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Development of a second-generation environmentally superior technology for treatment of swine manure in the USA

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A B S T R A C T

New swine waste management systems in North Carolina need to meet high performance standards of an environmentally superior technology (EST) regarding nitrogen, phosphorus, heavy metals, pathogens, ammonia and odor emissions, and remain affordable and simple to operate. The objective of this study was to develop a second-generation treatment system that can achieve high EST standards at reduced costs. The system used solids separation, nitrification/denitrification and phosphorus removal/disinfection, and was demonstrated at full-scale on a 5145-head swine farm during three production cycles (15-months). Removal efficiencies were: 98% suspended solids, 97% ammonia, 95% phosphorus, 99% copper and zinc, 99.9% odors, and 99.99% pathogens. The system met EST standards at 1/3 the cost of the previous version. Animal health and productivity were enhanced; hog sales increased 32,900 kg/cycle (5.6%). These results demonstrated that: (1) significant cost reductions were achieved by on-farm implementation and continued engineering improvements, and (2) the new waste management system substantially benefited livestock productivity.

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1. Introduction

Disposal of animal wastes from concentrated animal agriculture poses serious challenges. Currently, implemented technologies for animal waste management have drawbacks including: the odor, pathogens and air pollution; the acreage needed for disposal; and the potential water contamination due to rainfall and flooding (Mallin, 2000; Szogi and Vanotti, 2003). In the USA, anaerobic lagoons are widely used to treat and store liquid manure from confined swine production facilities (Barker, 1996a; RTI, 2003). Environmental and health concerns with the lagoon technology include emissions of ammonia (Aneja et al., 2000; Szogi et al., 2006), odors (Schiffman et al., 2001; Loughrin et al., 2006), pathogens (Sobsey et al., 2001; Vanotti et al., 2005a), and water quality deterioration (Mallin, 2000). Thus, there is interest in technologies that could replace anaerobic lagoons with more environmentally sustainable systems.

In July 2000, a government–industry–university framework was initiated in North Carolina to address these issues (Williams, 2007). This framework established an agreement between the state Attorney General and swine industry to develop and demonstrate environmentally superior waste management technologies (EST). An EST needs to be technically, operationally and economically feasible, and be able to meet the following environmental performance standards: (1) eliminates the discharge of animal waste to surface waters and groundwater through direct discharge, seepage, or runoff; (2) substantially eliminates atmospheric emissions of ammonia; (3) substantially eliminates the emission of odor that is detectable beyond the boundaries of the parcel or tract of land on which the swine farm is located; (4) substantially eliminates the release of disease-transmitting vectors and airborne pathogens; and (5) substantially eliminates nutrient and heavy metal contamination of soil and groundwater (Williams, 2009).

In March 2006, five of the 18 technologies tested under this agreement were shown to be capable of meeting the environmental performance criteria necessary for the technologies to be considered EST (Williams, 2009). Four of the selected technologies processed dewatered manure solids in centralized facilities using composting, high-solids anaerobic digestion, or gasification processes, and produced a variety of products such as class A composts, organic fertilizers, and energy. The other selected technology was a solids separation/nitrification–denitrification/soluble phosphorus removal system ("Super Soils" technology) that treated the liquid waste stream on-farm.

Since the on-farm treatment system satisfied all five environmental standard requirements for EST, and significant cost reduction improvements were identified, a second-generation version of the technology was subsequently designed, implemented, and demonstrated at a full-scale on another finishing farm in North

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Carolina during 2006–2008. In addition to meeting the technological standards of the first generation of this technology, the second generation was designed to reduce capital, maintenance, and operational expenses.

In this paper, we report on the changes incorporated in the second-generation system to reduce overall cost of the technology, the environmental performance obtained (water quality, odor, and pathogens), and discuss how each component of the system contributed towards meeting EST standards. In addition, we report on characteristics of the separated solid fraction, energy use, operational considerations, and livestock productivity and economic benefits of the technology. Performance verification was done at a full-scale under steady-state conditions in a 5145-head swine farm during a 15-month period and included cold and warm weather conditions and three cycles of pig production.

2. On-farm multistage wastewater treatment system

The 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 the anaerobic swine lagoon technology commonly used in the USA to treat swine waste (Vanotti et al., 2005b, 2007b; Vanotti and Szogi, 2008).

2.1. First-generation system: meeting of EST standards

The first-generation version of the technology was first pilot tested for two years at the North Carolina State University's Lake Wheeler Rd. Swine Unit (Vanotti et al., 2003a). Subsequently, the same system was scaled-up (125:1) for performance verification of EST. It was installed and demonstrated at full-scale for two years on Goshen Ridge farm, a 4360-head swine finishing operation in Duplin County, NC (Vanotti et al., 2007b; Vanotti and Szogi, 2008). The system removed from the wastewater 97.6% of the suspended solids, 99.7% of BOD, 98.5% of TKN, 98.7% of ammonia ($NH_4^+ - N$), 95.0% of total P, 98.7% of copper, 99.0% of zinc, and 98% of malodorous aromatic compounds (Vanotti et al., 2007b). It also reduced 96.9% of greenhouse gas (GHG) emissions (Vanotti et al., 2008), and produced a sanitized effluent with reduction in the number of pathogenic bacteria to non-detectable levels (Vanotti et al., 2005a). In addition, the system transformed the old lagoon into an aerobic reservoir within a year, that significantly effected lagoon odor (Loughrin et al., 2006), and eliminated 90% ammonia emissions from lagoon cleanup (Szogi et al., 2006). The separated solids were transported off-site to a centralized composting facility for processing into value added products (Vanotti et al., 2006a).

3. Methods

3.1. Development of second-generation system to improve cost and reliability

The second-generation system was designed and developed with the primary objective to reduce its costs (capital and operating costs) while maintaining its capability to meet the EST environmental standards previously documented. The changes were based on three factors: (1) experiences gained during full-scale demonstration of the first-generation system (Vanotti et al., 2007b); (2) a quantitative definition of the metrics or target environmental performance standards of an EST (Williams, 2009); and (3) the incorporation of new science out of the research pipeline (Vanotti et al., 2007a). While volume and strength values based on the old technology served well to design a highly effective first-generation treatment system, the new information obtained after demonstration of the technology at full-scale indicated that more economical treatment systems were feasible.

