A Comparison of the Performance of Three Swine Waste Stabilization Systems

Submitted To:

Kurt Roos
AgSTAR Program
U.S. Environmental Protection Agency
1200 Pennsylvania Ave. NW (6202J)
Washington, DC 20460

Submitted By:

Eastern Research Group, Inc.
35 India Street, 4th Floor
Boston, MA 02110

Prepared By:

John H. Martin, Jr. Ph.D.

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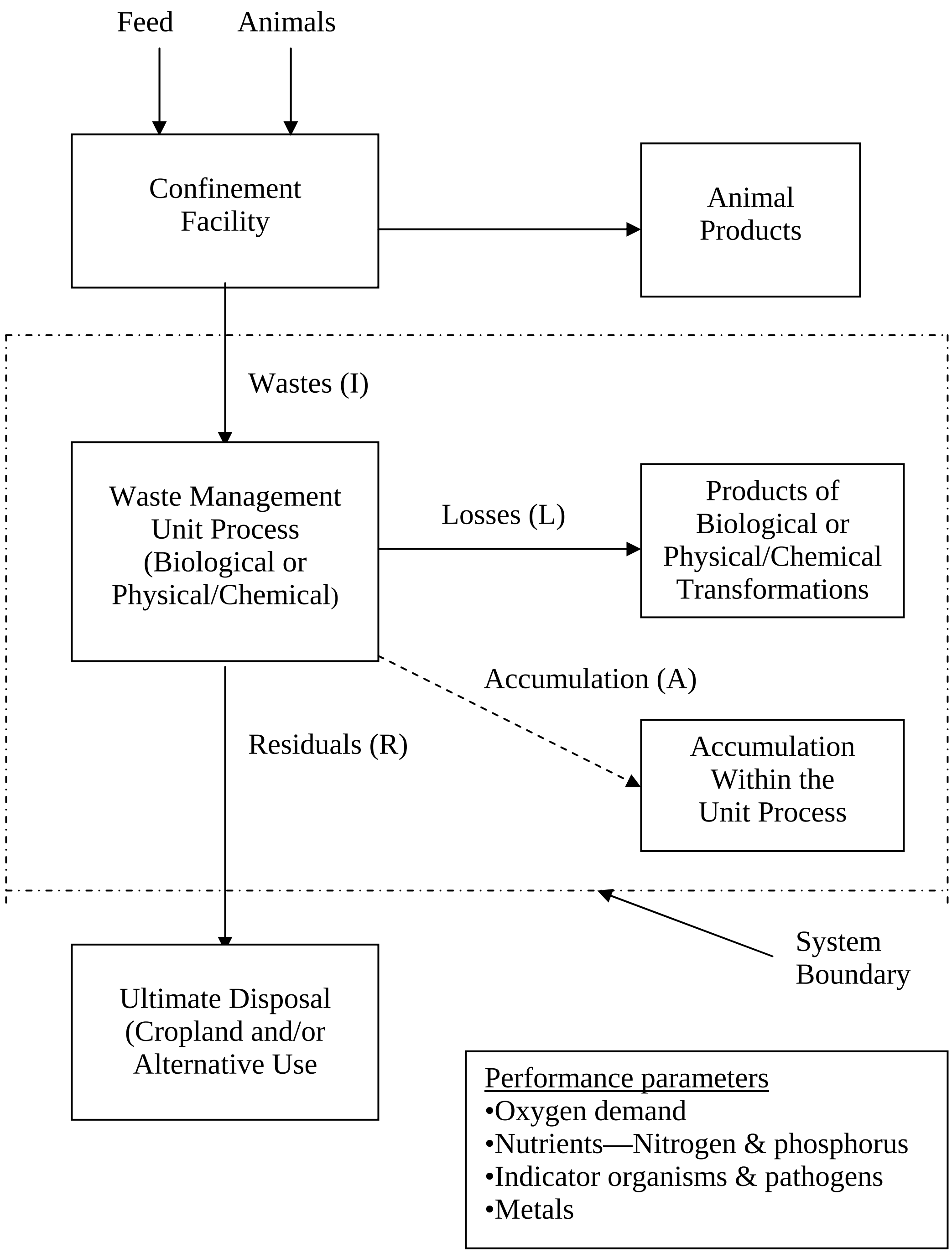
PREFACE

This report summarizes the results from one of a series of studies designed to: 1) more fully characterize and quantify the protection of air and water quality provided by waste management systems currently used in the swine and dairy industries; and 2) delineate associated costs. The overall objective of this effort is to develop a better understanding of: 1) the potential of individual system components and combinations of these components to ameliorate the impacts of swine and dairy cattle manures on environmental quality; and 2) the relationships between design and operating parameters and the performance of the biological and physical/chemical processes involved. A clear understanding of both is essential for the rational planning and design of these waste management systems. With this information, swine and dairy producers and their engineers, as well as the regulatory community, will have the ability to identify specific processes or combinations of processes that will effectively address air and water quality problems of concern.

The following schematic illustrates the comprehensive mass balance approach that is being used for each unit process in these performance evaluations. When a system is comprised of more than one unit process, the performance of each process is characterized separately. Then, the results are aggregated to characterize overall system performance. This is the same approach commonly used to characterize the performance of domestic and industrial wastewater treatment and chemical manufacturing unit processes. Past characterizations of individual processes and systems performance frequently have been narrowly focused and have ignored the generation of side streams of residuals of significance and associated cross media environmental quality impacts. A standardized approach for cost analysis using uniform boundary conditions also is a key component of this comparative effort.



