Nitrification/Denitrification in Intermittent Aeration Process for Swine Wastewater Treatment

By Jiayang Cheng[1] and Bin Liu[2]

Abstract: A continuous-flow intermittent aeration (IA) process has been studied for nitrogen removal from anaerobically digested swine wastewater with high ammonium content. High nitrogen removal efficiency of average 91% total Kjeldahl nitrogen and 92% NH_4-N was achieved in an IA system with an alteration of 1-h aeration and 1-h nonaeration. Nitrification and denitrification were found to be responsible for the nitrogen removal in the system. Nitrite and nitrate in the effluent were less than 1.0 mg/L and 8.0 mg/L, respectively. The specific nitrification and denitrification rates of the single-sludge IA culture were determined through batch experiments as 2.79–3.70 mgNO_3-N/g volatile suspended solids-h and 0.59–1.03 mgNO_3-N/g volatile suspended solids-h, respectively. In the IA process, the aeration period created favorable conditions for nitrifying bacteria (dissolved oxygen = 4–6 mg/L and oxidation-reduction potential = 80–100 mV), while the nonaeration period provided good environment for denitrifying bacteria (dissolved oxygen < 1 mg/L and oxidation-reduction potential as low as 0 mV). Ammonia volatilization in the IA process was negligible (<0.008%). Denitrification activity in the IA process prevented nitrate from accumulation and significant pH change in the system, which is critical for nitrogen removal from swine wastewater with high ammonium content.

INTRODUCTION

The swine industry has experienced a significant growth in the United States in the last decade. The pig number in the United States has increased from 53.8 million in 1989 to 62.2 million in 1998 (USDA 1999). In North Carolina, swine production has tremendously increased from 2 million in 1987 to 9.8 million in 1997 (NCDA 1988, 1998). Swine waste is usually washed out of the confinement houses, treated in an anaerobic lagoon, and applied to cropland for nutrient utilization. Some of the treated water in the anaerobic lagoon is normally recycled to wash the swine waste out of the houses. The regulations do not permit direct discharge of treated animal wastewater to any surface water course. Because of the tremendous growth of swine production and limited cropland in states like North Carolina, there are growing environmental concerns with the current waste management system, especially the nutrient management. There is a great interest in developing innovative technologies to remove nutrients from the wastewater.

Swine wastewater has high organics and nutrient contents, compared with municipal wastewater. Nutrient removal from swine wastewater has been investigated by many researchers in the last two decades (Timmermans and Van Haute 1983; Blouin et al. 1988; Osada et al. 1991; Bortone et al. 1994; Liao and Maekawa 1994; Maekawa et al. 1995; Lee et al. 1997; Bicudo et al. 1999). Bortone et al. (1994) studied an anaerobic/anoxic sequencing batch reactor system and found that nitrogen removal from anaerobically treated swine wastewater is relatively difficult because of its low COD (chemical oxygen demand)/N ratio. Lee et al. (1997) reported an enhancement of biological nutrient removal performance by using supplemental organic matter, such as acetate or fermented swine waste, as an extra carbon source for denitrification in sequencing batch reactors. Fermentation of primary sludge could produce short-chained volatile fatty acids (VFAs), which were effective as carbon sources for denitrification and phosphorus removal (Lee et al. 1997). Bicudo et al. (1999) reported an effective nitrogen removal in an aerobic/anoxic process in sequencing batch treatment of raw swine wastewater, but the cost of operation is very expensive because of the high oxygen demand of the raw swine wastewater.

There are two major challenges to adopt the traditional nitrification/denitrification processes in swine wastewater treatment. First, oxidation of ammonium would cause the pH to drop during the nitrification process, which may inhibit the nitrifying activities because nitrifying bacteria (especially nitrite oxidizing bacteria) are very sensitive to pH (Bitton 1994). This drop in pH during the nitrification process for municipal wastewater treatment may not be significant because of the low ammonium content, but it is significant for swine wastewater due to the high ammonium level. Second, addition of supplemental organic matter, such as methanol or acetate in the denitrification process, makes the process too costly for the swine industry.

Liao and Maekawa (1994) studied an intermittent aeration process in which aeration and nonaeration were alternately repeated, and observed significant nitrogen removal in the process. Total nitrogen (TN) and ammonium nitrogen (NH_4-N) were, respectively, removed by up to 30% and 40% from an anaerobically treated swine wastewater in an intermittent aeration tank with an alternation of 1-h aeration and 1-h nonaeration. It was believed that the alternate aeration and nonaeration created aerobic and anoxic conditions for nitrification and denitrification, respectively. The alternate nitrification and denitrification prevented nitrite and nitrate from accumulation. Therefore, the nitrification activity could stay at a high rate and higher removal efficiency could be achieved. However, nitrification and denitrification activities were not verified for the intermittent aeration culture in the previous studies.

In this research, a continuous-flow intermittent aeration (IA) process for nitrogen removal from anaerobically digested swine wastewater was investigated. The nitrification and denitrification capabilities of the IA culture were observed, and the rates of nitrification and denitrification of the swine wastewater were determined through batch experiments.

MATERIALS AND METHODS

Intermittent Aeration

Raw wastewater obtained from a swine operation unit at Lake Wheeler Road Field Laboratory of North Carolina State

[1]Asst. Prof., Biol. and Agric. Engrg. Dept., North Carolina State Univ., Raleigh, NC 27695-7625 (corresponding author). E-mail: jay_cheng@ncsu.edu

[2]Grad. Res. Asst., Biol. and Agric. Engrg. Dept., North Carolina State Univ., Raleigh, NC 27695.

Note. Associate Editor: Joseph Flora. Discussion open until January 1, 2002. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on July 15, 2000; revised March 7, 2001. This paper is part of the ***Journal of Environmental Engineering***, Vol. 127, No. 8, August, 2001. ©ASCE, ISSN 0733-9372/01/0008-0705–0711/$8.00 + $.50 per page. Paper No. 22387.

