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Development of environmentally superior treatment system to replace anaerobic swine lagoons in the USA

Matias B. Vanotti [a,*], Ariel A. Szogi [a], Patrick G. Hunt [a], Patricia D. Millner [b], Frank J. Humenik [c]

[a] United States Department of Agriculture, ARS, Coastal Plains Research Center, 2611 W. Lucas Street, Florence, SC 29501, USA
[b] United States Department of Agriculture, ARS, Sustainable Agricultural Systems Laboratory and Environmental Microbial Safety Laboratory, 10300 Baltimore Avenue, Building 001, Rom 140, Beltsville, MD 20705, USA
[c] North Carolina State University, College of Agriculture and Life Sciences, Animal Waste Management Programs, Box 7927, Raleigh, NC 27695, USA

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Abstract

A full-scale treatment system for 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 swine houses and for crop irrigation. The system was tested during one year in a 4400-head finishing farm as part of the Agreement between the Attorney General of North Carolina and swine producers Smithfield Foods, Premium Standard Farms and Frontline Farmers to replace traditional waste treatment anaerobic lagoons with environmentally superior technology. The on-farm system removed 97.6% of the suspended solids, 99.7% of BOD, 98.5% of TKN, 98.7% of soluble ammonia (NH_4^+–N), 95.0% 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. Based on performance obtained, it was determined that the treatment system met the Agreement's technical performance standards that define an environmentally superior technology. These findings overall showed that cleaner alternative technologies are technically and operationally feasible and that they can have significant positive impacts on the environment and the livestock industry.

Keywords: Manure treatment; Pathogen inactivation; Nitrification–denitrification; Phosphorus and ammonia removal; Confined swine production; Piggery

1. Introduction

Minimizing livestock manure's impact on the environment is one of USA agriculture's major challenges. When properly managed, manure can be used to provide nutrients to crops and to improve soil properties through accretion of soil organic matter. However, improperly managed manure can pose a threat to soil, water, and air quality in addition to human and animal health. Anaerobic lagoons are widely used to treat and store liquid manure from confined swine production facilities (Barker, 1996). Environmental and health concerns with the lagoon technology include emissions of ammonia (Aneja et al., 2000; Szogi et al., 2005), odors (Loughrin et al., 2006; Schiffman et al., 2001), pathogens (Sobsey et al., 2001; Vanotti et al., 2005a), and water quality deterioration (Mallin, 2000). Thus, there is a major interest in developing alternative swine manure treatment systems that can also address these environmental and health problems.

* Corresponding author. Tel.: +1 843 669 5203x108; fax: +1 843 669 6970.
E-mail address: vanotti@florence.ars.usda.gov (M.B. Vanotti).

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Widespread objection to the use of anaerobic lagoons for swine manure treatment in North Carolina prompted a state government-industry framework to give preference to alternative technologies that directly eliminate anaerobic lagoons as a method of treatment. The full-scale treatment demonstration described in this paper was conducted within this framework. 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 on 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 USA. 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 (Williams, 2001):

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. Subsequently, the selected technologies completed design, permitting, construction, startup, and performance verification under steady-state operational conditions. In July 2005, five of the 18 technologies tested were shown to be capable of meeting the environmental performance criteria necessary for the technologies to be considered environmentally superior (Williams, 2004, 2005). Four of the five technologies selected treated separated manure solids using composting, high-solids anaerobic digestion, or gasification processes, and only one of the technologies selected treated the entire swine waste stream on-farm. This on-farm technology used liquid–solid separation, nitrification/denitrification, and soluble phosphorus removal processes linked together into a practical system. It was developed to replace anaerobic lagoon technology commonly used in the USA to treat swine waste (Vanotti et al., 2005b).

In this new manure treatment system, solids and liquid are first separated with polyacrylamide (PAM) polymer and filtration process, followed by treatment of the liquid stream using biological nitrogen (N) removal process, and then by phosphorus (P) extraction using a lime precipitation process. Flocculation treatment using PAM increases separation of suspended solids and carbon compounds from liquid swine manure (Vanotti and Hunt, 1999). Along with the solids, there is a significant separation of organic nutrient elements contained in small suspended particles typical of these wastes. For example, Vanotti et al. (2002) analyzed the fractions in liquid swine manure that are potentially removable by phase separation and found that 80% of the total suspended solids (TSS), 78% of the N and 93% of the P were contained in particles less than 0.3 mm in size. Soluble ammonia (NH_4^+–N) and soluble P (PO_4), which usually constitute 35–65% of total N and 15–30% of total P, are mostly unaffected by polymer separation. Biological removal of N by combined nitrification and denitrification processes (NDN) is regarded as the most efficient and economically feasible method available for removal of N from wastewaters (Focht and Chang, 1975; Tchobanoglous and Burton, 1991; Furukawa et al., 1993). Once NH_4^+–N and carbonate alkalinity concentrations are substantially reduced with nitrification treatment, the subsequent addition of hydrated lime [$Ca(OH)_2$] rapidly increases the pH of the liquid above 9, thereby promoting formation of calcium phosphate precipitate with small amounts of chemical added (Vanotti et al., 2003b).

The treatment system was first pilot tested for two years at the North Carolina State University's Lake Wheeler Road Swine Unit (Vanotti et al., 2003a). A full-scale version of the system was subsequently constructed in a swine farm in North Carolina for demonstration and performance verification of environmentally superior technology. In this paper, we report the water quality improvements by the treatment system operating at full scale. In addition, we report on characteristics of the separated solid fractions, energy balance of the system, and operational considerations. Performance verification was done during a one year period and included cold and warm weather conditions.

