ABATEMENT OF AMMONIA EMISSIONS FROM SWINE LAGOONS USING POLYMER-ENHANCED SOLID-LIQUID SEPARATION

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ABSTRACT. *A study was conducted to determine the effects of solid-liquid separation of liquid swine manure on ammonia emissions from lagoons. This determination was done at full-scale in two contiguous swine production units that had similar animal production management. One of these units was maintained as a control using the anaerobic lagoon treatment method. In the second production unit, solids were removed from liquid manure using an enhanced-polymer solid-liquid separation treatment prior to lagoon storage. The ammonia gas fluxes from both lagoons were measured simultaneously during a 10-month period (Feb.-Nov., 2004) using passive flux samplers. On average, the solid-liquid separation treatment separated 85% of total suspended solids (TSS), 60% of total solids (TS), 73% of chemical oxygen demand (COD), 81% of organic N, and 8% of total ammoniacal N (TAN) from the liquid entering the lagoon. Ammonia emissions from the anaerobic lagoon control totaled 12,542 kg N/yr (13,633 kg N/ha/yr). This compares to lower ammonia emissions of 3,426 kg N/yr (or 3,684 kg N/ha/yr) from the anaerobic lagoon treated with solid-liquid separation. Although water quality changes were modest in the treated lagoon with respect to the control, total annual* NH_3 *emissions abatement in the lagoon with solid-liquid separation was 73% with respect to the anaerobic lagoon control. These results overall demonstrate that solid-liquid separation technologies can substantially reduce ammonia emissions from anaerobic swine lagoons.*

Keywords. *Ammonia emissions, Ammonia volatilization, Nitrogen, Anaerobic swine lagoons, Manure, Swine, Pigs.*

Numerous studies have shown that widespread use of anaerobic lagoons to treat and store liquid manure from confined swine production in North Carolina's Coastal Plain can contribute to atmospheric NH_3 deposition and air pollution (Arogo et al., 2003a; Battye et al., 2003; Mallin, 2000; Walker et al., 2000a, 2000b). Thus, there is major public interest in North Carolina to develop and demonstrate best control technologies that can lessen or eliminate ammonia emissions from confined swine production (Aneja et al., 2006).

Solid-liquid separation is a simple technology that has the potential to reduce ammonia emissions from swine lagoons. Traditionally, solid-liquid separation has been used as a method to reduce lagoon solids buildup by separating solids from raw or flushed manure prior to lagoon input (Barker, 1996). Solid-liquid separation methods include physical processes such as sedimentation, centrifuging, screening, or filtering (Day and Funk, 2002). Usually, solid-liquid separation efficiencies of manure separators are in the range of about 20% to 68% removal (Chastain et al., 2001; Burton and Turner, 2003; Westerman and Arogo, 2005). However, separation efficiencies can be augmented by chemical addition of coagulants and flocculants to bind together the small particles of solids into larger clumps (Sievers et al., 1994; Vanotti and Hunt, 1999; Vanotti et al., 2002). Along with the solids, solid-liquid separation combined with flocculation using polyacrylamide (PAM) polymer has been found to separate 85% to 88% of organic N from the liquid phase (Vanotti et al., 2002, 2005).

Szogi et al. (2006) evaluated annual NH_3 emissions reduction from a treatment lagoon serving 4,360 finishing swine that was replaced with a new on-farm technology. This technology consisted of solid-liquid separation with PAM, nitrification-denitrification, and soluble phosphorus removal (Vanotti et al., 2007), and met North Carolina environmentally superior technology (EST) criteria (Williams, 2006). Szogi et al. (2006) found that this combination of treatment technologies tackling both the organic N and the soluble ammonia N reduced annual NH_3 emissions from the lagoon by 90%, from 13,633 to 1,311 kg N/ha/year.

A separate study was conducted on another treatment lagoon also serving 4,360 finishing swine in North Carolina to demonstrate the environmental benefit of solid-liquid separation as a stand-alone technology. This demonstration project was funded by Farm Pilot Project Coordination Inc. (FPPC), a non-profit organization designated by Congress (Public Law 107-76), to assist in implementing innovative treatment technologies to address the growing waste issues associated with animal feeding operations (AFOs). Our objective was to quantify the magnitude of NH_3 emissions from a swine anaerobic lagoon retrofitted with only a polymer-enhanced solid-liquid separation treatment plant. The annual abatement of NH_3 emissions was estimated by comparing total emissions from the retrofitted lagoon with an

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anaerobic lagoon that had similar design and animal production management.

MATERIALS AND METHODS

SITE DESCRIPTION

The study was conducted at Goshen Ridge Farm near Mount Olive, Duplin County, North Carolina. The farm had three finishing units under identical animal production and waste treatment managements. Each unit had six barns with 4,360-head finishing pigs and an anaerobic lagoon for treatment and storage of manure, but only two units were used in this study.The third production unit was retrofitted with a wastewater treatment system to fully replace the anaerobic lagoon (Szogi et al., 2006; Vanotti et al., 2007). Manure was collected in barns using slatted floors and a pit-recharge system typical of many farms in North Carolina (Barker, 1996). In each production unit, pits were drained weekly by gravity into the anaerobic lagoons. After lagoon treatment (retention time of about 180 days), the liquid was sprayed onto nearby crop and hay fields. Lagoon liquid was also recycled in a closed loop to recharge the pits under the barns of each production unit; this made possible flushing of accumulated manure in the pits. Lagoon dimensions and monthly average live animal weight (LAW) computed from farm production records are presented in table 1. The relationship between N production by pigs and their weight was 0.29 kg N/1000 kg LAW/day (Szogi et al., 2006).

