Evaluation of Second-Generation Multistage Wastewater Treatment System for the Removal of Malodors from Liquid Swine Waste

John H. Loughrin,* Matias B. Vanotti, Ariel A. Szogi, and Nanh Lovanh USDA-ARS

Wastewater quality and malodors in a second generation implementation of environmentally superior technology (EST) were monitored over three cycles of pig (*Sus scrofa*) production and 15 mo. The wastewater treatment system consisted of three modules: solids separation, biological N removal, and P recovery/wastewater disinfection. While approximately more than 90% of the wastewater suspended solids were removed in the first stage of treatment, little reduction in malodorous compounds occurred, indicating that malodors largely remained with the liquid waste stream. The greatest improvements in wastewater quality occurred in the N treatment module where ammonium was removed through nitrification/denitrification processes: there was more than 99% reduction in aromatic malodorous compounds (e.g., *p*-cresol, skatole) and almost 90% reduction in volatile fatty acids (e.g., propanoate and butanoate) in N module effluent as compared to raw flushed manure. The system performed consistently well in wastewater odor removal, even during the first cycle of livestock production when system performance was being optimized. These findings showed that the combination of the processes of solids removal and biological N treatment into a practical treatment system can be very effective in reducing malodors from livestock wastewater.

Typically, waste from confined swine and dairy feeding operations (CAFOs) is treated and/or stored in anaerobic earthen lagoons before application on cropland (Barker, 1996). Malodors generated during this time are the source of potential complaints and may pose environmental and health risks (USEPA, 1996; Schiffman et al., 2005). Thus there is interest in technologies that could replace anaerobic lagoons with more environmentally sustainable systems.

In July 1997, the state of North Carolina enacted House Bill 515, the "Clean Water Responsibility and Environmentally Sound Policy Act" which established a moratorium on the construction of new swine rearing operations. Because of this moratorium, a government/industry-sponsored framework was established in 2000 to develop and establish EST. The agreement defined EST as "any technology, or combination of technologies that is permittable by the appropriate governmental authority; is determined to be technically, operationally, and economically feasible for an identified category or categories of farms as described in the agreements and, finally; meets the following 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, 2001).

In March 2006, 5 of 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, 2004, 2005, and 2006). Only one of the five selected technologies treated the entire swine waste stream on-farm and provided dewatered manure solids amenable for transport off farm and land application or generation of value-added products with additional treatment. The other four selected technologies processed separated manure solids using composting, high-solids anaerobic digestion, or gasification processes that produced a variety of products such as class A composts, organic fertilizers, and energy.

Copyright © 2009 by the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Published in J. Environ. Qual. 38:1739–1748 (2009).
doi:10.2134/jeq2008.0430
Received 26 Sept. 2008.
*Corresponding author (john.loughrin@ars.usda.gov).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

J.H. Loughrin and N. Lovanh, USDA-ARS, Animal Waste Management Res. Unit, 230 Bennett Ln., Bowling Green, KY 42104; M.B. Vanotti and A.A. Szogi, USDA-ARS, Coastal Plains Soil, Water and Plant Res. Center, 2611 West Lucas St., Florence, SC 9501-1242.

Abbreviations: BOD, biological oxygen demand; CAFOs, confined animal feeding operations; COD, chemical oxygen demand; EST, environmentally superior technologies; NH_3–N, ammonia nitrogen; TKN, total Kjeldahl nitrogen; TS, total solids; TSS, total suspended solids; VFA, volatile fatty acids; VS, volatile solids; VSS, volatile suspended solids.

Consequently, in July 2007 the State of North Carolina enacted Senate Bill 1465 that made permanent the five environmental performance standards of an EST as a requirement for the construction of new swine farms or expansion of existing swine farms in North Carolina (NC General Assembly, 2007). It also established a Lagoon Conversion Program that provides financial incentives to assist producers in the conversion of anaerobic swine lagoons to EST.

The on-farm technology used liquid-solid separation, nitrification/denitrification, and soluble P removal processes linked together into a practical system. It was developed to replace anaerobic lagoon technology commonly used in the United States to treat swine waste (Vanotti et al., 2005b).

The first-generation version of the technology was installed and demonstrated full-scale on Goshen Ridge, a 4400-head swine finishing farm in Duplin County, NC (Vanotti et al., 2007a). After the system was operational, discharge of raw manure into the anaerobic lagoon was halted, transforming it into an aerobic reservoir within a year. The system removed 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 and 99.0% of zinc (Vanotti et al.,2007a). Separated solids were transported off-site to a composting facility for processing into value added products. In addition, the system effectively removed 98% of malodorous aromatic compounds from the wastewater (Loughrin et al., 2006a), effected improvements in lagoon odor (Loughrin et al., 2006b), reduced 96.9% of greenhouse gas (GHG) emissions (Vanotti et al., 2007b), and produced a sanitized effluent with reduction in the number of pathogenic bacteria from >4 logs to nondetectable levels (Vanotti, 2004; Vanotti et al., 2005a).

Since the treatment system satisfied the environmental standards for EST, a second generation version of the technology was implemented and demonstrated full-scale on another finishing farm in North Carolina. In addition to meeting the technological standards of the first generation of this technology, this system was designed to reduce capital, maintenance, and operational expenses. A detailed list of changes made to the second generation system to lower system costs and improve reliability may be obtained in Vanotti and Szogi (2007). Briefly, the most significant changes incorporated into the second generation were:

- The solid-liquid separation operation was reduced from a 24/7 operation into a 2 d per week operation using a higher-capacity separator (rotary press). It also produced separated solids with higher solids content (25%), which improved handling and made transport of the material more economical.

- The biological N treatment was simplified with the elimination of some tanks and replacement of immobilized nitrifiers with high-performance, suspended nitrifiers.

- The P separation process was also greatly simplified with the simultaneous separation of the P sludge and manure solids (Garcia et al., 2007).

In that complaints due to malodorous emissions are a primary factor in public concerns over CAFO permitting, assessing wastewater malodor reductions in the second generation implementation of this system was critical. To do this, samples were obtained from successive stages of the wastewater treatment process and analyzed for malodorous compounds and other wastewater quality indicators during full-scale demonstration of the technology. The evaluation was done from December 2006 through February 2008 comprising three cycles of swine production.