2. Methods

2.1. Site description

The full-scale demonstration facility was installed on Goshen Ridge farm (Unit 1) near Mount Olive, Duplin Co., North Carolina, and evaluated intensively during one year under steady-state conditions. The production unit contained six swine barns with 4360-head finishing pigs total, and a traditional anaerobic lagoon (0.9 ha) for treatment and storage of manure. Manure was collected

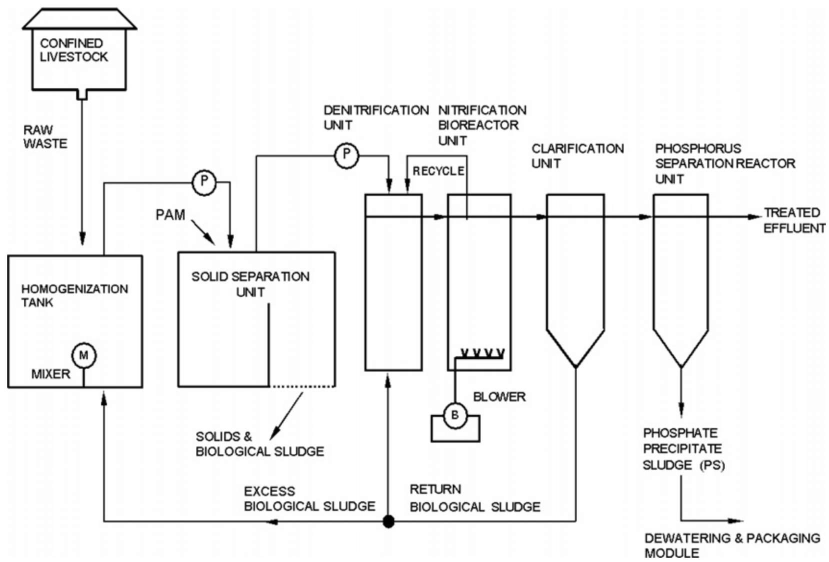

Fig. 1. Schematic drawing of the swine waste treatment system without lagoon.

under the barns using slatted floors and a pit-recharge system typical of many farms in North Carolina (Barker, 1996). The production unit with its traditional lagoon system was operational for about four years before the new waste treatment plant started operation. During traditional management, every week the liquid manure contained in the pits was completely drained by gravity into the anaerobic lagoon. After treatment in the lagoon (retention time = 180 days), the liquid was sprayed onto nearby fields growing small grains and forages. Lagoon liquid was also recycled (in a closed loop) to recharge the pits under the barns and facilitate flushing of the newly accumulated manure.

Once the treatment plant was operational, flow of raw manure into the lagoon was discontinued. Barn pits were flushed once a week as it was done before, but liquid manure was diverted into a 388-m^3 homogenization tank. Transfer rate was rather quick using a high capacity pump (1.9 m^3/min). Typically, half of the six barns were emptied on Monday and the other half on Thursday. The manure collected in the homogenization tank was kept well mixed using a submergible mixer (3.5 kW, 12.1 m^3/min flow, ABS Pumps Inc., Meriden, CT[1]). From there, the liquid manure received continuous treatment. The treatment system consisted of three process units in series: polymer-enhanced solid–liquid separation, biological N removal, and alkaline phosphorus extraction (Fig. 1).

2.2. On-farm treatment system

The treatment system used was a system without lagoon (Vanotti et al., 2005b, Fig. 1) comprised of (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 (Fig. 2).

The on-farm system was constructed and operated by a private firm, Super Soil Systems USA of Clinton, North Carolina. It was implemented using three process units or modules (Fig. 3). The first process unit in the system – the Ecopurin solid–liquid separation module, developed by the Spain-based firm Selco MC of Castellon – quickly separated solids and liquid using polymer flocculation and dewatering equipment. The solid–liquid separation module was housed in a building of its own. It was automated through the use of a programmable logic controller (PLC) for a 24-h/day operation (Square D, Schneider Electric, North Andover, MA). Treatment parameters such as polymer rate, wastewater flow, and mixing intensity were set by the operator using a tactile screen in a control panel. Well mixed raw manure was continuously pumped from the homogenization tank to the separation module. Flow rate was uniform at 2 m^3/h during the year-long demonstration. The liquid manure was first reacted in a mixing chamber with a polymer solution (cationic polyacrylamide) that flocculated the suspended solids, and then it was passed through a rotating screen (0.2 mm opening size) that separated the flocs. Subsequently, a dissolved air flotation unit (DAF) polished the liquid effluent while a small belt filter press (Monobelt, Teknofanghi S.R.L., Italy) further dewatered the screened solids. The solid–liquid

[1] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the US Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