Where: $L = I - (R + A)$
(I and R are measured and
L and A are estimated)

Figure 1. Illustration of a standardized mass balance approach to characterize the performance of animal waste management unit processes.

SUMMARY AND CONCLUSIONS

This report presents a comparison of the efficacy of three stabilization systems in reducing the air and water pollution potential of swine wastes based on materials balances developed from results of analyses of samples collected over a 12-month period. The three systems are: a covered anaerobic lagoon followed by an effluent storage pond previously used as a combined treatment and storage lagoon for a farrow-to-wean operation; a minimally aerated single-cell lagoon with ozone injection; and a single-cell anaerobic lagoon for finishing operations.

The covered lagoon-storage pond system with biogas capture and utilization reduced methane (CH_4) emissions by 154,486 m^3 per year or 66.3 m^3 per unit of confinement capacity. The estimated value of the captured CH_4 when utilized to generate electricity is between $17,140 and $23,805 per year, assuming the avoided cost of $0.06 per kWh. In contrast, the estimated CH_4 emissions from the minimally aerated and single-cell anaerobic lagoons, respectively, are 31.3 m^3 and 34.7 m^3 per unit of confinement capacity annually, which translates into 169,123 m^3 and 281,000 m^3 per year. The estimated reduction in CH_4 emissions by minimum aeration is no greater than approximately 14 percent at an electrical cost of about $4,000 per year. However, the greenhouse gas emissions associated with the generation of the electricity used for aeration will at least partially offset this reduction. Assuming 1.02 kg CO_2 are emitted per kWh generated for coal-fired power production (Spath *et al*., 1999), an estimated 67 metric tons of sequestered CO_2 are emitted in combination with other air and water pollutants annually to achieve this possible maximum reduction in CH_4 emissions of 14 percent or 19 metric tons per year. Given the much higher potency of CH_4 as a greenhouse gas, this analysis could lead to the conclusion that minimum aeration has merit as a method of reducing greenhouse gas emissions from animal manures. Such a conclusion would be flawed, however, due to a failure to recognize the greater potential of biogas capture and utilization to reduce emissions of CH_4 and sequestered CO_2 by reducing fossil fuel use.

Estimated ammonia nitrogen emissions as percentages of total nitrogen loading from these three swine waste management systems were similar: 61 percent for the covered lagoon-storage pond system, 47 percent from the minimally aerated lagoon, and 56 percent from the single-cell anaerobic lagoon. However, 56 percent of the total nitrogen loss via ammonia volatilization from the covered lagoon-storage pond system was from the storage pond. This finding is further confirmation of the ability of impermeable lagoon covers to reduce ammonia nitrogen emissions from anaerobic lagoons for animal wastes and the relatively low potential of combustion of biogas to be a source of emissions of oxides of nitrogen.

With respect to reduction in the water pollution potential of swine wastes, the performance of all three systems was similar. This is an expected finding given the similarity in the organic loading rates: 46 kg per 1,000 m^3 per day for the covered lagoon, 56 kg per 1,000 m^3 per day for the minimally lagoon, and 66 kg per 1,000 m^3 per day for the single-cell anaerobic lagoon. However, results of a study by Hill and Sobsey (2002) demonstrate the superiority of two cell systems, such as the covered lagoon-storage pond system evaluated in this performance comparison, in reducing the densities of pathogens, including *Salmonella*, and indicator organisms.

As shown in Table 11, land requirements, on a nitrogen application rate basis, for disposal of effluent withdrawals from the covered lagoon-storage pond system are at least 50 percent less than the requirements for the two other systems evaluated. Land requirements on a phosphorus application rate basis are essentially the same for all three systems. Therefore, there is no offset of the other benefits realized from the covered lagoon-storage pond system, including superior pathogen reduction and reduced CH_4 emissions.

Based on the results of this performance comparison, it appears reasonable to conclude that the covered anaerobic lagoon-storage pond approach for managing swine wastes will result in a substantial reduction of CH_4 emissions for these wastes during stabilization and storage to protect water quality. In addition, this two-cell system provides the additional advantage of greater pathogen reductions. Even though an economic analysis was not within the scope of this performance comparison, it also appears reasonable to conclude that the value of the captured biogas as a fuel provides at least some return on invested capital and operating costs. In contrast, anaerobic lagoons do not generate any revenue, and minimum aeration does not appear to provide any additional benefits commensurate with the additional cost.

INTRODUCTION

This report presents a comparison of the efficacy of three stabilization systems in reducing the air and water pollution potential of swine wastes. The three systems are: a covered anaerobic lagoon followed by an effluent storage pond, a minimally aerated single-cell lagoon with ozone injection, and a single-cell anaerobic lagoon. All three of these systems are located in central North Carolina. The minimally aerated and anaerobic lagoons provide for both stabilization and storage. These functions are separated in the covered lagoon-storage pond system. The criteria used for the characterization of performance of each system are methane (CH_4) and ammonia nitrogen (NH_3-N) emissions and the mass reductions in total solids, volatile solids (VS), chemical oxygen demand, total Kjeldahl nitrogen (TKN), organic nitrogen, ammonia nitrogen (NH_4-N), total phosphorus, orthophosphate phosphorus, and pathogens through physical and biological processes.

The covered anaerobic lagoon-storage pond system is used in the management of waste from a 4,240-head capacity farrow-to-wean operation with an average of 3,600 gestating and 640 lactating sows. The storage pond previously was operated as a combined anaerobic stabilization and storage lagoon. Based on physical dimensions, the covered anaerobic lagoon has an estimated constant operating volume of 25,842 m^3 (912,500 ft^3), and the maximum capacity of the effluent storage pond is 52,426 m^3 (1,851,200 ft^3). The biogas collected from the covered anaerobic lagoon fuels an engine-generator set.