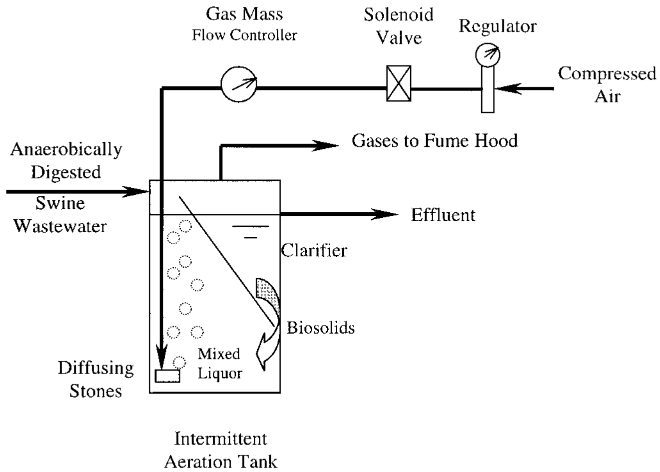

FIG. 1. Diagram of Lab-Scale Intermittent Aeration System for Nitrogen Removal from Anaerobically Digested Swine Wastewater

University was first treated in a 20 L continuous-flow biofilm anaerobic digester for degradation of organic compounds (Liu 1999). The effluent of the anaerobic digester then continuously flowed into an IA tank for nutrient removal. Two identical plexiglass IA tanks ($18.5 \times 18.5 \times 38$ cm) were used in this study as duplicates. Fig. 1 shows the schematic of a laboratory continuous-flow intermittent aeration system for nitrogen removal from anaerobically digested swine wastewater. As shown in the figure, the aeration tank was divided by a separating board into an aeration zone and a clarification zone. The two zones were connected by a slot at the low end of the board. Actual working volume of the aeration zone in each tank was 6 L, the clarification zone was 2 L, and the rest of the tank volume was in head space. Air was delivered to the aeration zone through two cylindric diffusing stones (D = 22 mm and L = 25 mm) (Fisher Scientific Co., Pittsburgh, Pa.) at the bottom of the tank. Biosolids would settle down in the clarification zone and drop back to the aeration zone through the slot. Supernatant in the clarification zone flowed out of the system as effluent. Intermittent aeration was achieved in the tank by alternating aeration and nonaeration. No mixing was provided during the nonaeration periods to minimize oxygen transfer from the head space to the mixed liquor. Biomass settling was not significant during the nonaeration periods because of a relatively short period of time (1 h). Air delivery to each aeration tank was on for 1 h and off for the following hour, which was carried out with a solenoid valve controlled by an electronic timer (ChronTrol Corp., San Diego, Calif.). Compressed air was regulated to 10 psi and air flow was controlled by a gas mass flow controller (Cole-Parmer Instrument Co., Vernon Hills, Ill.). Based on the COD loading in the influent and the estimated oxygen utilization efficiency of the system, an air flow rate of 500 standard mL/min was delivered to each aeration tank during the aeration periods.

To start up the IA tank, 500 mL of activated sludge and 500 mL of denitrifying culture were introduced into each tank as seed culture. The activated sludge and the denitrifying culture were obtained from the aeration basin and the denitrification reactor, respectively, at Neuse River Wastewater Treatment Plant, a typical domestic wastewater treatment plant in Raleigh, N.C. The plant is providing treatment for municipal wastewater from City Raleigh. The IA tank was operated at room temperature (about 25°C). The influent flow rate was 2 L/day or the hydraulic retention time (HRT) in the IA tank was 3 days. Two hundred mL of mixed liquor were wasted from the aeration zone every day during an aeration period and the average VSS (volatile suspended solids) concentration in the mixed liquor was 1,980 mg/L. Effluent from an IA tank, which was about 1.8 L/day, was flowing out from the clarification zone and the average VSS concentration in the effluent was 103 mg/L. Therefore, the mean cell residence time in the IA tank was about 20 days.

Analytical Methods

Chemical Analysis

Samples from the influent and the effluent of each IA tank were collected weekly to monitor the performance of the IA systems. The samples were analyzed for TKN (total Kjeldahl nitrogen), NH_4-N, NO_3-N, NO_2-N, TP (total phosphorus), o-PO_4-P, COD, TOC (total organic carbon), pH, TSS (total suspended solids), and VSS in the Environmental Analysis Laboratory of Biological and Agricultural Engineering Department at North Carolina State University. EPA Methods (EPA 1983) 351.2, 350.2, 352.1, 353.2, 410.4, and 415.1 were used for the analyses of TKN, NH_4-N, NO_3-N, NO_2-N, COD, and TOC, respectively. Standard Methods (APHA 1995) 4500-P C, 4500-P F, 4500-H^+, 2540 D, and 2540 E were used for TP, o-PO_4-P, pH, TSS, and VSS analyses, respectively.

DO and ORP Measurement

Dissolved oxygen (DO) and oxidation-reduction potential (ORP) in the aeration zone were measured during the aeration and non-aeration periods. YSI 52 dissolved oxygen meter and YSI 5739 oxygen probe (YSI Inc., Yellow Springs, Ohio) were used to measure the DO. The ORP was measured using an Accumet metallic combination platinum/Ag/AgCl electrode and Accumet AP62 pH/mV meter (Fisher Scientific Co., Pittsburgh, Pa.).

Ammonia Volatilization Measurement

Boric acid absorption method was used for monitoring possible ammonia volatilization from the IA tanks. In the experiments, the IA tank was sealed with only one gas outlet. All the gases out of the IA tank were conducted to pass through a 500 mL 0.32 M boric acid solution in a flask. Any ammonia in the gases would be absorbed by boric acid. The boric acid solution was then analyzed for ammonium after the experiment and ammonia volatilization could be quantified. The ammonia absorption tests were conducted in both IA tanks for three different time periods—24, 48, and 72 h. Fresh boric acid solution was prepared right before each experiment and was immediately analyzed for ammonium after the experiment.

