Comparison of saline wastewater treatment performance of SBR with repeated starvation under aerobic and non-aerobic conditions

B. H. Moon, S. S Kim, C. H. Yoon and K. H. Park

ABSTRACT
This study investigated the effects of repeated starvation and feeding on the performance of a sequencing batch reactor (SBR) used for treating saline wastewater. The effects of aerobic and non-aerobic conditions on the sludge during starvation were evaluated to recover the performance of the SBR in terms of floc size and pollutant removal after resuming wastewater feeding. The floc size, fractal dimension, sludge volume index (SVI), specific oxygen uptake rate (SOUR), and pollutant removal efficiency were monitored. Experiment results revealed that the floc size and fractal dimensions decreased during starvation under both aerobic and non-aerobic conditions and increased after re-feeding wastewater. However, the difference in floc physical characteristics and performance depended on the starvation condition and was pronounced as starvation and re-feeding were repeated. The floc size and fractal dimensions decreased from 152.7 to 72.2 and 1.98 to 1.79 at the end of the fourth starvation period, resulting in deterioration of the sludge settleability and effluent quality. On the other hand, the floc size and fractal dimensions decreased from 158.7 to 135.7 and 1.95 to 1.81 at the end of the fourth starvation period but remained relatively constant after sludge adaptation. Some correlations were observed between the parameters monitored in this study. The results showed that maintaining the sludge under non-aerobic conditions was an effective strategy for reducing the effects of repeated starvation.

Key words | floc characteristics, repeated starvation, saline wastewater, sequencing batch reactor

INTRODUCTION
In many biological wastewater treatment plants, large fluctuations are observed in the hydraulic and organic loadings to the wastewater treatment plants due to the nature of source such as wastewater collection from tourist regions, race tracks, and fish markets. Extreme weekly and seasonal fluctuations, wherein flows vary between weekdays and weekends, can cause the wastewater flows to cease temporarily. The cycles of cessation and resumption of wastewater treatment plants inflows are repeated periodically due to the nature of its source. As a result, the sludge performing the biological wastewater treatment is repeatedly exposed to alternating periods of excess substrate availability, substrate limitation, and complete starvation. The repetition of starvation and re-feeding periods can significantly influence the overall performance of biological wastewater treatment plants. The performance of biological wastewater treatment plants depends on microbial activities and settleability after repeated starvation.

A number of researchers have investigated the effect of starvation on biological wastewater treatment. These previous studies suggested that keeping the sludge under anoxic or non-aerobic conditions is a better strategy for maintaining the biomass activities during starvation than keeping the sludge under aerobic conditions (Morgenroth et al. 2000; Lopez et al. 2006; Lu et al. 2007; Yilmaz et al. 2007). However, these investigations were limited to single period of starvation...
impacts and focused mostly on biological activities. The application of single period of starvation on biological wastewater treatment performance does not provide reliable information for appropriate sludge maintenance during the periods without feed. In biological wastewater treatment, the treatment performance is influenced not only by the biological activities, but also by the physical characteristics of floc. Changes in environmental conditions lead to changes in bacterial activity and death, and their adaptation to starvation conditions leads to important changes in floc structure and sludge settleability properties (Barbusinski & Koscielniak 1997; Nellenschulte & Kayser 1997; Cabezás et al. 2009). The effects of repeated starvation on the physical characteristics of floc, which plays an important role in determining the solid–liquid separation efficiency of the biological wastewater treatment process, have been rarely reported. In addition, the effects of repeated starvation on the performance of an SBR in terms of pollutant removal, especially for treating saline wastewater, have not been reported in the literature. Therefore, the effect of repeated starvation on the physical characteristics of floc in relation to the removal efficiencies needs to be investigated. It is necessary to assess the biological wastewater performance by repeating starvation and re-feeding in order to properly manage the sludge during periods of no wastewater flow and to meet the local effluent regulations. One of the challenges for the treatment of such wastewater is to cope with the repeated fluctuations in the wastewater flow linked to industrial activities.