The minimally aerated single-cell lagoon is used in the management of waste from a 5,400-head capacity finishing operation. The estimated maximum capacity of this lagoon is 27,500 m^3 (971,025 ft^3), again based on physical dimensions. The single-cell anaerobic lagoon is used in the management of the waste from an 8,100-head capacity finishing operation. The estimated maximum capacity of this lagoon is 33,130 m^3 (1,169,820 ft^3).

For all three systems, wastes are collected in fill and draw pits, commonly known as pull plug pits, under slatted floors. These pits are recharged with stabilized wastewater following scheduled draining. For the covered lagoon-storage pond system, this recycled wastewater is taken from the storage pond. For the other two systems, the lagoons, above the level of the accumulation of settled solids, are the sources of the wastewater for pit recharge. For all three systems, excess stabilized wastewater and accumulated precipitation are disposed of by periodic irrigation. Thus, only the covered lagoon operates as a constant volume reactor. Wastewater volume in the storage pond of the covered lagoon-storage pond system and the two other lagoons vary as a function of precipitation excess over evaporation and irrigation withdrawals.

METHODOLOGY

The data sets used to characterize the performance of the three swine waste management systems for all parameters, except indicator organisms and pathogens, were provided by Dr. Jiayang Cheng, Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina. Each data set contains more than a 12-month record of influent and effluent concentrations of the parameters used in these characterizations of process performance. For each system, both influent and effluent samples were collected for analysis on an approximately bi-weekly basis. All data sets also included records of stabilized effluent withdrawals for disposal by irrigation. The data set for the covered anaerobic lagoon-storage pond system also included records of covered lagoon temperatures, precipitation, and daily biogas utilization.

To characterize reductions of indicator organisms and pathogens in the covered lagoon-storage pond system, results of a study of this system comparing influent, covered lagoon effluent, and storage pond selected indicator organism and pathogen densities by Hill and Sobsey (2002) were used. Hill and Sobsey did not study the other two lagoons described above but did compare influent and lagoon densities in two other anaerobic lagoons for swine wastes as well as comparing influent, lagoon effluent and storage pond densities in an uncovered anaerobic lagoon-storage pond system. Thus, the work of Hill and Sobsey provides a basis for characterizing the performance of the anaerobic lagoon evaluated in this report with respect to indicator organism and pathogen reduction as well as the significance of covers in anaerobic lagoon-storage pond systems.

As noted earlier, each farm employs fill and draw pits for manure collection that are recharged after draining with stabilized wastewater. Thus, measured influent concentrations reflect not only raw waste characteristics but also characteristics of the recycled wastewater, and a simple comparison of influent and effluent characteristics on either a concentration or mass basis would not provide an accurate characterization of system performance since loadings would be overestimated.

To more accurately quantify loadings to each system to provide for a more realistic assessment of performance, it was necessary to partition measured influent concentrations for each parameter of interest between the untreated wastes and the recycled effluent. This partitioning required several assumptions, because only recycled effluent concentrations and average daily flow through the covered lagoon digester, 164±65 m^3 per day, were known. Therefore, it was necessary to estimate the volume of raw waste discharged daily into each waste stabilization system as well as the volumes of stabilized effluent recycled for pit recharge for the anaerobic and minimally aerated lagoon systems.

Assuming an average sow live weight of 136 kg (300 lb), raw waste volume discharged to the covered lagoon-storage pond system was estimated to be approximately 19 m^3 (5,000 gal) per day. Thus, the recycled volume for this system was an estimated 145 m^3 (38,329 gal) per day. Estimates of raw waste volumes discharged daily for the two finishing operations were 21 m^3 (5,555 gal) per day for the minimally aerated lagoon and 31.5 m^3 (8,321 gal) per day for the anaerobic lagoon. These estimates where based on an assumption of an average weight per pig of 62.4 kg (137.5 lb). Assuming that the waste collection pits were full when drained, recycle volumes for these two systems were estimated respectively to be 171 m^3 (45,166 gal) and 255.5 m^3 (67,496 gal) per day. All raw waste volume estimates were based on U.S. Department of Agriculture's (1992) characterization of swine wastes.

In estimating daily raw waste volume for each system, it also was assumed that the maximum numbers of animals were present throughout the time period used for characterization of process performance. Obviously, this is unrealistic given the unavoidable occurrence of mortalities, but records indicating changes in animal populations with time were not available. However, there also was no realistic basis for estimating additions of water resulting from watering system spillage and cleaning activities. Thus, it seems reasonable to assume that the overestimation of waste volumes was at least partially compensated for by the inability to estimate volumes of additional water added to the waste collection pits.

The development of mass balances for each of the three systems analyzed also required two other assumptions. The first was that the biological and physical processes responsible for the observed reductions in the various parameters considered had reached quasi steady-state status. The adjective *quasi* is used in recognition that these types of waste management systems never operate under true steady-state conditions due to: 1) continual accumulation of inorganic and more slowly biodegradable organic compounds, and 2) seasonal variation in temperature that produces variation in the level of biological activity. The relatively small magnitudes of variation in effluent characteristics seem to justify this assumption of quasi steady-state conditions.