Nitrification and Denitrification Activities

Nitrification Activity Tests

To determine nitrification activity in the IA process, batch nitrification tests were conducted with the culture from the IA tanks. A 5-L glass bottle was used as the batch reactor. Four and a half liters of mixed liquor from an IA tank which had been operated at stable conditions for more than 37 weeks were introduced into the batch reactor for each batch nitrification test. Ammonium chloride (NH_4Cl) was added into the batch reactor to result in three different initial ammonium-nitrogen concentrations (56, 101, and 251 mg/L) in the batch tests. The ratio of carbon (TOC) to nitrogen (NH_4-N + NO_3-N + NO_2-N) or C/N at the beginning of each batch test was maintained the same as that in the influent to the continuous-flow IA tanks, which was 1.11, by adding methanol to the batch reactor. The batch reactor was well mixed with a magnetic stirrer, and continuously aerated through a diffusing stone (Fisher Scientific Co.) with an air flow rate of 500 mL/min. Forty mL samples were taken at designated intervals (from

0.5–3.0 h, depending on the initial NH_4-N concentration) and analyzed for NH_4-N, NO_3-N, NO_2-N, VSS, and pH. Each sample was immediately measured for pH and then acidified to a pH value of around 2.0 with sulfuric acid to prevent any microbial activity.

Denitrification Activity Tests

Denitrification activity of the culture in the IA tank was also studied in batch tests. In these batch tests, the IA tank was operated as a batch reactor without aeration. At the beginning of the batch tests, the batch reactor was spiked with potassium nitrate (KNO_3) to result in different initial concentrations of nitrate-nitrogen (59, 84, and 230 mg/L) in the batch tests. Each batch test was conducted after steady state of the IA process was achieved in the tank. The initial C/N ratio in the batch tests was maintained at 1.11, the same as in the influent to the continuous-flow intermittent aeration operation, by adding methanol to the batch reactor. Prior to the start of each batch test, the head space of the batch reactor was purged with argon gas to create an oxygen-free environment. This is important because denitrifying bacteria are sensitive to free oxygen. The batch reactor was then sealed and completely mixed with a magnetic stirrer. Mixed liquor samples (30 mL) were taken from the batch reactor at designated intervals (3–5 h, depending on the initial NO_3-N concentration) for analyses of NO_3-N, NO_2-N, VSS, and pH to monitor the denitrification activity. The samples were measured for pH and then acidified as previously described. Denitrification activity was tested by monitoring the change of nitrate and nitrite concentrations.

RESULTS AND DISCUSSION

To test the reproducibility, the same operational conditions were used at both continuous-flow IA tanks. Anaerobically digested swine wastewater with high nutrient levels (average 285 mg/L TKN, 221 mg/L NH_4-N, 67 mg/L TP, and 49 mg/L o-PO_4-P) and low C/N ratio (average 1.11) were continuously fed to the IA tanks. There was no nitrite or nitrate observed in the influent to the IA tanks. Intermittent aeration (aeration: nonaeration = 1 h: 1 h) was applied to the mixed liquor in both tanks. One hour aeration followed by another hour nonaeration was chosen, because it was found to be the better intermittent aeration pattern than the others for nitrogen removal from swine wastewater by Liao and Maekawa (1994). Similar performance or effluent water quality was observed in both tanks. Conversion of ammonium to nitrate or nitrification was immediately observed in both tanks. Fig. 2 shows the formation and disappearance of nitrate and nitrite in both continuous-flow IA tanks during an experiment of 57 weeks. Nitrate concentration in the effluent of both tanks was high in the first seven weeks, and started to decrease at the seventh week until it stabilized at a low level at Week 20. Significant nitrite was also observed for the first 15 weeks (Fig. 2). The nitrite concentration decreased to a very low level after the intermittent aeration process reached stable conditions at Week 20. The systems were in operation at stable conditions for 37 weeks. The average biomass concentration in the mixed liquor of the aeration zone in the IA tanks was 1,980 mgVSS/L. The data obtained from both systems were very similar, and the representative water quality data obtained from the influent and the effluent of IA Tank A from Weeks 20–57 are shown in Table 1. High nitrogen removal (average 91% TKN and 92% NH_4-N) was achieved in the IA tank. Very low levels of nitrate and nitrite remained in the effluent of the IA tank—less than EPA National Primary Drinking Water Standards: nitrate, 10 mg/L; nitrite, 1 mg/L (Liu and Liptak 1996). At the same time, organic waste was also degraded (average 57% COD and 61% TOC) and the pH stayed fairly stable. The main purpose of the IA system was to maximize nitrogen removal. A longer aeration period might improve the COD removal efficiency, but it might also deplete the carbon source which was necessary to support denitrifying bacteria in the following nonaeration period. Poor phosphorus removal was observed in the system. To achieve phosphorus removal by polyphosphate accumulation, it is necessary to operate the reactor with a cycling between anaerobic and aerobic conditions (Metcalf and Eddy 1991), which was not provided in the IA tanks in this study.

It was believed that nitrogen removal in the intermittent

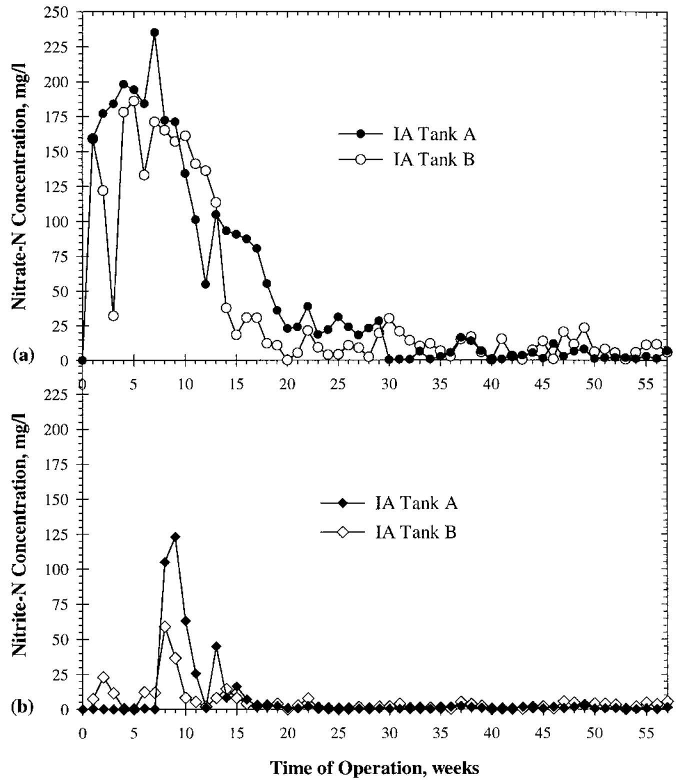

FIG. 2. Nitrate (a) and Nitrite (b) Concentrations in the Effluent of Continuous-Flow Intermittent Aeration Tanks Treating Anaerobically Digested Swine Wastewater with Average NH_4-N Concentration of 221 mg/L (operational conditions: aeration: nonaeration = 1 h: 1 h, hydraulic retention time = 3 days; mean cell residence time = 20 days)