Materials and Methods

Farm Description

The second generation wastewater treatment system was installed on a 5145-head finishing farm in Sampson County, North Carolina that produced an average weight of 585,280 kg of hogs (488,000 kg gain) each growing cycle. There were seven swine barns with a permitted capacity of 5145 head. There were two anaerobic lagoons of 0.58 ha each for the treatment and storage of manure. During the evaluation period the depth of the first lagoon varied from 1.98 to 2.33 m and that of the second lagoon varied from 3.05 to 3.13 m. Manure was collected under the barns using slatted floors and a pit-recharge system typical for North Carolina (Barker, 1996). Under previous management, lagoon liquid was recycled into the subfloor pits to facilitate waste flushing. With the new treatment system, the flushing of raw wastewater into the lagoons was discontinued, and the barns received only clean water from the treatment system. During the system evaluation period, three new batches of pigs were received 12–27 Dec. 2006, 14–31 May 2007, and 28 Sept.–27 Oct. 2007. Each batch was completed and sent to market about 130 d later.

Wastewater Treatment System Description

The on-farm system was constructed and operated by Super Soil Systems USA of Clinton, NC. It consisted of three process units: solid-liquid separation, biological N treatment, and wastewater disinfection/P removal (Fig. 1 and 2). For the first unit, subfloor wastewater was pumped weekly by a 946 L min^{-1} pump into a 379 m^3 capacity homogenization 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 process used polymer flocculation to enhance the separation of fine suspended particles (Vanotti and Hunt, 1999). Solids were separated with a rotary press separator (Fournier Industries Inc., Quebec, Canada) that had two polymer preparation tanks of 2.1 m^3 capacity, a polymer metering pump, manure feed pump, flocculator, and a dual 1.2-m rotary press. The prepared polyacrylamide 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}. Residence time in the homogenization tank was 2 d. Separated manure cake was transported offsite to a solids processing facility and converted to organic-based fertilizer, soil amendments, and plant growth media (Vanotti et al., 2006).

The separated wastewater was stored in a second 379 m^3 tank for 6.8 d and used to continuously feed the nitrification/denitrification module. The process used a predenitrification configuration (Vanotti and Szogi, 2007) where the denitrification tank is placed before the nitrification tank to effectively use the separated wastewater soluble carbon during the denitrification stage (without addition of external carbon). This configuration also reduces the organic load during the nitrification stage. 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 rotary lobe blower and 98 fine-air diffusers (Airflex, SSI, Poughkeepsie, NY). The process converted NH_4–N into NO_2–N and NO_3–N. A predenitrification configuration transformed NO_3 into N_2 gas where the nitrified wastewater was continually recycled into a 277 m^3 anoxic denitrification tank. In this tank, suspended denitrifying bacteria used soluble manure carbon to remove the NO_2 + NO_3. A settling tank was used to clarify the effluent and return the suspended bacteria into the N tanks. The rates of sludge and nitrified liquid recycling into the denitrification tank were 3.5 and 0.5 times the inflow rate, respectively, and overall liquid residence time in the N treatment module was 4.1 d. The clarified effluent was stored in a 277 m^3 tank and used to refill the barn pits.

In the third module, P was recovered as a calcium phosphate solid (Vanotti et al., 2003), and pathogens were reduced by the alkaline environment (Vanotti et al., 2005a). The effluent was treated 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 by a pH probe and controller (Model 53, GLI International, 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 and further dewatered using the solid/liquid separation unit in the first unit of the system (Fig. 1) and then combined with the manure solids for off-farm transport. A schematic of the treatment system process is shown in Fig. 1 while an aerial view is presented as Fig. 2.

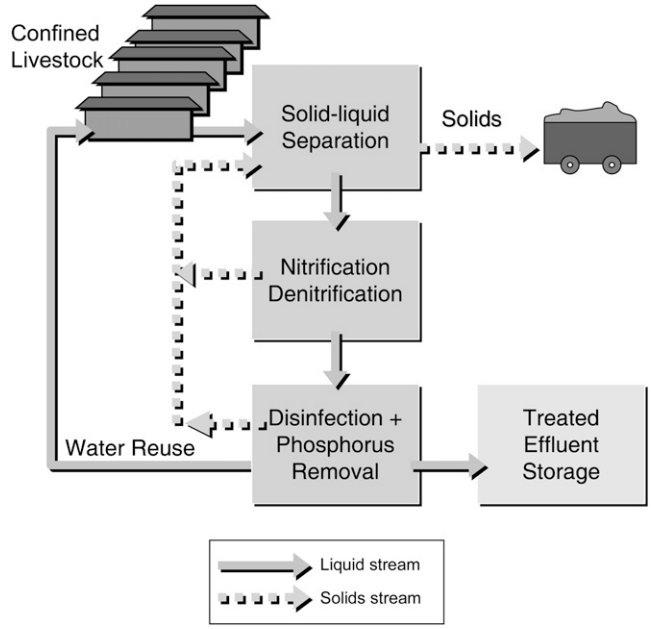

Fig. 1. Diagrammatic representation of the wastewater treatment process.

Once the system was operational, flow of raw manure into the lagoons was discontinued, and the barns were flushed with effluent from biological N treatment as described. Water in excess of that needed for barn flushing was stored in the lagoons.

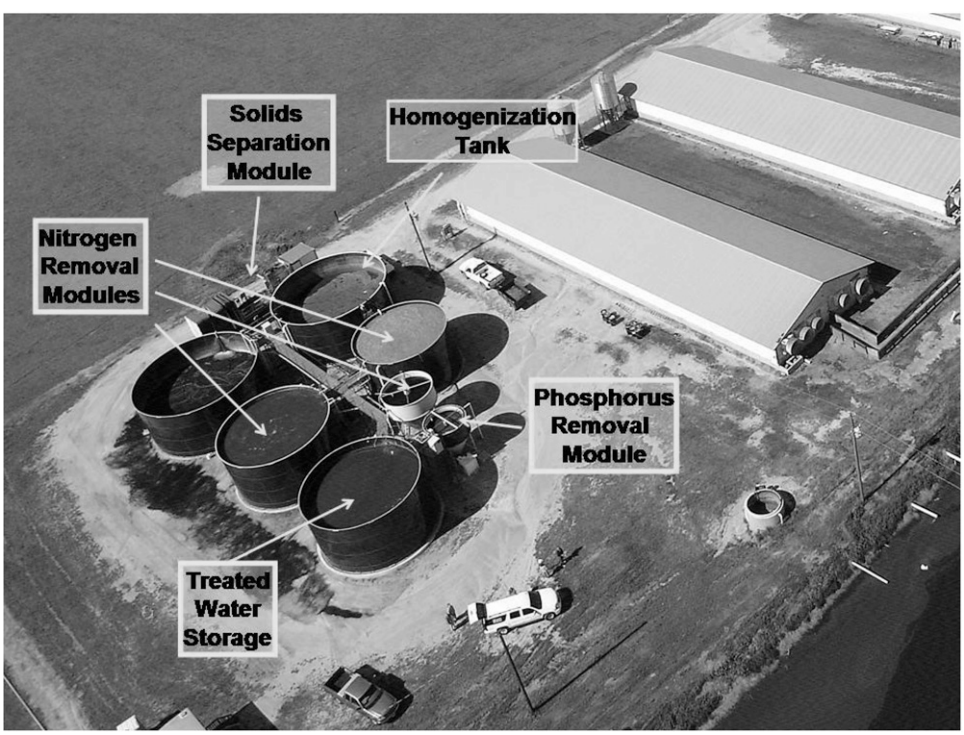

Fig. 2. Aerial view of second generation swine waste treatment system.