The most important changes incorporated into the second-generation system to lower costs and improve its reliability were (for detailed list, see Vanotti and Szogi, 2007):

1. Compared to the previous system installed at Goshen Ridge farm, a separated liquid tank was added in the new system between the solid–liquid separation and the biological N removal (NDN) unit (Fig. 1). The tank had same capacity as the homogenization tank and stored all the separated water generated during a week. This allowed high rate solid–liquid separation processing while providing the constant flow required by NDN.
2. The solid–liquid separation operation was reduced from a 24/7 continuous operation to a two-day per week operation using a high-capacity separator (flow rate increased from 33.3 L/min to 151.4 ± 7.6 L/min). A coarse rotary screen to remove hair was eliminated, and the lift station was reduced in size (from 1892 L/min to 946 L/min) to reflect the lower flushed volumes with new system. The separator used polymer injection, mixing, flocculation, and dewatering as before, but the dewatering portion was simplified with replacement of three mechanical devices (rotating screen, dissolved air flotation, and belt filter press) with one single device (rotary press) to accomplish the same task. The rotary press produced separated solids with higher solids content (solids increased from 18% to 25%) that improved handling and composting and made transport of the material more economical.
3. The biological N treatment (NDN) was simplified with the elimination of two tanks (a post-denitrification tank that injected methanol and an oxic tank) and with the replacement of immobilized nitrifiers with suspended nitrifiers. Tests done at full-scale during demonstration of the first-generation system showed a better performance with a pre-denitrification configuration that relied only on endogenous carbon for denitrification and that a three-tank configuration without methanol injection (Fig. 1) was better than a five-tank configuration with methanol injection. The new system used a new, high-performance nitrifying sludge that was well adapted to both high-ammonia wastewater and cold temperatures, which provided a lower cost alternative to the effective fluidized nitrification pellet technology previously used.
4. The phosphorus separation process was greatly simplified with the simultaneous separation of the P sludge and swine manure solids (Fig. 1). It incorporates the finding that simultaneous separation of two contrasting sludges using polymers is technically feasible. The combined separation process is more efficient in terms of polymer use, equipment and labor needs compared with a situation before in which two dewatering units were used to separate the same amount of solids (Garcia et al., 2007). The new system also used a larger settling tank (to accumulate P sludge for one week) and manual weekly removal (2-min) compared to the more complicated first-generation version that used a smaller tank and PLC automation to remove the P sludge several times per day. Thus, implementation of these changes not only reduced installation and operational cost of the overall treatment system but also improved its reliability.

3.2. Second-generation treatment system description

The second-generation treatment system was a system without lagoon (Vanotti et al., 2007a). It consisted of three process units: solid–liquid separation, biological nitrogen treatment, and wastewater disinfection/phosphorus removal (Fig. 1). The system was

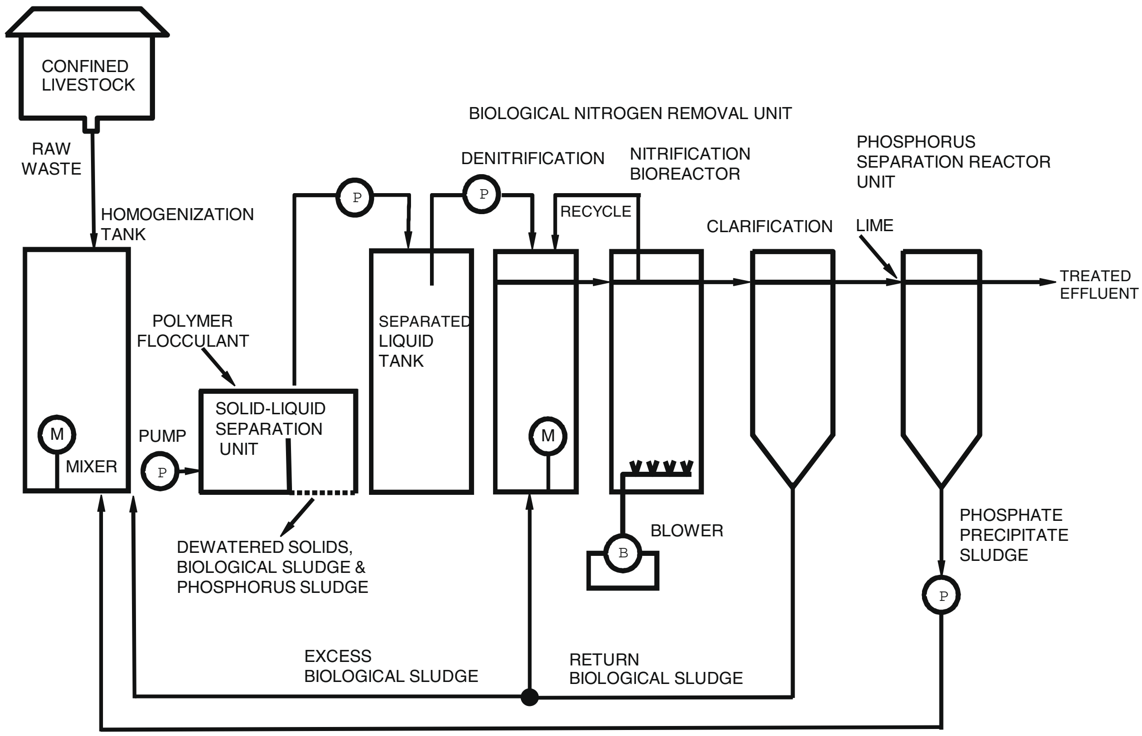

Fig. 1. Schematic drawing of the second-generation swine waste treatment system without lagoon using solids separation, nitrification–denitrification, and soluble phosphorus removal/disinfection.

constructed and operated by Super Soil Systems USA of Clinton, North Carolina.

For the first process unit, subfloor wastewater was emptied weekly by gravity into a receiving pit and lifted 4.5 m by a 0.95 m^3 min^{-1} pump into a 379 m^3 capacity homogenization tank. In this tank, the manure was kept well mixed using a 3.5 kW, 12.1 m^3 min^{-1} submersible mixer (ABS Pumps Inc., Meridien, CT). The homogenized wastewater stream proceeded to the liquid–solid separation unit. The separation process used polyacrylamide (PAM) flocculation to enhance the separation of fine suspended particles (Vanotti and Hunt, 1999; Garcia et al., 2007). Solids were separated with a rotary press separator (Cote et al., 2007). The separator (model 2-1200/3000A, Fournier Industries Inc., Quebec, Canada) had two polymer preparation tanks of 2.1 m^3 capacity, a polymer metering pump, manure feed pump, an in-line flocculator, and a dual channel, 1.20 m rotary press with a 10-HP (7.5-W) motor. The rotary press filtered the separated liquid through a 250 μm wedge-wire screen; the dewatering area inside the press was 3.0 m^2. It used internal pressure sensors and a restriction zone consisting of a vertical restrictor and actuator to control cake dryness and production. Magnetic flowmeters were used to control the mixing rate of polymer and wastewater. The prepared PAM solution contained 2.14 g polymer per L (0.2%) and was mixed with the wastewater at a rate of 6%. This resulted in a final polymer dosage of 128 mg L^{-1}. Process flow rate during the evaluation averaged 9.1 m^3 h^{-1}. Separated manure cake was transported offsite to a solids processing facility and composted (Vanotti et al., 2006a). The separated wastewater was pumped and stored into another tank identical to the homogenization tank (379 m^3) and then treated continuously in a nitrogen removal unit.

