korea); the other was anammox sludge from a lab-scale reactor. The lab-scale anammox reactor (working volume: 36 L) has been operating to treat an artificial wastewater including both 200 mg/L of ammonium and nitrite in the continuous-flow mode for a year. The reactor showed NRE of 85% and NRR of 1.4 kgN/m3/day. Each inoculum with the same biomass concentration of 2.0 g/L was mixed together.

2.2 Operational conditions

A high ammonium synthetic wastewater was used as the influent containing $(NH_4)_2SO_4$ (5.66 g/L) as 1,200 mg NH_4^+-N/L, $NaHCO_3$ (13.9 g/L), glucose (0 - 0.512 g/L) as 0 - 400 mg COD/L, KH_2PO_4 (0.272 g/L), $FeSO_4$-$7H_2O$ (0.045 g/L), EDTA (0.025 g/L).

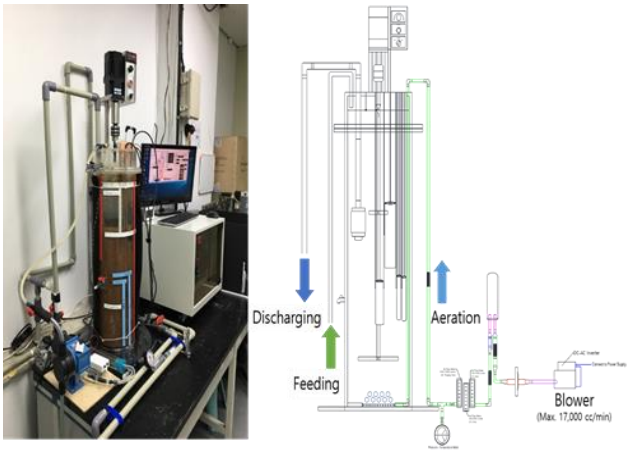


Fig. 1 A photograph and a schematic diagram of the sequencing batch reactor system for the single-stage deammonification

The deammonification SBR was operated with 25% (v/v) of volume exchange ratio in four phases according to feeding strategy under the conditions with COD (phases 1 and 2) or without COD (phases 3 and 4) (Fig 2). All phases had a basic batch cycle consisted of feed (1.5 min), aerobic condition(s) for partial nitritation (PN), anoxic condition(s) for anammox, settling (30 min), and discharging (2 min). The time-length for aerobic and anoxic periods were varied in the operational phases. Under the condition with COD, an additional anoxic condition for denitrification was put into the cycle before the aerobic condition.

During aerobic condition, an air-blower turned on with a minimum DO value of 0.1 mg/L and turned off at a maximum DO of 0.5 mg/L. The minimum pH value of 6.9 was set to finish the PN reaction by turning off the air-blower. The anoxic conditions for anammox and denitrification were also set to be ceased at pH 7.9 of the maximum value.

In phase 1, the SBR was operated with single feeding strategy consisted of the basic batch (feed-reaction (PN and anammox) -settling-discharging). The time for the aerobic and anoxic conditions was adjusted to achieve the NRE as higher than 90% throughout the PN and anammox reactions in the process. In phase 2, the SBR was operated with the nine-step feeding cycle with 6 sub-cycles of aerobic condition (21 min) and anoxic condition (30 min). During each aerobic condition in the sub-cycles, intermittent aeration (aeration (6 min) - break (9 min) - aeration (6 min)) was given, because time-dependent intermittent aeration is known to give better inhibition to further oxidation of nitrite to nitrate (Gilbert *et al*. 2014). The number of sub-cycle was changed from 6 to 4 in order to investigate the effect of the numbers of sub-cycles on deammonification.

