DEVELOPMENT OF AN ENVIRONMENTALLY SUPERIOR TREATMENT SYSTEM FOR REPLACING ANAEROBIC SWINE WASTE LAGOONS

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ABSTRACT

A full-scale treatment system for treatment of swine manure was developed to eliminate discharge to surface and ground waters and contamination of soil and groundwater by nutrients and heavy metals, along with related release of ammonia, odor, and pathogens. The system greatly increased the efficiency of liquid-solid separation by polymer injection to increase solids flocculation. Nitrogen management to reduce ammonia emissions was accomplished by passing the liquid through a module where bacteria transformed ammonia into harmless nitrogen gas. Subsequent alkaline treatment of the wastewater in a phosphorus module precipitated phosphorus and killed pathogens. Treated wastewater was recycled to clean hog houses and for crop irrigation. The system was tested during one year in a 4,400-head finishing farm as part of the Agreement between the Attorney General of North Carolina and Smithfield Foods/Premium Standard Farms to replace current anaerobic lagoons with environmentally superior technology. The system removed 97.6% of the suspended solids, 99.7% of BOD, 98.5% of TKN, 98.7% of ammonia, 95% of total P, 98.7% of copper and 99.0% of zinc. It also removed 97.9% of odor compounds in the liquid and reduced pathogen indicators to non-detectable levels. The existing anaerobic lagoon was transformed into an aerobic pond with low (< 30 mg/L) ammonia concentration. The treatment system was technically and operationally feasible. Based on performance obtained, it was determined that the treatment system met the Agreement's technical performance standards that define an environmentally superior technology. This project was considered an important milestone in the search of alternative treatment technologies, and justified moving ahead with innovation and evaluation of lower cost, next-generation systems.

KEYWORDS

Animal wastewater, manure, phosphorus, CAFO, nutrient recovery, nitrification, solid-liquid separation, PAM, pathogens, odor, swine lagoons

INTRODUCTION

Minimizing livestock manure's impact on the environment is one of U.S. agriculture's major challenges. When properly managed, manure can be used as nutrient sources for crops and to improve soil properties through accretion of soil organic matter. On the other hand, improperly managed manure can pose a threat to soil, water and air quality, and human and animal health. Currently, there is a government-industry framework in North Carolina for conversion of anaerobic swine waste lagoons and sprayfields to alternative technologies. In July 2000, the

Attorney General of North Carolina reached an agreement with Smithfield Foods, Inc. and its subsidiaries, the largest hog producing companies in the world, to develop and demonstrate environmentally superior waste management technologies for implementation onto farms located in North Carolina that are owned by these companies. In October 2000, the Attorney General reached a similar agreement with Premium Standard Farms, the second largest pork producer in the country. Taken together, Smithfield and Premium Standard represent over 75% of the hog farms in North Carolina. The agreement defines an environmentally superior technology (EST) as any technology, or combination of technologies, that (1) is permittable by the appropriate governmental authority; (2) is determined to be technically, operationally, and economically feasible and (3) meets the following five environmental performance standards:

1. Eliminate the discharge of animal waste to surface waters and groundwater through direct discharge, seepage, or runoff;
2. Substantially eliminate atmospheric emissions of ammonia;
3. Substantially eliminate the emission of odor that is detectable beyond the boundaries of the swine farm;
4. Substantially eliminate the release of disease-transmitting vectors and airborne pathogens;
5. Substantially eliminate nutrient and heavy metal contamination of soil and groundwater.

Selection of EST candidates to undergo performance verification involved a request of proposals and competitive review by the Agreement's Designee and a Panel representing government, environmental and community interests, the companies, and individuals with expertise in animal waste management, environmental science and public health, and economics and business management. This process yielded 18 technologies candidates among about 100 submitted projects. In July 2004, two of the technologies were shown to be capable of meeting the environmental performance criteria necessary for the technologies to be considered environmentally superior (Williams, 2004). One of the two technologies was designed to treat separated manure using high-solids anaerobic digestion system in a centralized facility, while the other was an on-farm technology designed to treat the entire waste stream from a swine farm using a solid separation, nitrification/denitrification, and soluble phosphorus removal system.

In this paper, we report the performance verification of the new on-farm treatment system designed to replace lagoons and provide an environmentally-safe alternative to traditional land application. Performance verification of the treatment system was done in a swine farm at full-scale during a one year period.

METHODOLOGY

The on-farm project was a collaborative, 3-year effort involving scientists, engineers, and personnel from private businesses, NCSU, and USDA. Engineering design and permitting of the alternative system were completed during the first year of the project, and construction and startup were completed in the second year. Subsequently, the system was evaluated during a one year operation period under steady-state conditions. Detailed descriptions of sampling, analytical methods, and monitoring procedures were provided by Vanotti (2004).

The implemented system without lagoon (Figure 1) comprised (a) a solid separation unit, wherein flocculants are used to clump suspended solids and increase separation efficiency, (b) a denitrification unit in direct fluid communication with a clarified effluent from the solid separation unit, (c) a nitrification unit in fluid communication with the denitrification unit, (d) a phosphorus separation reactor unit in fluid communication with the liquid effluent from the nitrification unit, and (e) a clarification unit between the nitrification unit and phosphorus unit. Homogenization and storage tanks were added to the system to integrate discontinuous operations, such as flushing and barn pit recharge, with continuous operation of the treatment system.

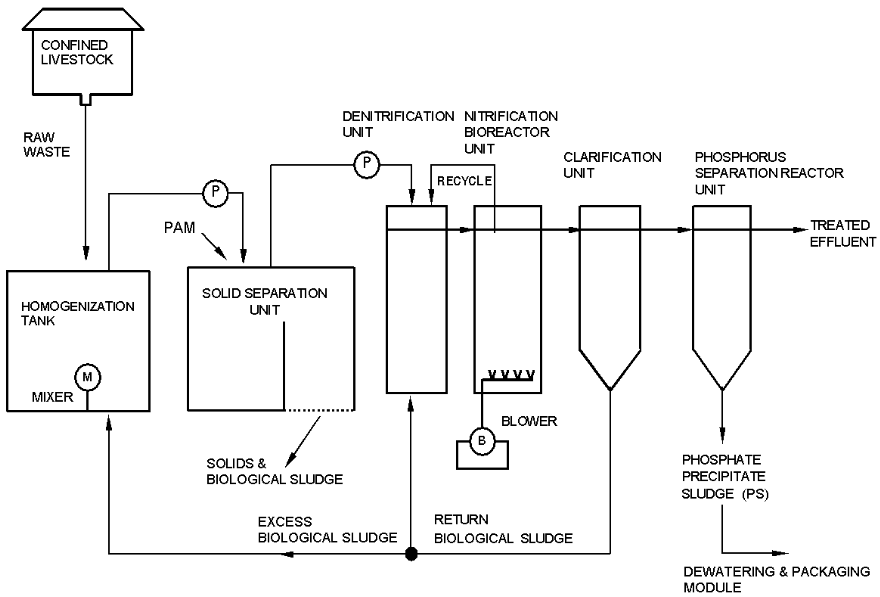

Figure 1. Schematic of the swine manure treatment system (Vanotti et al., 2005).