In 2004, production unit 2 was retrofitted with a solid-liquid separation system to treat all liquid raw manure accumulated in barn pits before lagoon storage while production unit 1 was maintained as a control using the anaerobic lagoon treatment method that was in place for the preceding five years. This anaerobic lagoon was also used as a control lagoon on a separate NH_3 emission evaluation study that combined solid-liquid separation and biological N treatment of liquid swine manure prior to lagoon storage (Szogi et al., 2006).

Animal production management remained the same in both production units 1 and 2 during the one-year study to evaluate the environmental benefit of high rate solid-liquid separation versus no separation prior lagoon storage. Barn pits were flushed once a week as before, but liquid raw manure in unit 2 was diverted into a 244-m^3 tank using a high capacity pump (1.5 m^3/min). Usually, half of the six barns were emptied on Tuesday and the other half on Friday. The raw manure collected in the homogenization tank was kept well mixed using a submersible mixer (4.7 HP, 12.1 m^3/min. flow, ABS Pumps Inc., Meriden, Conn.) while at the same time it was being pumped to the solids separator.

SOLID-LIQUID SEPARATION SYSTEM

The treatment plant was constructed and operated by a private firm, Super Soil Systems USA, Inc. (Clinton, N.C.). The solid-liquid separation module was the Ecopurin® unit (fig. 1) developed by the Spain-based firm Selco MC of Castellon (Martinez-Almela and Barrera, 2004). Treatment parameters such as polymer rate, wastewater flow, and mixing intensity were set by the plant operator using a tactile screen in a control panel. Well-mixed liquid raw manure was continuously pumped from the homogenization tank to the solid-liquid separation modular plant at a 2-m^3/h flow rate. A polymer solution (cationic PAM) was added to the liquid raw manure at a rate of 100 to 120 mg/L in a mixing chamber (mixer at 30 rpm) to flocculate the suspended solids prior to the solids-liquid separation through a rotating screen (200-μm opening size). Subsequently, a dissolved air flotation unit (DAF) further removed remaining solids from the liquid effluent while a small belt filter press (Monobelt, Teknofanghi S.R.L., Italy) dewatered the screened solids. The solid-liquid separation system treated an average of 30.8 m^3/d of liquid raw manure, dividing solids and liquid in two separate streams (fig. 2). The solids were removed daily from the farm and transported in trailers to a centralized solids processing plant for aerobic composting. The liquid stream was conveyed into the lagoon through a pipe connected to the liquid outlet of the modular treatment plant.

SOLIDS AND WATER ANALYSIS

Duplicate liquid grab samples of untreated and treated flushed manure were collected in 1-L plastic bottles every two weeks from the homogenization tank (before solid-liquid separation) and from the effluent pipe of the separation unit (after solid-liquid separation). Lagoon samples for water analysis were taken from the supernatant liquid within 0.30-m depth as follows: two 1.0-L composite samples were obtained from each lagoon by mixing in two separate buckets eight sub-samples collected around the lagoon using a 500-mL dipper with a 3.6-m long handle.

Figure 1. Full-scale modular solid-liquid separation treatment plant installed in Goshen Ridge farm, N.C.

Table 1. Main characteristics of the two production units.

Unit	Lagoon Treatment	Lagoon Surface (ha)	Lagoon Volume (m^3)	Steady State Live Animal Weight (kg)[a]	Total N Load (kg/day)[b]	Total N Load (kg/year)
1	Control	0.92	22,356	196,636	57.0	20,805
2	Solid-liquid separation	0.93	22,236	229,425	66.5	24,285

[a] Monthly mean of six barns (2003-2004, n = 24).

[b] Total N Load = [kg Steady State LAW × 0.29 kg N/1000 kg LAW/day]/1000.

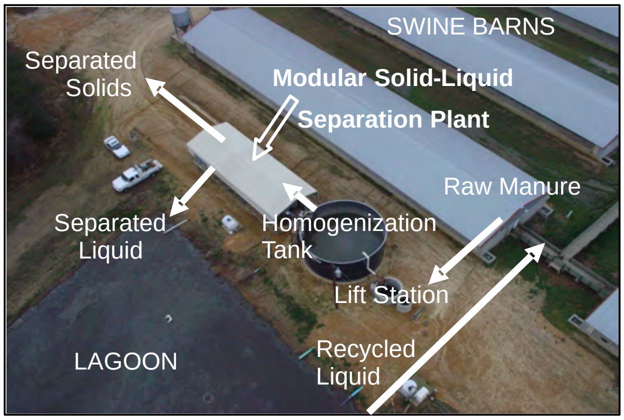

Figure 2. Aerial view of the solid-liquid separation modular plant, lagoon, homogenization tank, and swine barns.