A total of 12,600 m^3 of flushed manure was processed by the plant from 9 Dec. 2006 to 29 Feb. 2008, or an average of 28.1 m^3 d^{-1}. On average, flushed manure contained 19.7% recycled effluent from the treatment system and 80.3% manure, urine, and water wasted by pigs. Without considering the recycled liquid, the wastewater stream averaged 23 m^3 d^{-1} or 40 L per 455 kg live animal weight per day. This is similar to the industry average of 45.8 L per 455 kg live animal weight per day in feeder to finish operations using pit-recharge systems (Chastain et al., 1999). Manure generation was higher during the warmer months. For instance, it averaged 49.4 L per 455 kg animal weight per day in May-September and 22.7 L per 455 kg animal weight per day in October–April. The average volume used to refill each barn was approximately 14,000 L.

Water Sampling

Once monthly, duplicate 1-L grab samples were taken before and after each of the treatment modules as follows: (i) the untreated liquid manure in the mixing tank before solids separation, (ii) the effluent from the solid-liquid separation treatment, (iii) the effluent after the nitrification–denitrification treatment, and (iv) the effluent after the P removal treatment. In addition, liquid samples were also taken at intermediate points of the nitrification–denitrification treatment; specifically from the nitrification and the denitrification tanks.

The samples were transported on ice to the Florence, SC laboratory and subdivided for water quality and odors analyses. Fifty-milliliter subsamples for odor analysis were packed in ice and shipped overnight to the Bowling Green, KY laboratory where they were stored at approximately –20°C until analyzed. Odor analyses were performed within 1 mo of receipt.

Quantification of Aromatic Odor Compounds

Odor compounds (phenol, *p*-cresol, p-ethylphenol, indole and skatole) were extracted from wastewater samples using Twister stir bars (10 mm long by 0.5 mm phase thickness; Gerstel USA, Baltimore, MD) with a 1-mm polydimethylsiloxane (PDMS) coating, which had been thermally conditioned under a stream of high-purity N_2 at 250°C for 60 min before use. The stir bars were placed in glass vials fitted with Teflon-lined screw caps along with 10 mL of wastewater and stirred at 300 rpm for 1 h. The Twisters were then removed, rinsed with deionized water and blotted dry. The volatile compounds retained by the Twisters were desorbed in a Gerstel model TDSA thermal desorption unit interfaced to a Varian model 3800 gas chromatograph (GC) and Varian Star 2200 mass spectrometer (Varian Associates, Palo Alto, CA). After an initial time of 0.25 min, desorption of the stir bars was performed with an initial temperature of 100°C, programmed at 60°C min^{-1} to 260°C, and then held for 30 min. Compounds were transferred in splitless mode to a glass wool packed injection liner maintained at –50°C with liquid CO_2. Compounds were then transferred to the GC column with a 20:1 split ratio by raising the injector temperature at 12°C s^{-1} to 300°C. Compound separation was performed on a 30 m by 0.25 mm VF-23MS column (50/50 cyanopropylmethylpolysiloxane/PDMS stationary phase) with a film thickness of 0.25 μm (Varian, Inc.). The GC operating conditions were: He carrier constant flow rate of 1 mL min^{-1} and column oven at 60°C for 1 min, programmed at 7°C min^{-1} to 115°C, at 1.5°C min^{-1} to 140°C, and then at 15°C min^{-1} to 195°C. The mass spectrometer was operated in electron ionization mode with an emission current of 10 μA, a scan time of 0.35 s per scan, and a scan range of 45 to 225 amu. Odor compounds were quantified by a six-point external standard calibration using standards dissolved in 10 mL of water. For each odor compound measured in the wastewater, quantitation was based on its most prominent ion, while identification was based on computer matching of spectra in the National Institute of Standards and Technology database and retention times. Pearson correlation coefficients for each compound averaged above 0.99 while residual standard deviations (RSD) averaged <15% for all compounds except phenol, the RSD for which averaged 45.7%.

Quantification of Volatile Fatty Acids

Volatile fatty acids (VFA: acetic, propanoic, 2-methylpropanoic, butanoic, 3-methylbutanoic, and pentanoic acids) were determined by high performance liquid chromatography (Ultimate 3000 HPLC, Dionex Corp., San Francisco, CA). Wastewater samples were centrifuged at 10,000 rpm for 5 min. The supernatants were then filtered through a 0.2 μm-pore-size filter (Whatman, Florham Park, NJ). The filtered sample (10 μL) was injected into HPLC via an autosampler (Model WPS-3000SL Micro, Dionex Corp.). Sulfuric acid (5 mmol L^{-1}, RICCA Chemical Co., Arlington, TX) was filtered and used as mobile phase for an isocratic run. The mobile phase was pumped at 0.5 mL min^{-1} through a 300 by 7.8 mm (8 μm particle size) RHM Monosaccharide column (Phenomenex, Torrence, CA) held at a temperature of 65°C to a photodiode array detector (Model PDA-3000, Dionex Corp.) with wavelength set at 210 nm. Quantitation was based on a seven point calibration curve with correlation coefficients all above 0.999.

Water Quality Analyses

Wastewater analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, and WEF, 1998). Solids analyses of the treated and untreated liquid samples included total solids (TS), volatile solids (VS), total suspended solids (TSS), and volatile suspended solids (VSS). Total solids were the solids remaining after evaporation of a sample to constant weight at 105°C. Total suspended solids were the solids portion retained on a glass microfiber filter (Whatman grade 934-AH, Whatman, Inc., Clifton, NJ) after filtration and drying to constant weight at 105°C, while VS and VSS were the fractions of TS and TSS, respectively, that were lost on ignition in a muffle furnace at 500°C for 15 min. Therefore, TSS and VSS are measurements of TS and VS that are removable by solids separation.

Chemical analyses consisted of chemical oxygen demand (COD), 5-d biochemical oxygen demand (BOD5), ammonia-N (NH_3–N), total Kjeldahl N (TKN). For COD, we used the closed reflux, colorimetric method (Standard Method 5220 D). Ammonia-N was determined by the automated phenate meth-

od (Standard Method 4500-NH_3 G) 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 NO_3–N by the automated cadmium reduction method (Standard Method 4500-NO_3^-- F), as well as soluble COD and soluble BOD. The TKN was determined by the same phenate method adapted to digested extracts (Technicon Instruments Corp., 1977).