The full-scale demonstration facility was installed on a 4,400-head finishing farm in Duplin County, North Carolina. The system was constructed and operated by a private firm, Super Soil Systems USA of Clinton, NC. The system made use of three unit processes or modules (Figure 2). The first – the Ecopurin Solid-Liquid Separation Module, developed by the Spain-based firm Selco MC of Castellon – quickly separated solids and liquids. The second step used the Biogreen Nitrogen Removal Module, developed by Hitachi Plant Engineering & Construction Co. in Tokyo, Japan. The process used nitrifying bacteria entrapped in polymer pellets. After biological N treatment, the liquid went to the final step, the Phosphorus Separation Module developed by ARS. The process removes phosphorus as calcium phosphate with addition of only small quantities of liquid lime and without losses of ammonia. Additionally, pathogens are destroyed by alkaline pH.

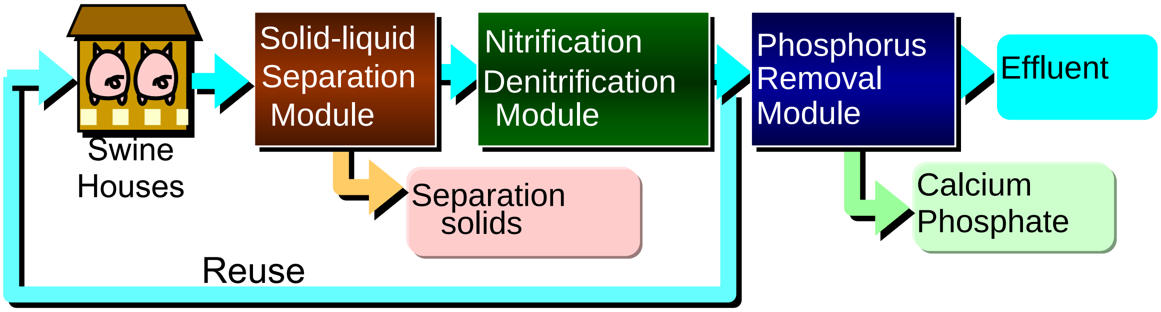

Figure 2. Diagram of the swine manure treatment system with individual modules implemented at Goshen Ridge farm, North Carolina.

General Operation of the Treatment System

The system was fully automated; using sensors integrated to programmable logic controllers for round-the-clock operation. All six barns in the facility were flushed once a week. Flushed manure was pumped into the homogenization tank where it was kept well mixed before solids separation. The solid-liquid separation module produced a solids stream and a liquid stream. The separated solids were removed from the farm every day using trailers, and the liquid effluent was lifted into the nitrogen module.

After going through nitrification and denitrification, the effluent from the nitrogen module was discharged into the clean water storage tank and used to recharge pits under the houses. Excess water not used to recharge the pits was gravity fed from the clean water storage tank into the phosphorus separation module. Treated effluent from the phosphorus module was stored in the existing lagoon before use in crop irrigation. Phosphorus bags were left to dry on a drying concrete pad and removed from the farm on a monthly basis (Figure 3).

Figure 3. Full-scale wastewater treatment system that replaced the swine lagoon.

The total system was completed with a centralized solids processing facility at Super Soil Systems USA headquarters in Sampson County, NC, where separated manure solids were subject to aerobic composting and blending processes to produce value-added products such as organic fertilizer, soil amendments, potting soil, and soilless media for use in horticultural markets.

Handling of Liquid Manure in the Barns

The barns used slatted floors and a pit-recharge system typical of many farms in North Carolina. A significant management change to optimize treatment was that the amount of liquid used for pit recharge was significantly less than typically used in pit-recharge systems. For example, before the new treatment system was installed, pits were refilled with lagoon liquid to the overflow level (23,000 gal/barn on this farm), and additional volume generated by the pigs during the week displaced pit liquid and overflowed into the lagoon. Once a week, the pits were completely emptied (flushed) into the lagoon using a pull-plug device.

Once the treatment plant was operational, flow of raw manure into the lagoon was discontinued and pits were refilled with liquid stored in the clean water tank that received N treatment. The frequency of flushing (once/week) was maintained, but the pits were not refilled to the overflow level as done before. Pit refill volume during treatment plant operation varied from 2,100 to 6,000 gal/barn, which is only 10 to 25% the amount of liquid previously used in the same pit-recharge system. Thus, volume of wastewater to be treated was significantly reduced.

Livestock and Manure Loading Conditions

New batches of pigs were received Jan-Feb 2003, June-July 2003, Nov-Dec, 2003, and March 2004. Total pig weight varied greatly within production cycles, from a low of about 200-300 Animal Units (1 AU=1000 lb) to a high of about 750 to 800 AU (Figure 4). Loading rates of solids and nutrients into the system were well correlated with changes in total pig weight. Nitrogen production averaged 0.29 lb N/1000 lb/day but varied from 0.18 to 0.42 lb N/1000 lb/day. Total suspended solids production averaged 1.93 lb TSS/1000 lb/day (range 1.1-3.4).

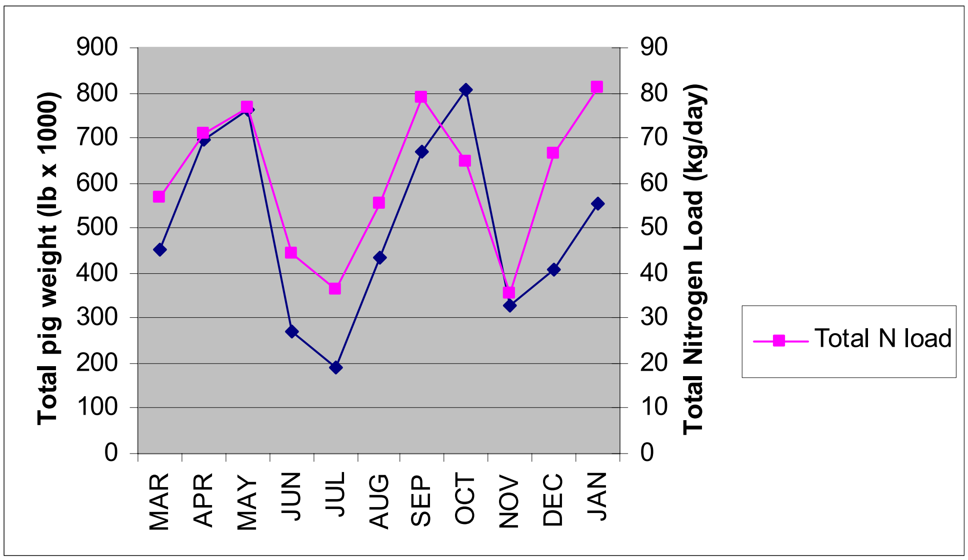

Figure 4: Changes of total nitrogen loading rates into the treatment system as affected by total pig weight in the barns (shown in blue color).