All water analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Chemical analyses consisted of total ammoniacal N (TAN), total Kjeldahl N (TKN), nitrite plus nitrate-N (NO_2+NO_3 -N), total phosphorus (TP), chemical oxygen demand (COD), and pH. After filtration of samples through a 0.45-µm membrane filter (Gelman type Supor-450, Pall Corp., Ann Arbor, Mich.), TAN was determined using Standard Method 4500-NH_3 G. The same filtrate was used to measure NO_2+NO_3-N using Standard Method 4500-NO_3 - F. The same analytical method to determine TAN adapted to digested extracts (Technicon Instruments Corp., 1977) was used to determine TKN after acid digestion of the samples. Total N was determined as TKN plus (NO_3-N+NO_2-N) and organic N as the difference between TKN and TAN. For COD determination, we used the closed reflux colorimetric method (Standard Method 5520 D). Water pH was determined electrometrically (Standard Method 4500-H^+ B). Total suspended solids (TSS) were determined gravimetrically after filtration using glass micro-fiber filters and drying to constant weight at 105°C (Standard method 2540 D). Total solids (TS) were determined after drying the liquid samples at 105°C (Standard Method 2540 B).

For the separated solids, one sample was collected from each trailer leaving the farm. After moisture determination, the solid samples from individual trailers were combined into two weekly samples for chemical analyses. Bulk density of separated solids was used to estimate the solids mass in each trailer (0.85 ± 0.04 kg/m^3 as measured 14 times during the study with calibrated 18.9-L buckets). Solids samples were analyzed for moisture content using a microwave analyzer (Omnimark Instrument Corp., Tempe, Ariz.). For TKN, solid samples were dried at 60°C in a forced-draft drier, digested with concentrated acid, and the extracts were analyzed with the automated method described before for liquid samples (Technicon Instruments Corp., 1977). Carbon (C) content was determined using a dry combustion analyzer (LECO Corp., St. Joseph, Mich.).

AMMONIA EMISSIONS EVALUATION

Emission Sampling

Ammonia emissions were determined with passive flux samplers (Ferm tubes) using the method of Schjoerring et al. (1992). A passive flux sampler consisted of two parallel sampling units in opposite directions, against and away from the NH_3 source to determine source and background emissions simultaneously. Each sampler unit had three 7-mm i.d. glass sampling tubes (Mikrolab Aarhus A/S, Hoejbjerg, Denmark) – length 100, 100, and 23 mm – connected by silicon rubber tubing. The two 100-mm tubes were coated with oxalic acid on the inner surface at 70 mm of the tube length. The 23-mm tube had a nozzle glued onto the free end. The nozzle was made of a 0.05-mm thick stainless steel disc with a 0.5-mm radius hole in its center. The purpose of the nozzle was to decrease the air speed inside the tubes to achieve a low friction resistance and high collection efficiency (Schjoerring et al., 1992).

At each lagoon, the passive samplers were placed at four fixed sampling locations (fig. 3), positioned on four masts at 0°, 90° 180°, and 270° around the circumference of the circular plots. This layout enclosed most of the lagoon surface within a circular sampling plot such that the emission source area was 77% and 63% of control and treated lagoon,

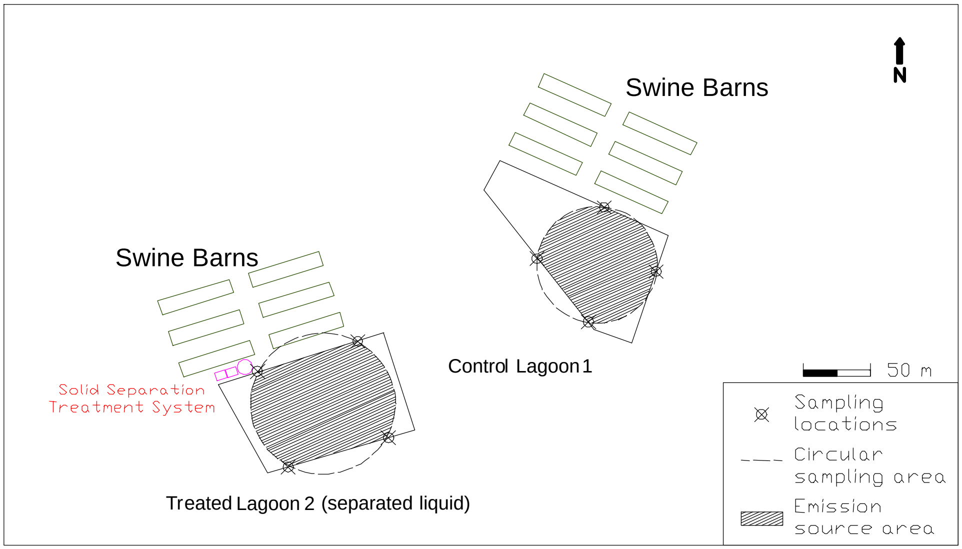

Figure 3. Schematic diagram of monitoring setup for the ammonia emission study for control lagoon 1 and treated lagoon 2, Duplin County, N.C.

respectively. In each fixed sampling location, NH_3 in air was collected in passive flux samplers placed at four heights (0.90, 1.65, 2.40, and 3.15 m, respectively) above the lagoon liquid surface.