In phase 3 under the condition with COD, then, the SBR was subsequently operated by introducing an additional denitrification period before the 6 sub-cycles. Finally, the reactor was operated with the multiple-step feeding cycle consisted of an anoxic period for denitrification, an aerobic

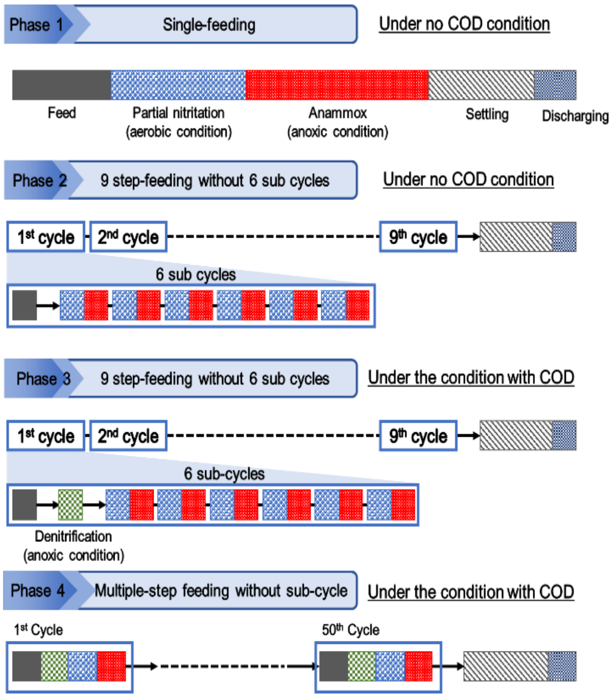


Fig. 2 Feeding strategy applied to the single-stage deammonification SBR in each operating phase

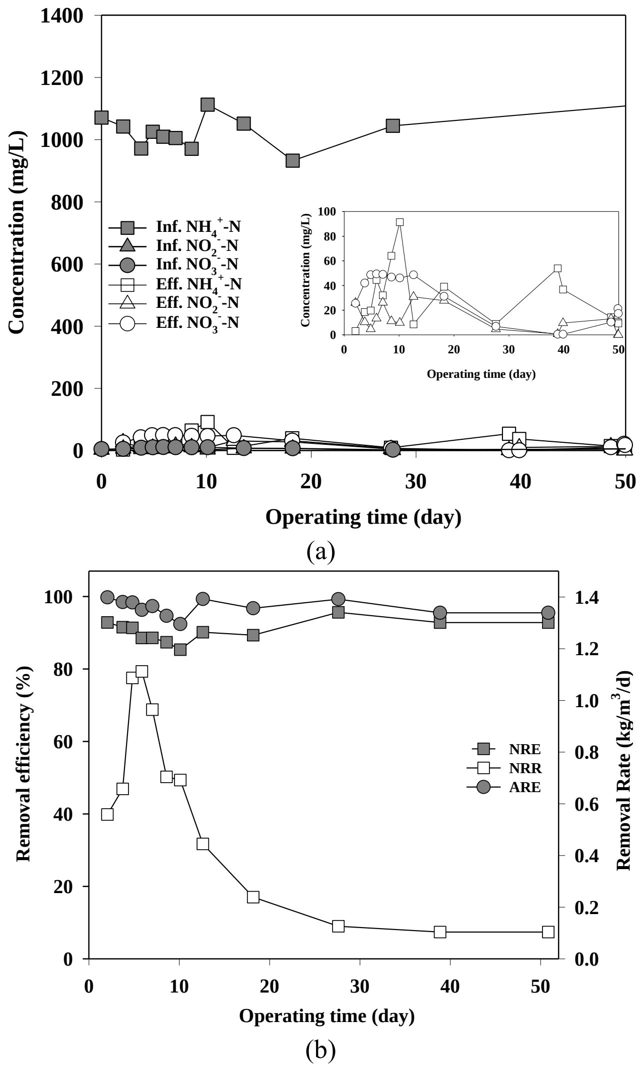


Fig. 3 Influent and effluent NH_4^+-N, NO_2^--N, and NO_3^--N concentrations (mg/L) (a) and nitrogen removal efficiency (NRE, %), ammonium conversion efficiency (ARE, %), nitrogen removal rate (NRR, kg/m^3/d) (b) at phase 1

period for PN, and another anoxic period for anammox (phase 4). The effect of the number of step feeding cycles was also tested by gradually reducing the cycle numbers from 50 to 40. Both of anoxic conditions for anammox and denitrification in phase 3 and 4 were set as 30 minutes.