Manure volume production varied from 8,100 to 14,600 gallons per day (based on monthly averages). A total of 3.34 million gallons of flushed manure was processed from March 1, 2003, to Jan. 15, 2004, or an average of 10,300 gallons per day. On the average, the flushed manure contained 33.7% recycle treated water (used to refill the pits), and 66.3% fresh manure (urine and feces) and drinking water wasted by pigs.

Solid-Liquid Separation Module Description

In contrast to systems that use slow anaerobic digestion of waste in lagoons, systems that use quick separation of solids and liquids can conserve much of the organic fraction of animal waste. However, to effectively recover the solids, some form of flocculation must be used. Polyacrylamides were found to be effective. The separation module used the Ecopurin process that was housed in a building of its own. It was automated through the use of a programmable logic controller (PLC) for a 24-hr/day operation. Treatment parameters such as polymer rate, wastewater flow, and mixing intensity were set by the operator using a tactile screen in a control panel. Flow rates varied from 2 to 4 m^3/h depending on manure treatment needs. The liquid manure was reacted with polymer to flocculate suspended solids and passed through a rotating screen. Subsequently, a dissolved air flotation unit (DAF) polished the liquid effluent while a small filter press dewatered the screened solids. The dewatered solids were transported daily to a centralized composting plant. The separated liquid was continuously pumped into the biological N removal module for further treatment.

Biological Nitrogen Removal Module Description

Once solids are removed, a relatively smaller amount of suspended organic waste remains in wastewater, but it still contains significant amounts of soluble ammonia and phosphorus. The second step, the biological removal of ammonia, involved the Biogreen process (Figure 5). The unique feature of the Biogreen process is that it uses nitrifying bacteria entrapped in polymer PEG gel pellets to increase concentration and effectiveness of bacterial biomass in the nitrification tank. These pellets were kept inside the tank by means of a steel screen structure. The nitrification tank at the farm contained 12 m^3 of the nitrifying pellets. Effective water volumes of the tanks were: denitrification = 263 m^3, nitrification= 110 m^3, settling=33 m^3.

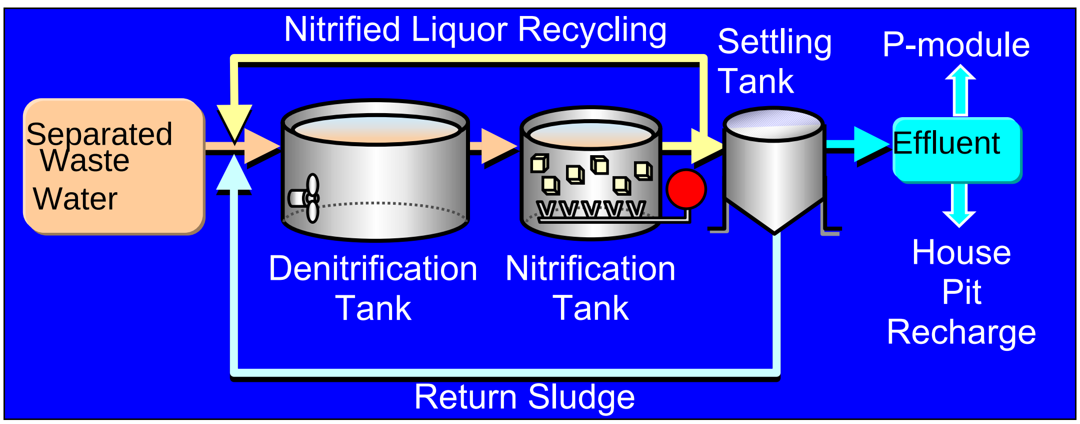

Figure 5: Diagram of the basic Biogreen process used in the wastewater treatment system for removal of ammonia in swine wastewater after going through solid-liquid separation.

The module was operated in three distinct ways during the evaluation period (April 1, 2003, to March 1, 2004):

1. Five-tank configuration without methanol addition that included all the tanks shown in Figure 5 plus a post-denitrification tank (110 m^3) and oxic tank (21 m^3) that were placed between the nitrification tank and the settling tank. This was done April 1 to July 15, 2003, and repeated again in cold weather October 1, 2003, to January 15, 2004 (6 months total).
2. Five-tank configuration as described above with methanol addition into the post-denitrification tank. This was done July 15 to October 30, 2003 (3.5 months).
3. Three-tank configuration as shown in Figure 5, with elimination (by-pass) of the post-denitrification and oxic tanks. This was done February 1, 2004, to March 1, 2004 (1 month). This simplified configuration proved to be the best choice for the system.

Phosphorus Removal Module Description

After biological N treatment, the wastewater flowed by gravity to the phosphorus separation module where phosphorus was recovered as calcium phosphate and pathogens were destroyed by alkaline pH. Figure 6 shows a schematic diagram of the phosphorus separation module installed at Goshen Ridge farm. Liquid was mixed with hydrated lime slurry in a reaction chamber. A pH controller was linked to the lime injector and kept the process pH at 10.5-11.0. The liquid and precipitate were separated in a settling tank. The precipitated calcium phosphate sludge was further dewatered using filter bags with a capacity of 50 lb each. Polymer was added to the phosphorus precipitate to enhance separation. Automation to the system was provided by sensors integrated to a programmable logic controller (PLC) for 24 hr/day operation. Treatment parameters such as process pH or frequency of sludge transfer were set by the operator using a second tactile screen located in the plant control panel. The lime slurry was a 30% suspension ready to use that was supplied in tote containers by Chemical Lime Company (Charlotte, NC).

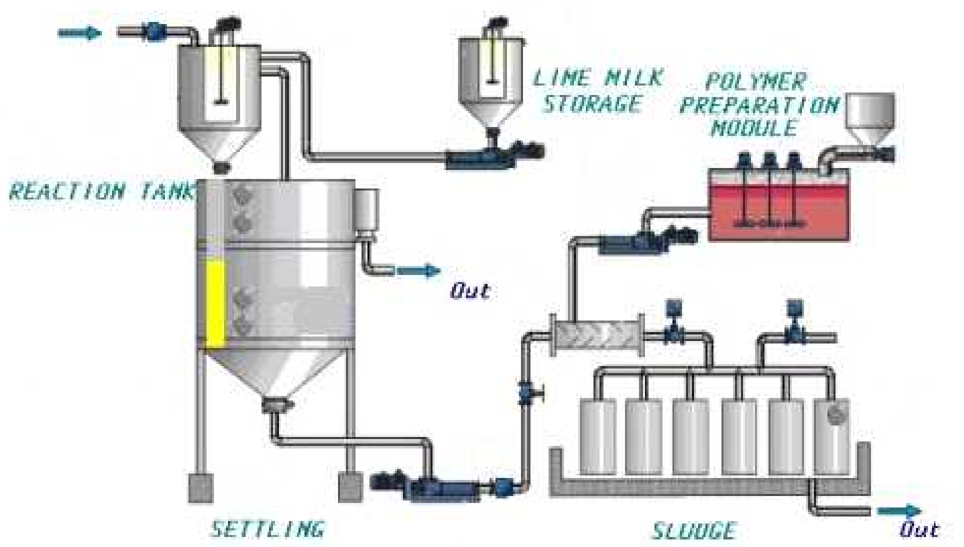

Figure 6. Schematic diagram of phosphorus separation module constructed in the full-scale manure treatment system demonstration project at Goshen Ridge farm.