The study involved investigating effects of repeated starvation under aerobic and non-aerobic conditions on the performance of an SBR used for treating saline wastewater. The effects of keeping the sludge under aerobic and non-aerobic conditions were assessed during this study.

MATERIALS AND METHODS

Two laboratory-scale SBRs (10 L) were operated in parallel using artificial saline wastewater. The synthetic saline wastewater was prepared with fish meal; its detailed composition can be found elsewhere (Moon et al. 2007). The synthetic saline wastewater contained 1,000–1,200 mg/L of COD\textsubscript{Cr}, 500–600 mg/L of COD\textsubscript{Mn}, 250–300 mg/L of T-N, 15–20 mg/L of T-P, and 10,000 mg/L of NaCl. The SBRs ran two cycles per day.

Each 12-h cycle comprised 5 min of filling time, 5.5 h of non-aerobic mixing time, 5.5 h of aerobic mixing time, 50 min of settling time, and 5 min of decanting time. In each cycle, 5 L of mixed liquor was wasted at the end of each aerobic period to maintain a sludge age of 10 days. The F/M ratio was 0.34 kg COD\textsubscript{Cr}/kg MLSS day or 0.17 kg COD\textsubscript{Mn}/kg MLSS day. Starvation tests were performed after the SBRs reached steady-state operation, as indicated by stable MLSS concentrations and pollutant removal efficiencies. After the SBRs reached steady-state conditions (70 days of reactor run), the supply of artificial saline wastewater was stopped for 5 days. During the 5-day starvation period, the sludge was maintained under aerobic and non-aerobic condition (only mixing without aeration). After the starvation period, the normal operation of the SBRs was resumed by feeding 100% of the artificial wastewater for 2 days. To investigate the effects of repeated starvation, four 5-day starvation and 2-day feeding periods were applied.

Chemical analysis of the samples was carried out according to the Standard Methods for Examination of Water and Wastewater (1998), except for COD. The Korean government regulates COD\textsubscript{Mn} instead of COD\textsubscript{Cr}, and therefore COD\textsubscript{Mn} was analysed in this study. For analysing COD\textsubscript{Mn}, a sufficient amount of AgSO\textsubscript{4} was added to the samples to eliminate chloride interference (Korean Standard Methods 2002). A diffraction particle sizer (Malvern Mastersizer/E model) was used to measure the particle size and fractal dimension. The fractal dimension (D\textsubscript{f}) was calculated from the raw light scattering data using Malvern Mastersizer/E, which was in accordance with the method proposed by Guan et al. (1998). The fractal dimension ranged from 1 to 3. The high value of the fractal dimension was related to round-shaped flocs.

RESULTS AND DISCUSSION

Effect of repeated starvation on floc size, fractal dimension, and SVI

The effect of repeated starvation and re-feeding on the floc size is illustrated in Figure 1. The floc size during the 5-day aerobic and non-aerobic starvation periods decreased from 152.7 to 115.4 and from 158.7 to 106.3, respectively. After resuming wastewater feeding for 2 days, the floc that had been starved under aerobic and non-aerobic conditions increased in size to 129.7 and 124.3, respectively. During the second aerobic and non-aerobic starvation periods, the floc size decreased to 96.2 and 98.4, respectively. After resuming wastewater feeding, the floc that had been starved under aerobic and non-aerobic conditions increased to 107.6 and 118.4, respectively. During the third starvation period, the floc size under the aerobic condition further decreased to 88.7 and, as the starvation and re-feeding was repeated, the
floc size under the aerobic condition continuously decreased to 72.2 μm at the end of the fourth starvation period. On the other hand, the floc size under the third non-aerobic starvation condition decreased for the first 2 days and did not decrease further. Then, the floc size under non-aerobic starvation condition increased slightly after re-feeding. It is interesting to note that the size of floc starved under the non-aerobic condition increased more rapidly after resuming wastewater feeding than that under the aerobic starvation condition. The sludge starved under the non-aerobic condition was able to maintain its floc size relatively well after its adaptation as starvation and re-feeding was repeated, reverting to its initial size.