TABLE 1. Characteristics of Influent and Effluent of Intermittent Aeration Tank (Tank A) Treating Anaerobically Digested Swine Wastewater at Stable Conditions (Weeks 20–57): Hydraulic Retention Time = 3 Days and Mean Cell Residence Time = 20 Days

Parameter	Influent average (Std. Dev.)[a]	Effluent average (Std. Dev.)[a]	Average removal efficiency (%)
TKN,[c] mg/L	285 (46.4)	27.0 (20.3)	91
NH_4-N, mg/L	221 (42.0)	18.0 (17.0)	92
NO_3-N, mg/L	ND[b]	7.9 (8.3)	—
NO_2-N, mg/L	ND[b]	0.9 (0.7)	—
TP, mg/L	67.0 (12.2)	65.0 (15.8)	3
o-PO_4-P, mg/L	49.0 (13.6)	55.0 (11.5)	—
COD,[d] mg/L	697 (155)	303 (74.6)	57
TOC,[e] mg/L	246 (47.6)	97.0 (30.0)	61
pH	7.34 (0.27)	7.72 (0.23)	—
TSS,[f] mg/L	364 (65.5)	141 (40.0)	61
VSS,[g] mg/L	302 (97.1)	103 (39.7)	66

[a]Standard deviation.
[b]Not detectable.
[c]Total Kjeldahl nitrogen.
[d]Chemical oxygen demand.
[e]Total organic carbon.
[f]Total suspended solids.
[g]Volatile suspended solids.

aeration process was a result of nitrification and denitrification (Osada et al. 1991; Liao and Maekawa 1994). To verify the hypothesis of nitrogen removal in the IA process, experiments were conducted to test three aspects of the nitrogen removal process: (1) ammonia volatilization from the IA tank was monitored to determine the percentage of nitrogen removal due to ammonia volatilization; (2) DO and ORP were measured during the cycles of aeration and nonaeration to determine the biological conditions at these two different periods; and (3) the intermittent aeration culture from the IA tank was studied in batch tests to determine its nitrification and denitrification activities and rates. The results are now presented.

Ammonia Volatilization from the IA Tanks

Ammonia volatilization from both IA tanks was monitored for different periods of time (24, 48, and 72 h) between Weeks 30 and 35, in duplicate. The results obtained from duplicate samples for each IA tank and the average data from IA Tanks A and B agreed within 10%. The representative average data from Tank A are demonstrated in Table 2. As shown in Table 2, a very small amount of ammonia volatilized from the IA tank. The nitrogen removal due to ammonia volatilization was less than 0.008%, which was negligible.

DO and ORP during Aeration and Nonaeration Periods

Dissolved oxygen and oxidation-reduction potential were measured in the IA tanks during both periods of aeration and nonaeration. The representative data are shown in Fig. 3. When an aeration period started, the DO jumped to about 6 mg/L. The DO concentration decreased slightly during the aeration period, but generally stayed above 4 mg/L. The ORP stayed in the range 80–110 mV during the aeration period. When a nonaeration period started 1 h later, the DO concentration dropped rapidly to around 1 mg/L. It continued to drop slowly during the nonaeration period and stayed between 0.2 and 1 mg/L. At the beginning of a nonaeration period, the ORP decreased rapidly and approached 0 mV at the end of the period. In order to achieve a high nitrification rate, DO has to be maintained around 4 mg/L in the mixed liquor (Metcalf and Eddy 1991; Maekawa et al. 1995). To create an anoxic environment for denitrifying bacteria, DO must be controlled under 1 mg/L (Metcalf and Eddy 1991). As shown in Fig. 3(a), the aeration and nonaeration periods in the IA tank provided favorable environments for nitrification and denitrification activities, respectively. Low ORP during the nonaeration period was also favorable to the denitrifying bacteria.

Nitrification Rate of the Intermittent Aeration Culture

Three nitrification batch tests with different initial ammonium-nitrogen concentrations (56, 101, and 251 mg/L) were carried out in a continuously aerated reactor with suspended biomass from an IA tank. All three tests were conducted under the same initial carbon to nitrogen ratio (C/N = 1.11). The results are shown in Fig. 4. In these batch tests, ammonium was oxidized to mainly nitrate and a small amount of nitrite. Total nitrogen including NH_4-N, NO_3-N, and NO_2-N in each batch test remained almost constant. The slight decrease of TN in the batch tests was probably due to the uptake of nitrogen by bacteria. In the batch test with an initial NH_4-N concentration of 56 mg/L, 88% of ammonium was nitrified mainly to nitrate after 8 h of the test [Fig. 4(a)]. The pH in this batch test remained almost constant (around 7.80). As the initial NH_4-N concentration increased to 101 mg/L, the percentage of ammonium nitrification decreased to 79% at the end of the 16-h test [Fig. 4(b)]. A slight pH decrease (from initial 7.84 to 7.43 at hour 16) was observed in the batch test. When the

TABLE 2. Average Ammonia Volatilization from Intermittent Aeration Tank (Tank A) Treating Anaerobically Digested Swine Wastewater at Stable Conditions for Different Monitoring Periods