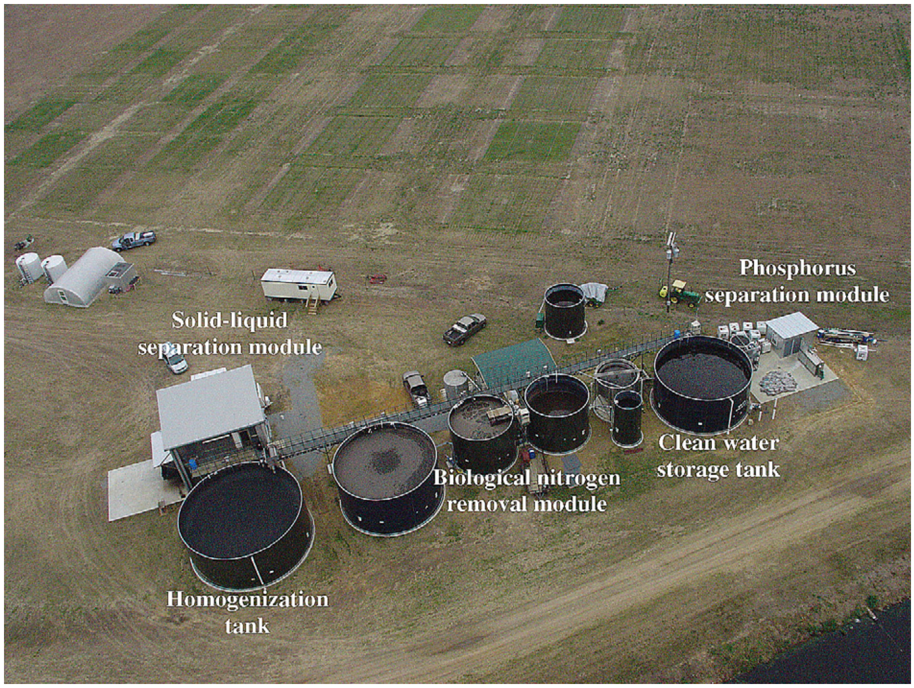

Fig. 2. Aerial view of the full-scale swine wastewater treatment system that replaced the anaerobic lagoon.

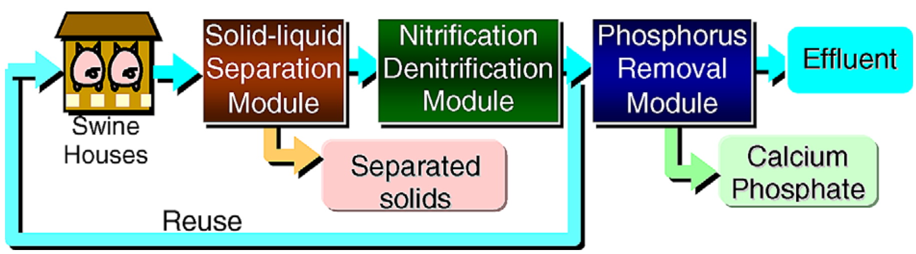

Fig. 3. Diagram of the swine manure treatment system with individual modules implemented at Goshen Ridge farm, North Carolina.

separation module produced a solids stream and a liquid stream. The solids were removed daily from the farm and transported in trailers to a centralized solids processing plant where they received aerobic composting. The liquid was lifted into the nitrogen removal module.

The second process unit in the system used a Biogreen nitrogen removal module (Hitachi Plant Engineering & Construction Co., Tokyo, Japan) that used nitrification/denitrification (NDN) to biologically convert NH_4^+–N into N_2 gas. The Biogreen process has a pre-denitrification configuration where nitrified wastewater is continuously recycled to an anoxic denitrification tank (Fig. 1). In this tank, suspended denitrifying bacteria uses soluble manure carbon contained in the liquid after separation to remove the nitrate and nitrite. The nitrification tank uses nitrifying bacteria immobilized in polymer gel pellets to increase the concentration and effectiveness of bacterial biomass (Vanotti and Hunt, 2000). Nitrifying 3-mm bio-cube pellets are kept inside the nitrification tank by means of a wedge-wire screen structure (1.5 mm opening). The full-scale Biogreen unit contained a 263-m^3 anoxic denitrification tank to remove soluble manure carbon and nitrate-N (NO_3–N), a 110-m^3 nitrification tank for conversion of NH_4^+ to NO_3^-, and a 33-m^3 tank for settling and recycling of suspended biomass solids to the denitrification tank or wasting excess biomass to the separation module (Fig. 1). The height of the liquid in these tanks was 4 m. The denitrification tank contained a submergible mixer (1.7 kW, 9.8 m^3/min flow, ABS Pumps Inc., Meriden, CT) and a concentration of 3–6 g/l mixed liquor suspended solids (MLSS). The nitrification tank contained 125 fine-bubble air diffusers (22.9-cm diameter) and 12 m^3 of polyethylene glycol (PEG) immobilized pellets. Air was provided with a 11.2 kW, rotary lobe blower (Kaeser Omega DB 165, Kaeser Compressors, Fredericksburg, VA). Nitrification activity of the pellets after 5 weeks of initial acclimation was 850 g N/100 l pellets/day. Corresponding nitrification activity of the 110-m^3 reactor tank (containing 12-m^3 of pellet media) was 102 kg N/day, or 0.93 kg N/m^3 reactor/day. Hydraulic retention time (HRT) of nitrification varied from 2.6 to 3.6 days (average = 2.8 day). Nitrified liquid and settled sludge were recirculated to the first denitrification tank at a rate average of 4.4 and 1.8 times the inflow rate, respectively.

After biological N treatment, the effluent was discharged into a 299-m^3 tank that stored water needed to recharge pits under the barns after barns were flushed. Excess water flowed by gravity from this storage tank into the phosphorus separation module developed by USDA-ARS (Vanotti et al., 2003b). This was the third and final process unit in the system. It was designed to recover soluble P (as calcium phosphate) and destroy pathogens by alkaline pH. In this module, liquid was first mixed with hydrated lime slurry in a reaction chamber. The lime slurry was a 30% $Ca(OH)_2$ suspension supplied in standard tote containers and ready to use (Chemical Lime Company, Charlotte, NC). A pH probe and controller linked to the lime injection pump kept the process pH at 10.5–11.0. The liquid and precipitate were subsequently separated in a 9-m^3 settling tank. The precipitated calcium phosphate was removed from the bottom of the tank with a pump and it was further dewatered using a 12-filter bag Draimad unit that also bagged the sludge (Teknobag-Draimad, Aero-Mod, Inc., Manhattan, KS). Anionic polymer was added in-line to the P precipitate to enhance separation by filter bags (Szogi et al., 2006). Bags containing the wet calcium phosphate were left to dry on a drying concrete pad and removed from the farm on a monthly basis. Process automation was provided by sensors integrated to another PLC for 24-h/day operation. Treatment parameters such as process pH or frequency of sludge transfer were set by the operator using a tactile screen located in the plant control panel. Clarified effluent from the P module was stored in the existing lagoon before use in crop irrigation. Cylindrical tanks used in the system were standard structures made of glass-fused to steel (Slurrystore, Engineered Storage Products Company, Dekalb, IL), while settling tanks were custom-made of stainless steel.