Nine data collection periods lasting 23 h each were done simultaneously for the two lagoons from February to November 2004. All measurements were made in dry weather conditions to avoid sampler's acid coating washed out by rain and at wind speeds below 10 m/s to prevent by-pass air flow (Sommer et al., 1996). After exposure, the samplers were retrieved from the masts and transported to the laboratory in closed plastic containers. In the laboratory, sampler tubes were disconnected and NH_3 extracted from individual 100-mm tubes by dissolving the oxalic acid coating with 3.0 mL of ultrapure (MilliQ) water per tube. The liquid extracts were analyzed for NH_3-N using the salicylate method (Method US 696C-82W, Braun+Luebbe, 1999) on a Braun+Luebbe Autoanalyzer III (Roselle, Ill.). Analyses included blanks that consisted of two unexposed sampler sets assembled, stored, transported, and extracted in the same way as the exposed samplers. Each NH_3 emission measurement per site involved the analysis of 64 liquid extracts from the tubes.

Ammonia Flux Estimate

The vertical NH_3 flux for each lagoon was determined from net horizontal fluxes by application of a mass balance method (Schjoerring et al., 1992). The average horizontal flux of NH_3 through two glass tubes facing the same direction was estimated according to the following equation (Sommer et al., 1996):

$$\text{Horizontal Flux } (F_{hz}) = \frac{(C_1 + C_2)V}{2 \times \pi \times r^2 \times K \times \Delta t} \qquad (1)$$

where C_1 and C_2 are the NH_3-N concentrations (μg NH_3-N/L) in two 100-mm tubes facing in the same direction (either background or emission source), V is the volume of water used to dissolve NH_3-N sorbed on the tubes, r is the radius of the hole in the stainless steel disc (0.5 mm), Δt is the time between the start and conclusion of the measurements, and K is an empirical correction factor for wind speed and direction effects on the sampler (K = 0.77; Schjoerring et al., 1992). Daily emission rates were estimated by calculating the net vertical fluxes of NH_3 at each lagoon by step-wise summation of the net horizontal flux over the height intervals covered by the passive flux samplers using the following equation (Schjoerring et al., 1992):

$$\text{Vertical Flux } (F_v) = \frac{1}{2r} \sum_{h=1}^{h=4} \sum_{m=1}^{m=4} (F_{hz,e} - F_{hz,s}) \Delta h \qquad (2)$$

where $F_{hz,e}$ is the horizontal flux from the emission source area (calculated from NH_3 concentrations in tubes facing to the inside of the circular plot, fig. 3) and $F_{hz,s}$ is the horizontal flux from the surroundings or background (calculated from NH_3 concentrations in tubes facing to the outside of the circular plot, fig. 3) at each height of measurement (h) with each mast (m), Δh is the height interval between flux samplers, and r is the radius of the circular plot enclosing the emission source. Net vertical NH_3 fluxes were reported as emission rates in kg NH_3 -N/ha/d.

Environmental parameters were measured separately at each lagoon site to assure that micrometeorological conditions were similar during the simultaneous lagoon NH_3 emission measurements. Meteorological measurements consisted of air temperature, wind speed and direction, and relative humidity at about 2 m above the lagoon liquid surface (Szogi et al., 2006).

Data management, descriptive statistics (PROC MEANS), regression (PROC REG), and Mean comparison (PROC TTEST and PROC UNIVARIATE) analyses of data were performed with version 8.0 of SAS (SAS, 1999). Total annual NH_3 emissions were obtained by fitting a Gaussian curve to daily NH_3-N emission data versus day of the year using Prism 4.0 software (GraphPad Software, Inc., San Diego, Calif.). The parameter AREA of this curve represents the total annual NH_3 emissions as follows:

$$y = (\text{AREA}/(\text{SD} \times (2\pi)^{0.5})) \times \exp(-0.5 \times ((x - \text{Mean})/\text{SD})^2) \quad (3)$$

where y = daily NH_3 emission, x = day of the year, and AREA, SD, and Mean are parameter estimates. This curve was chosen because it provided a good fit to changes in daily NH_3 emissions throughout the year both in terms of R^2 and test for normality of residuals (residuals = emissions observed – emissions predicted) using the Shapiro-Wilk test statistic (Delong and Yuang, 1988).

RESULTS AND DISCUSSION

SOLID-LIQUID SEPARATION TREATMENT

Beginning in February 2004, flushing of raw manure from the barns into lagoon 2 was halted. All liquid manure generated in the six barns adjacent to lagoon 2 was first processed through the solid-liquid separation treatment plant with the separated solid leaving the farm (figs. 2 and 3). Solid-liquid separation was effective in separating suspended solids and organic nutrients. By capturing the suspended particles early in the process, a large portion of the oxygen-demanding and organic nutrient compounds was removed from the liquid stream going into anaerobic digestion. On average, the solid-liquid separation treatment separated 85% of TSS, 73% of COD and 81% of organic N (table 2). However, the solid-liquid separation system separated only 8% of the TAN. Mostly in soluble form, TAN constituted almost 60% of TKN in flushed manure before solids separation (table 2, column 1). Burton and Turner (2003) found that solid-liquid separation by itself has little effect on the dissolved fraction. In a 10-month period (Feb. to Nov., 2004), the modular plant produced about 9,330 m^3 of separated liquid with an average TKN concentration of 702 mg/L. This liquid conveyed into the lagoon 6,550 kg of TKN, mostly in inorganic form (90%) as TAN.