Reducing floc size under both starvation conditions seems to be one of the physiological adaptations of the biological floc. It has been reported that the decay rate of bacteria such as heterotrophic bacteria, nitrifiers, and phosphorus accumulating organisms (PAOs) under non-aerobic starvation conditions was lower than those under aerobic starvation conditions (Siegrist et al. 1999; Lopez et al. 2006). It seems that the higher decay rates under aerobic starvation conditions play a significant role in the decrease of floc size. For the artificial saline wastewater treated in this study, the 2-day resuscitation period after 5 days of aerobic starvation was not enough to restore its initial floc size before the next starvation. The starvation led to small floc accumulation when the starvation was applied in series. However, the floc size under the non-aerobic condition decreased for 2 days and did not decrease further during the third starvation period; thus, application of the third starvation resulted in a less important effect than the second starvation. Because the floc size did not continue to decrease, floc size appeared to not depend solely on the previous starvation stress. This indicates that the floc starved under the non-aerobic condition had more resistant ability. The reasons for these phenomena are not clear but need to be further analyzed with the other physical characteristics monitored in this study. As starvation and re-feeding were repeated, the effect of starvation on the floc size under the non-aerobic condition was relatively insignificant compared to that under the aerobic condition.

Figure 2 shows the variation in the fractal dimension of floc during repeated starvation and re-feeding. Starvation leads to morphological changes in floc. It can be seen in Figure 2 that the fractal dimension of floc showed a trend similar to the floc size: the values of the fractal dimension of floc decreased under starvation conditions and increased after re-feeding wastewater. As the starvation and re-feeding were repeated, the fractal dimension of floc under the aerobic condition continuously decreased. During the first non-aerobic starvation period, the fractal dimension of floc decreased at a higher rate than that under aerobic conditions. However, as the non-aerobic starvation and re-feeding were repeated, the fractal dimension remained relatively constant.

Depending on the starvation conditions, some microbial groups will die and lyse, while other opportunist groups will grow. Jin et al. (2004) reported that sludge with high quantities of filamentous microorganisms corresponded to lower values of fractal dimension. The results obtained in this study indicate the filamentous-shaped floc, as measured by the low values of fractal dimension, had a competitive advantage over round-shaped floc, as measured by the high values of fractal dimension when the sludge was repeatedly exposed to alternating starvation and normal re-feeding conditions. In repeated starvation and re-feeding conditions, the floc that had lower fractal dimensions adapted rapidly to this transient condition. This observation suggests that the filamentous...
bacteria seemed to proliferate and have resistant ability during the starvation conditions. Beccari et al. (1998) reported that the filamentous bacteria produced by an intermittently fed continuous stirred tank reactor (CSTR) had low sensitivity to starvation. Variations in the fractal dimension and size were observed to be smaller under non-aerobic conditions as compared to those under aerobic starvation conditions. The starvation condition changed the floc size and fractal dimension in different ways. As the starvation and re-feeding were repeated, the differences in floc size and fractal dimension under aerobic and non-aerobic starvation conditions were pronounced. As the aerobic starvation and re-feeding were repeated, small and round-shaped floc proliferated, which indicated that pin-point floc and free bacteria dominated. However, as non-aerobic starvation and re-feeding were repeated, relatively stable-sized filamentous floc proliferated. The reduced size and formation of irregularly-shaped filamentous floc in the SBR under the starvation periods seem to indicate a selective advantage to increase the surface area, enabling easier access to the substrate surrounding the floc. The propagation patterns of floc size and fractal dimension in aerobic and non-aerobic starvation conditions were clearly different.