Results and Discussion

The evaluation period of December 2006 through February 2008 encompassed three cycles of pig production allowing assessment of system performance through a range of waste loading conditions and varying environmental conditions. Taken on average through the evaluation period, though, flushed wastewater was very high strength. Volatile solids, for example, averaged 15,600 mg L^{-1}, but ranged from 8400 mg L^{-1} up to about 37,000 mg L^{-1} while soluble BOD averaged 1240 mg L^{-1} and ranged from to 83 to more than 9000 mg L^{-1} (Table 1). These values are comparable to others obtained for raw flushed swine manure (Zhang et al., 2006). Other quality parameters such as COD (average 17,900 mg L^{-1}) and ammonia (average 1100 mg L^{-1}) were also typical of a high strength swine wastewater.

Average monthly volume of wastewater flushed from the housing was 966 m^3, and ranged from 396 up to 1745 m^3. System effluent volumes averaged 815 m^3, and ranged from 290 to 1666 m^3. Clean system effluent was used to recharge the housing pits and water in excess of this need was stored in the farm's old waste treatment lagoon to be used in crop irrigation. Average monthly air temperature was 15.6°C, and ranged from 8.0 to 23.0°C (Fig. 3).

Solids Separation Module

The first stage of the wastewater treatment process was solid-liquid separation via polymer flocculation (Fig. 1). This resulted in a large decrease in solids, COD and BOD in the separated wastewater. More than 50% of TS and 90% of TSS were removed while about 60% of COD and BOD were removed (Table 1). Soluble COD and BOD in the wastewater, however, were increased due to the polymer addition. Total Kjeldahl N was reduced by approximately 30% while ammoniacal N content was unaffected by solids separation. The separation process produced a relatively dry manure cake containing 24.9% solids; the process concentrated the suspended solids >25 times compared to the flushed manure.

The concentration of odor compounds in the wastewater was not dramatically affected by the solids separation process (Table 2). Phenol and *p*-cresol concentrations were reduced by approximately 30 and 20%, respectively, while *p*-ethylphenol, indole and skatole concentrations were essentially unchanged. This is likely due to these compounds' high polarities in that organic compound partitioning to solids decreases with compound polarity (Zeng and Noblet, 2002). Similarly, VFA content was reduced only by about 20% in the separated liquid as compared to raw flushed manure.

Biological Nitrogen Treatment

The next stage of the treatment process treated the separated liquid waste using a nitrification–denitrification process. Nitrification was accomplished in an aeration tank that used high-performance nitrifying bacteria adapted to high-strength wastewater. Air was supplied to these bacteria which converted NH_4 into NO_3. A predenitrification configuration transformed the NO_3 into dinitrogen gas in where the nitrified wastewater was continuously recycled into an anoxic denitrification tank. In this tank suspended denitrifying bacteria removed the NO_3 using most of the soluble carbon remaining in the wastewater after solid-liquid separation. Substantial improvements in wastewater quality were effected during biological N treatment (Table 1). The indices of wastewater quality were very similar in the denitrification and nitrification tanks as would be expected due to the continuous recirculation between these two tanks. Although TSS and VSS in the wastewater were increased due to the added suspended bacterial biomass, and TS and VS. were not measured for the same reason, we found that sCOD and sBOD were reduced by about 80 and 90%, respectively. Ammoniacal N was reduced by almost 95%.

The clarified effluent from these two tanks was stored in a clean water storage tank (276 m^3) and used to refill the barn pits. Although the N module effluent contained considerable TS (67% reduction), the TSS, VS, VSS, COD, and BOD were all reduced by 90% or better as compared to raw effluent. In addition, NH_4–N was essentially eliminated (94% reduction). The remaining oxidized N (NO_2 + NO_3) content of the N module effluent was 264 mg L^{-1}. As discussed later, we found that the reuse of this oxidized effluent to recharge the pits under the barns may help reduce odors in the facility.

The greatest improvements in malodorous compounds also occurred during biological N treatment (Table 2). In the anoxic denitrification process, reductions in aromatic malodorous compounds ranged from approximately 85% for phenol to about 97% for *p*-cresol. In the aerobic nitrification process, indole and skatole were reduced below our quantification limit of approximately 1 µg L^{-1} while phenol, *p*-cresol, and *p*-ethylphenol were also reduced to very low levels. The VFA were reduced by more than two-thirds in the denitrification module, and by more than 80% in the N module effluent as compared to raw flushed manure. It seems certain that the largest part of the reductions in malodorous compounds were due to their utilization by the suspended denitrification bacteria as a soluble carbon source in anaerobic respiration while aerobic respiration in the nitrification was responsible for further reductions.

Phosphorus Precipitation Module

The levels of malodors in the wastewater were already quite low in the effluent from the N treatment module and no further improvements in the wastewater odor were effected by P treatment. Due to the high pH of the P module effluent (>9), VFA was not measured at this stage due to possible damage to the monosaccharide HPLC column.

However, given the high pH of the effluent, VFA should not make a significant contribution to odor due to increased

Table 1. Wastewater quality parameters from December 2006 through February 2008. Data are the means of 15 duplicate monthly values from December 2006 through February 2008.

Parameter†	Homogenization tank	Separated liquid	Denitrification tank	Nitrification tank	Nitrogen module effluent	Phosphorus effluent	System efficiency, %‡
	concentration, mg L^{-1}						
TS	26,300 ± 3710	12,400 ± 1620	na§	na	8800 ± 960	8590 ± 934	67.3
TSS	9250 ± 1550	760 ± 152	1880 ± 385	1700 ± 334	208 ± 50.6	220 ± 38.5	97.6
VS	15,600 ± 2520	4450 ± 786	na	na	1870 ± 419	1470 ± 260	90.6
VSS	6780 ± 1190	530 ± 117	1490 ± 328	1350 ± 302	137 ± 44.9	99.3 ± 18.7	98.5
COD	17,900 ± 3450	7240 ± 1500	na	na	981 ± 202	768 ± 122	99.6
sCOD	4600 ± 1130	4980 ± 1060	955 ± 217	778 ± 145	762 ± 137	675 ± 97.5	85.3
BOD	5480 ± 1410	2400 ± 634	na	na	54.9 ± 12.6	23.2 ± 7.1	99.6
sBOD	1240 ± 542	2190 ± 603	106 ± 63.3	15.6 ± 3.1	14.5 ± 3.8	26.2 ± 14.9	97.9
NH_4–N	1100 ± 169	1110 ± 147	196 ± 51.5	61.9 ± 26.4	68.3 ± 26.5	66.3 ± 29.3	93.9
TKN	1740 ± 196	1270 ± 158	na	na	79.8 ± 24.2	100 ± 36.7	94.8
NO_x	4.28 ± 2.75	–¶	146 ± 62.6	283 ± 66.1	264 ± 66.1	171 ± 51.8	na
NO_2	0.58 ± 0.56	–	101 ± 59.3	203 ± 76.3	188 ± 68.5	136 ± 52.8	na

† TS = total solids; TSS = total suspended solids; VS = volatile solids; VSS = volatile suspended solids; COD = chemical oxygen demand; sCOD = soluble chemical oxygen demand; BOD = biochemical oxygen demand; sBOD = Soluble biological oxygen demand; NH_4–N = ammoniacal nitrogen; TKN = Total Kjeldahl nitrogen; NO_x = nitrate + nitrite; NO_2 = nitrite.