2.3 Analytic methods

After each cycle, the effluent was sampled and analyzed. Ammonium and COD concentrations were determined by water analysis Kit (Humas Co. Ltd., Daejoen, South Korea). Nitrite and nitrate concentrations were determined by ICS-1000 Ion Chromatography System (Dionex, Sunnyvale, CA, USA) employing a Dionex IonPac AS14 Analytical column 4 x 250 mm.

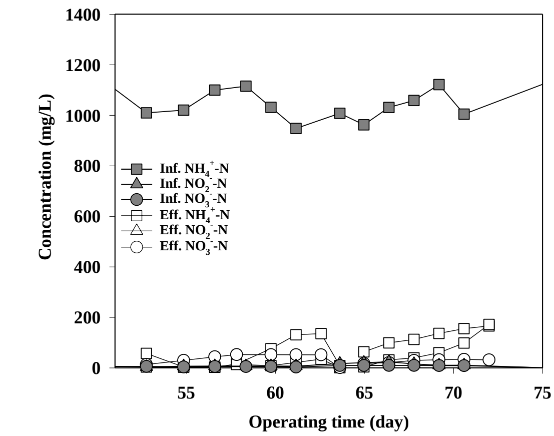
Online-monitoring data was automatically saved in an Excel file every minute and the data for control on the program was updated every three seconds using the median of three numbers in the three-second.

3. Results and discussion

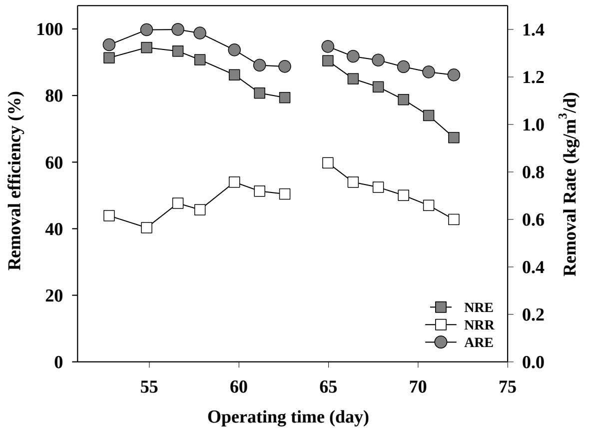
3.1 Deammofication by single and step feedings under the condition without COD

The first four batches of the single feeding operation showed the effluent concentrations of nitrogen compounds lower than 50 mg/L (Fig. 3a) and increase of NRR up to 1.11 kg-N/m^3/day (Fig. 3b). However, The NRR gradually decrease to lower than 0.10 kg-N/m^3/day. The single feeding gave a high initial ammonia concentration around 400 mg/L at each of batch cycles with a volumetric exchange ratio of 25%. The half of ammonia was oxidized to nitrite by PN reaction during the aerobic condition of longer than 15 hr. However, the followed anammox reaction required a more extended time as the batch cycles proceeded because the long aerobic condition for PN reaction and the high nitrite concentration might inhibit anammox activity. This resulted in the lower NRR.

In order to avoid the long aerobic condition and the high nitrite concentration, the amount of feed for a batch of the SBR was divided into 9 steps. Each cycle had the initial ammonia concentration of about 40 mg/L, which was then expected to be removed by the followed 6 sub-cycles consisting of aerobic and anoxic conditions. When the step-feeing strategy was applied, the first four batches showed the lower total nitrogen concentration in the effluent than single feeding (Fig. 4a). The ammonium concentration decrease to 2.04 mg-N/L and nitrite concentration was 2.85 mg-N/L. Moreover, the NRE and ARE were 97.1 % and 99.7%, respectively (Fig. 4b). The NRR was 0.57 kg-N/m^3/day and increased up to 0.76 kg-N/m^3/day during seven batches.