Monitoring period	NH_4-N collected in boric acid solution (mg)	Total nitrogen removed from IA tank (mg)	Percentage of volatilization (%)
24 h	0.035	423	0.008
48 h	0.055	846	0.007
72 h	0.090	1269	0.007

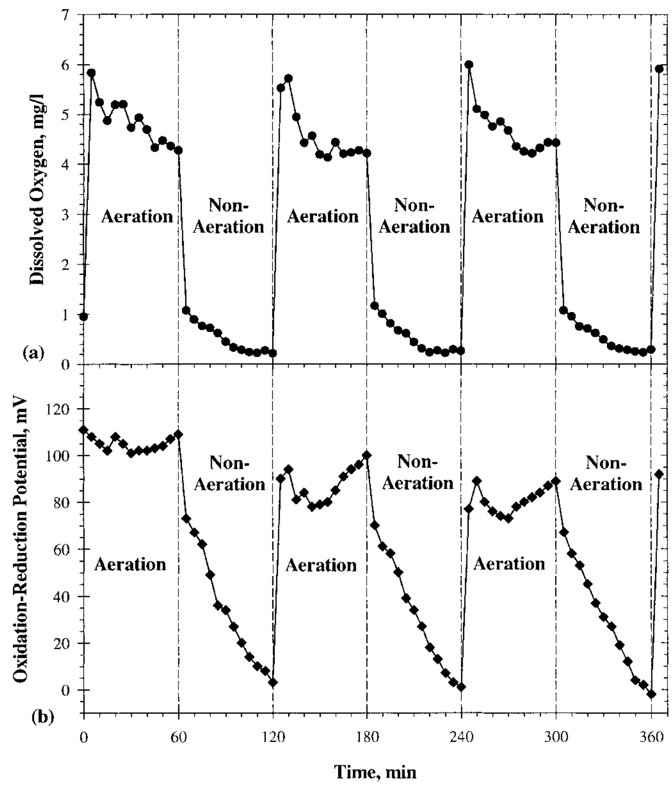

FIG. 3. Dissolved Oxygen (a) and Oxidation-Reduction Potential (b) Profiles in Continuous-Flow Intermittent Aeration Tank Treating Anaerobically Digested Swine Wastewater (operational conditions: aeration: nonaeration = 1 h: 1 h; hydraulic retention time = 3 days; mean cell residence time = 20 days)

initial NH_4-N concentration increased further to 251 mg/L, 40% of ammonium nitrification was observed at the first 24 h of the experiment, and no further nitrification occurred as the test went on [Fig. 4(c)]. Significant pH decrease (from initial 7.78 to 5.90 at hour 24) was found in this batch test. The pH stayed around 5.90 after the 24-h test. Low pH inhibited further nitrification in this batch test. The results obtained in this research agreed with the finding by Painter and Loveless (1983) that nitrification ceases at or below a pH of 6.0. The results also confirmed the conclusion by Liao and Maekawa (1994) that continuous aeration process for anaerobically digested swine wastewater with high ammonium level had lower nitrogen removal efficiency. Oxidation of ammonium to nitrate causes the pH to drop in the wastewater, and low pH inhibits further nitrification. A slight increase of biomass (VSS) concentration was observed in all three batch nitrification tests.

To determine ammonium oxidation rate of the IA culture, ammonium loadings to the biomass (VSS) in the batch reactor at different sampling times during each batch test were calculated, based on measured ammonium and biomass concentrations. The results are shown in Fig. 5. There were clearly two linear stages of ammonium oxidation in each batch nitrification

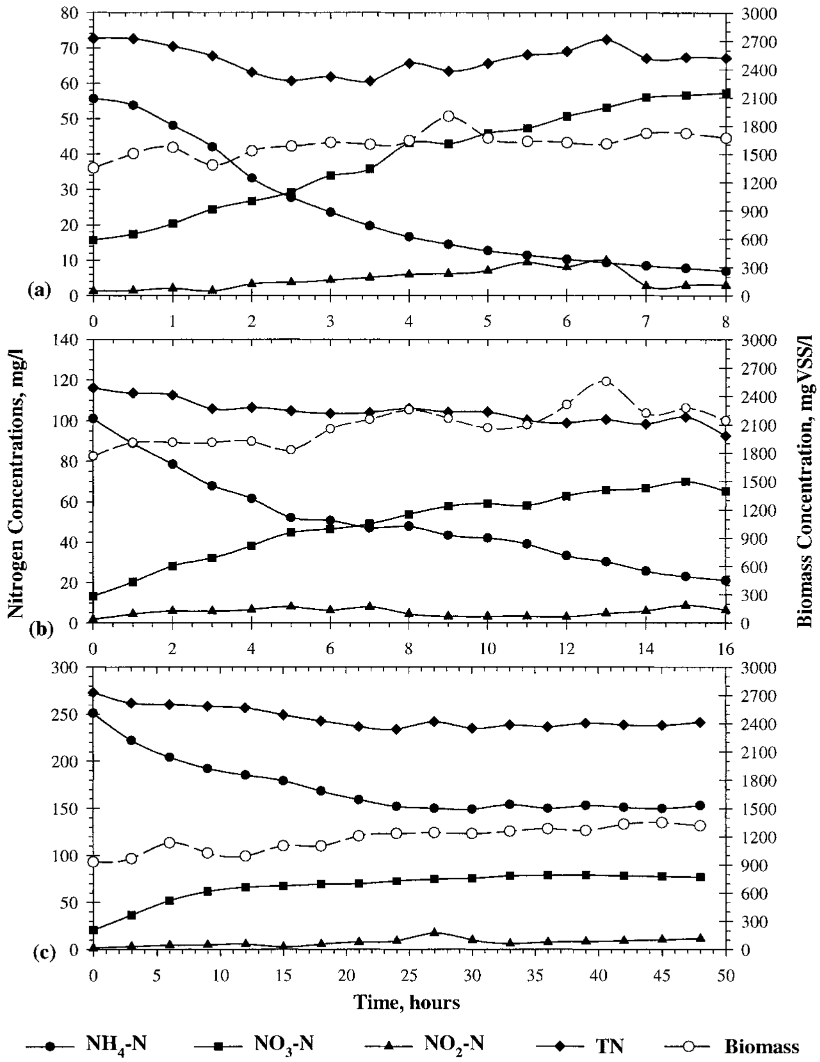

FIG. 4. Conversion of Ammonium to Nitrite and Nitrate by Mixed Culture from Steady-State Continuous-Flow Intermittent Aeration Tank Treating Anaerobically Digested Swine Wastewater in Batch Nitrification Tests with Initial NH_4-N Concentrations of (a) 56 mg/L, (b) 101 mg/L, and (c) 251 mg/L

