Treatment of liquid swine manure in the sequencing batch reactor under aerobic and anoxic conditions

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Fernandes, L., McKyes, E. and Barrington, S. 1991. Treatment of liquid swine manure in the sequencing batch reactor under aerobic and anoxic conditions. Can. Agric. Eng. 33:373-379. Laboratory studies were conducted on a sequencing batch reactor (SBR) for the treatment of screened liquid swine manure. The SBR was operated on the basis of a 24 hours cycle at 6 and 9 days hydraulic retention time and 20 days solids biological retention time. Nitrification and denitrification processes were carried out in the same reactor by alternating aerobic/anoxic conditions, and the tested time ratios were 19/3, 16/8, 14/8 and 10/12 (hours). The results from the overall performance indicated that above 99% NH3-N, 93% TKN, 97% COD and 97% TSS removal were achieved in the SBR treatment. Anoxic operation did not adversely affect the activity of the nitrifiers, and NO2-NO3-N concentration increased up to 230 mg/L following air supply. However, sludge settling was poor in those reactors functioning with an anoxic period greater than 8 hours. As a result of nitrification and denitrification, the removal of ammonia and nitrite plus nitrate nitrogen was 80 to 93%.

Des études de laboratoire ont été effectuées sur un réacteur séquentiel pour le traitement de lisier de porcs passé au tamis. Le réacteur fonctionnait selon un cycle de 24 heures, avec un temps de rétention hydraulique de 6 à 9 jours, et un temps de rétention biologique de solides de 20 jours. La nitrification et la dénitrification ont été effectuées dans le même réacteur en alternant les conditions aérobies et anoxiques; les rapports de temps des essais étaient de 19/3, 16/8, 14/8 et 10/12 heures. Les résultats de l'ensemble de ces essais indiquaient que plus de 99% de NH3-N, 93% de TKN, 97% de COD et 97% de TSS ont été enlevés par le traitement en réacteur. Le processus anoxique n'a pas eu d'effets négatifs sur l'activité des agents de nitrification, et la concentration de NO2-NO3-N a augmenté jusqu'à 230 mg/L après l'alimentation en air. Cependant, la décantation des boues était faible dans les réacteurs fonctionnant avec une période anoxique supérieure à 8 heures. Par suite de la nitrification et de la dénitrification, l'enlèvement de l'ammoniac et des nitrates ainsi que de l'azote des nitrates variait de 80 à 93%.

INTRODUCTION

In certain regions of Canada a considerable expansion has occurred in the swine industry, abetted by the availability of new types of feed and raising hog values in the market. As a result, large volumes of manure are generated which often cannot be accommodated safely by the land in the vicinity of the operation. Manure mismanagement, such as high land application rates, is responsible for the large concentration of pollutants and the deterioration of the water quality in the rivers of L'Assumption, St-Francois, Chaudiere and Yamaska from the Province of Quebec (Gangbazo and Blais 1987; Dupont et al. 1984; Couillard and Cluiz 1980). In an attempt to abate pollution problems and to prevent further degradation of the environment, livestock producers operating on an insufficient land base need to give serious consideration to animal waste treatment, whereby the stabilization and/or removal of organic carbon and nutrients is a priority.

The combined removal of carbon and nitrogen in a single stage biological reactor, incorporating nitrification and denitrification, has received greater attention in recent years. This type of treatment system offers considerable cost savings in terms of infrastructure required and process operation. The sequencing batch reactor (SBR) seem ideally suited for these requirements. Its versatile operational modes provide diverse environmental conditions i.e. aerobic and anoxic, within the reactor in a cyclic fashion which can enhance the oxidation of ammonia nitrogen and the subsequent reduction of nitrates. Lo et al.(1987), Zaloum et al. (1985), Alleman and Irvine (1980a, 1980b) and Irvine and Busch (1979), have presented the many advantages of the SBR. This system has shown very high efficiency, above 90%, in the removal of suspended solids, organic carbon and nitrogen from various types of dilute wastes. However, wastes with high concentrations of nitrogen and carbon, such as liquid manure, have not yet been tested in the SBR, and there is still a lack of information regarding general design concepts and process operation.

The objective of this research project was: 1) to evaluate the performance of sequencing batch reactor under aerobic/anoxic operating conditions, and 2) examine the stabilization and or removal of nitrogen and carbon from liquid swine manure.