The second assumption was that the stabilization of the effluent recycled for pit recharge was essentially complete. The basis of this assumption was the extremely long hydraulic retention time (HRT) with an even longer solids residence time due to settling for each system. Given the variable nature of the precipitation excess and irrigation withdrawals in the storage pond of the covered lagoon-storage pond system and the two other lagoons, the HRT in each also is variable. Estimates based on irrigation withdrawals from these systems suggest, however, that minimum HRTs are well in excess of a year.

RESULTS

Table 1 summarizes the results of the analyses of the influent physical and chemical parameter data sets for each of these three swine waste management systems. As the magnitudes of the standard deviations indicate, the observed influent and influent characteristics for each system varied substantially. The magnitudes of these variations suggest an inability to obtain representative samples for analysis and thus raise the question of data validity. Analyses of each parameter in each data set using the Kolmogorov-Smirnov One-Sample Test (Steel and Torrie, 1980) showed, however, that the observed values were approximately normally distributed ($P<0.05$). In addition, it was found, using Dixon's Criteria for Testing Extreme Observations in a Single Sample (Snedecor and Cochran, 1980), that extreme values could not be considered outliers ($P<0.05$). Thus, it was concluded that the mean values reported in Table 1 were reasonable estimates of the actual influent characteristics for each system.

Table 2 summarizes the results of the analyses of effluent samples for each of these three swine waste management systems. While the degree of variability in these data sets was less than that for the influent data sets, several values appeared to be possible outliers. Again, Dixon's Criteria for Testing Extreme Observations ($P<0.05$) was used to test the probability that these apparent outliers actually were extreme observations. As the result of these evaluations, several effluent concentration point estimates were deleted from the effluent data sets.

While one might expect statistically significant differences among the three systems in influent characteristics, analysis of variance (Snedecor and Cochran, 1980) revealed none ($P<0.05$). Obviously, the high degree of variance in these data sets contributed to this result. However, the relatively low volume of raw waste and the relatively high volume in recycled effluent in these influent samples, as noted earlier, also contributed to the similarities in influent characteristics. As shown in Table 2, the effluent characteristics differed little among the three systems.
Table 3 presents the results of the materials balances constructed to characterize the performance of the covered lagoon-storage pond system with respect the physical and chemical parameters considered. Table 4 illustrates the observed variation in biogas production and the estimated variation in the destruction of VS with seasonal variation in digester temperature. As noted in this table, estimated VS destruction was based on the generally accepted assumption of 0.749 m^3 of biogas produced per kg of VS destroyed (Metcalf and Eddy, Inc., 1991). Recently reported results by Pagilla *et al.* (2000) confirm the validity of this assumption. From the results presented in Table 4, one could conclude that approximately two-thirds of the VS in swine manure are readily biodegradable. It is probable, however, that this fraction is somewhat lower, since it is unrealistic to assume that the accumulation of less readily biodegradable VS in this covered lagoon did not contribute, to some degree, to the observed biogas production.

Tables 5 and 6 respectively present results of the materials balances constructed to characterize the performance of the minimally aerated and the anaerobic single-cell lagoons. Table 7 compares the performance of the three systems. As shown in this table, performance among these three systems generally differed little when the combined reductions for the covered lagoon-storage pond system are compared to the reductions for the two other lagoons. The one exception is the noticeably lower reduction in NH_4-N in the minimally aerated lagoon. The relatively high closure error for this parameter (Table 5) suggests that this reduction was even somewhat lower than the value estimated by the materials balance, possibly indicating that some simultaneous nitrification-denitrification was occurring in this system. However, no data are available to test the validity of this hypothesis.

Table 8 presents a previous comparison of performance these three swine waste management systems. While all of the estimates of reductions listed in Table 8 are lower than those determined in this investigation (Table 7), the substantial differences in estimated reductions in TKN and NH_4-N are especially noteworthy. It also should be noted that the results of this study suggest that there is little difference, as logic would suggest, among these three systems in reductions of TKN and NH_4-N in contrast to the previously reported evaluations.

Table 9 presents the results of hydraulic balances over 12-month periods for the three systems evaluated. The comparisons of the calculated values of evaporation by difference with the annual lake evaporation rate for central North Carolina, 96.5 cm per year, suggest that this value is a reasonable estimate of the rate of evaporation from swine manure lagoons and storage ponds in

this region. All three of these hydraulic balance periods include September 1999, when hurricane Dennis occurred. Thus, the precipitation totals are abnormally high.
In Table 10, $\log_{10}$ reductions in the densities of organisms used as indicators of fecal contamination and the possible presence of pathogens, the fecal coliform and enterococcus groups of indicator organisms and *Escherichia coli*, a member of the fecal coliform group in the covered lagoon-storage pond system are compared to reductions in an uncovered anaerobic lagoon-storage pond system and two single-cell anaerobic treatment and storage lagoons. Also compared in Table 10 are reductions in *Salmonella*, a pathogen commonly present in swine wastes, viable *Clostridium perfringens* spores, and somatic and F-specific coliphages, which are viral pathogens of *E. coli*. Reduction in viable *C. perfringens* spores has been suggested as a possible indicator of reductions protozoan parasite cysts and oocysts, such as *Giardia lambia* cysts and *Cryptosporidium parvum* oocysts, and helminth eggs, such those of *Ascais spp* Reductions of somatic and F-specific coliphages are possible indicators of reductions in enteric viruses. As noted earlier, Hill and Sobsey did not study the anaerobic treatment and storage lagoon sampled by Cheng. Thus, the results for the two anaerobic treatment and storage lagoons presented in Table 10 represent only an estimate of the reductions occurring in the anaerobic lagoon sampled by Cheng.