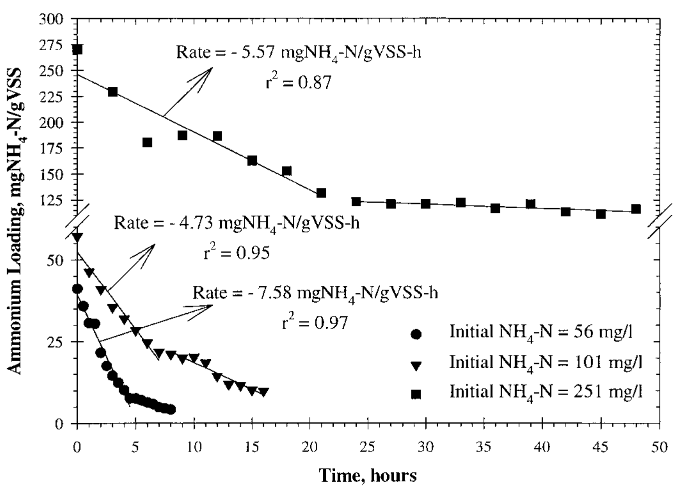

FIG. 5. Specific Ammonium Oxidation Rates of Mixed Culture from Steady-State Continuous-Flow Intermittent Aeration Tank Treating Anaerobically Digested Swine Wastewater in Batch Nitrification Tests with Different Initial NH_4-N Concentrations

test—a fast initial ammonium oxidation followed by a slow one. The specific ammonium oxidation rates at the first stages of the batch tests with different initial NH_4-N concentrations were relatively close (from 4.73 to 7.58 mgNH_4-N/gVSS-h).

Similar analysis was performed for specific nitrate formation rate of the IA culture. Fig. 6 illustrates nitrate formation per unit biomass over time in the three batch nitrification tests. A linear nitrate formation was observed in the batch test with initial NH_4-N concentration of 56 mg/L. Two linear stages of nitrate formation were found in the other two batch tests with higher initial NH_4-N concentrations (101 and 251 mg/L). The specific nitrate formation rates in the first linear stage in the three batch tests were in the range 2.79–3.70 mgNO_3-N/gVSS-h, which were within a range of 0.78–7.8 mgNO_3-N/gVSS-h reported in the literature (Table 3).

There are two biochemical reactions involved in the nitrification process: (1) oxidation of ammonium to nitrite by ammonia-oxidizing bacteria; and (2) oxidation of nitrite to nitrate by nitrite-oxidizing bacteria. The specific ammonium oxidation rate reflected the first reaction, while the specific nitrate formation rate involved both reactions. The specific ammonium oxidation rate was about twice of the specific nitrate formation rate in this study, indicating that ammonium oxidation and nitrite oxidation rates of the IA culture were quite close.

Denitrification Rate of the Intermittent Aeration Culture

To verify that denitrification was responsible for nitrogen removal in the IA process, the IA tank was operated as a batch reactor under anoxic conditions after a stable operation was achieved in the IA tank. Concentrated potassium nitrate (KNO_3) solution was added into the batch reactor to produce different initial concentrations of nitrate-nitrogen (59, 84, and 230 mg/L) at the beginning of the batch tests. Methanol was also added into the batch reactor as a carbon source to main-

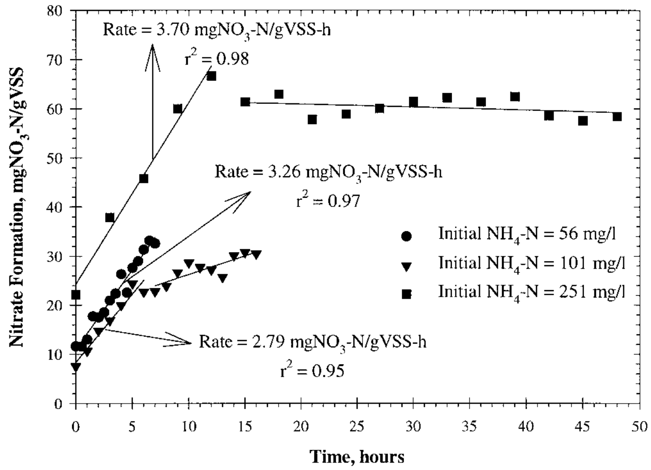

FIG. 6. Specific Nitrate Formation Rates of Mixed Culture from Steady-State Continuous-Flow Intermittent Aeration Tank Treating Anaerobically Digested Swine Wastewater in Batch Nitrification Tests with Different Initial NH_4-N Concentrations

TABLE 3. Comparison of Specific Nitrification Rates for Different Wastewaters Reported by Previous Researchers with This Study

Literature	Type of wastewater	Specific nitrification rate
Fan et al. (1996)	Domestic wastewater	0.97–2.50 $mgNO_3$-N/gVSS-h[a]
Harremoes and Sinkjaer (1994)	Domestic wastewater	0.91–1.12 $mgNO_3$-N/gVSS-h
Muller (1994)	Synthetic wastewater	0.78–1.81 $mgNO_3$-N/gVSS-h
Chudoba and Pannier (1994)	Municipal wastewater	7.8 $mgNO_3$-N/gVSS-h
Bortone et al. (1994)	Piggery wastewater	1.4 $mgNO_3$-N/gVSS-h
This study	Swine wastewater	2.79–3.70 $mgNO_3$-N/gVSS-h

[a]Volatile suspended solids.