‡ System efficiency compares reduction in concentration of water quality indicator in treated effluent (P effluent) with respect to influent (homogenization tank).

§ na = measurement not taken or inapplicable.

¶ Compound below detection limits.

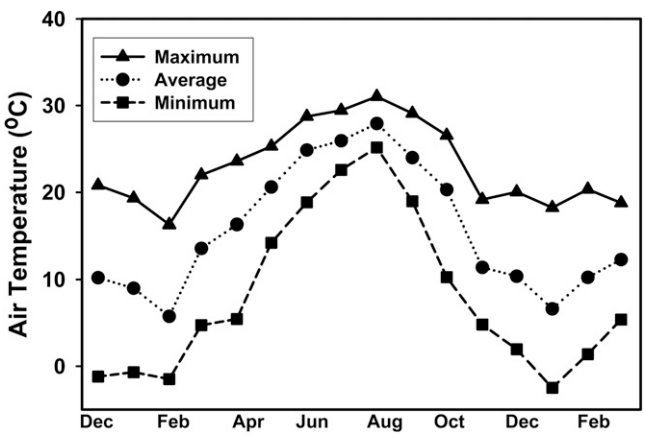

Fig. 3. Air temperature during the 15-mo water quality and odor monitoring period. Data are monthly maximum, average, and minimum of average daily temperatures.

solubility and, hence, decreased volatility (Spoelstra, 1980; Zhu, 2000).

Odor Reduction Performance of System during the Evaluation Period

As mentioned, the 15 mo evaluation period allowed assessment of the system performance over a wide range of waste loading conditions and environmental conditions. For instance, while the average total pig weight was approximately 317,000 kg, the actual monthly weight of livestock ranged from about 74,000 kg to more than 520,000 kg. Temperature also varied greatly, ranging from an average monthly value of about 7°C in February to about 28°C in August (Fig. 3).

Throughout the evaluation period, individual aromatic malodors were all reduced by greater than 99% and VFA by more than 80%. As stated, most of this odor reduction occurred in the N treatment module. Beyond this there was

Table 2. Average concentrations of malodorous compounds in treatment system wastewater stream from December 2006 through February 2008†.

Compound	Raw flushed manure	Separated liquid	Denitrification tank	Nitrification tank	Nitrogen module effluent	Phosphorus effluent
	aromatics concentration, μg L^{-1}					
Phenol	9370 ± 5050	10,800 ± 5210	1090 ± 466	90.6 ± 23.7	12.2 ± 4.2	17.7 ± 6.9
p-Cresol	49,000 ± 12,000	40,300 ± 9900	2140 ± 1490	41.7 ± 17.8	27.9 ± 16.9	25.7 ± 9.5
p-Ethylphenol	6660 ± 1380	6340 ± 1120	510 ± 271	tr‡	tr	tr
Indole	484 ± 138	413 ± 106	24.1 ± 12.0	5.4 ± 6.1	tr	tr
Skatole	3870 ± 1140	2660 ± 478	187 ± 95.2	tr	tr	tr
	volatile fatty acid concentration, mg L^{-1}					
Acetic	2190 ± 628	2170 ± 564	58.4 ± 50.3	tr	35.9 ± 30.3	–§
Propanoic	1230 ± 283	858 ± 229	207 ± 71.0	211 ± 83.4	111 ± 50.3	–
2-Methylpropanoic	180 ± 80.8	124 ± 31.9	585 ± 262	719 ± 303	567 ± 224	–
Butanoic	1200 ± 623	1660 ± 1350	69.8 ± 47.1	26.3 ± 14.7	21.0 ± 13.1	–
3-Methylbutanoic	902 ± 483	1290 ± 475	tr	22.7 ± 15.1	tr	–
Pentanoic	324 ± 172	367 ± 146	tr	76.7 ± 55.4	tr	–

† Data represent the mean of duplicate monthly determinations averaged over a 15 mo period.

‡ tr denotes <1 μg L^{-1} for aromatics, 20 mg L^{-1} for volatile fatty acids.

§ Not measured.

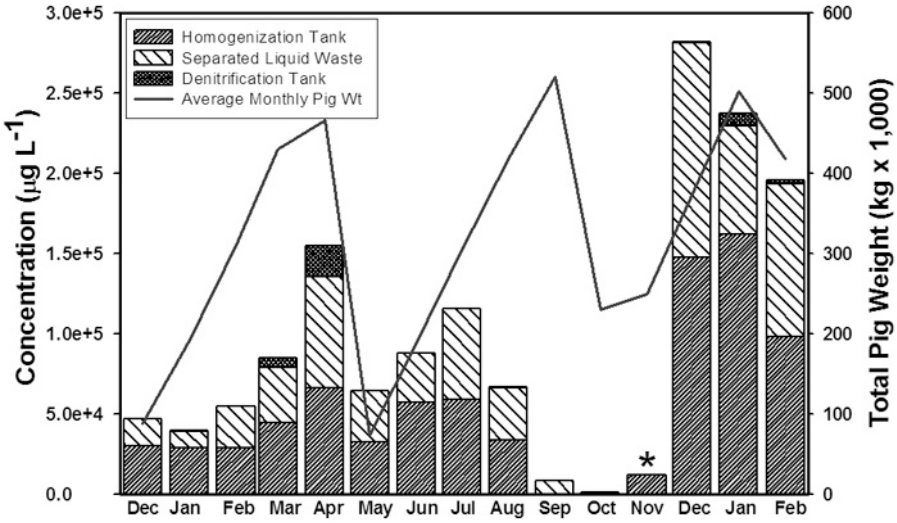

Fig. 4. *Para*-cresol concentrations at the first three stages of the wastewater treatment process with average monthly live pig weights. Asterisk for November 2007 indicates missing sample for separated waste water.

seasonal variation in waste loading rates, the concentration of odor compounds in raw flushed manure, and system performance through the N treatment module. This is discussed below in relation to *p*-cresol, the most abundant malodorous component of the wastewater.