Although the databases used for this comparison of performance contain results of determinations of total sulfur concentrations, the estimates of influent sulfur concentrations are far below expected values, based on typical rates of sulfur excretion by swine (American Society of Agricultural Engineers, 2001). For example, the calculated daily input of sulfur in excreted manure to the covered lagoon-storage pond system was negative. For the minimally aerated and single-cell anaerobic lagoons, the calculated daily values for sulfur input from excreted manure were less than10 percent of expected values. In addition, the average total sulfur concentration in the storage pond of the covered lagoon-storage pond system was higher than the average total sulfur concentration in the effluent from the covered lagoon. Thus, construction of sulfur balances to estimate hydrogen sulfide emissions was not possible.

DISCUSSION

As shown in Table 7, a covered anaerobic lagoon-storage pond system for managing swine wastes is capable of providing the same degree of waste stabilization and water pollution prevention as minimally aerated and anaerobic single-cell lagoons. This is not surprising given the similarities in estimated VS loading rates for these three facilities. They were 46 kg VS per 1,000 m^3 per day for the covered lagoon, 56 kg VS per 1,000 m^3 per day for the minimally aerated lagoon, and 66 kg VS per 1,000 m^3 per day for the anaerobic single-cell lagoon. The estimated loading rate for the covered lagoon and storage pond system was 15 kg VS per 1,000 m^3 per day. It should be noted that the storage pond in the covered lagoon-storage pond system originally was a single-cell anaerobic lagoon and is excessively large.

However, the covered lagoon-storage pond system clearly is a superior option for swine waste management considering the reduction in the emissions of CH_4 to the atmosphere and given the volume and monetary value of the biogas captured and utilized. Over the 12-month performance evaluation period for the covered anaerobic lagoon-storage pond system, 220,655 m^3 of biogas was captured and utilized to generate electricity and hot water (Table 4). Assuming a CH_4 to carbon dioxide (CO_2) ratio of 0.7, this translates into the capture and utilization of 154,486 m^3 of CH_4 per year or 66.3 m^3 per unit of confinement capacity per year for this farrow-to- wean operation. With the assumption that between 18 and 25 percent of the energy content of the CH_4 captured from the covered lagoon digester is recoverable as electricity (U.S. Environmental Protection Agency, 1997), the CH_4 captured has a value of between $17,140 and $23,805 per year assuming an avoided cost of $0.06 per kWh. Because heat produced in conjunction with the generation of electricity at this site is utilized, the value of the CH_4 captured actually is somewhat higher than the estimate presented above.

Assuming that the percentage VS conversion to biogas in the single-cell anaerobic lagoon also was 67.5 and the same ratio of CH_4 to CO_2, 0.7, the estimated CH_4 emissions from this lagoon is 281,000 m^3 annually or 34.7 m^3 per unit of finishing capacity per year for this finishing operation. Thus, the possible revenue not realized by conversion this facility to a covered lagoon-storage pond system is in the range of $31,177 to $43,300 per year without waste heat recovery and utilization.

Given the low organic loading rate and the absence of any significant difference in performance among these three swine waste stabilization systems, it appears reasonable to conclude that the aeration of the minimally aerated lagoon had little if any impact on performance. The aerator used was a 7.5 kW surface unit (Cheng *et al.*, 2000). The rate of oxygen transfer provided by this aeration unit under process conditions is unknown. However, it seems reasonable to assume the average of the typical range of oxygen transfer rates for surface aeration units under process conditions of 0.61 to 1.22 kg O_2 per kWh at 15 ϒC (Metcalf and Eddy, Inc., 1991) to assess the potential significance of the aeration of this lagoon. Thus, the estimated transfer rate at 1.22 kg O_2 per kWh for this lagoon is approximately 220 kg O_2 per day, which is slightly less than 10 percent of the daily COD loading for this lagoon (Table 5). Given the COD to VS ratio for the net waste load to this lagoon of 1.5 (Table 5), a 10 percent COD reduction aerobically translates into an estimated possible reduction in CH_4 emissions from 197,637 m^3 to 169,123 m^3 per year or from 36.6 m^3 to 31.3 m^3 per unit of confinement capacity per year for this finishing operation, a reduction of approximately 14 percent. The energy cost for aerator operation at $0.06 per kWh to realize this possible maximum of a 14 percent reduction in CH_4 emissions is approximately $4,000 per year.

However, the greenhouse gas emissions associated the generation of the electricity used for aeration will at least partially offset this reduction. Assuming 1.02 kg CO_2 emitted per kWh generated for coal fired power production (Spath *et al.*, 1999), an estimated 67 metric tons of sequestered CO_2 is emitted in combination with other air and water pollutants annually to achieve this possible maximum reduction in CH_4 emissions of 14 percent or 19 metric tons per year. Given the much higher impact of CH_4 as a greenhouse gas in comparison to CO_2, it could be concluded that this is a reasonable tradeoff. Such a conclusion would be flawed, however, because of the lack of consideration of the lost opportunity to more substantially reduce CH_4 emissions and eliminate emissions of sequestered carbon as CO_2 through the utilization of captured biogas as a fuel.