Significant amounts of C and organic nutrient compounds contained in liquid manure were recovered with the separated solids, enabling nutrient conservation and generation of organic value-added products such as aerobic compost (Vanotti et al., 2007). Separated solids were rich in C (38.2%) and organic N (4.7 %) (table 3). A total of 147 trailers containing 453 m^3 of separated solids was produced and left Goshen Ridge farm in a 10-month period (Feb. to Nov., 2004). This amount of manure solids weighed approximately 354,100 kg and contained 15.8 ± 1.5% solids (84.2% moisture), 21,468 kg of C, and 3,139 kg of N.

Table 2. Characteristics of flushed swine manure before and after polymer-enhanced solid-liquid separation treatment (Feb. - Dec., 2004), Goshen Ridge farm, Duplin Co., N.C.

Constituent[a]	Before Separation (mg/L)[b]	After Separation (mg/L)[c]	Mean Separation Efficiency[d] (%)
TSS	7260 ± 8345	710 ± 527	85 ± 13
TS	8904 ± 8679	2843 ± 1075	60 ± 13
TKN	1147 ± 509	702 ± 257	35 ± 16
TAN	684 ± 236	630 ± 205	8 ± 7
Organic N[f]	464 ± 349	79 ± 69	81 ± 12
$NO_2 + NO_3$-N	2.1 ± 3.9	0.05 ± 0.2	100
COD	12884 ± 12655	3043 ± 2357	73 ± 12
pH	7.6 ± 0.3	7.7 ± 0.3	--

[a] TSS = total suspended solids; TS = total solids; TKN = total Kjeldahl N; TAN = total ammoniacal N; $NO_2 + NO_3$-N = nitrate plus nitrate N; COD = chemical oxygen demand.

[b] Raw wastewater flushed from the swine barn. Data are means ± one standard deviation, n = 21.

[c] After solid-liquid separation treatment module.

[d] System efficiency compares reduction in concentration of water quality constituent after solid-liquid separation with respect to the influent (raw flushed manure).

[e] Except for pH.

[f] Organic N = difference between TKN and TAN.

Table 3. Percent solids and composition of solids from solid-liquid separation treatment.

Constituent	Concentration[a] (%)
Solids	15.8 ± 1.5[b]
Total Kjeldahl N	5.6 ± 0.6
Total ammoniacal N	0.28 ± 0.06
Organic N	4.7 ± 1.7
Total carbon	38.2 ± 2.6

[a] Concentration values are on a dry basis.

[b] Data are means ± standard deviations.

WATER QUALITY

Monitoring of water quality in the two anaerobic lagoons was initiated in 2002, two years before the solid-liquid separation modular plant started to operate in production unit 2. This two-year monitoring indicated that average concentrations of selected water quality indicators, shown in table 4, were within the characteristic range of values for these parameters in North Carolina's anaerobic lagoons (Bicudo et al., 1999). Since both production units had similar animal management and lagoon engineering design, their respective anaerobic lagoons had similar annual mean pH, TAN, TKN, COD, and TS concentrations in 2002 and 2003 (table 4).

Table 4. Water quality characteristics in the two lagoons of this study during two consecutive years before the separation treatment plant was operational, Goshen Farm, Duplin Co., N.C.[a]

Sampling Period	Lagoon	pH	TAN[b] (mg/L)	TKN (mg/L)	COD (mg/L)	TS (g/L)
Jan.-Dec. 2002	1	8.0 (0.2)	467 (118)	521 (122)	1658 (444)	3.5 (0.9)
	2	8.0 (0.2)	469 (121)	517 (115)	1656 (488)	3.6 (0.8)
Jan.-Dec. 2003	1	7.9 (0.1)	446 (102)	522 (127)	1482 (536)	3.2 (0.7)
	2	7.9 (0.1)	375 (124)	439 (140)	1356 (473)	2.8 (0.4)

[a] Data are annual means (standard deviation) of monthly composite samples, n = 12.

[b] TAN = total ammoniacal N; TKN = total Kjeldahl N; COD = chemical oxygen demand; TS = total solids.

Results from the monitoring study conducted to evaluate possible effects of water quality improvement on NH_3 emissions rates from the treated lagoon are presented in table 5. The criterion to determine water quality improvement was the reduction in concentration of selected water quality indicators. During 2004, the modular solid-liquid separation system separated about 85% of the manure solids in unit 2, but it produced modest improvements in lagoon liquid quality when looked at on an annual basis (Jan. to Dec., 2004). Differences in pH, TAN, TKN, and COD annual mean levels between the control lagoon and the lagoon with solid-liquid separation were statistically not significant ($P > 0.05$, table 5). However, differences in mean TS levels were significant between the two lagoons; TS levels in the treated lagoon were about 20% lower than TS content in the control lagoon as a result of solids removal during the same year (table 5).