Figure 4 graphs *p*-cresol concentration in raw flushed manure, separated liquid waste and the denitrification tank as well as average monthly livestock weights during the 15 mo evaluation period that comprised the three pig growth cycles. During the first and third pig cycles, which occurred during colder months, odor concentrations in raw flushed manure remained roughly proportional to total livestock weight. However, this was not true during the second pig growth cycle, which occurred during warmer months: the malodor compounds in the raw flushed manure declined in August by almost half despite a 20% increase in average livestock weight, and disappeared during September with market size pigs in the barns. Odor compounds in raw flushed manure were very low in October but increased dramatically in December and remained high during the rest of the third cycle of production. Similar trends were observed for TSS, COD, BOD, VS, and other indicators of organic strength measured in the study. Their concentrations were substantially lower in the flushed manure collected during the second pig cycle compared to first and third cycles in colder months. Plausible conjectures are the following: (i) change in animal feed intake (NRC, 1998) and/or feed formulation during warm weather affecting strength of manure; and (ii) accelerated biological decomposition of organic compounds due to higher temperatures in the under-floor pits before wastewater flushing. This could especially be due to the warmer temperatures resulting in increased denitrification. For example, Zhu et al. (2000) found the integrity of small particles (<0.5 mm) typical of swine manure is maintained within 5 d of animal excretion and that longer storage time reduces solids recovery due to biological decomposition. We feel certain that the same type of organic consumption that occurred in the denitrification tank also occurred in the recharge pits under the barns (with manure carbon serving as electron donor for the transformation of nitrate into N_2 gas) because nitrate concentration was substantial in the treated water used to recharge the pits (N effluent, Table 1) and about zero in the manure coming from the pits a week later (Homogenization tank, Table 1). In addition, the nitrate concentration in the recycle water was about three times higher in Aug.–Nov. 2007 period compared to that found during other months of the study. This is significant because it is during this time in the 15-mo study when odor compounds in flushed manure were unexpectedly low (Fig. 4). For example, the NO_2 + NO_3 concentration in the recycled water used to recharge the pits averaged 133 mg L^{-1} in the first 8 mo of the study (December 2006–July 2007), 471 mg L^{-1} in next 4 mo (August–November 07) when odorants in raw manure were the lowest (Fig. 4), and 152 mg L^{-1} in the last 3 mo (December 2007–February 2008).

Solids content of the raw flushed manure did not vary as much month to month as did malodors (Fig. 5). System performance remained high, with more than 90% of TSS, VS, and VSS consistently removed. This finding echoes a conclusion we drew earlier in which we linked improvements in water quality (e.g., sCOD, NH_3–N, alkalinity) due to waste treatment in the first generation of EST to reductions in malodorous compounds (Loughrin et al., 2006b). In the present study, we found that the concentration of aromatic malodors in raw flushed manure was at least roughly related to average monthly livestock weight. As expected, therefore, there was a good relationship between effluent strength as measured by TSS or VSS and effluent malodor (Fig. 6). Previously, we had noted good correlations between malodor concentrations and sCOD, sBOD, TKN, NH_4, NO_3, alkalinity and electrical conductivity in successive stages of the first generation treatment system (Loughrin et al., 2006a). However, in this study, correlation between these indicators of water quality and malodor was poor from the separated wastewater stage onward (data not shown). As mentioned, polar compounds such as skatole and *p*-cresol are known not to partition as strongly to solids

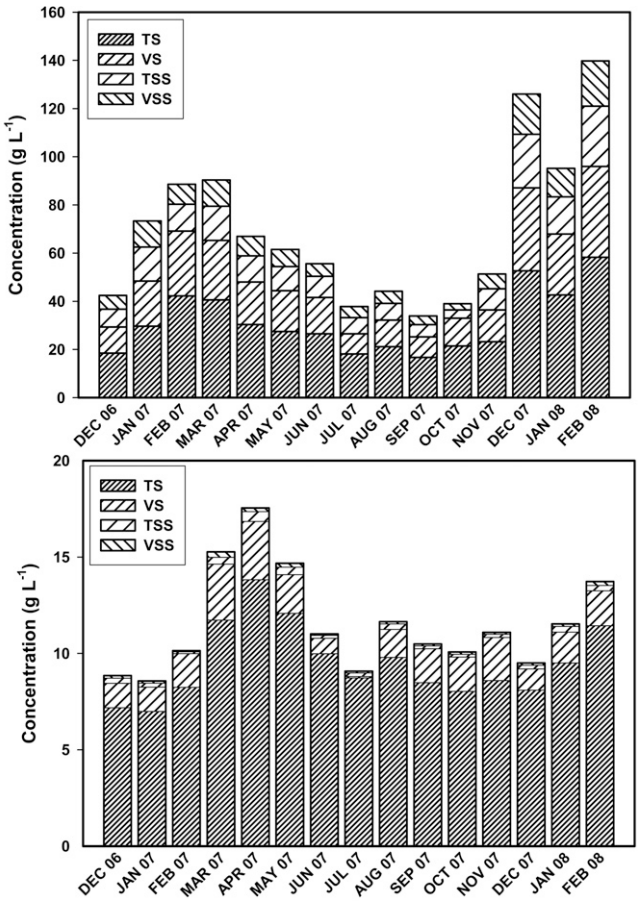

Fig. 5. Total solids (TS), total suspended solids (TSS), volatile suspended solids (VSS), and volatile solids (VS) in system influent (top) and effluent (bottom) from December 2006 to February 2008.

as do more hydrophobic compounds (Zeng and Noblet, 2002). When we analyzed the correlation between wastewater quality and reductions of malodorous compounds using liquid samples collected in the four treatment stages (raw, separated, N and P treated), the correlation coefficients obtained are very high but likely biased by the large improvements effected by the biological N treatment module, and limited inference should perhaps be drawn from them.

As stated, environmental conditions and waste loading varied greatly during the evaluation period. Despite this, the system efficiency for odor removal remained high with no <90% removal just through the denitrification stage (Fig. 4 and Table 2). This was true even during March–April when a faulty electrical connection to the blower in the N treatment module reduced the efficiency of N conversion. In addition, during the first third of the evaluation period, the original polymer formulation used in the first generation of EST did not perform optimally with the higher strength waste of the Tyndall farm (Vanotti and Szogi, 2007). Beginning in April, a new formulation increased the speed of separation to approximately 150 L min^{-1}, 60% more than the target value of 95 L min^{-1}.