It is probable, however, that the fraction of carbonaceous oxygen demand actually satisfied aerobically in this lagoon is substantially lower than 10 percent given the conservative assumption of an oxygen transfer rate of 1.22 kg O_2 per kWh and the 15 ΥC basis for the estimated oxygen transfer rate. Although no temperature data was collected at this site, the temperature data for the covered anaerobic lagoon (Table 4) suggest lower oxygen transfer rates due to temperatures significantly above 15 ΥC especially during the late spring, summer, and early fall months. Finally, the extremely low ratio of aeration unit size to lagoon volume, 0.27 kW per 1,000 m^3, indicates that mixing also was impairing oxygen transfer. With surface aeration units, typically 19 to 39 kW per 1,000 m^3 of lagoon volume is required to provide adequate mixing (Metcalf and Eddy, Inc.). Therefore, it seems reasonable to conclude that the actual reduction in CH_4 emissions resulting from the minimal aeration of this lagoon may be significantly less than 14 percent.

The nitrogen data presented in Table 3 suggests that the total Kjeldahl nitrogen reduction of 37 percent in the covered lagoon of the covered lagoon-storage pond system was due primarily to settling of solids containing organic nitrogen. As shown in this table, the estimated organic nitrogen reduction was 84 percent whereas the reduction in ammonia nitrogen was less than four percent. This minimal loss in ammonia nitrogen is consistent with past observations of negligible concentrations of ammonia nitrogen biogas produced in closed reactors. In contrast, organic nitrogen reductions in the storage pond were relatively low, 17 percent, and probably were due to primarily due to mineralization of organic nitrogen to ammonia nitrogen Although some settling of solids in the storage pond certainly was occurring, the amount probably was minimal given the estimated HRT in the covered lagoon of 157 days. Therefore, the nitrogen loss via ammonia volatilization from the covered lagoon-storage pond system is estimated to be about 61 percent of the net nitrogen loading with 56 percent occurring from the storage pond. This translates into a flux rate of 6.41 g NH_3-N per m^2-day or 28.9 g NH_3-N per head of confinement capacity per day Even if it is assumed that the closure error for ammonia nitrogen of 7.9 percent (Table 3) is due solely to an overestimate of ammonia nitrogen volatilization from the storage pond, the estimated average flux rate only is reduced to 5.88 g NH_3-N per m^2-day. The flux rate of 6.41 g NH_3-N per m^2-day is substantially higher than the previously reported estimates of 3.64 g NH_3-N per m^2-day Koelliker and Miner (1973), 0.51 ± 0.18 to 0.99 ± 1.38 g NH_3-N per m^2-day (Harper, *et al.*, 2000), and 2.74 ± 0.75 g NH_3-N per m^2-day (Aneja *et al*., 2000).

With the same assumption for TKN reduction of 37 percent by settling, the estimated loss of nitrogen via ammonia volatilization was lower from the minimally aerated lagoon, approximately 47 percent of the total nitrogen loading (Table 5), than from the covered lagoon-storage pond system. However, the loss of nitrogen via ammonia volatilization for the anaerobic single-cell lagoon, approximately 56 percent (Table 6), was similar to that from the covered lagoon-storage pond system. The assumption of a TKN reduction by settling of about 33 percent seems reasonable given the prediction, based on biogas production (Table 4), that approximately 34 percent of raw waste VS also settle in the covered lagoon. It is probable, however, that some fraction of this settled TKN, which is the organic fraction of TKN since ammonia is soluble, will be mineralized to ammonia with time and be subject to loss via volatilization.

The estimated ammonia nitrogen flux rates for the minimally aerated and single-cell anaerobic lagoons; 22.7 g NH_3-N per m^2-day and 39.9 g NH_3-N per m^2-day, respectively; differ substantially from each other. However, the flux rates on a per head of confinement capacity-day basis differ somewhat less, 15.1 g NH_3-N per head of confinement capacity-day for the minimally aerated lagoon versus 19.9 g NH_3-N per head of confinement capacity-day or the single-cell anaerobic lagoon. This difference is explained, at least partially, by the difference in lagoon surface area per head of confinement capacity, 0.66 m^2 per head for the minimally aerated lagoon versus 0.50 m^2 per head for the single-cell anaerobic lagoon. Because the storage pond in the covered lagoon-storage pond system was excessively large as noted earlier, the surface area per head of confinement capacity for this structure is 4.5 m^2 per head. Thus, it can be seen that the common expressing ammonia flux rates for lagoons for swine and other animal wastes on a unit surface area basis is of little value given that surface area per animal is an important variable.

As shown in Table 10, two cell systems clearly are superior to single-cell systems in reducing the densities of indicator organisms and pathogens in swine wastes. This is an expected finding given the attenuation of the impact of continual re inoculation of organisms in a two-cell system, which performs hydraulically more like a plug flow reactor. The reason or reasons for the apparent superiority of the covered lagoon-storage pond system in comparison to the conventional lagoon-storage pond system are unclear, however. It simply could be a reflection of a difference in HRT or temperature or both. Hill and Sobsey (2002) did not report HRTs or temperatures.

When the nitrogen and phosphorus withdrawn from these three systems (Tables 3, 5, and 6) are compared on a normalized basis as percentages of net loads (Table 11), the covered lagoon-storage pond system reduces land requirements by at least 50 percent for disposal of stabilized effluent on a nitrogen application rate basis. For effluent disposal on a phosphorus application rate basis, land requirements for all three systems are approximately equal. Therefore, the covered lagoon-storage pond system also provides a distinct advantage in reducing land requirements for disposal of effluent withdrawals in situations where nitrogen limits application rates. Although the covered lagoon-storage pond system does not provide a similar advantage in situations where phosphorus limits application rates, the other benefits of the covered lagoon-storage pond system are realized with no offset of an increase in land requirements for effluent disposal.

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Table 1. Results of the analyses of influent data sets for the covered lagoon-storage pond and the minimally aerated and anaerobic treatment and storage lagoon swine waste management systems to estimate typical physical and chemical characteristics.