The N removal unit used nitrification/denitrification (NDN) to biologically convert $NH_4^+ - N$ into N_2 gas. Nitrification was performed in an aeration tank (227 m^3) that used high-performance nitrifying bacteria adapted to high strength wastewater and cold temperatures. Air was supplied continuously with a 10-HP positive displacement lobe blower (Sutorbilt, Gardner Denver, Quincy, IL) and 98 fine-air diffusers (Airflex, SSI, Poughkeepsie, NY). Nitrification converted NH_4-N into NO_2-N and NO_3-N. A pre-denitrification configuration transformed NO_3 into N_2 gas where the nitrified wastewater was continually recycled into a 277 m^3 anoxic denitrification tank (DN) (Fig. 1). In this tank, suspended denitrifying bacteria used soluble manure carbon in the liquid after separation to remove the $NO_2^- + NO_3^-$. The denitrification tank contained a submersible mixer (1.7 kW, 9.8 m^3 min^{-1} flow, ABS Pumps Inc., Meridien, CT). A settling tank (14.3 m^2) was used to clarify the effluent and return the suspended biomass solids to the DN tank (or wasting excess biomass to the separation module) (Fig. 1). The height of the liquid in these tanks was 4 m. The rates of sludge and nitrified liquid recycling into the DN tank were 3.5 and 0.5 times the inflow rate, respectively. Flow rates were adjusted with manual valves once per week based on manure volume generation rates using 12 L calibrated buckets and a stopwatch. Doppler flowmeters were also installed but they were less reliable than the bucket calibration. The concentration of mixed liquor suspended solids (MLSS) was maintained at 2–4 g L^{-1}. The operator used a settling test (15 min, 1 L) to estimate MLSS in both denitrification and nitrification tanks based on an empirical relationship obtained during first four months of operation: [solids vol. (ml/L) = −66.7 + 0.1132 MLSS (mg/L); r^2 = 0.759]. The clarified effluent was stored in a 277 m^3 clean water tank and re-used as needed to recharge barn pits after they were flushed. Excess water flowed by gravity from this storage tank into the third and last stage.

In the third stage, P was precipitated as a calcium phosphate solid (Vanotti et al., 2003b), and pathogens were reduced by the alkaline environment (Vanotti et al., 2005a). The effluent was mixed with hydrated lime slurry [12% $Ca(OH)_2$] in a 0.3 m^3 reaction chamber. The pH of the process was maintained at 9.5–9.7 by a pH probe and controller (Model 53, GLI Int., Milwaukee, WI) linked to the lime injection pump. Lime consumption was 1.18 kg m^{-3}. The P precipitate was separated in a settling tank (8.8 m^2), further dewatered using the solids separation unit in the first unit of the system (Garcia et al., 2007), and combined with the manure solids for off-farm transport. Clarified effluent from the P module was stored in the existing lagoon before use in crop irrigation. All cindrical tanks were standard structures made of glass fused to steel, while settling tanks were custom-made of stainless steel.

3.3. Site description

The second gen full-scale demonstration facility was installed on B&B Tyndall farm near Clinton, Sampson Co., NC and evaluated under steady-state conditions during a 15-month period that included three swine production cycles. The farm contained seven swine barns with a permitted capacity of 5145 head.

During the previous three growing cycles (2005–2006), the farm produced an average of 584,000 kg total live weight (487,000 kg net gain) in each growing cycle (5296 pigs/cycle). Manure was collected under the barns using slatted floors and a pit-recharge system typical of many swine farms in North Carolina (Barker, 1996b). The traditional system had two anaerobic lagoons of 0.58 ha each for treatment and storage of the manure flushed from the barns. After treatment in the lagoon (retention time = 180 days), the liquid was sprayed onto nearby fields growing small grains and forages. Under this traditional management, lagoon liquid was recycled (in a closed loop) into the barns to recharge the pits under the slotted floor and facilitate flushing of the newly accumulated manure.

Once the treatment plant was operational (December 2006), flow of raw manure into the lagoon was discontinued. The liquid manure was diverted into a homogenization tank and treated with the new system without lagoon. During the evaluation of the second-generation system, new batches of pigs were received December 12–27, 2006, May 14–31, 2007, and September 28–October 27, 2007; which were completed and sent to market about 130 days later. A total of 5148 pigs and 598,970 kg live weight (503,950 kg gain) were produced in the first production cycle using the new system; 5197 pigs and 609,740 kg live weight (510,128 kg gain) were produced in the second production cycle; and 5396 pigs and 642,060 kg live weight (528,460 kg gain) were produced in the third cycle.

3.4. 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 three treatment processes in the system as follows: (1) the untreated liquid manure in the mixing tank before solid–liquid separation, (2) after solid–liquid separation treatment, (3) after biological N treatment, and (4) from the final effluent after P treatment. 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, and the ARS Animal Waste Management Research Unit in Bowling Green, KY, for odor analyses.

Wastewater flows throughout the system were measured with five liquid-level ultrasonic probes and data logger (SR50 Sonic Ranging Sensor and CR800 data logger, Campbell Scientific Inc., Logan, UT). The liquid-level probes were placed on top of the homogenization tank, separated water tank, clean water tank, and settling tanks. Actual volume dynamics were calculated using recorded measurements of liquid height and area of the tanks. This allowed precise calculations of manure flush volumes, separation activity and flow, feed rate into N system, clean water recycle, and sludge wasting. We also monitored air and water temperatures, precipitation, DO, ORP, and process pH that were connected to the data logger. Process data and sampler information were retrieved daily from the Florence, SC, laboratory for analysis and summarization using SAS software.

To calculate electrical power use, we measured run-time (hours/day) of all electrical devices installed in the plant that contributed to the power consumption by the system. Average run-time was multiplied by power use of each electrical device (kW) to calculate daily power requirements (kWh/day).

3.5. Analytical methods

All water quality analyses were performed as described by Vanotti and Szogi (2008) using standard methods (APHA, AWWA, and WEF 1998). Water quality analyses consisted of total solids (TS), total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), soluble COD, 5-d biochemical oxygen demand (BOD_5), soluble BOD_5, ammonia ($NH_4^+ - N$), nitrate plus nitrite ($NO_3^- + NO_2^- - N$), total Kjeldahl N (TKN), organic N, orthophosphate-P (PO_4), total P (TP), organic P, copper (Cu), zinc (Zn), pH, alkalinity, and electrical conductivity (EC).

The separated solids were analyzed according to Szogi and Vanotti (2007). Reduction in odor was characterized by measuring in the liquid the concentration of five odor compounds characteristic of swine manure (phenol, *p*-cresol, *p*-ethylphenol, indole, and skatole) as described by Loughrin et al. (in press). 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).

4. Results and discussion

4.1. Livestock production cycles and wastewater loadings during system evaluation

Monthly average total pig weight in the seven barns varied greatly within production cycles from a low of 74.0 tonnes (metric) to a high of 519.3 tonnes; the amount of manure that went through the treatment system varied accordingly, from 12.8 $m^3\ d^{-1}$ (396 $m^3\ mo^{-1}$) to 56.3 $m^3\ d^{-1}$ (1745 $m^3\ mo^{-1}$) (Fig. 2), and so did the total nitrogen and phosphorus loads, varying from 20.9 to 97.1 kg TKN d^{-1} (average = 58.3 kg d^{-1}) and from 5.1 to 21.5 kg TP d^{-1} (average = 14.5 kg d^{-1}). Peak monthly TKN and TP loads were consistent among pig production cycles: TKN loads were 92.1 kg d^{-1} in April 2007, 88.4 kg d^{-1} in August 2007, and

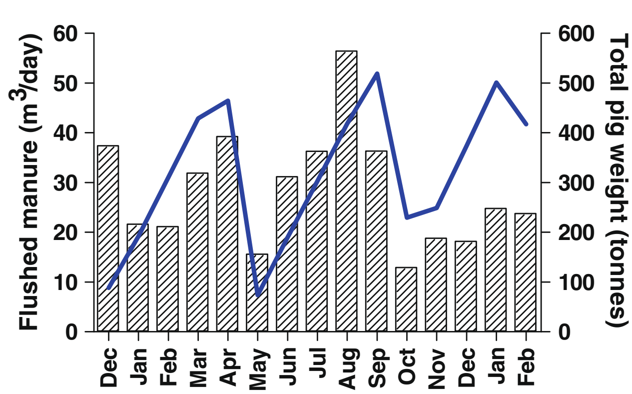

Fig. 2. Changes in monthly total live weight of the pigs during three production cycles (line) and average daily flushed manure volume collected from seven barns into the homogenization tank (bars) at Tyndall farm during demonstration of the wastewater treatment system (December 2006–February 2008).