tain the same initial C/N ratio of 1.11. The results obtained from the three batch denitrification tests are demonstrated in Fig. 7. As shown in the figure, denitrification activities occurred immediately in all three batch tests. No nitrite was observed in the batch tests. Denitrification was complete in 35 and 48 h in the batch tests with initial NO_3-N concentrations of 59 and 84 mg/L, respectively [Fig. 7(a,b)]. Biomass con-

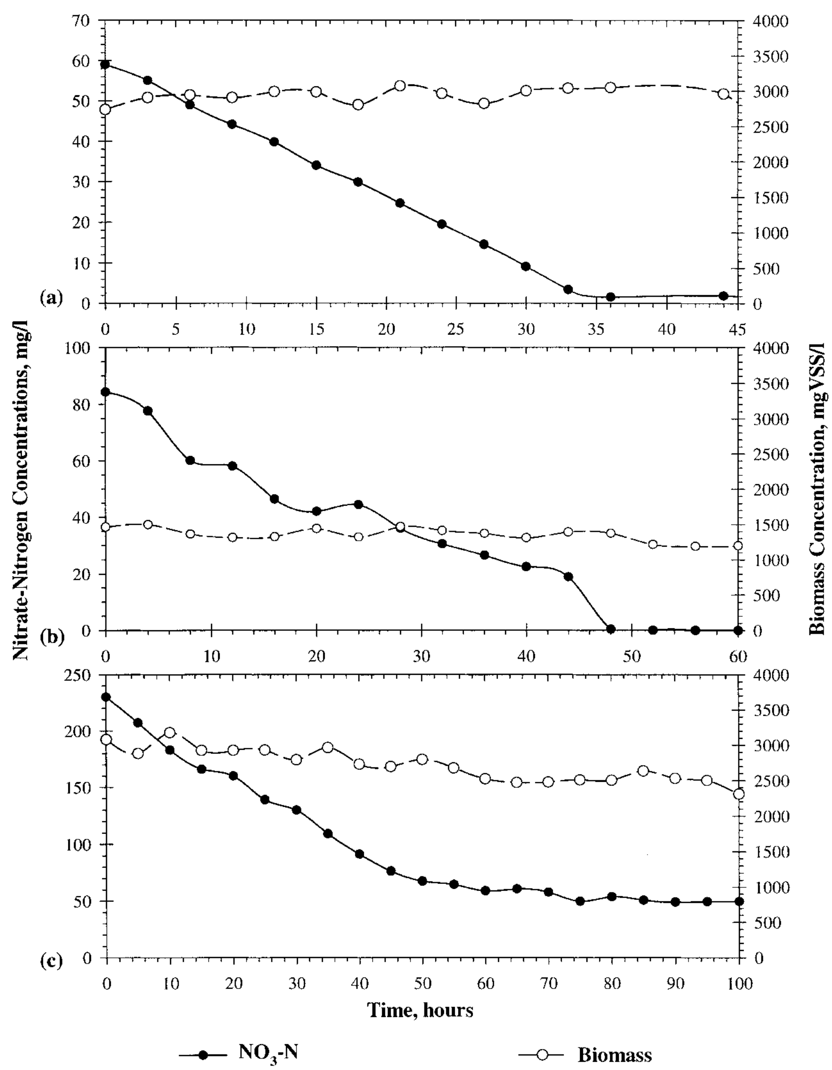

FIG. 7. Nitrate Reduction by Mixed Culture from Steady-State Continuous-Flow Intermittent Aeration Tank Treating Anaerobically Digested Swine Wastewater in the Batch Denitrification Tests with Initial NO_3-N Concentrations of (a) 59 mg/L, (b) 84 mg/L, and (c) 230 mg/L

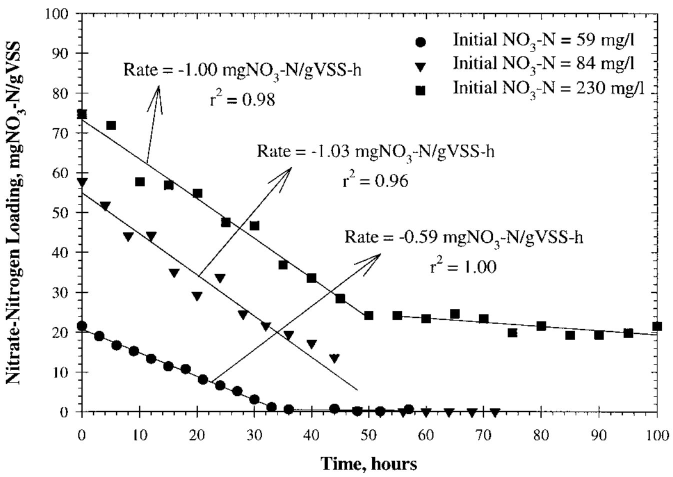

FIG. 8. Specific Denitrification Rates of Mixed Culture from Steady-State Continuous-Flow Intermittent Aeration Tank Treating Anaerobically Digested Swine Wastewater in Batch Denitrification Tests with Different Initial NO_3-N Concentrations

centration in these two batch tests was almost constant. The pH values in the batch tests were fairly stable between 7.5 and 7.9. In the third batch test with a higher initial nitrate concentration (230 $mgNO_3$-N/L), an initial fast denitrification was observed until hour 50 [Fig. 7(c)]. At the same time, pH in the batch reactor increased from initial an 7.48 to 8.20 at hour 50. Soluble COD decreased from about 600 mg/L to about 260 mg/L. After 50 h of the test, denitrification activity was very low and finally stopped at around hour 75. No more COD consumption was observed, and COD remained at around 240 mg/L after 75 h. A slight decrease of biomass concentration was observed in this batch test. The high pH probably inhibited the denitrification activity after 50 h of the test, because the optimal pH for denitrifying bacteria is around 7.0 (Bitton 1994).

Similar to the analysis of specific nitrification rate, analysis was performed for the specific denitrification rate of the IA culture, based on the NO_3-N and biomass data in the batch tests. The results are shown in Fig. 8. Linear denitrification was obvious in the batch tests with lower initial nitrate concentrations of 59 and 84 $mgNO_3$-N/L, and the specific denitrification rates were 0.59 and 1.03 $mgNO_3$-N/gVSS-h, respectively. A rapid linear denitrification was also shown in the first 50 hours of the third batch test with high initial NO_3-N concentration of 230 mg/L. The specific denitrification rate during that period was 1.00 $mgNO_3$-N/gVSS-h.