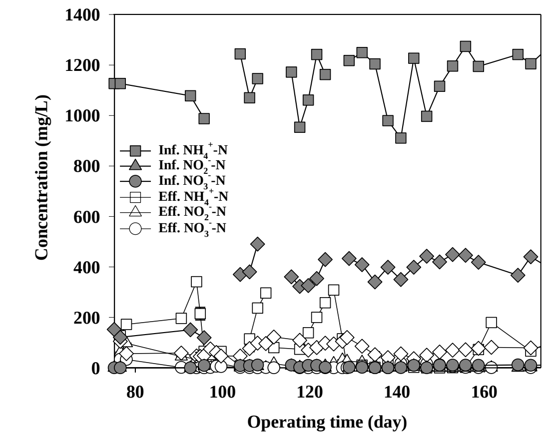


(a)



(b)

Fig. 4 Influent and effluent NH_4^+-N, NO_2^--N, and NO_3^-- N concentrations (mg/L) (a) and nitrogen removal efficiency (NRE, %), ammonium conversion efficiency (ARE, %), nitrogen removal rate (NRR, $kg/m^3/d$) (b) at phase 2



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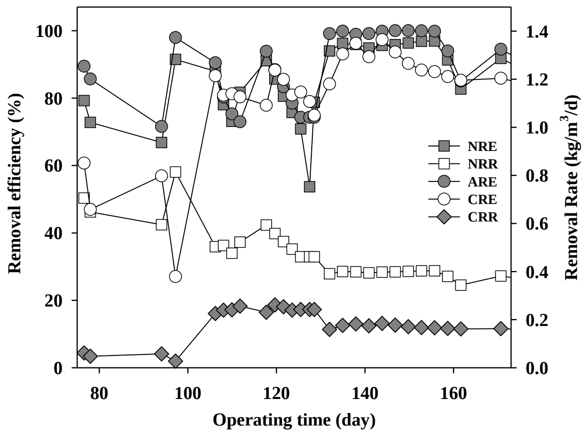


(b)

Fig. 5 Influent and effluent NH_4^+-N, NO_2^--N, and NO_3^--N concentrations (a) and nitrogen removal efficiency (NRE, %), ammonium conversion efficiency (ARE, %), nitrogen removal rate (NRR, $kg/m^3/d$), COD removal efficiency (CRE, %), and COD removal rate (CRR, $kg/m^3/d$) (b) at phase 3

However, when the number of sub-cycle was changed from 6 to 4 after day 65 to enhance the NRR by increasing the allocated ammonia concentration to each sub-cycle from about 7 mg/L to 10 mg/L, the effluent ammonium and nitrite drastically increased. The increased ammonium and nitrite concentration reflected that anammox activity was lower than to correspond with PN activity and getting worse. The NRE and ARE were also dropped to 69.3% and 86.2%, respectively. Thus, 6 sub-cycles were chosen as the more appropriate to deammonification of the nine-step feeding strategy and used for the next phase.

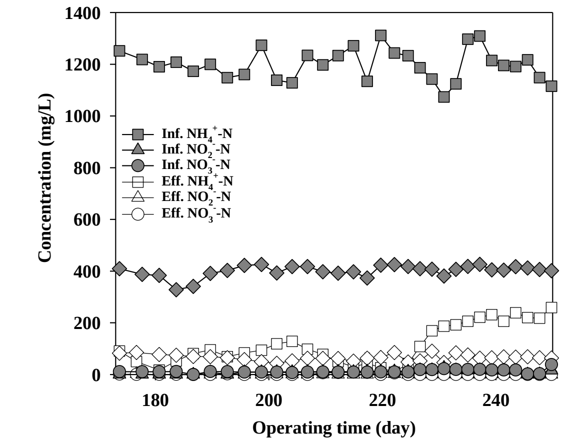
3.2 Deammofication by step feeding strategies under the condition with COD