97.1 kg d^{-1} in January 2008; corresponding TP loads were 20.5, 21.5, and 21.5 kg d^{-1}. The average live animal weight (LAW) in the seven barns during the 3-cycle evaluation period (December 9, 2006–February 29, 2008) was 320.5 tonnes (706,670 lbs), a value that is also referred to as steady-state live weight (SSLW). A total of 12,600 m^3 (3.3 million gallons) of flushed manure was processed by the treatment system during the same period, or an average of 28.1 m^3 d^{-1} (Table 1). On average, flushed manure contained 19.7% recycle effluent from the treatment system (used to refill the pits) and 80.3% newly generated manure, urine, and water wasted by pigs. The recycled volume used to refill and flush each barn was approximately 14 m^3. Without considering the recycled liquid, the liquid manure stream averaged 23.0 m^3 day^{-1} or 90 L per 1000 kg live animal weight (LAW) per day (net manure, Table 1). This is similar to the industry average of 101 L per 1000 kg LAW per day in feeder to finish operations in the USA (1.62 ft^3/1000 lb/day or 6.2 L/pig/day, average pig weight = 135 lb) (Chastain et al., 1999). Manure generation was higher during the warmer months. For instance, it averaged 109 per 1000 kg LAW per day in May–September and 50 L per 1000 kg LAW per day in October–April.

4.2. Reduction in water volumes

The total amount of flushed manure treated by the plant (manure/wasted water plus recycled water) was much lower than lagoon management. For example, the average 28.1 m^3 per day of raw manure flushed from the barns (Table 1) was equivalent to 116 L/1000 kg LAW/day. This is 3.7 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) for lagoon technology using pit-recharge systems in the USA (Chastain et al., 1999). This lower volume was obtained by reducing the amount of liquid recycle into the barns to a minimum needed for effective cleanup of the barn pit. In turn, the reduced volume to be treated in the new system increased equipment efficiency (reduced size of treatment tanks, pipes, pumps, mixers) and increased polymer use efficiency due to the higher strength waste (Vanotti et al., 2002). In addition, the lower volume provided extra storage capacity for raw manure in the pits under the barns. For example, the effective volume capacity in the seven barn pits was 610 m^3 (87 m^3 per barn) while the pit volume needed for storing raw manure (plus recharge liquid) using a weekly flushing schedule with the new system was only 197 m^3 (28.1 m^3/day × 7-days, Table 1). Thus, the 413 m^3 unused pit volume added about 18-days extra storage capacity (22.6 m^3/day, Table 1) to the minimum manure collection storage needed for the 7-day flushing cycle. This is desirable in case the system becomes inoperable for a short time, as in the case of electric power outages during hurricanes in North Carolina. We also found that using lower volumes of a clean liquid to recharge the pits under the barns reduced the ammonia concentration in the barn's air and increased animal productivity compared with the previous lagoon management situation that used large amounts of lagoon liquid with high ammonia for the same task (Szogi and Vanotti, 2008).

One of the important lessons learned through implementation and testing at real scale of the new technology is that the use of engineering table values obtained from the old technology (lagoon) to design new alternative treatment technologies (without lagoon) will invariably result in oversized, costly system designs. Thus, when actual testing data (volume, solids, peak nutrient loads, etc.) from alternative systems are available, their use will significantly improve design, engineering calculations, and cost of the next generation treatment systems, and provide better assessment to industry and society on what is needed to change.

4.3. Water quality improvement by second-generation treatment system

Treatment performance obtained during full-scale demonstration is presented in Table 2, which shows the values of various water quality indicators as the liquid passed through each treatment module and the overall system efficiency. The on-farm system lowered concentration of constituents in the wastewater effluent as follow: 97.1% of TSS, 98.3% of VSS, 89.9% of VS, 96.2% of COD, 99.4% of BOD_5, 95.9% of TKN, 96.6% of NH_4-N, 88.1% of TN, 92.9% of TP, 99.2% of Cu, 98.9% of Zn, 77.5% of alkalinity, and 56.6% of EC. These high treatment efficiencies were obtained during a 15-month period with average daily air temperatures ranging from −2.5 to 31.1 °C and large variations in the strength of the manure (Fig. 3). The results are also consistent with the efficiencies obtained with the more expensive first-generation treatment system (Vanotti et al., 2007b).

Removal efficiencies by the treatment system were also determined using a mass approach (Table 3). This mass approach utilized the element concentration as well as water flows throughout the plant and also water reuse in the barns. Total mass values were the sum of monthly calculations (December 2006 through February 2008). During three cycles of pig production, the treatment system removed 241 tonnes (t) of total solids (TS), 192.5 t of volatile solids (VS), 22.2 t of total N, and 6.0 t of total P (Table 3). System removal efficiencies obtained on a mass basis were: 97.7% of TSS, 98.7 of VSS, 91.6% of VS, 96.7% of COD, 99.6% of BOD_5, 96.3% of TKN, 97.0% of NH_4-N, 87.7% of TN, 95.2% of TP, 99.5% of Cu, and 99.1.9% of Zn (Table 3), which are similar to the concentration basis efficiencies (Table 2).

Data in Table 2 show the key contributions of each component of the technology towards the total efficiency of the system. Solid–liquid separation with polymers was effective in separating suspended solids, oxygen-demanding organic compounds, and organic nutrients and heavy metals by capturing the suspended particles. This efficient removal of suspended solids early in the treatment train is a significant departure from treatment typically used in municipal wastewater systems because it recovers most of the organic carbon and organic nutrient compounds contained in the liquid manure, therefore enabling conservation and generation of value-added products. It was also significant for economic design of N and P treatment of the liquid. Instead of the oxygen being used to break down organic compounds, it was used in the subsequent biological aeration treatment to more efficiently convert NH_4-N to NO_3-N. In addition to NH_4 removal, the NDN module removed most of the carbonate alkalinity during nitrification and most of the soluble carbon (soluble COD, soluble BOD_5) during denitrification. With the removal of soluble C, most of the odor causing compounds disappear (Loughrin et al., in press), and with the removal of the natural buffers NH_4 and carbonate alkalinity,

Table 1
Wastewater flows through the swine wastewater treatment system.