CONCLUSIONS

Intermittent aeration process was confirmed as an efficient system for nitrogen removal from anaerobically digested swine wastewater. High nitrogen removal (average 91% TKN and 92% NH_4-N) was achieved in the IA system. Nitrification and denitrification were verified to be responsible for nitrogen removal from the swine wastewater. Nitrification and denitrification rates of the IA culture were determined through batch tests. The specific nitrification and denitrification rates of the IA culture were 2.79–3.70 $mgNO_3$-N/gVSS-h and 0.59–1.03 $mgNO_3$-N/gVSS-h, respectively. These findings could be used for designing pilot- and full-scale intermittent aeration systems for nitrogen removal from anaerobically digested swine wastewater. In the IA process, the aeration period created favorable conditions for nitrifying bacteria (DO = 4–6 mg/L and ORP = 80–100 mV), while the nonaeration period provided good environment for denitrifying bacteria (DO < 1 mg/L and ORP as low as 0 mV). Ammonia volatilization in the IA process was negligible (<0.008%). Denitrification activity in the IA process prevented nitrate from accumulating and significant pH change in the system, which is critical for nitrogen removal from swine wastewater with high ammonium content.

ACKNOWLEDGMENTS

The writers would like to thank Rachel Huie, Chris Hayes, and Indira Thillai for their help in chemical analysis and Drs. John Classen, Philip Westerman, and Sarah Liehr for their assistance in editing the manuscript. This paper is No. 2000-07 of the Journal Series of the Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, N.C. 27695-7625. This study was funded by the Animal and Poultry Waste Management Center of North Carolina State University. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF). (1995). *Standard methods for the examination of water and wastewater*, 19th Ed., Washington, D.C.

Bicudo, J. R., Classen, J. J., Goldsmith, C. D., and Smith, T. (1999). ‘‘Effects of aeration cycles and hydraulic retention time on the sequential batch treatment of flushed swine manure.’’ *Adv. in Envir. Res.*, 3(1), 58–73.

Bitton, G. (1994). *Wastewater microbiology*, Wiley, New York.

Blouin, M., Bisaillon, J.-G., Baudet, R., and Ishaque, M. (1988). ‘‘Aerobic biodegradation of organic matter of swine waste.’’ *Biol. Wastes*, 25, 127–139.

Bortone, G., Malaspina, F., Stante, L., and Tilche, A. (1994). ‘‘Biological nitrogen and phosphorus removal in an anaerobic/anoxic sequencing batch reactor with separated biofilm nitrification.’’ *Water Sci. and Technol.*, 30(6), 303–313.

Chudoba, P., and Pannier, M. (1994). ‘‘Nitrification kinetics in activated sludge with both suspended and attached biomass.’’ *Water Sci. and Technol.*, 29(7), 181–184.

EPA. (1983). ‘‘Methods for chemical analysis of water and waste.’’ Cincinnati, Ohio.

Fan, X.-J., Urbain, V., Qian, Y., and Manem, J. (1996). ‘‘Nitrification and mass balance with a membrane bioreactor for municipal wastewater treatment.’’ *Water Sci. and Technol.*, 34(1–2), 129–136.

Harremoes, P., and Sinkjaer, O. (1994). ‘‘Kinetic interpretation of nitrogen removal in pilot scale experiments.’’ *Water Res.*, 29, 899–905.

Lee, S.-I., Park, J.-H., Ko, K.-B., and Koopman, B. (1997). ‘‘Effect of fermented swine wastes on biological nutrient removal in sequencing batch reactors.’’ *Water Res.*, 31(7), 1807–1812.

Liao, C.-M., and Maekawa, T. (1994). ‘‘Nitrification/denitrification in an intermittent aeration process for swine wastewater.’’ *Envir. Sci. and Health*, B29(5), 1053–1078.

Liu, B. (1999). ‘‘Anaerobic digestion and intermittent aeration for swine wastewater treatment.’’ MS thesis, North Carolina State Univ., Raleigh, N.C.

Liu, D. H. F., and Liptak, B. G. (1996). *Environmental engineers' handbook*, 2nd Ed., Lewis Publishers, Boca Raton, Fla.

Maekawa, T., Liao, C.-M., and Feng, X.-D. (1995). ‘‘Nitrogen and phosphorus removal for swine wastewater using intermittent aeration batch reactor followed by ammonium crystallization process.’’ *Water Res.*, 29(12), 2643–2650.

Metcalf and Eddy. (1991). *Wastewater engineering: Treatment, disposal, reuse*, 3rd Ed., McGraw-Hill, New York.

Muller, E. B. (1994). ‘‘Bacterial energetics in aerobic wastewater treatment.’’ PhD thesis, Vrije Universiteit, The Netherlands.

NCDA. (1988). 1987 North Carolina Agricultural Statistics, North Carolina Department of Agriculture, Raleigh, N.C.

NCDA. (1998). 1997 North Carolina Agric. Stat., N.C. Dept. Agric., Raleigh, N.C.

Osada, T., Haga, K., and Harada, Y. (1991). ‘‘Removal of nitrogen and phosphorus from swine wastewater by the activated sludge units with the intermittent aeration process.’’ *Water Res.*, 25(11), 1377–1388.

Painter, H. A., and Loveless, J. E. (1983). ‘‘Effect of temperature and pH values on the growth-rate constants of nitrifying bacteria in the activated sludge process.’’ *Water Res.*, 17, 237–248.

Timmermans, P., and Van Haute, H. A. (1983). ‘‘Denitrification with methanol: Fundamental study of the growth and denitrification capacity of *hypomicrobium sp*.’’ *Water Res.*, 17, 1249–1255.

U.S. Department of Agriculture (USDA). (1999). 1998 National Agricultural Statistics, United States Department of Agriculture, Washington, D.C.