The development of floc size and fractal dimension is a progressive process that is induced by the repetition of starvation. Gaval & Pernell (2005) showed that repetitive stresses triggered a progressive increase in filamentous bacteria. According to their repetitive theory as well as the experimental observation in this study, floc size and fractal dimension in an SBR subjected to periodic starvation can be classified into two types: (1) in repeated starvation under aerobic conditions, floc size and fractal dimension remained at the values after the aerobic starvation condition; and (2) there was downward staircase development with a decrease of floc size and fractal dimension when the starvation and re-feeding were repeated. Under the non-aerobic starvation condition, its effects on floc physical characteristics were transient, and the floc characteristics returned to their initial values after resuming normal operation. It would appear that the floc size and fractal dimension response amplification after repeated starvation depends on the sludge maintenance.

The physical characteristics of floc, such as floc size, fractal dimension, and density, are well known to affect the sludge settleability. Jang & Schuler (2007) reported that sludge with higher polyphosphate content has a higher sludge density, resulting in better settleability. Lopez et al. (2006) reported that activated sludge under aerobic starvation conditions had less polyphosphate content and a higher percentage of cells that had damaged membranes. They also showed that cell lysis and protozoan predation are enhanced under aerobic starvation. Decay of PAOs is greatly reduced under non-aerobic storage as compared to aerobic storage conditions. Therefore, relatively higher-density floc with polyphosphate could be generated under non-aerobic starvation conditions. Under aerobic conditions, more severe effects of starvation on the physical characteristics of floc result in the deterioration of sludge settleability. The combination of non-aeration and substrate depletion is less detrimental to SVI than conditions where oxygen concentration is high and substrate is low (Figure 3). These findings suggest that keeping the sludge under non-aerobic conditions would be a better strategy for recovering the sludge settleability during starvation periods.

Effect of repeated starvation on SOUR

SOUR trended similarly to floc size and fractal dimension, as illustrated in Figure 4. The SOUR before the starvation was 9.81 for the aerobic condition and 10.08 for the non-aerobic condition. After the first 5-day starvation, the SOUR dropped to 2.88 after aerobic starvation and 0.55 after non-aerobic starvation. The decrease of SOUR indicated a loss of the respiratory activity. This response was similar that obtained by Coello Oviedo et al. (2005). They reported that the largest decrease of 88% in oxygen uptake occurred within the first 4 days of aerobic starvation, which is similar to the result obtained in this study. However, after non-aerobic starvation, SOUR significantly decreased to 0.54. The very low SOUR measured after non-aerobic starvation was partially caused by the negligible decrease in the MLSS concentration under non-aerobic starvation compared to relatively greater

**Figure 3** | Effect of repeated starvation and re-feeding on sludge settleability.
decrease in the MLSS under aerobic starvation. As the starvation and re-feeding were repeated, the effect of starvation under the non-aerobic condition was reduced. The SOUR changes were similar to the floc size changes, which decreased during the starvation condition and then recuperated gradually after resumption of wastewater feeding.

Figure 4 shows the correlation between the floc size and SOUR. Initially, SOUR measured from the aerobic starvation reactor was slightly higher than that from the non-aerobic reactor (10.1 compared to 9.8 mgO₂/mg MLSS h × 10⁻³). However, after three repeated starvation and re-feeding cycles, the SOUR after aerobic starvation decreased to 0.41 while the SOUR after non-aerobic starvation decreased to 4.53. The SOUR in the first starvation decreased significantly faster after non-aerobic starvation than after aerobic starvation. However, the SOUR under aerobic starvation condition continuously decreased, while the SOUR under non-aerobic starvation condition increased after the second starvation period. After the first 5 days of starvation, SOUR decreased abruptly. There were similar trends observed among floc size, fractal dimension, SVI, and SOUR. For aerobic condition, the decrease in floc size and fractal dimension correlated with the increase in the SVI and the decrease in SOUR. These results suggest that larger floc size and well-settling sludge have a faster oxygen uptake rate.