RESULTS AND DISCUSSION

Solid-Liquid Separation Performance

Solids separation efficiency was consistently high with an average of 93% TSS separation. This high-separation efficiency was obtained with liquid manure TSS concentration that varied from about 4000 mg/L to 28,000 mg/L (Figure 7).

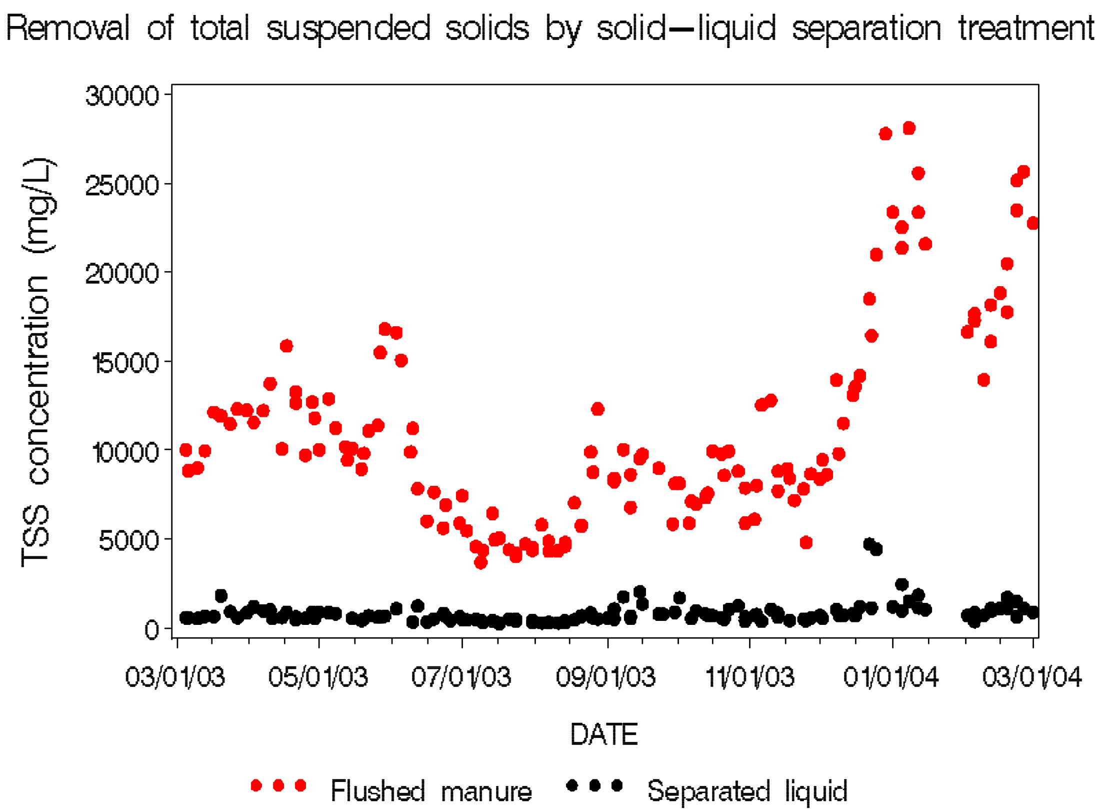

Figure 7: Total suspended solids (TSS) concentration in liquid swine manure before and after solid-liquid separation treatment.

During the year-long evaluation, the solids separation module also removed 93% of the volatile suspended solids, 77% of COD, 39% of nitrogen, 94% of zinc and copper, and 70% of phosphorus from the wastewater (Table 1). Reduction of organic compounds such as COD is an important system consideration for the efficiency of the nitrification treatment.

Soluble ammonia and soluble phosphate concentrations changed little (< 4 and 11% reduction, respectively) with solids separation treatment. In contrast, organic N and P were effectively captured in the solids, resulting in average concentration reductions of 84 and 90%, respectively.

A total of 748 m^3 of solids were separated and left Goshen Ridge farm in a 10.5-month period from March 1, 2003, to Jan 15, 2004. This amount of manure weighed approximately 596,200 kg (1,314,300 lb or 657 tons) and contained 18.2% (± 1.3%) of solids (81.8% moisture), 40,805 kg of carbon, 5,379 kg of nitrogen, 3,805 kg of phosphorus, 280 kg of copper, and 281 kg of zinc. The separated solid waste was converted into organic plant fertilizer, soil amendments, and energy at the centralized solids processing facility.

Table 1: Removal of solids, oxygen demanding compounds, nutrients and heavy metals from liquid swine manure by the solid-liquid separation unit.

Water Quality Parameter	Raw Liquid Swine Manure mg/L (± s.d.)	Liquid After Solids Separation Treatment mg/L (± s.d.)	Reduction Efficiency (%)
Total Suspended Solids (TSS)	11,072 (5,660)*	766 (392)	93
Volatile Suspended Solids (VSS)	8,100 (4,804)	558 (282)	93
Chemical Oxygen Demand (COD)	16,881 (9,058)	3,957 (2,390)	77
Biochemical Oxygen Demand (BOD_5)	3,405 (2,495)	1,311 (1,244)	61
Total Kjeldahl Nitrogen (TKN)	1,617 (557)	988 (322)	39
Total Phosphorus (TP)	573 (215)	170 (44)	70
Zinc	25.9 (11.3)	1.5 (1.9)	94
Copper	26.2 (11.5)	1.5 (1.7)	94
pH	7.60 (0.19)	7.91 (0.15)	

*Data are means (± standard deviation) of one-year evaluation (March 1st , 2003 – March 1st , 2004, n=135).

Rate of polymer application varied from 106 mg/L to 178 mg/L as a consequence of fluctuations in wastewater strength during production cycles (average rate = 135.8 mg/L of dry polymer). Polymer use efficiency based on solids removal increased with wastewater strength. For example, polymer use efficiency increased from 32 g TSS separated/g polymer (3.04 g polymer/100 g TSS) to 190 g TSS separated/g polymer (0.56 g polymer/100 g TSS) with changes in TSS concentration from 4.90 to 23.7 g/L (monthly averages). Thus, polymer treatment is more economical with higher-strength flushed manure. The average polymer use efficiency obtained during the evaluation was 76.8 g TSS separated/g polymer (1.63 g polymer/100 g TSS).