2.3. Wastewater sampling and monitoring

Liquid samples were collected twice per week using four refrigerated automated samplers (Sigma 900max, American Sigma, Inc., Medina, NY) placed before and after each of the treatment modules in the system as follows: (1) the untreated liquid manure in the mixing tank before solids separation, (2) the effluent from the solid–liquid separation treatment (post-separation), (3) the effluent after the nitrification–denitrification treatment (post-N removal), and (4) the effluent after the phosphorus and pathogen elimination treatment (post-P removal). Each sample was the composite of four sub-samples taken over a 3.5-day period. Samples were transported on ice to the ARS Coastal Plains Research Center in Florence, SC, for water quality analyses, or overnight shipped with cold packs to the ARS Sustainable Agricultural Systems Laboratory and Environmental Microbial Safety Laboratory in Beltsville, MD, for microbiological analyses.

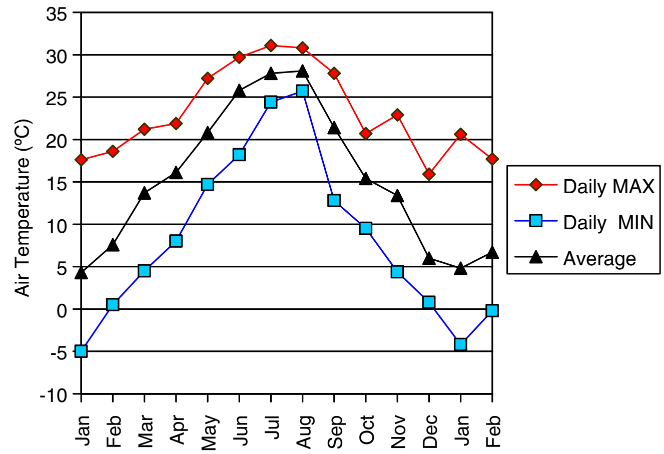

Fig. 4. Air temperature during January 2003–February 2004. Data are max and min of average daily temperatures and monthly average of average daily temperatures.

Wastewater flows throughout the system were measured with several calibrated flowmeters adapted to the characteristics of the liquid: raw manure transported from the barns into the homogenization tank was measured with a doppler flowmeter, liquid and sludge flows in the N and P modules were measured with magnetic flowmeters, and treated effluent was measured with a paddle-wheel flowmeter. Monitoring and process data were obtained every 5 min using a SCADA network (Monitor Pro v7, Schneider Automation, Inc., North Andover, MA) connected to the programmable logic controller (PLC) that provided plant automation. The data were temporarily stored in an industrial computer (IPC-6806, Advantech Co., Cincinnati, OH) at the farm and transmitted weekly to the Florence laboratory for analysis and summarization using SAS software (SAS, 2003).

To calculate electrical power use, we measured run-time (hours/day) of all electrical devices (35) installed in the plant that contributed to the power consumption by the system. This was done with the SCADA monitoring system that counted total hours of use during a 275-day period (April 2003–January 2004). Average run-time was multiplied by power use of each electrical device (kW) to calculate daily power requirements (kW h/day).

Performance evaluation included cold and warm weather conditions with average daily air temperatures ranging from −4.2 to 31.1 °C (Fig. 4).

2.4. Analytical methods

Wastewater analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, AWWA and WEF, 1998). Total solids (TS), total suspended solids (TSS), and volatile suspended solids (VSS) were determined with Standard Method 2540 B, D, and E, respectively. Total solids are the solids remaining after evaporation of a sample to constant weight at 105 °C and include TSS and dissolved solids (DS). Total suspended solids are the solids retained on a 1.5-μm glass microfiber filter (Whatman grade 934-AH, Whatman, Inc., Clifton, NJ) after filtration and drying to constant weight at 105 °C, while VSS is the fraction of the TSS lost on ignition in a muffle furnace at 500 °C for 15 min.

Chemical analyses consisted of pH, electrical conductivity (EC), chemical oxygen demand (COD), soluble COD, 5-d biochemical oxygen demand (BOD_5), soluble BOD_5, ammonia (NH_4^+–N), nitrate plus nitrite ($NO_3^- + NO_2^-$), total Kjeldahl N (TKN), orthophosphate-P (PO_4), total P (TP), copper (Cu), and zinc (Zn). For COD, we used the closed reflux, colorimetric method (Standard Method 5220 D). The orthophosphate (PO_4–P or soluble P) fraction was determined by the automated ascorbic acid method (Standard Method 4500-P F) after filtration through a 0.45-μm membrane filter (Gelman type Supor-450, Pall Corp., Ann Arbor, MI). The same filtrate was used to measure NH_4–N by the automated phenate method (Standard Method 4500-NH_3 G), and $NO_3^- + NO_2^-$ by the automated cadmium reduction method (Standard Method 4500-NO_3^- F). Total P and TKN were determined using acid digestion (Gallaher et al., 1976) and the automated ascorbic acid and phenate methods adapted to digested extracts (Technicon Instruments Corp., 1977). The organic P fraction is the difference between total P and PO_4 analyses and includes condensed and organically bound phosphates. The organic N fraction is the difference between Kjeldahl N and NH_4^+–N determinations. Alkalinity was determined by acid titration to the bromocresol green endpoint (pH = 4.5) and expressed as mg $CaCO_3$/l. Cu and Zn were measured in acid digestion extracts using inductively coupled plasma (ICP) analysis (Standard Method 3125A).