When the influent including COD (~ 400 mg/L) was supplied to the SBR, an additional anoxic condition for denitrification was introduced between the feed and the sub-cycle of aerobic and anoxic periods in the nine-step feeding (Phase 3). Several studies also allocated the additional anoxic condition for denitrification after every step-feed (Kartal *et al*. 2008; Langone *et al*. 2014; Qin *et al*. 2017).

After a long period for stabilizing the process from day 76 to day 128, the nine-step feeding showed the lower the effluent nitrogen compounds compared to previous conditions (Fig 5a). The nitrogen removal trend of phase 3 was similar to that of phase 2. The ammonium removed during a sub-cycle was around 7 mg-N/L. Effluent nitrate decreased from 17.03 mg-N/L to 4.47 mg-N/L and COD was 64.79 mg/L. CRE showed above 80% and the NRE reached again to 99.7% as denitrification reaction balanced with PN and anammox reaction. NRR and CRR were achieved to 0.403 kg-N/m^3/d and 0.118 kg-COD/m^3/d, respectively (Fig 5b).

In phase 4, the operational strategy for the deammonification process was modified by many cycles consisted of feed, anoxic, aerobic, and anoxic conditions without sub-cycle to make a very stable condition. Different numbers of cycles, 50, 45 and 40, were investigated to achieve an enhanced performance as well as high NRE.

The effluent concentration of nitrite decreased to less than 0.1 mg-N/L and COD also decreased, and lower concentration was achieved than the previous phase (Fig. 6). The concentration of effluent ammonium decreased and increased again when the number of cycles decreased from 50 to 40 via 45. At 40 cycles, 0.518 kg-N/m^3/d of NRR was



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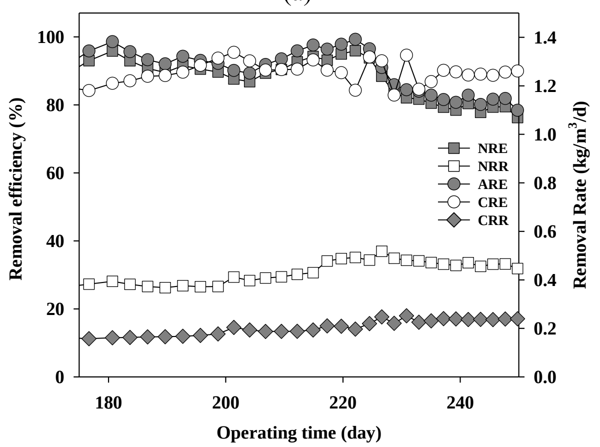
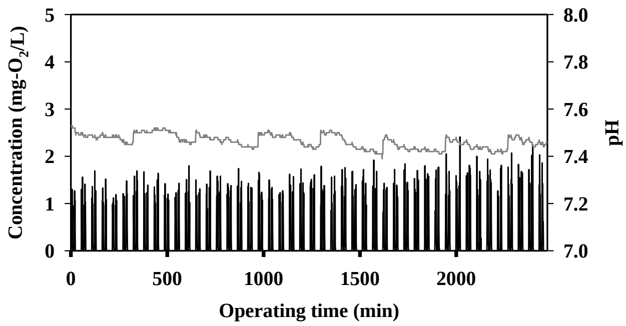


(b)

Fig. 6 Influent and effluent NH_4^+-N, NO_2^--N, and NO_3^--N concentrations (a) and nitrogen removal efficiency (NRE, %), ammonium conversion efficiency (ARE, %), nitrogen removal rate (NRR, kg/m^3/d), COD removal efficiency (CRE, %), and COD removal rate (CRR, kg/m^3/d) (b) at phase 4