Flow path	Total volume[a] (m^3)	Average flow rate (m^3/day)
Raw flushed manure from barns into homogenization tank	12,595	28.1
Effluent from solid–liquid separation into nitrogen module	12,781	28.5
Treated effluent recycled to flush barns (pit recharge)	2475	5.5
System effluent to storage pond (former lagoon)	10,305	23.0
Net manure produced in the barns[b]	10,119	22.6

[a] Monitoring values for period December 9, 2006–February 29, 2008 (14.7 months).
[b] Net manure generated in the barns = raw flushed manure minus treated effluent recycled to flush barns.

Table 2
Wastewater treatment plant performance and system efficiency at Tyndall farm, North Carolina.

Water quality parameter[a]	Raw liquid swine manure, mg/l[b] (±sd)	After solid–liquid separation treatment, mg/l[b] (±sd)	After biological N treatment, mg/l[b] (±sd)	After phosphorus treatment, mg/l[b] (±sd)	System efficiency[c] (concentration basis) (%)
TSS	11,113 (6194)	1212 (1032)	219 (205)	326 (225)	97.1
VSS	8412 (4917)	858 (768)	147 (127)	144 (110)	98.3
TS[d]	28,888 (12,258)	13,815 (5145)	9520 (2200)	9725 (2449)	66.3
VS	17,117 (8595)	5209 (2959)	1785 (825)	1722 (1096)	89.9
COD	20,666 (13,197)	7885 (5323)	997 (461)	790 (397)	96.2
Soluble COD	7065 (6026)	5798 (4089)	806 (323)	644 (274)	90.9
BOD_5	6820 (6084)	3032 (2694)	52 (50)	38 (47)	99.4
Soluble BOD_5	2499 (2537)	3009 (2373)	16 (14)	15 (12)	99.4
TKN	2007 (769)	1414 (553)	121 (127)	83 (111)	95.9
$NH_4^+ - N$	1251 (616)	1190 (455)	103 (128)	43 (79)	96.6
Organic N	735 (434)	206 (227)	32 (38)	34 (47)	95.4
Oxidized N[e]	1 (5)	0	229 (182)	156 (148)	–
Total N[e]	2008	1414	350	239	88.1
Total P	494 (228)	170 (79)	85 (28)	35 (21)	92.9
Soluble P	86 (49)	79 (37)	73 (28)	18 (16)	79.1
Organic P	396 (267)	58 (55)	11 (12)	12 (14)	97.0
Copper	16.0 (10.9)	2.01 (2.54)	0.17 (0.08)	0.13 (0.07)	99.2
Zinc	24.2 (12.3)	2.91 (2.91)	0.36 (0.46)	0.26 (0.27)	98.9
Alkalinity	6882 (2188)	5372 (1540)	1288 (875)	1547 (815)	77.5
pH	7.85 (0.33)	7.81 (0.22)	7.96 (0.53)	9.71 (0.70)	–
EC (mS/cm)	14.55 (4.28)	13.67 (4.05)	6.86 (1.43)	6.32 (1.42)	56.6
Odor compounds, (ng/ml)[f]	71,269 (14,733)	63,642 (12,366)	40 (17)	44 (11)	99.9
Total fecal coliforms, (log10/ml)[g]	4.11 (0.19)	3.47 (0.16)	0.84 (0.23)	0.17 (0.18)	99.99

[a] Values are mean (±standard deviation) for 107 sampling dates during three pig growth cycles (December 9, 2006–February 29, 2008), except for odor compounds and pathogen indicator determinations.
[b] Units are mg/l except for EC, pH, odors and pathogens.
[c] System efficiency (concentration reduction) = [(Influent Conc.–Effluent Conc.)/Influent Conc.] × 100.
[d] Total solids (TS) = total suspended solids (TSS) + dissolved solids.
[e] Oxidized-N = NO_3-N + NO_2-N (nitrate plus nitrite); total N = TKN + Oxidized-N.
[f] Odor compounds are the sum of concentrations of five malodorous compounds contained in the liquid (phenol, *p*-cresol, *p*-ethylphenol, indole, and skatole) that are characteristic of swine manure. Values are means (±standard error) of 15 monthly determinations (December 2006–February 2008).
[g] Total fecal coliforms values are means (±standard error) of $\log_{10}$ colony forming units (cfu) per ml for duplicate samples of six monthly determinations (January–June 2007).

the subsequent P removal is easier (Vanotti et al., 2003b). The alkaline conditions also destroys the pathogens (Vanotti et al., 2005a), which is an important objective of treatment to meet the high standards of an EST.

4.4. Solid–liquid separation with polymers

The efficiency of solid–liquid separation using polymer flocculation was consistently high, with an average separation efficiency of 89.1% for TSS and 89.8% for VSS (Table 2). This high-separation efficiency was obtained with liquid manure TSS concentrations that varied from about 1000 mg L^{-1} to 30,000 mg L^{-1} (Fig. 3) and VSS concentrations from about 900 mg L^{-1} to 25,000 mg L^{-1}. The solids separation unit was effective at removing compounds associated with the suspended solids in the manure; it removed 70% of the VS, 62% of COD, 72% of organic N, 66% of TP, 87% of zinc, and 88% of copper (Table 2). Total kjeldahl nitrogen was reduced by 30%, while NH_4-N content was mostly unaffected (5%). Soluble P also passed through (8% reduction), reflecting the fact that solid–liquid separation *per se* has little effect on the dissolved fraction. The substantial removal of heavy metals Cu and Zn by solid–liquid separation was also observed in the first-generation system previously evaluated, and it is one of the treatment objectives of EST. These trace elements are used as feed additives to promote growth in pigs and produce metal-enriched manure, which has been linked to contamination of soil around confined animal facilities with risks of becoming toxic to plants and grazing animals (Lopez Alonso et al., 2000; Bolan et al., 2004). Fortunately, both Cu and Zn can be removed effectively from the liquid manure before land application using the polymer-enhanced solid–liquid separation as shown in this study.

4.4.1. Characteristics of the separated solids

The separated solids were transported daily to a centralized solids processing facility (Super Soil Systems USA, Hickory Grove site) located about 6 km from the farm. In this facility, the manure solids were mixed with cotton gin waste, composted and converted into EPA Class A material used for manufacture of organic plant fertilizer, soil amendments, and plant growth media (Vanotti et al., 2006a). The separated solids that left the farm were monitored during the first 6 months of the study (December 9, 2006, to June 2, 2007). During this period, a total of 4750 m^3 of raw manure was separated that produced 90 trailers containing 274 m^3 of solids. This amount of manure weighed 214,580 kg (473,070 lbs.) and contained 24.9% ± 3.1% of solids (75.1 ± 3.1% moisture), 21,984 kg of carbon, 2709 kg of nitrogen, 1663 kg of phosphorus, 60 kg of copper, and 92 kg of zinc. To accomplish this task, the solids separator unit used 610 kg of dry polymer for flocculation of the fine solids and separation enhancement. On a dry basis, the separated solids contained 5.18 ± 0.47% TN, 3.17 ± 0.45% TP, 42.08 ± 2.02% total carbon, 0.82 ± 0.21% K, 2.79 ± 0.94% Ca, 1.40 ± 0.44% Mg, 0.76 ± 0.09% S, 0.12 ± 0.04% Cu, and 0.17% ± 0.06 Zn.