Solids samples were analyzed for moisture content using a microwave moisture analyzer. Dry solids samples were digested with concentrated acid, and the extracts were analyzed for TKN and TP with the automated methods described before. Carbon content was determined using a dry combustion analyzer.

Reduction in odor was characterized by measuring concentration of six odor compounds characteristic of swine manure (phenol, *p*-cresol, *p*-ethylphenol, *p*-propylphenol, indole, and skatole) directly in the liquid using gas chromatography and the method of Loughrin et al. (2006). Microbiological analyses of liquid samples were done using the standard protocols for pathogens and indicator microbes for the examination of wastewater (Vanotti et al., 2005a).

3. Results and discussion

3.1. Livestock and manure inventory

Pig inventory, live weight, and manure production data are summarized in Table 1. New batches of pigs were received January–February 2003, June–July 2003, November–December 2003, and March 2004. The pigs did not receive antibiotics, and the meat was marketed with a different label indicating this change. Total live animal weight (LAW) in the production unit averaged 237,000 kg but varied greatly within a growing cycle from a low of about 90,000 to 150,000 kg to a high of about 350,000 to 365,000 kg.

Manure production varied from 30.7 to 43.2 m^3 per day (Flushed manure, Table 1). Volume production was generally higher in warmer months. The system treated an average of 39 m^3 per day of raw manure flushed from the barns (Table 2). On the average, the flushed manure contained 33% recycled treated water (used to refill and flush the pits) and 67% manure and wasted water (urine, feces, water wasted by pigs). The manure and wasted water production (raw flushed manure – effluent recycled to barns, Table 2), which constitutes the newly generated manure, averaged 26.3 m^3 per day or 110 l/1000 kg LAW/day. This is consistent with expected table values of 101 l/1000 kg LAW/day (1.62 ft^3/1000 lb/day or 6.2 l/pig/day) for manure and wasted water production in feeder-to-finish operations in the USA (average pig weight = 135 lb or 61.2 kg) (Chastain et al., 1999). On the other hand, the total amount of flushed manure treated by the plant (manure/wasted water plus recycled water) was much lower than what is considered typical in feeder-to-finish operations in the USA. For example, the average 39 m^3 per day of raw manure flushed from the barns (Table 2) was equivalent to 165 l/1000 kg LAW/day. This is 2.6 times lower than the volume of 424 l/1000 kg LAW/day (6.80 ft^3/1000 lb/day or 25.9 l/pig/day) considered typical for pit-recharge systems in the USA (Chastain et al., 1999). This lower volume was obtained by a change in pit management incorporated with the new system that reduced the amount of recycle liquid into the barns to a minimum needed for effective

Table 1
Inventory of pigs and manure volume generation at Goshen Ridge farm (Unit 1) during demonstration of the new wastewater treatment system

Pigs and manure information	March	April	May	June	July	August	September	October	November	December	January
Number of pigs	3978	3975	3441	978	2787	4115	4015	3749	2831	4120	3814
Weight/pig (kg)	51.7	79.4	101.6	84.4	20.9	48.1	75.8	98.0	65.8	45.4	85.7
Total weight (Mg)	206	316	347	122	87	198	304	365	149	186	326
Flushed manure (m^3/day)[a]	30.7	32.6	36.3	36.0	43.2	45.0	55.3	48.1	33.3	36.0	34.1
Pit recharge (m^3/day)[b]	–	19.3	17.8	17.8	16.7	7.9	8.7	15.1	6.8	10.6	8.7

[a] Flushed manure is the average daily volume received in the homogenization tank.
[b] Pit recharge is the average daily volume treated liquid recycled from the clean water storage tank to the barns.

Table 2
Wastewater flows through the swine wastewater treatment system

Flow path	Total volume[a] (m^3)	Average flow rate (m^3/day)
Raw flushed manure to homogenization tank	12,050	39.0
Separated effluent to nitrogen module	12,070	39.1
N-treated effluent recycled to refill barns	3934	12.7
N-treated effluent to phosphorus module	8179	26.5
P-treated effluent to storage pond (former lagoon)	7975	25.8

[a] Monitoring values for period April 15, 2003, to March 1, 2004 (10.5 months).

cleanup of the barn pit. In turn, this change in management resulted in a lower volume (38%) of total flushed manure compared with management in traditional lagoon systems, which increased efficiency in terms of equipment (tanks, pumps, pipes, mixers), footprint, etc.

3.2. Water quality improvement by 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 on-farm system removed 97.6% of TSS, 98.9% of VSS, 97.4% of COD, 99.7% of BOD, 98.5% of TKN, 98.7% of NH_4^+–N, 95.0% of TP, 94.1% of soluble P, 98.7% of Cu, and 99.0% of Zn (Table 3).

Data in Table 3 and Fig. 5 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 early in the process, most of the volatile and oxygen-demanding organic compounds were removed from the liquid stream. This early removal of suspended solids in the treatment train is a significant departure from wastewater treatment processes typically used in municipal systems because (1) it recovers the organic carbon and nutrient compounds contained in liquid manure, therefore enabling conservation and generation of organic value-added products, and (2) instead of breaking down organic compounds, the oxygen in subsequent biological aerobic treatment is used efficiently to convert NH_4^+–N. This is particularly important in animal treatment systems because as shown in Table 3, the effluent after solid–liquid separation contained significant amounts of N (953 mg/l), mostly soluble forms (NH_4^+). The NH_4^+–N was treated effectively in the biological N removal module. This module also consumed remaining carbon (BOD, COD) during denitrification, and alkalinity during nitrification. Soluble P contained in the liquid was not significantly changed by either liquid–solid separation or N treatment, but it was reduced significantly after treatment in the P-module (Table 3), and recovered as a solid calcium phosphate material.