MATERIALS AND METHODS

The experimental setup consisted of four bench scale sequencing batch reactor systems. The reactors, with an inner diameter of 140 mm and the height of 400 mm, were fabricated from acrylic plastic cylinders and provisions were made for service connections. Figure 1 shows the relevant features of the experimental setup. The air flow rate into the reactors was about 1.7 L/min per litre of mixed liquor, which allowed the dissolved oxygen concentration to be maintained above 2.5 mg/L, and also contributed to the mixing of the liquid content. Additional mixing was provided by a magnetic stirrer.

For this study, fresh manure from a growing finishing herd
was collected from the bran drain and diluted with tap water to obtain feed material with a total solids concentration of about 4%. In barns equipped with liquid manure systems, it is common for dry matter to range from 3 to 5% in swine waste (Dupont et al. 1984). Subsequently, the feed was screened through the microscreening unit with a 0.1 mm mesh screen (Fernandes et al. 1988). The filtrate was stored at -20°C. Prior to use, a required volume of filtrate was thawed and brought to the temperature of 20 ± 2°C, at which the reactors functioned.

The operating volume of the reactors was 3 litres. Initially, the reactors were seeded with 500 ml of municipal activated sludge. The systems were acclimatized to swine waste by gradually increasing the feed strength over a period of 30 days. The SBR functioned on the basis of a 24 hours cycle and according to the sequential phasing shown below:

<table>
<thead>
<tr>
<th>MODE</th>
<th>REACTOR CONDITION</th>
<th>TIME (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>Add 0.33 to 0.5 L of waste based on HRT. Magnetic stirring on and aeration off.</td>
<td>3.0</td>
</tr>
<tr>
<td>React</td>
<td>Reactor operates at the maximum volume. Continuous stirring of mixed liquor. Air supply between 9.0 to 18.0 h. Anoxic (air off) between 3.0 to 9.0 h. Aerate 1.0 h before final settling. Waste 0.15 L of mixed liquor to provide 20 days sludge age.</td>
<td>19.0</td>
</tr>
<tr>
<td>Settle</td>
<td>Aeration and stirring off. Quiescent mode to allow solids settling.</td>
<td>1.0</td>
</tr>
<tr>
<td>Draw</td>
<td>Discharge between 0.183 to 0.35 L of supernatant.</td>
<td>0.5</td>
</tr>
<tr>
<td>Idle</td>
<td>Pause period, air and stirring off.</td>
<td>0.5</td>
</tr>
</tbody>
</table>

This research work was designed to investigate the fate of nitrogen species in the SBR treatment process. To achieve nitrogen removal, variations in the reactor cycle were introduced to encourage the exogenous and endogenous carbon denitrification. For this effect four different aerobic/anoxic, i.e. nitrification and denitrification operating modes were examined during fill and react sequences. The time ratios selected were: 19/3, 16/6, 14/8 and 10/12 hours of aerobic/anoxic conditions. Furthermore, each of the operating modes was tested in reactors functioning at 6 and 9 days hydraulic retention time (HRT). Previous investigations conducted by Fernandes (1989) indicated that an HRT between 6 to 9 days produced high quality treated effluent. Considering the time required for the establishment of nitrifying bacteria, a 20 days biological solids retention time (BSRT) was selected for the experiments.

Before testing the reactors intensively, a period of 2.5 times BSRT was allowed for sludge washout and to approach a stage of equilibrium. Moreover, a minimum of 20 days was permitted for adaptation following a change in the reactor operation. Each of the SBR operating conditions was tested in a single reactor over a period of 35 days after achieving quasi steady state. The reactors were sampled twice a week for influent waste, mixed liquor and the treated effluent. At the end of each trial, track analyses were conducted to cover the entire cycle of 24 hours. The physico-chemical analyses were performed according to APHA (1985), and included total suspended solids (TSS), volatile suspended solids (VSS), sludge volume, pH, dissolved oxygen (DO), chemical oxygen demand (COD), total Kjeldahl nitrogen, ammonia nitrogen (NH3-N) and nitrite and nitrate nitrogen (NO2-NO3-N).

RESULTS AND DISCUSSION

Effect aerobic/anoxic conditions

Tables I and II, summarize the results of the various physical and chemical parameters used for the evaluation of the SBR process performance. Each of these results is an average of ten data obtained during the test period of 35 consecutive days, after the reactors had reached equilibrium state.