The manure solids separated with the rotary press were drier than the first-generation system previously evaluated that used a rotating screen and filter press, 24.9% solids and 18.2%, respectively. This drier material was more amenable for the composting process. It is also a better situation for its use in energy production using gasification and combustion processes. The energy analyses composition of the separated solids showed that the heat content of separated solids averaged 5106 ± 1446 kJ/kg (2195 ± 622 Btu/lb) on the as-produced basis and 20,290 ± 1065 kJ/kg (8729 ± 458 Btu/lb) on a dry basis. For comparison, the heat content of coal consumed in the USA averages 15,109 kJ/kg (6500 Btu/lb) for

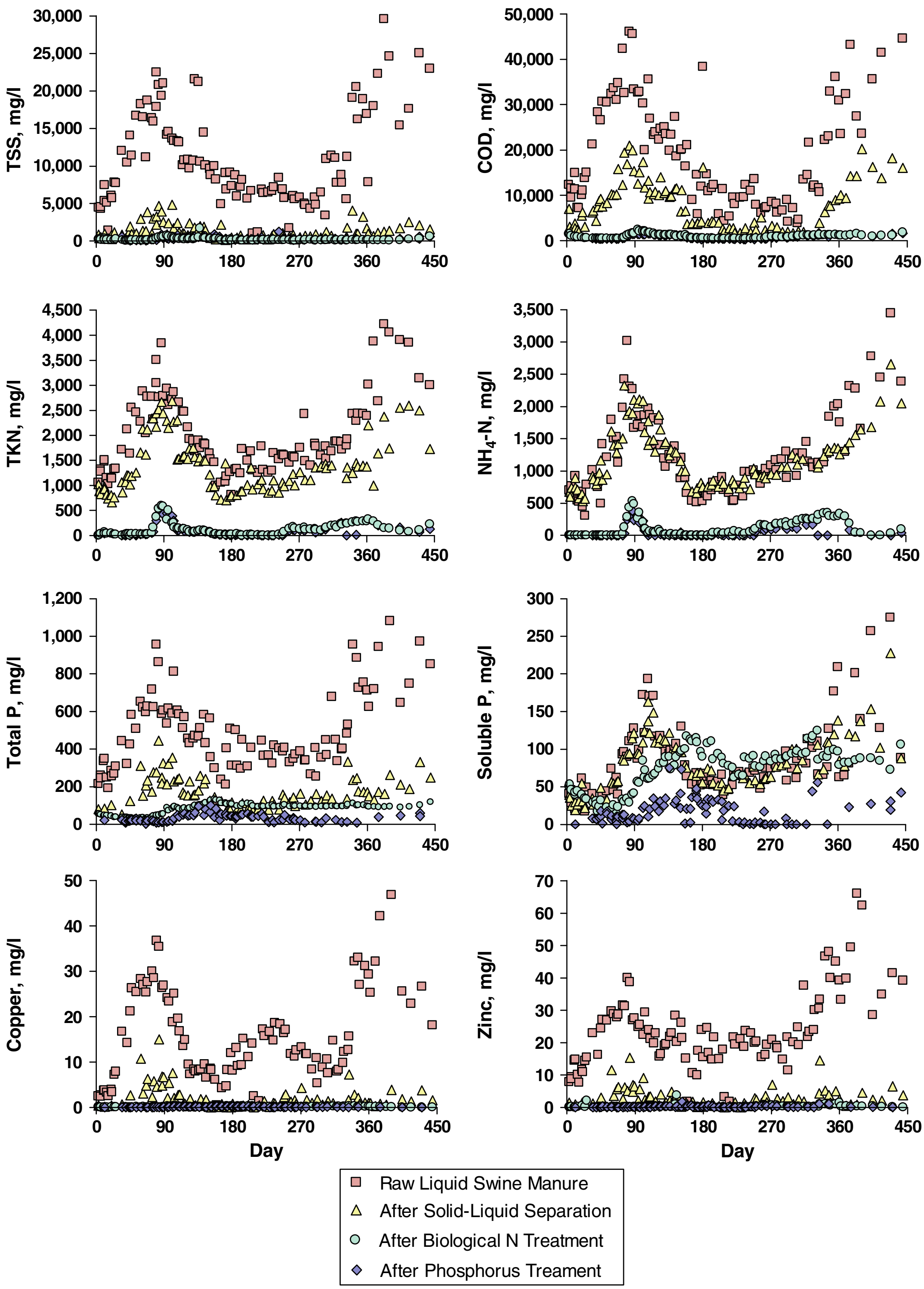

Fig. 3. Water quality improvements (TSS, COD, TKN, NH_4^+-N, TP, Soluble P, Cu and Zn) in the on-farm wastewater treatment system at Tyndall farm, North Carolina, as liquid raw swine manure passes through solid–liquid separation, biological N removal, and soluble P removal processes. Data show performance verification at steady-state conditions during three pig growth cycles from December 9, 2006 (day = 1) to February 29, 2008 (day = 448).

brown coal (lignite), 19,758 kJ/kg (8500 Btu/lb) for sub-bituminous coal, and 27,893 kJ/kg (12,000 Btu/lb) for bituminous.

4.5. Biological nitrogen treatment

The next stage of the treatment system treated the separated liquid waste using an NDN process. After solids separation, the liquid contained significant amounts of N and P, mostly in soluble form (NH_4-N and Soluble P), as well as alkalinity (Table 2). Nitrification was accomplished in an aeration tank that used high-performance nitrifying bacteria adapted to high-strength wastewater, which converted NH_4^+-N into NO_3^- and NO_2^-. The system had a pre-denitrification configuration where the nitrified wastewater was continuously recycled into an anoxic denitrification tank

Table 3
Mass loadings, removals, and system efficiency at Tyndall farm, North Carolina, during three pig growth cycles from December 9, 2006–February 29, 2008 (14.7 months).

Water quality parameter	System load (flushed manure) [*A*] kg	Treated effluent recycled to barns [*B*] kg	System effluent (after phosphorus treatment) [*C*] kg	Total mass removed by system kg	System efficiency[a] (mass basis) (%)
TSS	139,353	560	3251	135,542	97.7
VSS	105,411	384	1396	103,631	98.7
TS	363,701	23,481	99,013	241,208	70.9
VS	214,419	4240	17,679	192,501	91.6
COD	261,780	2467	8667	250,646	96.7
BOD_5	89,784	128	369	89,287	99.6
TKN	26,101	279	945	24,877	96.3
NH_4^+-N	16,513	210	483	15,820	97.0
Total N	26,116	748	3119	22,248	87.7
Total P	6486	196	304	5986	95.2
Copper	209.0	0.4	1.1	207.5	99.5
Zinc	305.5	0.9	2.7	301.9	99.1

[a] System efficiency (mass removal) = $\{1-[C/(A-B)]\} \times 100$.