Large amounts of odor compounds were flushed from the housing each month (Fig. 7). At maximum, we estimated that almost 120 kg of aromatic malodors were flushed in December 2007 and almost 20 metric tons of VFA were flushed during February 2008. In that more than 99% of aromatic malodorants were removed in the waste treatment process and substantial improvements were also effected in VFA concentrations, these numbers are presumably reflective of overall improvements in air quality from the farm as noted for ammonia emissions in the first generation of EST (Szogi et al., 2006) and are likely to substantially improve lagoon odor (Loughrin et al., 2006b).

Conclusions

The central goal in implementation of the second generation wastewater treatment system was to achieve the environmental performance of the first generation at substantially reduced costs. Results from this study and Vanotti and Szogi (2007) show that this goal was realized. The treatment system performed well as measured by wastewater odor reduction even during the first third of the evaluation period when system per-

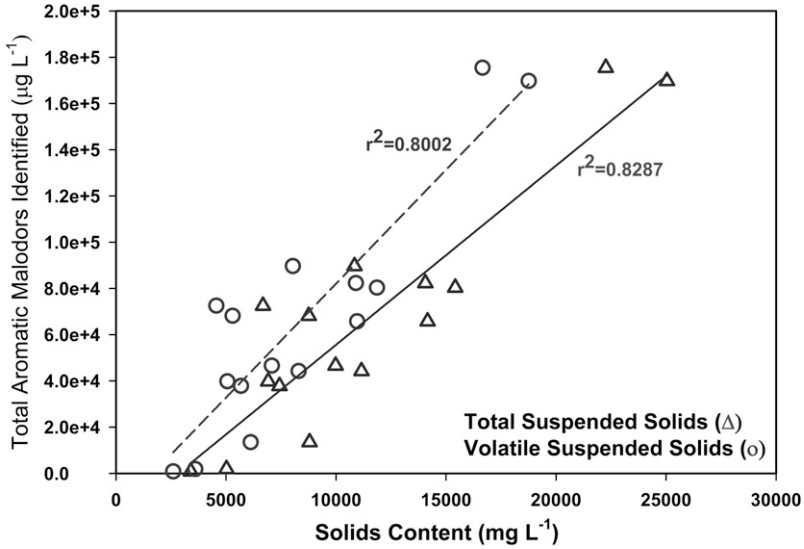

Fig. 6. Relationship between total identified aromatic compounds and solids content of raw flushed wastewater.

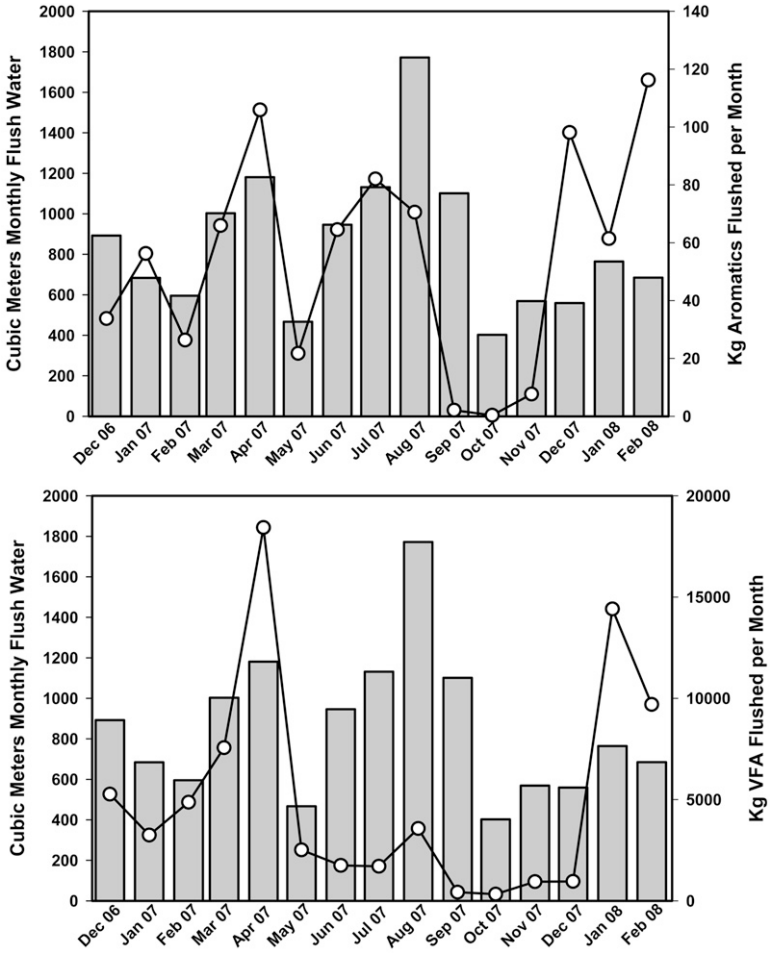

Fig. 7. Estimates of total malodorous aromatic and volatile fatty acids flushed per month along with total volume of water used to flush housing waste pits (bars).

formance was being optimized. We found also that most of the odor reduction in the treatment system occurred during denitrification that occurred in the biological N removal. Beyond the other environmental benefits that should be provided by EST such as ammonia reduction, EST should also substantially improve local air quality as the lagoon is removed as a source of odor. In addition, air quality in the building should be improved due to recycling of clean water from the system to recharge pits rather than using lagoon liquid.

Acknowledgments

This research was part of USDA-ARS National Program 206: Manure and By-Product Utilization; ARS Project 6657-13630-001-00D "Innovative animal manure treatment technologies for enhanced environmental quality." It was partially funded by the North Carolina Department of Justice, Office of the Attorney General through the Smithfield Foods Environmental Enhancement Fund Grant Agreement, USDA-ARS Project 6657-13630-003-04/NCSU Subcontract no. 2005-0978-03. The authors thank Mr. and Mrs. Billy Tyndall for providing their farm for this study; personnel of Super Soil Systems USA for their help with design, construction, and operation of the treatment system; and Prestage Farms for providing animal production records at B&B Tyndall farm. The authors acknowledge Joe St. Claire's assistance for performing GC-MS analyses, Mike Bryant's assistance for performing HPLC analyses and Aprel Ellison's assistance in collection of wastewater samples and water quality analyses.

References

APHA, AWWA, and WEF. 1998. Standard methods for the examination of water and wastewater. 20th ed. American Public Health Assoc., American Water Works Assoc., and Water Environment Federation, Washington, DC.

Barker, J.C. 1996. Lagoon design and management for livestock waste treatment and storage. North Carolina Coop. Ext. Serv. Publ. EBAE 103–83. Available at http://www.bae.ncsu.edu/programs/extension/publicat/wqwm/ebae103_83.html (accessed 11 Aug. 2008; verified 27 Apr. 2009).