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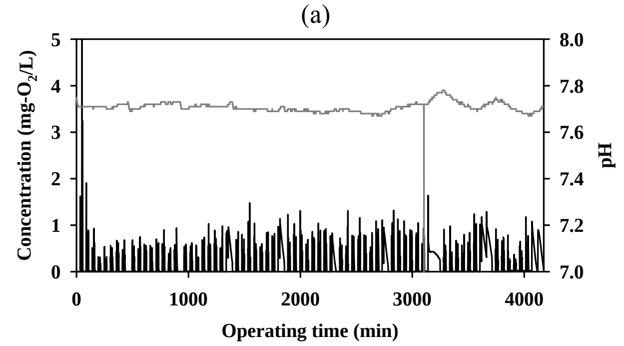

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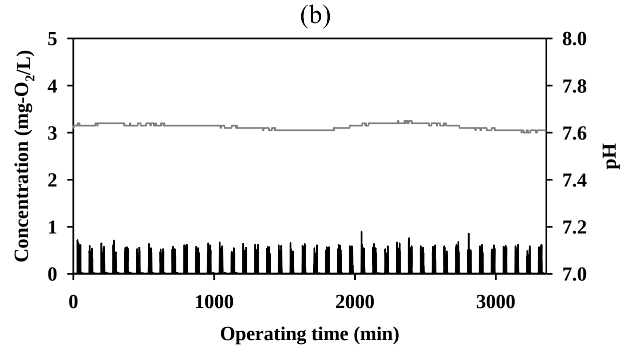

(c)

Fig. 7 The pattern of DO (black line) and pH (gray line) in single-stage deammonification SBR at phase 2 (a), phase 3 (b), and phase 4 (c)

obtained and NRE of over 94.2% was maintained for 47 days. The CRE and CRR were higher than those of previous phases were.

Consequently, the multiple-step feeding strategy without sub-cycle greatly improved the deammonification performance and showed stable removal efficiency and rate of both nitrogen and COD by inducing three reactions (denitrification, PN, and anammox) for deammonification on the given time.

3.3 Monitoring of operating parameters in single-stage deammonification SBR

Various sensor values such as DO, pH, ORP, and EC, were monitored during the operation of deammonification SBR with step feeding strategies (phases 2, 3, and 4). Some representative patterns of the operating parameters are shown in Fig. 7 (DO and pH) and Fig. 8 (ORP and EC).

In the case of nine-step feeding with sub-cycle under the condition without COD (phase 2) and with COD (phase 3), DO promptly decreased after a peak around 1.2 mg-O_2/L by the intermittent aeration during aeration periods in sub-cycles. The pattern of DO peaks slightly increased when there was a lack of ammonium concentration at the final of a batch in phase 2 (Fig. 7a), while the pattern was lower and unstable when COD was present (Fig. 7b). In phase 4 of multiple-step feedings without sub-cycle, DO was quite stable and decreased further around 0.5 mg-O_2/L, this seemed to be caused by COD oxidation. (Fig. 7c).

The pattern of pH seemed to reflect the cycle of the substrate feeding in the condition without COD (Fig. 7a). When the substrate was fed, the pH increased and then gradually decreased during repeated aeration conditions for PN producing protons. However, the pH pattern was not informative as an indicator to monitor and control the process under the condition with COD (Fig. 7b and c).

ORP and EC were also evaluated as possible parameters for monitoring the state of the process (Fig. 8). The EC pattern was severely fluctuating and not stable enough to reflect the operational state of the process in all tested operating phases. Although several studies reported that the EC pattern helped mirror the state of the process (Choi *et al.* 2018; Choi *et al.* 2019), the pattern of EC in this study seemed difficult to use for the monitoring process of single-stage deammonification.