Biological Nitrogen Removal Performance

Once the proper mixers and recirculation equipment were in place, and tanks filled with wastewater, it took about four weeks for the nitrifying bacteria to be fully acclimated to the high-strength swine wastewater. Acclimation process was carried out in a stepwise procedure where flow loads were gradually increased from 25% of the flow being processed by the separation module to 100% (full-scale). Changes in nitrification activity of the immobilized pellets were assessed weekly during acclimation period using bench reactors and 6-h batch tests. In four weeks, nitrification activity increased from about 1 kg N/m^3-pellet/day to > 7 kg N/m^3-pellet/day. For design purposes, pellets were considered fully acclimated with an activity of 6 kg N/m^3-pellet/day that was equivalent to a nitrification capacity of 72 kg N/day in the treatment module (containing 12 m^3 of pellets).

Nitrogen loading rates into the nitrogen removal module fluctuated greatly (150%) within production cycles. These loading fluctuations were well correlated with changes in total pig weight in the barns (Figure 8). TKN loading rate averaged 37 kg/day and varied monthly from 20 to 50 kg/day. Ammonia-N loading rate averaged 32 kg/day and varied monthly from 18 to 45 kg/day. The N process responded well to these highly changing N loading conditions as evidenced by performance (Figure 9)

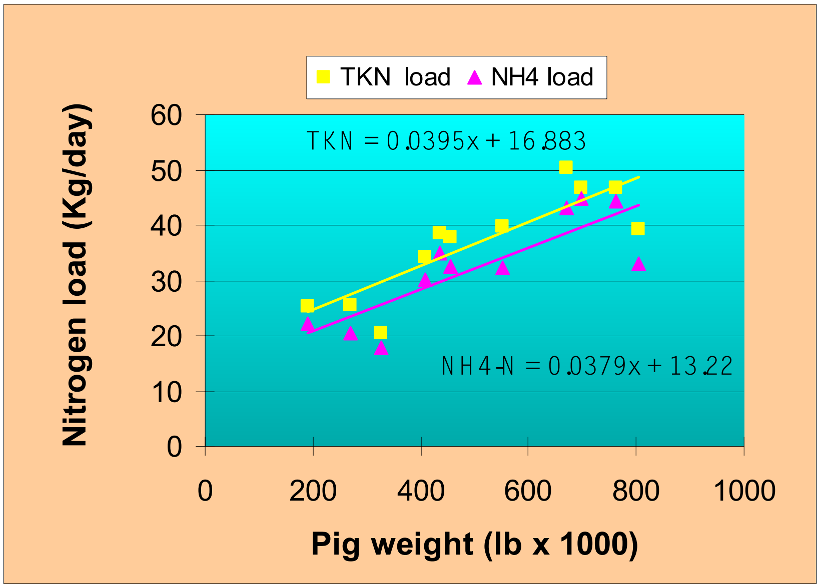

Figure 8: Changes in total Kjeldahl nitrogen (TKN) and ammonia (NH_4-N) loading rates into the biological N removal module as affected by total pig weight variation in the barns.

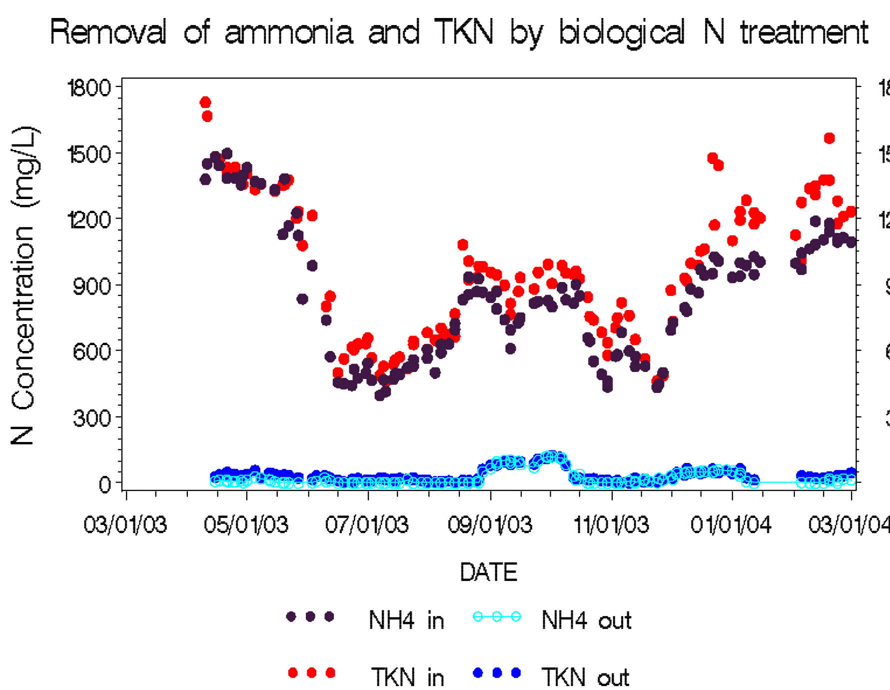

Figure 9: Ammonia (NH_4-N) and Total Kjeldhal Nitrogen (TKN) concentration in liquid swine manure before and after biological N treatment. Influent is the liquid after solids separation.

Water temperatures during cold weather (Dec 2003, Jan 2004, and Feb 2004) were: 11.9 to 13.0°C for the monthly averages and > 4.2°C for the daily average. Corresponding air temperatures during the cold weather were: 4.8 to 6.7°C for monthly averages and > -4.2°C for the daily average.

Ammonia removal efficiencies of the Biogreen process were consistently high (> 95%) during both the first month acclimation period and the subsequent 10 months evaluation (Figure 9). These high process efficiencies were obtained with influent ammonia concentrations varying from 400 to 1500 mg/L and loading rates varying from about 20 to 50 kg N/day. After solids separation, most of the TKN was made of soluble ammonia; therefore, removal efficiencies for TKN were also high (> 95%). Influent TKN concentration varied from 460 to 1730 mg/L. The treatment also significantly reduced alkalinity, volatile solids, BOD, and COD concentrations in the liquid effluent (Table 2).

Data in Table 2 show detailed performance data of the streamlined 3-tank nitrogen removal module. Operational considerations, such as recirculation between tanks (nitrified liquor recycle and return sludge) and aeration of nitrification tank, were the same as before. The simplified system performed optimally under the most demanding conditions: winter weather and high N loads when total pig weight was highest in the production cycle.

Table 2: Removal of TKN, ammonia, and oxygen-demanding compounds from separated liquid swine manure by biological N removal module (Biogreen process) using streamlined three-tank configuration (DN1, Nitrification, and Settling).

Water Quality Parameter	Liquid After Solids Separation Treatment (mg/L)	Liquid After Biological N Treatment (mg/L)	Reduction Efficiency (%)
Alkalinity (mg/L)	6,013*	1,040	83
Volatile Suspended Solids (VSS)	741	132	82
Chemical Oxygen Demand (COD)	4,943	808	84
Biochemical Oxygen Demand (BOD_5)	1,716	66	96
Soluble BOD_5	1,482	37	98
Total Kjeldahl Nitrogen (TKN)	1,279	29	98
Ammonia Nitrogen (NH_4-N)	1,091	7	99
Oxidized N (NO_3-N + NO_2-N)	0	210	--
Total N (TKN + Oxidized N)	1,279	239	81
pH	7.99	7.31	--

*Data are averages of a one month evaluation (Feb. 1, 2004, to March 1, 2004, n=13).