In the reactors operating at condition 9/20 (HRT/BSRT) and
Table I. Summary of treatment efficiency: SBR operating at 9/20 (HRT/BSRT, days) and various aerobic/anoxic periods

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent Waste</th>
<th>Effluent</th>
<th>Aerobic/Anoxic during full and react (h)</th>
<th>19/3</th>
<th>16/6</th>
<th>14/8</th>
<th>10/12</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃-N (mg/l)</td>
<td>1265</td>
<td></td>
<td></td>
<td>2.2</td>
<td>2.4</td>
<td>6.1</td>
<td>11.5</td>
</tr>
<tr>
<td>NO₂-NO₃-N (mg/l)</td>
<td>6.2</td>
<td></td>
<td></td>
<td>182.1</td>
<td>150.4</td>
<td>102.9</td>
<td>74.5</td>
</tr>
<tr>
<td>*Inorganic N (% removal)</td>
<td>-</td>
<td></td>
<td></td>
<td>85.5</td>
<td>88.0</td>
<td>91.4</td>
<td>93.2</td>
</tr>
<tr>
<td>TKN (mg/l)</td>
<td>2580</td>
<td></td>
<td></td>
<td>185</td>
<td>200</td>
<td>250</td>
<td>275</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>31,175</td>
<td></td>
<td></td>
<td>845</td>
<td>815</td>
<td>830</td>
<td>1250</td>
</tr>
<tr>
<td>TSS (mg/l)</td>
<td>10,690</td>
<td></td>
<td></td>
<td>283</td>
<td>307</td>
<td>296</td>
<td>350</td>
</tr>
<tr>
<td><strong>Sludge Volume (ml)</strong></td>
<td>-</td>
<td></td>
<td></td>
<td>475</td>
<td>510</td>
<td>635</td>
<td>800</td>
</tr>
</tbody>
</table>

* Based on the sum of NH₃-N and NO₂-NO₃-N
** Sludge volume occupied by the mixed liquor after 30 min of settling in 1.0 L graduate cylinder.

Table II. Summary of treatment efficiency: SBR operating at 6/20 (HRT/BSRT, days) and various aerobic/anoxic periods

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent Waste</th>
<th>Effluent</th>
<th>Aerobic/Anoxic during full and react (h)</th>
<th>19/3</th>
<th>16/6</th>
<th>14/8</th>
<th>10/12</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃-N (mg/l)</td>
<td>1195</td>
<td></td>
<td></td>
<td>5.5</td>
<td>9.3</td>
<td>14.8</td>
<td>217.0</td>
</tr>
<tr>
<td>NO₂-NO₃-N (mg/l)</td>
<td>5.8</td>
<td></td>
<td></td>
<td>230.8</td>
<td>195.7</td>
<td>136.5</td>
<td>9.7</td>
</tr>
<tr>
<td>*Inorganic N (% Removal)</td>
<td>-</td>
<td></td>
<td></td>
<td>80.3</td>
<td>83.0</td>
<td>87.0</td>
<td>-</td>
</tr>
<tr>
<td>TKN (mg/l)</td>
<td>2410</td>
<td></td>
<td></td>
<td>270</td>
<td>305</td>
<td>355</td>
<td>460</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>30,680</td>
<td></td>
<td></td>
<td>1105</td>
<td>1075</td>
<td>1120</td>
<td>1595</td>
</tr>
<tr>
<td>TSS (mg/l)</td>
<td>11,852</td>
<td></td>
<td></td>
<td>326</td>
<td>360</td>
<td>427</td>
<td>539</td>
</tr>
<tr>
<td><strong>Sludge Volume (ml)</strong></td>
<td>-</td>
<td></td>
<td></td>
<td>500</td>
<td>625</td>
<td>740</td>
<td>936</td>
</tr>
</tbody>
</table>

* Based on the sum of NH₃-N and NO₂-NO₃-N
** Sludge volume occupied by the mixed liquor after 30 min of settling in 1.0 L graduate cylinder.
During the aerated react period, the ammonia concentration was sharply to less than 2 mg/L. The increase in ammonia concentration was caused by the strength of the influent liquid which was 1265 mg/L NH3-N/L. Furthermore, there is a strong possibility that ammonium ions were released during the metabolism of organic nitrogen either through fermentative deamination or oxidative degradation permitted by oxygen transfer across the air wastewater interface. Simultaneously, removal of ammonia could have also taken place to drive the energy required for growth and maintenance, and/or transformed in less than 14 hours, and a low concentration was maintained until the end of the cycle. The consumption of ammonia was mainly due to two reasons: a) the nitrifying bacteria oxidized ammonium to nitrite and nitrate to drive the energy required for growth and maintenance, and b) ammonium provided with the nitrogen element, which is essential for cell synthesis.