	Covered anaerobic lagoon -----and storage pond-----		Minimally aerated treatment and storage lagoon	Anaerobic treatment and storage lagoon
Concentration, mg/L	Gestation	Farrowing	Grow-finish	Grow-finish
Total solids	11,841±3,977	12,128±4,401	13,239±7,266	12,430±6,631
Total volatile solids	7,748±2,858	7,851±3,372	8,900±5,657	8,256±4,773
Fixed solids	4,093±1,213	4,277±1,228	4,379±1,838	4,434±1,886
Chemical oxygen demand	17,119±7,298	18,362±7,998	13,170±6,932	13,294±7,377
Total Kjeldahl nitrogen	1,589±463	1,614±499	1,550±518	1,591±718
Organic nitrogen	632±232	624±248	659±386	621±371
Ammonia nitrogen	957±294	990±292	891±213	983±368
Total phosphorus	426±188	342±152	544±358	526±355
Orthophosphate phosphorus	213±76	178±62	318±184	313±195
Number of observations	40	40	29	29

Table 2. Results of the analyses of effluent data sets for the covered lagoon-storage pond and the minimally aerated and anaerobic treatment and storage lagoon swine waste management systems to estimate typical physical and chemical characteristics.

	Covered anaerobic lagoon -----and storage pond-----		Minimally aerated treatment and	Anaerobic treatment and
Concentration, mg/L	Covered lagoon	Storage pond	storage lagoon	storage lagoon
Total solids	2,821±130	2,052±348	2,936±146	2,805±193
Total volatile solids	852±125	583±163	811±149	740±129
Fixed solids	1,970±93	1,469±251	2,118±187	2,030±312
Chemical oxygen demand	1,095±165	659±148	1,303±154	1,131±166
Total Kjeldahl nitrogen	1,107±58	317±113	724±96	659±108
Organic nitrogen	160±58	71±23	127±35	124±25
Ammonia nitrogen	947±48	245±96	597±73	535±93
Total phosphorus	98±8	42±3	84±11	82±9
Orthophosphate phosphorus	85±9	36±4	76±9	73±6
Number of observations	24	24	29	29
Time period	1/99-12/99	1/99-12/99	4/99-3/00	4/99-3/00

Table 3. Summary of covered lagoon-storage pond swine waste management system performance.

	Net loads, kg/day	Covered lagoon reductions, kg/day	Covered lagoon reductions, %	Storage pond reductions, kg/day	Storage Pond reductions, %
Total solids	1667	1502	90.1	129	7.7
Total volatile solids	1194	1139	95.4	44	3.7
Fixed solids	472	363	76.9	85	18.0
Chemical oxygen demand	2813	2729	97.0	79	2.8
Total Kjeldahl nitrogen	217	81	37.3	138	63.6
Organic nitrogen	94	79	84.0	16	17.0
Ammonia nitrogen	127	5	3.9	122	96.1
Total phosphorus	57	47	82.5	9	15.8
Orthophosphate phosphorus	27	18	66.7	7	25.9

Table 3. Continued.

	System reductions, kg/day	System reductions, %	Discharged via irrigation, kg/day	Discharged via irrigation, %	Closure error*, %
Total solids	1631	97.8	83	5.0	2.8
Total volatile solids	1183	99.1	24	2.0	1.1
Fixed solids	448	94.9	60	12.7	7.6
Chemical oxygen demand	2808	99.8	27	1.0	1.0
Total Kjeldahl nitrogen	219	100.1	13	6.0	6.9
Organic nitrogen	95	101.1	3	3.2	4.2
Ammonia nitrogen	127	100.0	10	7.9	7.9
Total phosphorus	56	98.2	2	3.5	1.8
Orthophosphate phosphorus	25	92.2	1	3.7	-3.7

*A positive closure error means the sum of estimated lagoon reductions and irrigation withdrawals exceeds estimated net loading.

Table 4. Variation in covered anaerobic lagoon temperature, biogas production, and estimated volatile solids reduction with time.

Month	Average digester temperature, °C	Biogas production, m^3/month*	Volatile solids added, kg/month	Volatile solids destroyed, kg/month†	Volatile solids destroyed, % of added
January	11.3	6,863	37,014	9,160	24.7
February	14.4	15,450	33,432	20,622	61.7
March	17.3	17,047	37,014	22,754	61.5
April	22.6	18,424	35,820	24,592	68.7
May	28.8	24,468	37,014	32,658	88.2
June	28.2	27,361	35,820	36,520	102.0
July	28.9	25,900	37,014	34,570	93.4
August	31.5	23,069	37,014	30,791	83.2
September	28.3	16,372	35,820	21,852	61.0
October	23.3	16,303	37,014	21,760	58.8
November	21.5	14,752	35,820	19,689	55.0
December	16.3	14,646	37,014	19,549	52.8
Average	22.7	—	—	—	67.5

*Based on biogas utilization.

†Based on 0.749 m^3 of biogas per kg (12 ft^3 per lb) of volatile solids destroyed

Table 5. Summary of minimally aerated lagoon swine waste management system performance.