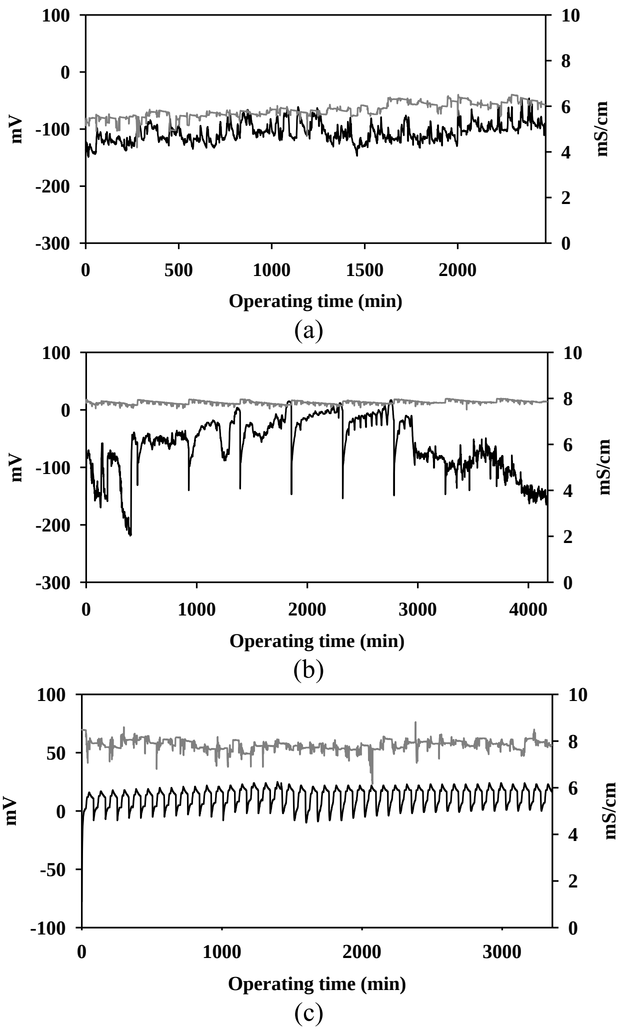

Fig. 8 The pattern of ORP (black line) and EC (gray line) in single-stage deammonification SBR at phase 2 (a), phase 3 (b), and phase 4(c)

The patterns of ORP in the step feeding with sub-cycles were too unstable and complex to understand the status of the process (Fig.8a and b). However, the ORP pattern in phase 4 of multiple-step feeding without sub-cycle showed very regular mountain-shaped curves (Fig 8c). When the influent was fed, the ORP dropped sharply and recovered to over zero mV during the anaerobic condition for denitrification. Then the curve was a constant increase during the aerobic condition for PN, followed by a gradual decrease during the anoxic condition for anammox. Therefore, as like the previous study that utilized the magnitude of ORP to monitor the strength of reaction steps for deammonification (Lackner *et al*. 2012a; 2012b), the ORP pattern in this study also seemed to be able to apply to monitor and control each reaction period for deammonification in the multiple-step feeding strategy without sub-cycle.

4. Conclusions

Various feeding strategies for single-stage deammofication in an SBR were evaluated under the condition with or without COD. The multiple-step feeding strategies without sub-cycle showed better performance: NRE 98.6-99.7% and NRR 0.403-0.518 kg-N/m^3/day. Thus, in the presence of COD, the multiple-step feeding without sub-cycles can contribute to the well-balanced deammonification consisted of PN, anammox, and denitrification in single-stage SBR. Unlike DO, pH, and EC, which did not sufficiently reflect the reaction step of each phase, the pattern of ORP seemed to be a possible key parameter for monitoring and controlling the deammonification in SBR with the multiple-step feeding without sub-cycle. However, further study on the correlation between ORP and each reaction step under various conditions should be required to achieve more efficient and stable nitrogen removal performance through more precise process diagnostics and control in a single-stage SBR operation.

Acknowledgments

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