Table 3
Removal of suspended solids, COD, BOD, nutrients, and heavy metals by on-farm wastewater treatment system at Goshen Ridge farm, North Carolina[a]

Water quality parameter	Raw liquid swine manure, mg/l (±s.d.)	After solid–liquid separation treatment, mg/l (±s.d.)	After biological N treatment, mg/l (±s.d.)	After phosphorus treatment, mg/l (±s.d.)	Removal efficiency with system (%)
TSS	11,051 (5914)	823 (637)	122 (68)	264 (154)	97.6
VSS	8035 (5016)	591 (456)	77 (54)	85 (50)	98.9
TS[b]	13,216 (5394)	4452 (1475)	3710 (694)	3339 (586)	74.7
COD	16,138 (8997)	3570 (2104)	617 (192)	445 (178)	97.4
Soluble COD	3129 (2017)	2289 (1499)	525 (164)	393 (166)	87.4
BOD_5	3132 (2430)	1078 (1041)	33 (25)	10 (16)	99.7
Soluble BOD_5	909 (935)	624 (656)	9 (16)	7 (8)	99.2
TKN	1584 (566)	953 (305)	34 (30)	23 (24)	98.5
NH_4^+–N	872 (329)	835 (292)	23 (34)	11 (19)	98.7
Organic N	712 (325)	111 (96)	12 (11)	11 (12)	98.5
Oxidized N[c]	1 (3)	1 (3)	224 (100)	224 (105)	–
Total N[d]	1584	954	258	247	89.4
Total P	576 (224)	174 (53)	147 (30)	29 (16)	95.0
Soluble P	135 (40)	121 (33)	134 (24)	8 (7)	94.1
Organic P	440 (197)	49 (41)	13 (19)	19 (16)	95.7
Copper	26.8 (12.2)	1.54 (1.82)	0.53 (0.28)	0.36 (0.26)	98.7
Zinc	26.3 (11.9)	1.47 (1.85)	0.40 (0.28)	0.25 (0.30)	99.0
Alkalinity	5065 (1791)	4345 (1555)	529 (323)	735 (263)	85.5
pH	7.60 (0.19)	7.91 (0.15)	7.24 (0.74)	10.49 (0.57)	–
EC (mS/cm)	10.44 (3.09)	10.39 (2.87)	5.13 (0.79)	4.86 (0.87)	–

[a] Values are mean (standard deviation) for 121 sampling dates (April 15, 2003–March 1, 2004).
[b] Total solids (TS) = Total suspended solids (TSS) + Dissolved solids.
[c] Oxidized-N = NO_3–N + NO_2–N (nitrate plus nitrite).
[d] 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 2).

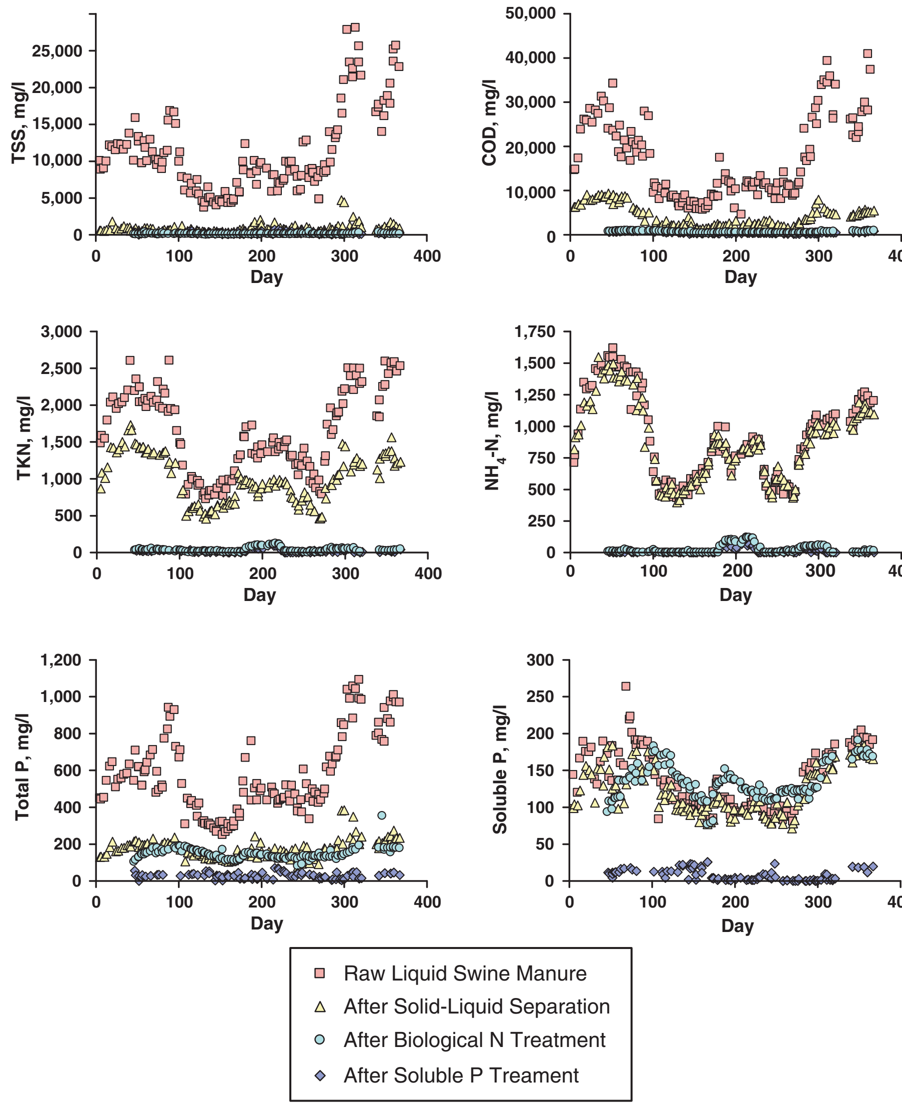

Fig. 5. Water quality improvements (TSS, COD, TKN, NH_4^+–N, TP and soluble P) in the on-farm wastewater treatment system at Goshen Ridge farm, North Carolina, as liquid swine manure passes through solid–liquid separation, biological N removal, and soluble P removal modules. Data show performance verification at steady-state conditions from March 1, 2003 (day = 1) to March 1, 2004 (day = 367).