(Fig. 1). In this tank, suspended denitrifying bacteria transformed the NO_3^- and NO_2^- into dinitrogen gas and consumed most of the soluble carbon remaining in the wastewater after solid–liquid separation. On average, the biological N treatment reduced COD and BOD_5 by 87% and 98%, respectively, with respect to their concentration in wastewater after solid–liquid separation. Ammonia (NH_4^+-N) removal efficiencies were high (average = 91%, Table 2). These high N removal efficiencies were obtained with influent NH_4^+-N concentrations varying from about 530 to 2650 mg L^{-1} (Fig. 3) and monthly loading rates varying from about 13 to 61 kg N day^{-1}. Influent TKN concentration varied from 660 to 2700 mg L^{-1} (Fig. 3), and monthly loading rates varied from 16 to 72 kg N day^{-1}. After solids separation, most of the TKN was in NH_4^+ form. This explains the high removal efficiencies for TKN (91%). The biological N removal process responded well to the highly changing N loading conditions as well as cold temperatures experienced during evaluation. Water temperatures during cold weather (December–February) were 9.4–11.3 °C for the monthly averages and 8.0–9.1 °C for the daily minimum averages. Removal efficiencies by the NDN process during cold weather (December–February, two winters) were 96.0 ± 2.6% for NH_4^+-N and 93.7 ± 1.8% for TKN; which are similar to removals of 94.0 ± 3.0% NH_4^+-N and 96.5% ± 2.1% TKN obtained during the warmest months (June–August).

In order to start the evaluation in winter (December 2006) with a fully functional biological N removal unit, a conditioning phase of the nitrification bacteria was conducted during 40 days (October–November 2006) as soon as the nitrogen tanks, air supply system, and corresponding pump and mixers were installed, while construction of other parts of the system were being completed. The nitrification tank was inoculated with 1 L of acclimated lagoon nitrifying sludge (ALNS) adapted to high-ammonia swine wastewater and low temperatures. The conditioning phase used fill-and-draw batches using lagoon wastewater that was rich in ammonia. At the beginning, batch cycles lasted about 10 days and were progressively shortened, as the nitrification biomass increased, to about 2-day cycles by the end of November 2006 when the N removal unit was brought in-line continuously. The resulting nitrifying biomass concentration was 1280 mg MLSS L^{-1} or 1020 ML SS L^{-1}, with a nitrification activity of 14.44 ± 1.25 mg N/L-reactor/h (20.8 mg N/g MLVSS/h). Considering a nitrification tank volume of 227 m^3, the initial nitrification capacity of the unit was 95.0 kg N/day. The average MLSS and MLVSS in the nitrification tank during the evaluation (December 06–February 08, $n = 53$) were 2450 ± 1680 mg L^{-1} and 1980 ± 1440 mg L^{-1}, respectively.

The N removal unit produced a relatively clean, oxidized, and deodorized effluent with 103 mg L^{-1} of NH_4-N, 229 mg L^{-1} of NO_3-N + NO_2-N, 219 mg L^{-1} of TSS, and 52 mg L^{-1} of BOD_5 (Table 2). This effluent (post-N treatment) was used to refill the pits under the barns and facilitate flushing. It replaced the dirtier lagoon liquid that was used for flushing under the previous lagoon management. As a result of recycling cleaner water to refill barn pits, ammonia concentration in air in the barns was reduced. Szogi and Vanotti (2008) reported that, compared with the previous lagoon system, the new system lowered ammonia concentrations in the barn exhaust air by an average of 75.1%, from 11.3 to 2.8 ppm.

4.6. Phosphorus treatment

Wastewater from biological nitrogen treatment in excess of that needed to recharge the barn pits went to the third process unit where soluble PO_4-P was recovered as calcium phosphate and the liquid was disinfected by the high process pH (Fig. 1). The reaction produced calcium phosphate precipitate, which was separated in a settling tank. The P precipitate was further dewatered using the solid–liquid separation unit in the front of the plant and combined with the manure solids (Garcia et al., 2007). The process is based on the distinct chemical equilibrium between phosphorus and calcium ions when natural buffers are substantially eliminated (Vanotti et al., 2003b). For example, the biological N removal step eliminated >90% of the NH_4^+-N and substantially reduced bicarbonate alkalinity (from 5.4 to 1.3 g L^{-1}) which, in turn, affected the succeeding P separation step by promoting formation of calcium phosphate with smaller amounts of lime added (Vanotti et al., 2003b).

Removal efficiencies of the soluble phosphate using the P-removal unit (process pH 9.5) averaged 75% for wastewater containing 13–125 mg L^{-1} PO_4-P (Table 2, Fig. 3). They are lower than efficiencies of 94% obtained in the previous first generation project using a process pH of 10.5 (Vanotti et al., 2007b). In the second generation project, we lowered process pH to economize lime chemical because a very high level of P treatment was not needed. To meet the EST standard for TP, a 50% reduction was sufficient. This compares with a 66% reduction (77% by mass) removal by the polymer-enhanced solid–liquid separation unit. Thus, the main contribution of the P-removal unit with regards to meeting EST standards was not the phosphorus standard but the pathogen standard (4-log reduction) due to the high pH that, in addition to precipitate calcium phosphate, disinfects the effluent.

4.7. Odor and pathogen reduction by second-generation treatment system

An additional benefit of aerobic biological N treatment was the reduction of malodorous compounds. This was another important environmental standard of the EST. Odor compounds (phenol, *p*-cresol, *p*-ethylphenol, *p*-propylenphenol, indole, and skatole) were measured in the liquid at the successive stages of the treatment system (Table 2). Results showed a 99.9% reduction in the treated effluent compared to the untreated swine manure. As seen in Table 2, most of the odor compounds present in the liquid swine manure remained in the liquid after the solid–liquid separation and were effectively destroyed during the biological N treatment step. Loughrin et al. (in press) indicated that the largest part of reductions in malodorous compounds in this system was due to their utilization by the suspended denitrification bacteria as a soluble carbon source in anaerobic respiration while aerobic respiration in the nitrification is responsible for further reductions.

The treatment system was also very effective in reducing pathogens in liquid swine manure (Table 2). Results showed a consistent trend in reduction of microbial indicators as a result of each step in the treatment system. The largest reduction overall was obtained in the biological N treatment (2.6 log), but it was not enough to meet the EST criteria of 4-log pathogen reduction (99.99%). This level of treatment was reached in the P unit. The reductions in pathogens and microbial indicators in the treated liquid (post P-treatment) relative to that present in the untreated swine manure were: total coliforms = 99.97%, fecal coliforms = 99.99%, enterococci = 99.99%, and Salmonella = 100%. In the previous study (Vanotti et al., 2007b), the P unit was run at pH 10.5 and produced a sanitized effluent with reduction of pathogens to non-detectable levels. Thus, a process pH of 10.5 in the P unit would be recommended to produce a sanitized effluent for situations where total microbial disinfection of effluents is needed, and a process pH of 9.5 would be appropriate for meeting 4-log pathogen reduction standard of an EST.

4.8. Animal health and productivity

Animal health and productivity of the animals benefited from improved environment in the barns as a result of the change in the waste management system; mortality decreased 57%, daily weight gain increased 11%, and feed conversion improved 5.4% compared to the traditional lagoon management (Vanotti and Szogi, 2007). With the new manure system (December 2006–February 2008, three growing cycles), the farmer sold an average of 5247 pigs/cycle with a total live weight of 616,900 kg. The net gain per cycle was 514,200 kg. Compared with previous lagoon management (2005–2006), the farmer sold 32,900 kg more hogs (a 5.6% increase) per growing cycle using the new manure system. These results are consistent with the observations of Barker (1996c) on the substantial animal production advantages that can be realized by improvements in manure management in swine production buildings.