The biological system generated very little amounts of waste sludge. This is because most of the organic and oxygen-demanding compounds in the liquid were separated by the solid-liquid separation process or consumed during denitrification before aeration treatment. Sludge was wasted every day by diverting < 1 m^3 of the return sludge from the settling tank into the solids separation module (homogenization tank). Waste sludge volume averaged 220 gal/day (6,482 gal/month) in the period April 1, 2003, to March 1, 2004. Average TSS concentration was 6,346 mg/L, and the corresponding amount of dry sludge wasted was 156 kg/month. Assuming 93%

separation efficiency of TSS, this wasted sludge contributed 145 kg of dry solids per month to the separated manure, or 1.4% of the total separated waste (596,200 kg containing 18.2% solids in 10.5 months). All the separated biological sludge solids left the farm mixed in the manure solids, and the separated liquid was returned to the biological N system (Figure 1).

Performance of the Soluble Phosphorus Removal Module

Removal efficiencies of the soluble phosphate using the P-removal module averaged 94% for wastewater containing 77 to 191 mg/L PO_4-P (Figure 10 and Table 3). A total of 285 bags of calcium phosphate product containing 1,160 lb of P was produced and left the farm in a 9-month period. The concentration grade was 24.4 ± 4.5% P_2O_5. Each bag weighed an average of 34.8 kg and contained 8.1 kg of dry matter (23.3% solids and 76.7% moisture). The phosphorus was > 90% plant available based on standard citrate P analysis used by the fertilizer industry.

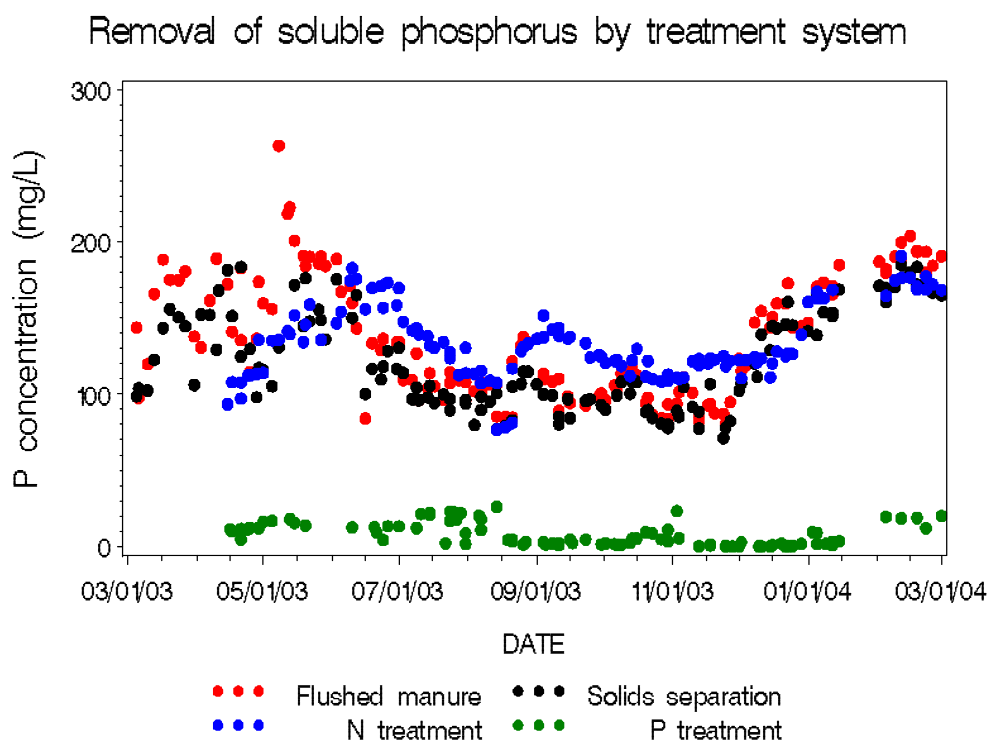

Figure 10: Concentration of soluble phosphorus in the wastewater as it passes through the treatment system components.

The high pH (10.5) in the phosphorus removal process is necessary to produce calcium phosphate and kill pathogens. However, the liquid is poorly buffered, and the high pH in the effluent decreases readily once in contact with the air. For example, treatment of 1 L liquid using 2 L/min aeration reduced the pH from 10.5 to < 9 in about 2 h. In the treatment plant, most of the treated effluent was stored in the former lagoon that, with time, was converted into an aerobic pond. We did not detect a pH increase in the pond water after one year of operation and > 2 millions gallons of treated effluent added.

Table 3: Removal of phosphorus from liquid swine manure after biological N treatment using USDA-ARS developed process.

Water Quality Parameter	Liquid After Biological N Treatment	Liquid After Phosphorus Treatment	Efficiency (%)
pH	7.24*	10.49	--
Alkalinity, mg/L	529	735	--
Electrical Conductivity, mS/cm	5.13	4.86	--
BOD_5 , mg/L	33	10	70
Soluble phosphorus , mg/L	134	8	94

* Data are means for the period of April 15, 2003 - March 1, 2004 (n=121).

Performance of the Total Wastewater Treatment System

System performance data were obtained during 10.5 months from April 15, 2003, to March 1, 2004, when all three modules were in-line. The complete system removed 97.6% of the suspended solids (TSS), 99.7% of BOD, 98.5% of TKN, 98.7% of ammonia, 95% of total P, 98.7% of copper, and 99.0% of zinc (Table 4).

Data in Table 4 show the unique contributions of each technology component to the efficiency of the total treatment system. Solid-liquid separation was effective separating suspended solids and organic nutrients. By capturing the suspended particles, most of the volatile and oxygen-demanding organic compounds weree removed from the liquid stream. Instead of breaking down organic compounds, the oxygen in the aeration treatment was used efficiently to convert ammonia. The effluent from the solids separation contained significant amounts of N and P mostly in the soluble form. The ammonia was treated effectively in the N module. The treatment also consumed remaining carbon (BOD, COD) in the pre-denitrification step. Soluble phosphorus was not significantly changed by liquid-solid separation or nitrogen treatment (Figure 10) but reduced significantly in the P-module where P was recovered as a calcium phosphate material.

A mass-balance approach was required to understand system removal of total N and oxidized N (nitrite + nitrate). Mass balance utilized nutrient concentration as well as water flows. Water flows corresponding with system performance evaluation period are provided in Table 5. We calculated that 870 kg of oxidized-N was removed by denitrification in the closed loop recycling N treated water to the barns during the 10.5-month system evaluation period. The amounts of total N (TKN + oxidized N) contained in the flushed manure and the treated effluent were 19,100 kg and 2,020 kg, respectively. Thus, total N removal on a mass basis (TN in – TN out) was 89.4%. Most (91%) of the remaining N was oxidized N. A significant amount was further removed by denitrification in the lagoon, most likely by combination with the existing sludge. Nitrate was first noticeable (2 mg/L) in the lagoon liquid in August 2003, but concentration remained very low (<36 mg N/L) in the subsequent months (Oct. 2003-May 2004).