Considerable variability in water quality parameter concentrations occur in anaerobic lagoons, probably due to lagoon loading rate and facility type (Bicudo et al., 1999). In addition, N concentration in lagoon liquid varies seasonally, usually increasing in winter with the highest concentration at the end of winter (March) and decreasing in summer with the lowest at the end of summer (September). Westerman et al. (2006) indicate that this fluctuation of N concentration in lagoons is due to the effect of temperature on both microbial activity and NH_3 volatilization increase during warm weather. In our study, we found similar seasonal trends in both lagoons for TAN, TKN, TS, and COD concentrations, all of which decreased during warm weather (fig. 4). Perhaps more important to note is the rate of seasonal change in concentrations, which was more pronounced in the retrofitted lagoon than in the control lagoon. For example, TAN concentration from March to September declined 39% in the control lagoon and 71% in the lagoon with solid-liquid separation pre-treatment. Corresponding COD changes were 32% and 71%, respectively. These changes started to be

Table 5. Water quality characteristics in anaerobic lagoon control and anaerobic lagoon with solid-liquid separation treatment (Jan. to Dec. 2004), Goshen Ridge farm, Duplin Co., N.C.[a]

Production Unit	Lagoon Treatment	pH	TAN (mg/L)	TKN[b] (mg/L)	COD (mg/L)	TS (mg/L)
1	Control	8.0 ± 0.2	364 ± 90	406 ± 80	1284 ± 228	2911 ± 92
2	Solid-liquid separation	8.1 ± 0.2	344 ± 143	391 ± 142	1203 ± 623	2352 ± 402
Level of Significance (P)						
	Paired t-test	0.16	0.29	0.48	0.51	< 0.0001
	Wilcoxon sign test	0.33	0.38	0.49	0.50	0.0002

[a] Data are means (standard deviation) of duplicate monthly composite samples.

[b] TAN = total ammoniacal N, TKN = total kjeldahl N, COD = chemical oxygen demand, and TS = total solids.

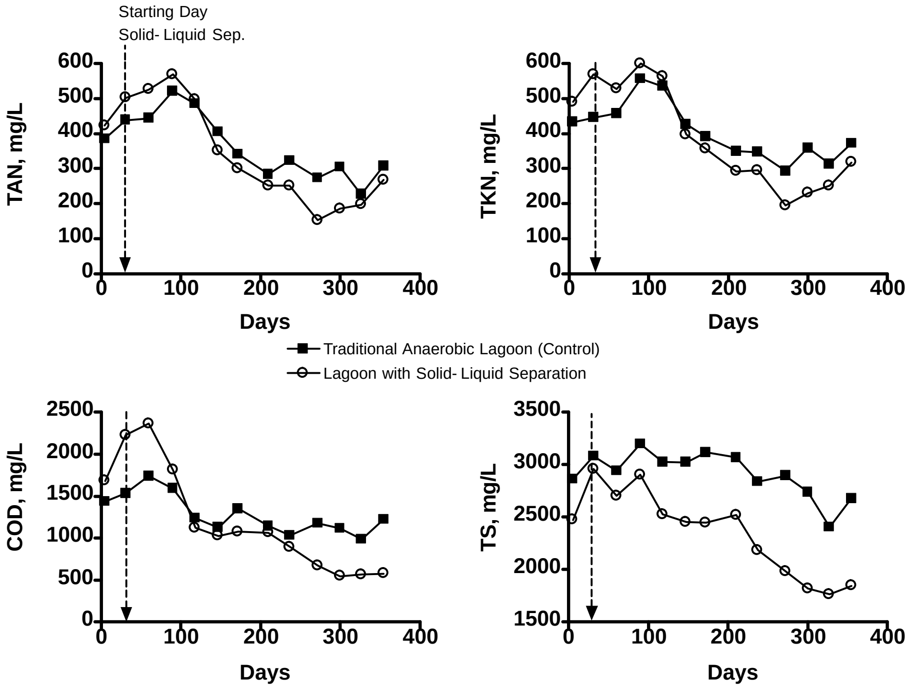

Figure 4. Water quality changes for the two lagoons during evaluation of the solid-liquid separation treatment plant (Jan. to Dec., 2004). Each data point is the average of two composite samples. The vertical arrow indicates the day that the modular plant started operation (Day 32, 1 Feb. 2004).

noticed when concentrations of TAN, TKN, and COD in both lagoons reversed order after about 88 days of operation of the solid-liquid separation plant (Day 119, fig. 4). A possible explanation for the relative decrease in TAN and COD in the treated versus control lagoon is that interruption of solids input into the treated lagoon determined both a reduction in COD and organic N (table 2). Consequently, this combined reduction in organic C and N substrate most probably diminished the microbial transformation of organic N into TAN. Although NH_3 volatilized from both lagoons, continuous removal of solids during warm months (March to Sept.) resulted in a larger seasonal decrease of TAN concentration in the treated lagoon than in the control.