The treatment system was also effective in reducing odor-generating compounds and pathogen indicator microorganisms contained in the liquid (Table 4). 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 each treatment step on odor reduction. The largest odor reduction

Table 4
Removal of odor compounds and pathogen indicator microorganisms by on-farm wastewater treatment system at Goshen Ridge farm, North Carolina

	Raw liquid swine manure	After solid–liquid separation treatment	After biological N treatment	After phosphorus treatment	Removal efficiency with system (%)
Odor compounds, ng/ml (±s.e.)[a]	206.78 (52.62)	181.69 (77.98)	4.61 (2.00)	4.29 (2.44)	97.6
Total fecal coliforms, $\log_{10}$/ml (±s.e.)[b]	3.74 (0.36)	3.09 (0.29)	1.01 (0.23)	BDL	>99.9

[a] Values are means (standard error) of five determinations (September–October 2003). Odor compounds are the sum of concentrations of six malodorous compounds contained in the liquid (phenol, *p*-cresol, *p*-ethylphenol, *p*-propylphenol, indole, and skatole) that are characteristic of swine manure.
[b] Values are means (standard error) of $\log_{10}$ colony forming units (cfu) per ml for duplicate samples of four determinations (July–December, 2003). BDL = below detectable limit, indicates there were no colonies to count.

was observed after the liquid passed through aeration in the nitrogen treatment. Overall, the treatment system eliminated 97.9% of the odor compounds. Microbiological analyses showed a consistent trend in reduction of fecal coliforms as a result of each step in the treatment system. It confirmed pilot studies (Vanotti et al., 2005a) that the phosphorus removal step via alkaline calcium precipitation produces a sanitized effluent.

3.3. Solid–liquid separation module

Efficiency of solid–liquid separation using polymer flocculation was consistently high with an average of 93% TSS separation. This high-separation efficiency was obtained with liquid manure TSS concentrations that varied from about 4000 mg/l to 28,000 mg/l (Fig. 5). Application rate of PAM varied from 106 to 178 g/m^3 (average = 136 g/m^3) corresponding to the changes in wastewater strength. The solids separation module also removed 93% of the volatile suspended solids, 78% of COD, 40% of TKN, 94% of zinc and copper, and 70% of TP from the wastewater (Table 3). As mentioned before, this reduction of organic compounds such as COD is an important system consideration for the efficiency of subsequent nitrification treatment. Soluble NH_4^+ and P concentrations changed little (4.2% and 10.4% reduction, respectively) with solids separation treatment. In contrast, organic N and P were effectively captured in the solids, resulting in average concentration reductions of 84.4% and 88.9%, respectively.

A total of 748 m^3 of solids were separated and left the farm in a 10.5-month period. This amount of manure weighed 596,200 kg and contained 18.2% (±1.3%) solids (81.8% moisture), 40,805 kg of carbon, 5379 kg of N, 3805 kg of P, 280 kg of Cu, and 281 kg of Zn. The separated solid waste was composted in a centralized solids processing facility and converted into organic plant fertilizer, soil amendments, and plant growth media (Vanotti, 2005).

3.4. Biological N removal module

Ammonia (NH_4^+–N) removal efficiencies of the Biogreen process were consistently high (average = 97%, Table 3). These high process efficiencies were obtained with influent NH_4^+–N concentrations varying from about 400 to 1500 mg/l (Fig. 5) and loading rates varying from about 18 to 45 kg N/day (average = 32 kg/day). After solids separation, most of the TKN was made of NH_4^+–N; therefore, removal efficiencies for TKN were also high (96%). Influent TKN concentration varied from 460 to 1730 mg/l, and loading rates varied from 20 to 50 kg N/day (average = 37 kg/day). Nitrogen loading rates into the N removal module fluctuated greatly (150%) within production cycles. These N loading fluctuations were well correlated ($r = 0.83$) with changes in total pig weight in the barns [N load (kg TKN/day) = 17.4 + 0.0820 live weight (Mg)]. The biological N removal process responded well to these highly changing N loading conditions as well as cold temperatures experienced during evaluation. Water temperatures during cold weather (December 2003–February 2004) were 11.9–13.0 °C for the monthly averages and >4.2 °C for the daily average. Corresponding air temperatures were 4.8–6.7 °C for monthly averages and >−4.2 °C for the daily average (Fig. 4).

Due to additional denitrification in the pits under the barns, a mass balance was required to understand system removal of total N. Mass balance utilized nutrient concentration (Table 3) as well as corresponding water flows (Table 2). Oxidized N contained in the recycled water was reduced from 224 mg/l to 1 mg/l after 7-day retention in the pits under the barns. We calculated that an additional 870 kg of oxidized N was removed by denitrification in this closed loop during the 10.5-month period summarized in Tables 2 and 3. The amounts of total N (TKN + oxidized N) contained in the flushed manure and the treated effluent were 19,100 kg and 2020 kg, respectively. Thus, total N removal on a mass basis ($TN_{in} - TN_{out}$) was 89.4%. A significant amount of N was further removed by denitrification in the former lagoon that stored the final effluent produced by the treatment plant. For example, oxidized N in the system effluent was reduced from 241 to 11 mg/l after storage in the former lagoon (average June 2003–May 2004), with lower final concentration (average 2 mg/l) during warmer months and higher final concentration (average 20 mg/l) during coldest months, thus indicating a biological process. This additional N removal by denitrification in the former lagoon increased total N removal efficiency of the system from 89.4% to 97.9%. Thus, when the new treatment system is retrofitted into a typical North Carolina facility and the old lagoon is used for water storage, removal of N by de-nitrification during final storage is an important consideration for total N removal design of the entire system.