Table 4: Removal of suspended solids, COD, BOD, nutrients, and heavy metals by total treatment system at Goshen Ridge farm.

Water Quality Parameter	Raw Flushed Manure (mg/L)	After Solids Separation Treatment (mg/L)	After Biological N Treatment (mg/L)	After Phosphorus Treatment (mg/L)	System Efficiency (%)
TSS	11,051*	823	122	264	97.6
VSS	8,035	591	77	85	99.0
COD	16,138	3,570	617	445	97.4
BOD_5	3,132	1,078	33	10	99.7
TKN	1,584	953	34	23	98.5
NH_4-N	872	835	23	11	98.7
Organic N	712	111	12	11	98.5
Oxidized N**	1	1	224	224	--
Total N***	1,584	954	258	247	84.4
Total P	576	174	147	29	95.0
Soluble P	135	121	134	8	94.1
Copper	26.8	1.54	0.53	0.36	98.7
Zinc	26.3	1.47	0.40	0.25	99.0
pH	7.60	7.91	7.24	10.49	--
EC (mS/cm)	10.44	10.39	5.13	4.86	--

* Data are means for the period of April 15, 2003 - March 1, 2004 (n=121).
**Oxidized-N = NO_3-N + NO_2-N (nitrate plus nitrite)
*** Total N = TKN + Oxidized-N. System efficiency for Total N = 89.4% on a mass balance basis. This considers that 33% of the N-treated effluent was recycled in a closed loop to refill barns where oxidized N was eliminated (Table 5).

Table 5: Wastewater flow in treatment plant during period April 15, 2003, to March 1, 2004, corresponding to total system operation.*

Flow Path	Totals Gallons	Average Flow (Gallons/Day)
Raw Flushed Manure to Homogenization Tank	3,183,300	10,302
Separated Effluent to Nitrogen Module	3,188,500	10,319
N-Treated Effluent to Refill Barns	1,039,200	3,363
N-Treated Effluent to Phosphorus Module	2,160,700	6,993
P-Treated Effluent to Storage Pond (Lagoon)	2,106,900	6,818

*Raw flushed manure, effluent recycle to barns, and phosphorus measured with flowmeters. Separated effluent value incorporates the balance of polymer water and separated solids.

Reduction of Odor Compounds by Treatment System

The treatment system was also effective in reducing odor-generating compounds contained in the liquid (Table 6). By measuring directly in the liquid the concentration of compounds typically associated with bad smell in animal wastes, we were able to quantify the potential of the effluent to produce offensive odors and the effect of treatment on odor reduction. The largest reduction was observed after the liquid passed through aeration in the nitrogen treatment. Removal efficiency was particularly high for skatole and p-cresol, major contributors to malodor in liquid swine manure. The treatment system eliminated 97.9% of the odor compounds evaluated (Table 6).

Table 6: Reduction of odor compounds contained in the liquid by the treatment system at Goshen Ridge farm.

	Raw Flushed Manure ppb (± s.e.)	After Solids Separation Treatment ppb (± s.e.)	After Biological N Treatment ppb (± s.e.)	After Phosphorus Treatment ppb (± s.e.)	System Efficiency (%)
Phenol	11.76 (2.03)*	5.35 (1.36)	3.47 (1.35)	2.17 (1.23)	81.3
p-Cresol	34.87 (7.60)	53.45 (39.47)	0.08 (0.03)	0.06 (0.01)	99.8
Ethylphenol	21.55 (12.18)	13.94 (8.16)	0.07 (0.03)	0.05 (0.01)	99.8
4-Propylphenol	5.24 (0.99)	3.82 (1.06)	0.08 (0.03)	0.06 (0.01)	98.9
Indole	3.52 (1.89)	4.78 (0.42)	0.84 (0.53)	0.23 (0.16)	93.5
Skatole	129.84 (27.93)	100.35 (27.51)	0.07 (0.03)	1.72 (1.02)	98.7
Total	206.78	181.69	4.61	4.29	97.9

*Data are means (standard error) of measurements taken September 2003 - October 2003 (n=5). System efficiency compares reduction of odor compound concentration in liquid after phosphorus treatment with initial concentration in raw flushed manure.

Reduction of Microbial Indicators of Fecal Contamination by Treatment System

The treatment system was also effective in reducing pathogen indicators in liquid swine manure (Table 7). Values are means (standard error) of $\log_{10}$ MPN bacteria per mL for duplicate samples for four sampling dates (July, Sept, Nov, and Dec 2003). BDL (below detectable limit) indicates there were no colonies to count; upper threshold limit value was 10 colony forming units/mL (1 colony/100 µL).

Results showed a consistent trend in reduction of microbial indicators as a result of each step in the treatment system. Results also confirmed pilot studies that the phosphorus removal step via alkaline calcium precipitation produces a sanitized effluent. Total Gram Negative, Fecal coliforms, *E. coli*, and Enterococci were reduced to non-detectable levels (< 10 cfu/mL).

Table 7: Microbiological analyses of liquid manure effluent before treatment and at each step of the treatment system.

Indicator Microorganism	Raw Flushed Manure log_{10}/mL (± s.e.)	After Solids Separation Treatment log_{10}/mL (± s.e.)	After Biological N Treatment log_{10}/mL (± s.e.)	After Phosphorus Treatment log_{10}/mL
Total Gram Negative	6.58 (1.59)	6.29 (1.82)	3.46 (1.11)	BDL
Total Coliforms	4.49 (0.45)	3.84 (0.50)	2.11 (0.70)	BDL
Total Fecal Coliforms	3.79 (0.36)	3.09 (0.29)	1.01 (0.23)	BDL
Total Enterococci	5.73 (0.41)	4.84 (0.28)	2.67 (0.55)	BDL
E. coli present	+	+	+	-

Anaerobic Lagoon Conversion into Aerobic Pond

We monitored water quality of all three lagoons on the same farm starting one year before treatment operation started in Unit 1. During 2002, the lagoons stored and treated the liquid manure from six houses each (Barns 1-6, 7-12, and 13-18) with similar number of pigs and production management (Figure 11). Concentrations of nitrogen, COD, BOD, volatile solids, and electrical conductivity in 2002 were similar among lagoons (Table 8). Total nitrogen concentration in the three lagoons fluctuated yearly from a high at the end of winter of about 700 mg/L to a low at the end of summer of about 350 mg/L. Ammonia-N followed the same pattern and varied from about 600 to 300 mg/L, respectively (Figure 12).

Figure 11. Aerial photo shows Farm Unit 1 (front), Unit 2, and Unit 3 (back).

Table 8: Changes in water quality in Goshen Ridge lagoons.