Chastain, J.P., J.J. Camberato, J.E. Albrecht, and J. Adams. 1999. Swine manure production and nutrient content. p. 1–17. *In* South Carolina confined animal manure managers certification program. Clemson Univ., Clemson, SC.

Garcia, M.C., M.B. Vanotti, and A.A. Szogi. 2007. Simultaneous separation of phosphorus and manure solids with polymers. Trans. ASABE 50:2205–2215.

Loughrin, J.H., A.A. Szogi, and M.B. Vanotti. 2006a. Reduction of malodorous compounds from liquid swine manure by a multi-stage treatment system. Appl. Eng. Agric. 22:867–873.

Loughrin, J.H., A.A. Szogi, and M.B. Vanotti. 2006b. Reduction of malodorous compounds from a treated swine anaerobic lagoon. J. Environ. Qual.

35:194–199.

NC General Assembly. 2007. Senate Bill 1465: Performance standards for animal waste management systems that serve swine farms; lagoon and sprayfield systems prohibited. General Assembly of North Carolina, Session 2007, Session Law 2007–523. Available at http://www.ncga.state.nc.us/enactedlegislation/statutes/pdf/bysection/chapter_143/gs_143-215.10i.pdf (verified 27 Apr. 2009).

NRC. 1998. Nutrient requirements of swine. 10th rev. ed. National Research Council, Subcommittee on Swine Nutrition. Natl. Academy Press, Washington, DC.

Schiffman, S.S., C.E. Studwell, L.R. Landerman, K. Berman, and J.S. Sundy. 2005. Symptomatic effects of exposure to diluted air sampled from a swine confinement atmosphere on healthy human subjects. Environ. Health Perspect. 113:567–576.

Spoelstra, S.K. 1980. Origin of objectionable odorous components in piggery wastes and the possibility of applying indicator components for studying odour development. Agric. Environ. 5:241–260.

Szogi, A.A., M.B. Vanotti, and A. Stansbery. 2006. Reduction of ammonia emissions from treated anaerobic swine lagoons. Trans. ASABE 49:217–225.

Technicon Instruments Corp. 1977. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests (dialyzer). Industrial method 337–74W/B. Technicon Instruments Corp., Tarrytown, NY.

United States Environmental Protection Agency. 1996. Swine CAFO odors: Guidance for environmental impact assessment. Available at http://www.epa.gov/earth1r6/6en/xp/odor.pdf (accessed 11 Aug. 2008; verified 24 Apr. 2009).

Vanotti, M.B., and P.G. Hunt. 1999. Solids and nutrient removal from flushed swine manure using polyacrylamides. Trans. ASABE 42:1833–1840.

Vanotti, M.B., A.A. Szogi, and P.G. Hunt. 2003. Extraction of soluble phosphorus from swine wastewater. Trans. ASABE 46:1665–1674.

Vanotti, M.B. 2004. Evaluation of environmentally superior technology: Swine waste treatment system for elimination of lagoons, reduced environmental impact, and improved water quality. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase1report04/A.9Super%20Soil%20final.pdf (accessed 11 Aug. 2008; verified 27 Apr. 2009). North Carolina State Univ., Raleigh.

Vanotti, M.B., P.D. Millner, P.G. Hunt, and A.Q. Ellison. 2005a. Removal of pathogen and indicator microorganisms from liquid swine manure in multi-step biological and chemical treatments. Bioresour. Technol. 96:209–214.

Vanotti, M.B., A.A. Szogi, and P.G. Hunt. 2005b. Wastewater treatment system. U.S. Patent 6893,567. U.S. Patent Office. Washington, DC.

Vanotti, M.B., P.D. Millner, A.A. Szogi, C.R. Campbell, and L.M. Fetterman. 2006. Aerobic composting of swine manure solids mixed with cotton gin waste. *In* Proc. 2006 ASABE Annual Int. Meet., Portland, OR. 9–12 July 2006. Paper no. 064061. ASABE, St. Joseph, MI.

Vanotti, M.B., and A.A. Szogi. 2007. Evaluation of environmental superior technology contingent determination–Second generation super soil technology. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/supersoils2ndgeneration/ss2ndgenerationreport.html (accessed 11 Aug. 2008; verified 24 Apr. 2009). North Carolina State Univ., Raleigh.

Vanotti, M.B., A.A. Szogi, P.G. Hunt, P.D. Millner, and F.J. Humenik. 2007a. Development of environmentally superior treatment system to replace anaerobic swine waste lagoons in the USA. Bioresour. Technol. 98:3184–3194.

Vanotti, M.B., A.A. Szogi, and C.A. Vives. 2007b. Greenhouse gas emission reduction and environmental quality improvement from implementation of aerobic waste treatment systems in swine farms. Waste Manage. 28:759–766.

Williams, C.M. 2001. Smithfield and Premium Standard Farms program implementation. p. 18–21. *In* G.B. Havenstein (ed.) Proc. Int. Symp. Addressing Animal Production and Environ. Issues. Sheraton Imperial, Research Triangle, NC. 3–5 October. North Carolina State Univ., Raleigh.

Williams, C.M. 2004. Development of environmentally superior technologies. Report for technology determination per agreements between the Attorney General of North Carolina and Smithfield Foods, Premium Standard Farms, and Frontline Farmers. 26 July 2004. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase1report04/phase1report.htm (accessed 11 Aug. 2008; verified 24 Apr. 2009).

Williams, C.M. 2005. Development of environmentally superior technologies. Phase II report for technology determination per agreements between the Attorney General of North Carolina and Smithfield Foods, Premium Standard Farms, and Frontline Farmers. 25 July 2005. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase2report05/phase2report.htm (accessed 11 Aug. 2008; verified 24 Apr. 2009).

Williams, C.M. 2006. Development of environmentally superior technologies. Phase III report for technology determination per agreements between the Attorney General of North Carolina and Smithfield Foods, Premium Standard Farms, and Frontline Farmers. 8 Mar. 2006. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase3report06/phase3report.htm (accessed 11 Aug. 2008; verified 24 Apr. 2009).

Zeng, E., and J. Noblet. 2002. Theoretical considerations on the use of solid-phase microextraction with complex environmental samples. Environ. Sci. Technol. 36:3385–3392.

Zhang, Z., J. Zhu, J. King, and W. Li. 2006. A two-step fed SBR for treating swine manure. Process Biochem. 41:892–900.

Zhu, J. 2000. A review of microbiology in swine manure odor control. Agric. Ecosyst. Environ. 78:93–106.

Zhu, J., P.M. Ndegwa, and A. Luo. 2000. Changes in swine manure solids during storage may affect separation efficiency. Appl. Eng. Agric. 16:571–575.