4.9. Electrical power use

A total of 265 kW.h/d were needed to operate the second-generation treatment system on this 5145-pig farm. This compares with 404 kW.h/d required by the first-generation version of the system to provide similar level of treatment on a 4360-pig farm (Vanotti et al., 2007b). The separation portion of the treatment consumed 22.8 kW.h/d or 9% of the total power used; 7.3 kW.h/d was used to mix manure in the homogenization tank and 15.5 kW.h/d was used to operate the separation equipment (pumps, in-line mixer, and rotary press). The biological N removal module consumed 231.6 kW.h/d or 87% of the total power used by the system; about 80% of this (186.8 kW.h/d) was used to power the air blower for the nitrification process, and the remainder was consumed by mixer and pumps. The phosphorus separation module consumed <4% of the total power (9.8 kW.h/d), and <0.5% (0.92 kW.h/d) was used to flush the barns (lift station) and recycle the water to the barns.

The improvements in the second-generation system reduced power consumption by 44.4%, from 92.7 to 51.5 kW.h/d per1000-head. The largest reductions were due to simplifications made in the solid–liquid separation (from 34.1 to 4.4 kW.h/d per1000-head) and the phosphorus treatment (from 5.1 to 1.9 kW.h/d per1000-head). Energy savings in the biological N treatment were small, from 55.4 to 45.0 kW.h/d per1000-head, because both projects used the same basic nitrification process that required intensive aeration for ammonia oxidation. Thus, any significant savings in power requirements by the system in the future will come from changes in the N treatment. These changes could be in the intrinsic biology of the N removal module, such as the incorporation of anammox (Vanotti et al., 2006b) that utilizes about half the aeration required by classical NDN to convert ammonia into N_2, or by separation of ammonia so it is not oxidized at all, such as the incorporation of ammonia recovery systems using gas permeable membranes or stripping.

4.10. Operator requirements

The second-generation system was more labor efficient and easier to operate than the first-generation system. Improved reliability and operation simplicity were important considerations during design of the second-generation system. It relied less on electronic sensors and programmable logic controllers, and more on manual controls and simple operator input. For example, the solids separation had higher treatment capacity that allowed operation during normal working hours as opposed to 24/7. The functioning of the biological N treatment was more stable and predictable with the addition of the separated water tank and constant feeding. Similarly, the operation of the P module was made easier with the simultaneous separation process that eliminated P dewatering equipment and solids handling.

The operator needs to receive two weeks of company training that includes information on specialized plant equipment, operation and maintenance, safety and health aspects, identification and reporting of problems, and simple troubleshooting. With widespread adoption of EST's, it will be necessary for the NC Department of Environment and Natural Resources, Division of Water Quality to establish operator training/certification requirement for permitted ESTs. Our observations indicate that a trained operator can safely operate three farms within a 20-mile radius, each farm providing treatment to about 6000 pigs. In addition to the plant operator, successful operation of the technology also requires support from an engineer technician having a 2- to 4-year engineering 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, calibrations, electronics, or parts replacement.

4.11. Economic considerations

The cost of the re-designed second generation (Super Soil Systems) technology was substantially reduced compared to a first-generation system previously evaluated, while achieving the efficient environmental performance of EST. The actual cost calculated for the Tyndall farm study was $132.24 per 454 kg (1000 lbs) steady-state live animal weight (SSLW) per year (Williams, 2007), or its equivalent of $7.13 per finished pig (using turnover rate of 2.5 growing cycles per year and standard weight of 135 lb/head for farrow-to-finish operation). The $132 value is a 10-year annualized cost calculation as mandated by the EST determination process and represents the initial investment over a 10-year economic life plus operational and maintenance costs. It was 1/3 of the cost of the first-generation system ($399.71 per 1000 lbs SSLW yr^{-1};

Williams, 2009) and closer to the cost of the anaerobic lagoon-sprayfield technology (\$85 per 1000 lbs SSLW yr^{-1}; Williams, 2007).

When one considers the many direct and indirect benefits brought about by the cleaner hog waste technology, farmers and society may not be able to afford not to convert to the new technologies. Direct economic benefits to the producer from implementation of the new technology (and the resulting cleaner environment) include the sale of GHG emission reduction credits, water quality credits, and improvements in animal productivity. The value from GHG emission reductions due to anaerobic lagoon replacement with the new aerobic system was about \$32.46 per 1000 lbs SSLW yr^{-1} (\$1.75/finished pig) (Vanotti et al., 2008). Additional economic benefits from improvements in animal productivity and health by replacing the lagoon technology with the cleaner technology may amount to \$120.15 per 1000 lbs SSLW yr^{-1} (\$6.13 per finishing pig) (Vanotti and Szogi, 2007). Combined, the carbon credits and productivity benefits have the potential to pay for all the cost of treatment.

Another potential direct benefit to farmers is the trading of water quality credits (nitrogen and phosphorus) within a watershed (Ribaudo et al., 2007). With 50 nutrient credit programs already established throughout the USA, it is anticipated that water quality credits will be important to livestock producers adopting new manure treatment technologies. Water quality trading allows a point-source discharger such as a municipal wastewater treatment plant to meet Clean Water Act obligations by acquiring credits from other sources such as farms that implement innovative measures to reduce N and P pollution. With the large mass of nutrients removed by the new technology (Table 3), and considering current prices of \$5.02/kg N (\$11.06/lb. N) and \$2.29/kg P (\$5.04/lb. P) (Chesapeake Bay Watershed Nutrient Credit Exchange, Ritchmond, VA, 2007), the benefits to the farmer implementing new technology may be substantial, even at trading ratios for non-point sources of 2:1.

Policymakers should also take into consideration benefits to society associated with reducing environmental releases from swine farms. The Research Triangle Institute International (RTI, 2003) estimated the monetized economic benefits to North Carolina households of changes in environmental quality resulting from the generalized adoption of alternative waste technologies (2300 swine operations). Results indicated that adoption of technologies that provides a 50% reduction of ammonia emissions and associated fine particulate matter (PM_{fine}) account for an estimated benefit of \$190 million/year in avoided human health impacts (RTI, 2003), or \$233 per 1000 lbs SSLW yr^{-1} (Rudek and Shao, 2007).

The remarkable cost reductions made after the first prototype system was tested at full-scale supports recommendations that "the optimal method of achieving continued cost reductions from alternative technologies is to install targeted technologies on a sufficient number of farms to facilitate continued engineering improvements, value-added product market development, and other cost reduction methods" (Williams, 2007). Consequently, in 2007 the State of North Carolina enacted legislation that established a Lagoon Conversion Program to financially assist producers in the conversion of anaerobic swine lagoons to EST (NC General Assembly, 2007). The new legislation also made permanent in North Carolina the five environmental performance standards of an EST as requirement for the construction of new swine farms or expansion of existing swine farms.

5. Conclusion

The central goal in development and implementation of the second-generation manure treatment system was to achieve the high environmental performance of the first generation at substantially reduced costs. The new system met all environmental EST standards in a full-scale demonstration, as measured by the various indicators of water quality, odor reduction and disinfection, at 1/3 the cost of the previous version. We found that animal health and productivity were enhanced with the cleaner environment, with additional benefits to the producer. Thus, cleaner treatment technologies can have significantly positive impacts not only on the environment but also on livestock productivity.

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