The biological N removal system generated very little amount of waste sludge. This is because most of the organic compounds were separated by the liquid–solids separation before NDN treatment. 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. Biological sludge was wasted every day by diverting <1 m^3 of the return sludge from the settling tank into the homogenization tank for dewatering in the solid–liquid separation module (Fig. 1). A total 24.54 m^3 of sludge was wasted per month with an average TSS concentration of 6346 mg/l that contributed 145 kg of dry solids per month to the separated manure solids (93% separation efficiency). Thus, the waste sludge from NDN process contributed only 1.4% to the total amount of separated waste (596,200 kg containing 18.2% solids in 10.5 months, Section 3.3).

3.5. Soluble phosphorus separation module

Removal efficiencies of the soluble phosphate using the P-removal module averaged 94% for wastewater containing 77–191 mg/l PO_4–P (Table 3). The process is based on the distinct chemical equilibrium between phosphorus and calcium ions when natural buffers are substantially eliminated (Vanotti et al., 2003b). It was discovered that reduction of carbonate and ammonium buffers during nitrification substantially reduces the $Ca(OH)_2$ demand needed for optimum P precipitation and removal at high pH (Vanotti et al., 2005b). For example, the biological N removal step eliminated 97% of the NH_4^+–N and substantially reduced bicarbonate alkalinity (from 4345 to 529 mg/l) which, in turn, affected the succeeding P separation step by promoting formation of calcium phosphate with smaller amounts of lime added. The average lime consumption to reach the set point pH of 10.5 was 567 g/m^3.

The high pH (10.5) in the phosphorus removal process is necessary to produce calcium phosphate and kill pathogens (Vanotti et al., 2005a). 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 effluent using 2 l/min aeration in bench studies reduced the pH from 10.5 to <9 in about 2 h (Vanotti et al., 2003a). However, natural aeration during storage may be equally effective to lower pH.

A total of 285 bags of calcium phosphate product containing 526 kg of P was produced and left the farm during a 9-month period. The concentration grade was $24.4 \pm 4.5\%$ 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.

3.6. Electrical power use

Data in Table 5 show the electrical power use by each process unit and the entire system in both kW h/day (first column) and kW h/m^3 to compare with other processes. A total of 404 kW h/day was needed to operate the treatment system on the 4360-pig farm. The separation portion of the treatment consumed 37% of the total power used by the system; 36% of this (54.17 kW h/day) was used to mix manure in the homogenization tank, while the remainder (94.6 kW h/day) was used to operate the separation equipment (pumps, polymer mixer, rotating screen, DAF, and filter press). The biological N removal module consumed 57% of the total power (230.27 kW h/day); 59% of this (136.62 kW h/day) was used to power the air blower, and the remainder was consumed by mixers and pumps. The phosphorus separation module consumed <6% of the total power, and <1% was used to flush the barns and recycle the water to the barns.

Table 5
Electrical power use by the wastewater treatment system

Unit process	Power consumption per process unit and system (kW h/day)	Power consumption per m^3 of wastewater treated[a] (kW h/m^3)
Barn flush (lift station) and recycle to barns	2.60	0.050
Homogenization tank	54.17	1.389
Solids separation	94.60	2.426
Biological N treatment	230.27	5.889
Phosphorus treatment	22.30	0.842
Total system	403.94	10.357

[a] Volumes treated are shown in Table 2. Total system calculation uses total raw flushed manure volume (30 m^3/day).

3.7. Operator requirements

A manual of operation and maintenance was developed as part of the demonstration. The system requires an operator with a high-school education. The operator needs to receive 2 weeks training by the company that includes detailed information on plant equipment, operation and maintenance, safety and health aspects, identification and reporting of malfunction, and simple troubleshooting. Our observations indicate that a trained operator can safely operate two farms within a 20-mile radius, each farm providing treatment to 4500–9000 pigs. In addition to the plant operator, successful operation of the technology also requires support from an engineer technician having a 2–4-year engineer technology degree and mechanical/electrical skills. This person can provide support to about 10 farms so that each plant is visited about twice a month to work on specialized maintenance issues such as system checks, software, electronics, or parts replacement.

4. Conclusions

Treatment technologies are needed that can replace lagoons, capture nutrients, reduce emissions of ammonia and nuisance odors, kill harmful pathogens, and generate value-added products from manure. A system of swine wastewater treatment technologies was developed to accomplish all of these tasks. The system was tested at full scale in a 4400-head finishing farm as part of an Agreement between the Attorney General of North Carolina and swine producers Smithfield Foods and Premium Standard Farms to replace current anaerobic lagoons with Environmentally Superior Technology.

Major goals in the demonstration and verification of a new wastewater treatment system for swine manure were achieved including replacement of anaerobic lagoon treatment and consistent treatment performance under cold and warm weather conditions, with varying solid and nutrient loads typical in animal production. The on-farm system greatly increased the efficiency of liquid–solid separation by polymer injection to increase solids flocculation. Nitrogen management to reduce NH_3 emissions was accomplished by passing the liquid through a module where bacteria transformed NH_4^+ into harmless nitrogen gas. Subsequent alkaline treatment of the wastewater in a P module precipitated P and produced a disinfected liquid effluent.

It was verified that the treatment system 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 (Williams, 2004). These findings overall showed that cleaner alternative technologies can have significant positive impacts on the environment and the livestock industry. This project was considered an important milestone in the search of alternative treatment technologies in the USA and justified moving ahead with innovation and evaluation of second-generation systems.

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