	Net loads, kg/day	Lagoon reductions, kg/day	Lagoon reductions, %	Discharged via irrigation, kg/day	Discharged via irrigation, %	Closure error*, ± %
Total solids	2040	1978	97.0	115	5.6	2.6
Total volatile solids	1530	1513	98.9	32	2.1	1.0
Fixed solids	479	434	90.6	83	1.7	7.9
Chemical oxygen demand	2302	2279	99.0	51	2.2	1.2
Total Kjeldahl nitrogen	174	159	91.4	28	16.1	7.5
Organic nitrogen	105	103	98.1	5	4.8	2.9
Ammonia nitrogen	69	56	81.2	23	33.3	14.5
Total phosphorus	90	88	97.8	3	3.3	1.1
Orthophosphate phosphorus	48	46	95.8	3	6.2	2.1

*A positive closure error means the sum of estimated lagoon reductions and irrigation withdrawals exceed estimated net loading.

Table 6. Summary of single cell anaerobic lagoon swine waste management system performance.

	Net loads, kg/day	Lagoon reductions, kg/day	Lagoon reductions, %	Discharged via irrigation, kg/day	Discharged via irrigation, %	Closure error*, ± %
Total solids	2850	2726	95.6	145	5.1	1.0
Total volatile solids	2180	2157	98.9	38	1.7	1.0
Fixed solids	754	690	91.5	105	13.9	1.0
Chemical oxygen demand	3526	3490	99.0	58	1.6	1.0
Total Kjeldahl nitrogen	289	268	92.7	34	11.8	4.5
Organic nitrogen	146	142	97.3	6	4.1	1.4
Ammonia nitrogen	145	128	88.3	28	19.3	7.6
Total phosphorus	130	127	97.7	4	3.1	1.0
Orthophosphate phosphorus	71	69	97.2	4	5.6	2.8

*A positive closure error means the sum of estimated lagoon reductions and irrigation withdrawals exceeds estimated net loading.

Table 7. Comparisons of performance of the covered anaerobic lagoon and the covered anaerobic lagoon and storage pond system with the minimally aerated and anaerobic treatment and storage lagoons.

	------------------------Reductions, %------------------------			
Parameter	Covered anaerobic lagoon	Covered anaerobic lagoon and storage pond	Minimally aerated treatment and storage lagoon	Anaerobic treatment and storage lagoon
Total solids	90.1	95.0	97.0	95.6
Volatile solids	95.4	98.0	98.9	98.9
Fixed solids	76.9	87.3	90.6	91.5
Chemical oxygen demand	97.0	99.0	99.0	99.0
Total Kjeldahl nitrogen	37.3	94.0	91.4	92.7
Organic nitrogen	84.0	96.8	98.1	97.3
Ammonia nitrogen	3.9	92.1	81.2	88.3
Total phosphorus	82.5	96.5	97.8	97.7
Orthophosphate phosphorus	66.7	96.3	95.8	97.2

Table 8. Previously reported comparisons of performance of the covered anaerobic lagoon and the covered anaerobic lagoon and storage pond system with the minimally aerated and anaerobic treatment and storage lagoons (Cheng et al. 2000).

	------------------------Reductions, %------------------------			
Parameter	Covered anaerobic lagoon	Covered anaerobic lagoon and storage pond	Minimally aerated treatment and storage lagoon	Anaerobic treatment and storage lagoon
Total solids	75.1	82.6	77.5	72.8
Volatile solids	87.3	92.2	90.2	88.9
Chemical oxygen demand	88.9	96.2	89.0	89.1
Total Kjeldahl nitrogen	30.3	79.2	53.7	50.9
Ammonia nitrogen	-1.1	72.2	34.2	34.7
Total phosphorus	75.2	89.6	84.9	83.0
Orthophosphate phosphorus	62.6	83.4	75.5	73.1

Table 9. Annual hydraulic balances for the covered lagoon digester-storage pond and the minimally aerated and anaerobic single cell lagoons.

	Covered lagoon digester-storage pond	Minimally aerated single cell lagoon	Single cell anaerobic lagoon
Net influent volume, m^3/yr	6,927	7,695	11,511
Precipitation, m^3/yr	35,115	17,161	22,827
Total	42,042	24,856	34,338
Irrigation withdrawals, m^3/yr	14,763	14,314	18,896
Evaporation by difference, m^3/yr	27,279	10,542	15,442
Average annual lake evaporation[*], m^3/yr	23,026	11,030	16,366
Error in closure based on average annual lake evaporation, m^3/yr	4,343	-488	-924
Error in closure[†], %	119	96	94
Balance period	1/99-12/99	6/99-5/00	4/99-3/00

[*]Assuming the annual lake evaporation rate for central North Carolina of 96.5 cm/yr.
[†](Evaporation by difference/annual lake evaporation) x 100

Table 10. Comparison of indicator organism and pathogen $\log_{10}$ reductions in two cell and single cell anaerobic lagoons for swine waste stabilization and storage.

	Covered lagoon digester-storage pond	Conventional anaerobic lagoon-storage pond	Single cell anaerobic lagoon	Single cell anaerobic lagoon
Fecal coliforms	3.6	2.6	2.0	1.6
Escherichia coli	3.6	2.7	2.0	1.5
Enterococci	3.3	2.7	1.8	1.8
Salmonella	2.7	2.4	0.8	1.8
C. perfringens spores	2.5	1.7	0.7	0.8
Somatic coliphages	3.0	2.5	1.9	1.4
F-specific coliphages	3.0	3.1	1.4	1.1

Table 11. Comparison of relative land requirements for effluent disposal from covered lagoon-storage pond and single cell minimally aerated and anaerobic lagoons swine waste management systems.

Application rate basis	Covered lagoon-storage pond	Minimally aerated lagoon	Single cell anaerobic lagoon
Nitrogen	x	2 x	2.7 x
Phosphorus	x	0.9 x	0.9 x