AMMONIA EMISSIONS

NH_3 Background Emissions

Vertical net NH_3 fluxes using the passive sampler method are estimated only when the horizontal NH_3 flux from the emission source is bigger than that of the background (Sommer et al., 1996). Background emissions could be significantly influenced by atmospheric NH_3 re-deposition from nearby spray fields, animal housing adjacent to the lagoon, and portions of the lagoon that were not within the circular plot depending on speed and direction of the wind (fig. 3). To account for wind speed and direction effects on the sampler, a correction factor (K) is included in the mass balance (eq. 2; Schjoerring et al., 1992). Wind measurements (not required by the passive sampler method) in both lagoon sites showed that predominant direction was N-S with cold weather during which, NH_3 volatilization rates from the lagoon were very low (table 6). During warm weather, the background NH_3 levels remained low with respect to the emission source. Most probably, the predominant winds in S-N direction did not greatly enhanced the NH_3 in samplers facing the portions of the lagoon outside the sampling circle (fig. 3) In all nine 23-h collecting periods, vertical NH_3 fluxes from the surroundings of both lagoons were much lower than those from the emission source (table 6). Background fluxes were not significantly different between lagoons during cold or warm weather (paired *t*-test, $P > 0.01$, table 6).

Seasonal Effect

In geographic regions with concentrated livestock production, NH_3 emissions typically display strong seasonal patterns, with maximums happening during the summer (Gilliland et al., 2003). This seasonal pattern has also been observed in anaerobic swine lagoons, with maximum NH_3 fluxes occurring during summer (Aneja et al., 2000; Blunden et al., 2006). In our study, we found similar seasonal patterns for both lagoons (fig. 5). During the cold season (February, March, and November, 2004; air temperature < 10°C), mean emission rates in both lagoons were low (7.1 and 4.2 kg

Table 6. Vertical ammonia fluxes components (emission source and surroundings) for cold and warm weather in lagoon 1 (control) and treated lagoon 2 (solid-liquid separation), Duplin Co., N.C.[a]

Weather Conditions	Lagoon	Vertical Fluxes (kg NH_3-N/ha/d)	
		Source	Surroundings
Cold[b]	Control	9.7 (6.4)	2.5 (1.4)
Cold	Treated	6.7 (5.4)	2.5 (1.2)
t-test		NS[c]	NS
Warm[d]	Control	78.9 (14.2)	16.1 (6.3)
Warm	Treated	22.2 (9.34)	5.8 (3.2)
t-test		0.0001	NS

[a] Calculated using equation 2.
[b] Means (standard deviation) of February, March, and November 2004, air temperature < 10°C.
[c] NS = Not significant differences (P > 0.01), paired t-test.
[d] Means (standard deviation) of April to September 2004, air temperature > 10°C.

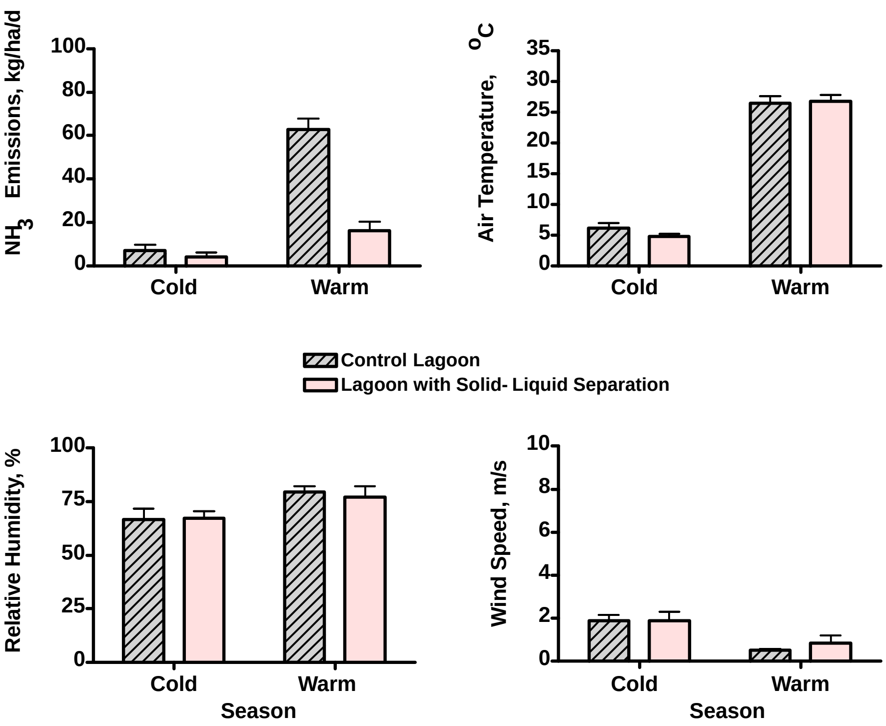

Figure 5. Mean ammonia (NH_3) emission rates, air temperatures, relative humidities and wind speeds during cold and warm weather for the control lagoon and lagoon with solid-liquid separation treatment, Goshen Ridge farm, Duplin Co., N.C. Cold season data obtained in February, March, and November 2004, air temperature < 10°C; warm season data obtained from April to September 2004, air temperature > 10°C. Error bars represent one standard deviation of the mean.

NH_3-N/ha/day). During the warm season (April to September, 2004; air temperature >10°C), emissions increased in both lagoons, but emission rates were distinctly higher in the control lagoon (fig. 5). Roughly, a four-fold significant difference (*t*-test, $P < 0.01$) was observed between the control anaerobic lagoon (62.8 kg NH_3-N/ha/day) and lagoon with solid-liquid separation (16.4 kg NH_3-N/ha/day) during the warm season.