The profile displayed by oxidized nitrogen forms in Fig. 2 is sharply in contrast with the one observed for ammonia. At the start of the cycle the mixed liquor remaining in the reactor contained 190 mg/L of NO2-NO3-N. Under a non aerated fill, denitrification took place and a steep drop in oxidized nitrogen occurred at a rate of 62.7 mg/L·h-1, and only 6.2 mg/L of oxidized nitrogen were detected at the end of fill sequence. It is apparent that denitrifying bacteria thrive under the anoxic environment rich in oxidized nitrogen forms and organic carbon which was being supplied by the influent waste. With the advent of the aerated react sequence, the NO2-NO3-N concentration started to rise rapidly and it reached a level of 190 mg/L in about 16 hours, after which it stabilized at an average value of 200 mg/L. NO2-NO3-N was produced at a rate of 12.5 mg/h, and nitrification was essentially completed in about 15 hours.

As shown in Figs. 3 to 5, the inorganic nitrogen profiles displayed by reactors with 6 to 12 hours anoxic periods are quite similar in appearance to Fig. 2, except for the react sequence in which case NO2-NO3-N followed two distinct paths. With an aerated react, the nitrification process resurfaced and proceeded at a rate of 12.0 to 14.7 mg NH4-N/h. Nitrification occurred at a faster rate in the first 12 hours, and then it slowed down due to limited amounts of readily available ammonium ions. Once the biological nitrification was nearly completed, it was advantageous to cut the air supply and permit the facultative heterotrophic bacteria to utilize oxidized nitrogen as a suitable electron acceptor. With this in mind, three denitrification periods of 3, 5 and 9 h were tested towards the end of the react sequence. The results indicate that the highest drop in oxidized nitrogen was 69 mg/L, and it occurred in the reactor with 9 h of anoxic react. For reactors with 3 and 5 h of anoxic react, the NO2-NO3-N decrease was 29 and 52 mg/L, respectively. The denitrification rate in these reactors was in the range of 7.6 to 10.4 mg NO2-NO3-N/h. These values
9 h of anoxic react period

4 h of anoxic fill period

3 h of anoxic fill period

2 h of anoxic fill period

1 h of anoxic fill period

0 h of anoxic fill period

A typical pattern for total soluble nitrogen during a cycle of 24 h is depicted in Fig. 7. The trends displayed are very similar to those observed for ammonia nitrogen, except that a higher proportion of ammoxidation to nitrate was due to the production of pyrophosphate ions from the fill sequence, which were then cycled to nitrate via the enhanced denitrification reaction. The concentration of N\textsubscript{NH3} and N\textsubscript{NO2} is pH dependent, and the former will increase when pH is in the basic range while the latter is favored by low pH. It is conceivable that the liquid manure, treated in the SBR under the conditions studied, presented an adequate buffering capacity to maintain a favorable pH for the growth of nitrifiers. Figure 6 is a characteristic example of pH track analysis. In general, the influent waste was quite neutral, and the pH showed a slow increase during anoxic operation. The maximum increase observed was about 0.8 units, which was possibly related to the release of hydroxide ions from the denitrification reaction and deamination of organic nitrogen. In the aerated reactor sequence, the pH dropped by as much as 1 unit due to the production of hydrogen ions from the oxidation of ammonium to nitrite. It was interesting to note that the nitrifying bacteria were well-established in the SBR treatments system. As a matter of fact, the absence of dissolved oxygen for a period of time was not expected to critically affect the nitrifying bacteria. Figure 8 is a characteristic example of COD track analysis. The concentration of COD (mL/L) decreased inversely with the influent COD during the fill sequence. Fig. 2 is a typical pattern for total soluble nitrogen during a cycle of 24 h. The trends displayed are very similar to those observed for ammonia nitrogen, except that a higher proportion of ammoxidation to nitrate was due to the production of pyrophosphate ions from the fill sequence, which were then cycled to nitrate via the enhanced denitrification reaction. The concentration of N\textsubscript{NH3} and N\textsubscript{NO2} is pH dependent, and the former will increase when pH is in the basic range while the latter is favored by low pH. It is conceivable that the liquid manure, treated in the SBR under the conditions studied, presented an adequate buffering capacity to maintain a favorable pH for the growth of nitrifiers. Figure 6 is a characteristic example of pH track analysis. In general, the influent waste was quite neutral, and the pH showed a slow increase during anoxic operation. The maximum increase observed was about 0.8 units, which was possibly related to the release of hydroxide ions from the denitrification reaction and deamination of organic nitrogen. In the aerated reactor sequence, the pH dropped by as much as 1 unit due to the production of hydrogen ions from the oxidation of ammonium to nitrite.
the TKN concentration was much higher because of the organic nitrogen fraction which was about 0.55 in the influent liquid manure. For reactors operating with 3 hours anoxic, the TKN rose to 490 mg/L at the end of the fill, as a result of the influent waste strength coupled with a low rate of microbial consumption taking place in the reactor. In the aerobic react stage, the TKN decreased progressively until it reached a low value of 200 mg/L. From the results obtained for the removal of NH₃-N and TKN it is apparent that biodegradation of organic nitrogen occurred at a much slower rate, may be due to its complex structure. Reactors operating at 8 and 12 hours anoxic were less efficient in the biodegradation of TKN, since as much as 280 mg/L was detected in the final effluent. Possibly the type of microbial population established in these reactors was less successful in breaking down organic nitrogen compounds to its elementary constituents, which could then be metabolized by the microorganisms.