Year	Lagoon	pH	TKN mg/L	NH_4-N mg/L	NO_3-N mg/L	COD g/L	VSS mg/L	BOD_5 mg/L	EC mS/cm
2002 (Jan-Dec)	Unit 1*	8.0	505	464	0	1.7	192	207	7.7
	Unit 2	8.0	521	467	0	1.7	225	170	7.2
	Unit 3	8.0	517	469	0	1.7	225	196	7.3
2003 (Jan-Dec)	Unit 1	8.0	230	186	4	0.9	136	131	4.9
	Unit 2	7.9	522	447	0	1.5	215	214	7.0
	Unit 3	7.9	439	375	0	1.4	245	222	6.1
2004 (Jan-Feb)	Unit 1	8.0	45	23	34	0.3	50	16	3.4
	Unit 2	7.9	440	411	0	1.5	189	237	6.4
	Unit 3	7.9	530	462	0	2.0	255	571	6.4

*Unit 1 (Barns 1-6): Lagoon received flushed manure during 2002 and liquid from treatment plant after December 2002. Units 2 and 3 (Barns 7-12 and 13-18): Lagoons received flushed manure during 2002 to 2004. The three units maintained similar number of pigs and production management. Data are averages of duplicate samples collected monthly.

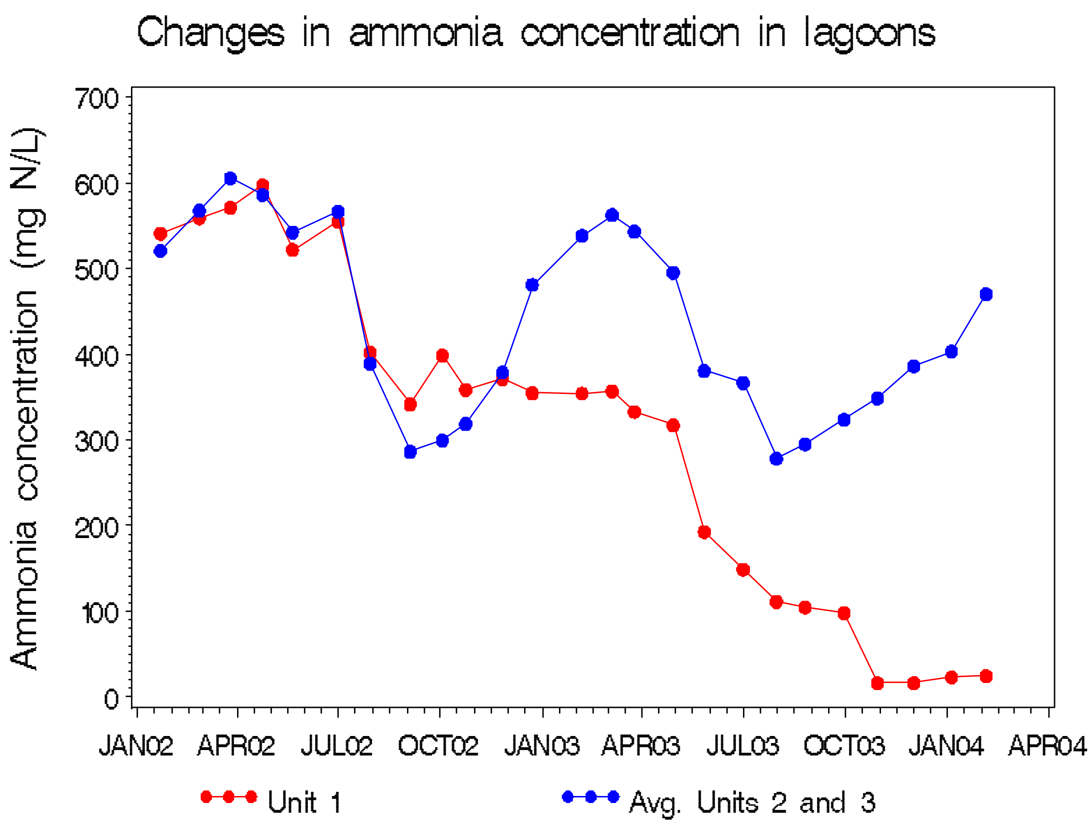

Figure 12: Changes in ammonia nitrogen concentration with time in Goshen Ridge lagoons. Unit 1 (Barns 1-6): Lagoon received flushed manure during 2002 and liquid from treatment plant after December 2002. Units 2 and 3 (Barns 7-12 and 13-18): Lagoons received flushed manure in 2002, 2003, and 2004.

Significant differences in water quality characteristics among lagoons were observed starting in 2003 after manure flush to lagoon #1 was halted and 100% of the manure generated was processed through the treatment plant. The quality of the liquid in lagoon #1 was rapidly improved during 2003 as cleaned effluent replaced dirty liquid (Table 8). Ammonia concentration stabilized at a low value of about 20 mg/L in Nov. 2003 (Figure 12). Average data for the first two months of 2004 show significant improvements in a variety of water quality parameters; reductions in concentrations were 96% BOD, 83% COD, 95% ammonia, 91% TKN, and 47% electrical conductivity.

Lagoon #1 color changed from brown to blue in summer 2003; the lagoon was converted into an aerobic pond by fall 2003. Dissolved oxygen (DO) concentration was monitored in fall 2003 and winter 2004 (Oct 2003-Mar 2004, n=5); it averaged 3.41 mg/L in lagoon #1, 0.51 mg/L in lagoon #2, and 0.57 mg/L in lagoon #3.

CONCLUSIONS

Major goals in the demonstration and verification of the new wastewater treatment system for swine manure were achieved including replacement of anaerobic lagoon treatment, and consistent treatment performance, with varying solid and nutrient loads typical in animal production. The system greatly increased the efficiency of liquid-solid separation by polymer injection to increase solids flocculation. Nitrogen management to reduce ammonia emissions was accomplished by passing the liquid through a module where bacteria transformed ammonia into harmless nitrogen gas. Subsequent alkaline treatment of the wastewater in a phosphorus module precipitated phosphorus and killed pathogens.

The system was tested during one year in a 4,400-head finishing farm as part of the Agreement between the Attorney General of North Carolina and Smithfield Foods/Premium Standard Farms to replace current anaerobic lagoons with environmentally superior technology. It was verified that the technology was technically and operationally feasible. Based on performance results obtained, it was determined that the treatment system met the Agreement's technical performance standards that define an Environmentally Superior Technology. This project was considered an important milestone in the search of alternative treatment technologies, and justified moving ahead with innovation and evaluation of lower cost, next-generation systems.

ACKNOWLEDMENTS

This research was part of USDA-ARS National Program 206: Manure and Byproducts Utilization; CRIS Project 6657-13630-001-00D "Improved animal manure treatment methods for enhanced water quality." Technology verification was partially funded by North Carolina State University and its sponsor Smithfield Foods, Inc. through USDA Agreement 58-6657-2-202, NCSU Subcontract #2001-0478-02. The authors are grateful to Dr. Mike Williams, NCSU Animal & Poultry Waste Management Center, and to the scientists, engineers, and personnel from technology providers Super Soil Systems USA, Selco MC of Spain, and Hitachi Plant Engineering & Construction Co. of Japan for their contribution to the success of this project.

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