Treatment Effect

The total annual NH_3 emission for each lagoon is represented by the area under the curves in fig. 6. On an annual basis, NH_3 emissions from the control lagoon totaled 12,542 kg N/lagoon/yr (or 13,633 kg N/ha/yr). This emission compares to 3,440 kg N/lagoon/yr (or 3,699 kg N/ha/yr) emitted from the anaerobic lagoon with the solid-liquid separation treatment retrofit.

Total annual NH_3 emissions abatement in the lagoon with solid-liquid separation was unexpectedly large, about 73% with respect to the anaerobic lagoon control (fig. 6), because differences in TAN levels between lagoons were modest on an annual mean basis (fig. 4).

The significant difference in NH_3 emissions exhibited between lagoons cannot be fully explained through parameters (TAN, TKN, temperature, wind, and relative humidity) that were essentially the same in both lagoon and normally thought to govern NH_3 fluxes. On a mass basis, the N mass reduction was significant (about 40%) in the treated lagoon, but this difference is less than the difference in N mass emitted from the lagoons (73%). Moreover, our results seem to be against to what emission models suggest that NH_3 fluxes varies widely with temperature, pH, suspended solids and TAN concentration of lagoon water, atmospheric NH_3 concentration above the water surface, and wind speed (Ni, 1999; De Visscher et al., 2002; Liang et al., 2002; Arogo et al., 2003b). Therefore, we propose the following mechanism to explain the NH_3 emission differences between the control and treated lagoons. With high efficiency solid-liquid separation, significant amounts of volatile solids are removed that normally would contribute to anaerobic digestion in a treatment lagoon – but NH_3 is known to pass through in soluble form (Burton and Turner, 2003). It is well

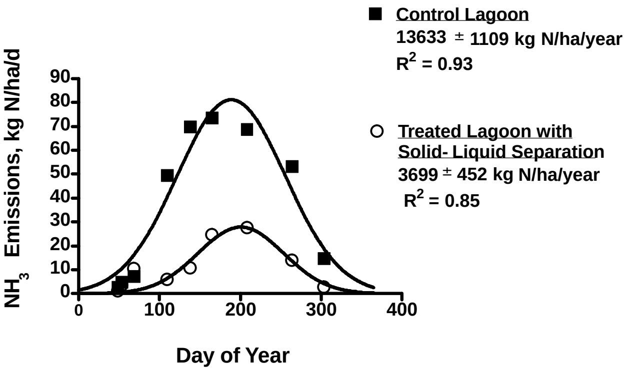

Figure 6. Change in daily rate of ammonia emissions throughout the year for the anaerobic lagoon control and lagoon with a solid-liquid separation retrofit. The total annual ammonia emissions were estimated by the area under each regression curve (eq. 3). Equation parameters are: AREA = 13633, SD = 67.04, and MEAN = 188.9 for the control lagoon; and AREA = 3699, SD = 53.02, and MEAN = 200.7 for the lagoon with solid-liquid separation treatment.

known that anaerobic digestion converts volatile solids into methane and carbon dioxide (Safley and Westerman, 1988; Sharpe and Harper, 2002; Hamilton et al., 2006). In turn, these gases are normally bubbling through the anaerobic lagoon surface. Several investigators indicated that gas bubbling strips NH_3 from lagoon liquid (Blouin et al., 1990; Sievers, 1995; Vanotti and Hunt, 2000). However, it was observed that the treated lagoon with solid-liquid separation did not have bubbling. Therefore, it is plausible that the higher NH_3 emissions of the control lagoon are the result of the concurrent loss of gases by bubbling and free NH_3 from the liquid surface.

CONCLUSION

We conducted a study to determine the effects of enhanced polymer solid-liquid separation on NH_3 emission rates of anaerobic swine lagoons. This study was conducted on a facility with two nearby swine production units that had similar animal production management and lagoon design. In one production unit, the anaerobic lagoon treatment method was maintained as a control. In the other production unit, a full-scale solid-liquid separation modular plant removed about 85% of TSS from flushed manure prior to lagoon input. We were able, therefore, to quantify environmental benefit of reducing NH_3 emissions by removing solids and associated organic nutrients with the use of enhanced-polymer solid-liquid separation technology. On an annual basis, NH_3 emissions from the lagoon control totaled 12,542 kg N/lagoon/yr (or 13,633 kg N/ha/yr) compared to 3,426 kg N/lagoon/yr (or 3,684 kg N/ha/yr) from the anaerobic lagoon with solid-liquid separation pre-treatment. Although water quality changes on an annual mean basis were modest in the retrofitted lagoon with respect to the control during the first year of treatment, total annual NH_3 emissions abatement in the lagoon with solid-liquid separation reduced NH_3 emissions by about 73% with respect to the anaerobic lagoon control. It is plausible that the higher NH_3 emissions of the control lagoon are the result of the concurrent loss of gases by bubbling and free NH_3 from the liquid surface since it was observed that the treated lagoon with solid-liquid separation did not have bubbling. These results overall demonstrate that use of a polymer-enhanced solid-liquid separation pre-treatment can substantially reduce NH_3 emissions from anaerobic swine lagoons used for confined swine production.

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