**SBR overall performance**

During the course of the present research, it was observed that the SBR has a high capacity for removal of inorganic nitrogen, defined here as ammonia plus oxidized nitrogen. As indicated in Tables I and II, the removal of inorganic nitrogen was between 80.3% to 93.2%. The TKN measured in the effluent was relatively low in the reactors where nitrification/denitrification was taking place. The average influent TKN concentrations were 2410 and 2580 mg/L, and the removal efficiency ranged from 81% to 93%. The analyses of the results do not show a significant difference between reactors operating with 3 and 6 hours anoxic periods. Nevertheless, a consistent trend was visible when anoxic operation increased from 3 to 12 hours. The total nitrogen concentration in the effluent was highest for the latter reactors, and most of it was in the organic form, since the accounted ammonia component was quite low.

After successful establishment of nitrification and denitrification, the SBR also demonstrated a good capacity for the removal of organic carbon. All reactors consistently maintained a high quality effluent with above 95% COD removal. There was no significant difference in terms of organic carbon removal between reactors operating with 3, 6 and 8 hours anoxic periods. For reactors operating at 6 and 9 days HRT with 12 hours anoxic, the COD concentrations released in the effluent were 1595 and 1250 mg/L, respectively. Presumably, by elongating the non-aeration time, the microbial population was shifted largely towards facultative and anaerobic species, which slowed the progress of carbon oxidation and utilization.

Typically, for reactors operating at 6 and 9 days HRT and with 3 to 12 hours anoxic, the TSS in the effluent ranged from 326 to 539 mg/L and 283 to 350 mg/L, respectively. Although the efficiency of SBR in solids removal was above 95%, it is obvious from Table I and II that prolonged anoxic conditions contributed to effluent deterioration. This fact also coincided with relatively poor floc settleability occurring especially in the reactors with 12 hour anoxic periods.

In general, rapid flocculation and good settling performance was displayed by the reactors operating at 3 and 6 hours anoxic. The flocs were relatively big and had a zone settling velocity between 1.2 and 1.5 m/h. The results from sludge volume tests show clearly that settling improved drastically as the anoxic time decreased from 12 to 3 hours. This improvement was in the order of 77% and 85%, for reactors operating at 6 and 9 days HRT, respectively.

**CONCLUSIONS**

The results from this experimental work show that liquid swine manure can be effectively treated in a sequencing batch reactor operating under appropriate conditions. The SBR functions on the basis of cyclic variations, and thus it permits considerable flexibility in the temporal coordination of reactor phases to provide the requisite conditions for the combined removal of carbon and nitrogen.

Nitrification and denitrification processes were conducted in the same reactor by including alternatively aerobic and anoxic periods in the SBR cycle. An anoxic fill sequence, rich in exogenous organic carbon, favoured denitrification and as a result oxidized nitrogen dropped from 190 to 6 mg/L in a period of 3 h. In the aerated react phase the ammonia accumulated during fill was oxidized to NO₂⁻-NO₃⁻-N. It was apparent that the nitrifiers were not inhibited by the anoxic operation and nitrification was accomplished within 15 hours, after that...
only residual amounts of NH3-N were detected in the reactors. Thus a second anoxic period was conducive to endogenous denitrification. However, this occurred at a much slower rate between 7 to 10 mg NO2-NO3-N/I, possibly due to limited amount of readily biodegradable soluble carbon.

For reactors operating at 6/20 and 9/20 (HRT/BSRT) with an anoxic fill plus react of 3 to 8 and 3 to 12 hours the removal of TSS, COD and inorganic nitrogen ranged from 95 to 97%, 94 to 98% and 80 to 93%, respectively. Based on the overall performance it is not recommended to operate the SBR for more than 8 hours anoxic, between fill and react sequences, because sludge settling process deteriorates and odour can be a problem. A major advantage associated with the SBR system is the cost savings due to air cut off during anoxic operation of fill and react sequences as well as in the settling, draw and idle phases of the cycle. From this study it was found that air supply could be reduced by about 42%, without affecting process performance.

ACKNOWLEDGEMENT.
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