Effect of repeated starvation on removal efficiencies

The effect of repeated starvation and re-feeding on the CODMn removal efficiencies is presented in Figure 5. The CODMn removal efficiencies before the starvation were 89.3% for the aerobic condition and 87.4% for the non-aerobic condition. After the first 5-day starvation period, the CODMn removal efficiencies decreased to 77.4% after aerobic starvation and 82.3% after non-aerobic starvation. The starvation had a direct effect on the performance of COD removal, since the performance was directly related to the concentration, viability, and physical characteristics of the biomass in the SBR. The decrease of COD after starvation is attributed to the reduction of the biomass concentration and the deterioration of the physical and biological characteristics of floc. The deterioration of the physical characteristics of floc due to decreased floc size, fractal dimension, and settleability resulted in increased effluent suspended solids. Starvation had less of an effect on the performance of the SBR under the non-aerobic condition compared to the aerobic condition. This was supported by the relatively lower reduction of pollutant removal after non-aerobic starvation and quicker recovery after resuming wastewater feeding, which could have been due to less deterioration of the physical characteristics of floc.

Figure 6 shows, for both SBRs, the variation in T-N concentration in the effluent. The SBRs achieved more than
55% T-N removal before starvation began. After the first starvation periods, T-N removal dropped to 40% and 50% under aerobic and non-aerobic conditions, respectively. T-N removal in both reactors further decreased even after re-feeding wastewater. After resumption of wastewater feeding, the T-N removal under the non-aerobic condition was lower than that under the aerobic condition. However, as starvation and re-feeding were repeated, slightly higher T-N removals under non-aerobic than aerobic conditions were observed.

In general, a typical activated sludge process achieves 20% to 30% T-N removal. This implies that most of the T-N removal is due to cell synthesis and the appropriate sludge maintenance. The T-N removal efficiency was not recovered. Several researchers have reported that the nitrifier decay rate is lower under non-aerobic than under aerobic conditions (Siegrist et al. 1999; Salem et al. 2006). Yilmaz et al. (2007) reported that the nitrogen removal was fully recovered in 4 days by a gradual increase of the wastewater load after starvation. But they also reported that it took about 30 days (two sludge ages) for the MLSS to return to the original level in both starvation studies. Taking into account the 100% resumption of saline wastewater feeding after starvation applied in this study, more recovery period would be required to reach the initial T-N removal rate and to differentiate the effectiveness of aerobic versus non-aerobic sludge maintenance. Further research is needed to elucidate the T-N removal after different starvation conditions for treating saline wastewater involved in nitrification and denitrification. The 2-day resuscitation periods applied in this study were not enough to differentiate T-N removal under aerobic and non-aerobic starvation conditions.

CONCLUSIONS

The findings suggest that, as the starvation and re-feeding cycles were repeated, the physical characteristics of floc and the pollutant removal efficiency depended on the starvation condition (aerobic and non-aerobic). The floc physical characteristics and pollutant removal efficiency remained constant after aerobic starvation and decreased with a decrease in the floc size and fractal dimension when starvation and re-feeding were repeated. Under the non-aerobic starvation condition, changes in floc physical characteristics and pollutant removal efficiency were transient and returned to their initial values after the resumption of normal operation. Thus, it would appear that the floc size and fractal dimension after repeated starvation depend on sludge maintenance.

Non-aeration resulted in high removal efficiency and also reduced the power and energy consumption. The results of this experiment confirm and suggest that maintaining sludge under non-aerobic conditions during fluctuating wastewater flows is an appropriate strategy for the recovery of biological wastewater treatment performance.

REFERENCES


Nellenschulte, T. & Kayser, R. 1997 Change of particle structure of sewage sludges during mechanical and biological processes with
regard to the dewatering result. Water Science and Technology 36(4), 293–306.