Reduction of Malodorous Compounds from Liquid Swine Manure by a Multi-Stage Treatment System

J. H. Loughrin, A. A. Szogi, M. B. Vanotti

Abstract. *A full-scale swine wastewater treatment system was designed and implemented to replace anaerobic lagoon treatment systems with a three-stage process of solids separation, biological nitrogen (N) removal, and phosphorus recovery. Our study had the objectives of evaluating both the system's efficiency for odor control and water quality parameters that better indicate odor reduction. This report presents data on the concentration in liquid of six selected malodorous compounds (phenol, p-cresol, p-ethylphenol, p-propylphenol, indole, and skatole) and 15 water quality parameters measured at the three successive stages of the treatment process. Solid phase extraction of odor compounds showed that the concentrations of malodorous compounds were reduced by almost 98% in the treated effluent as compared to untreated raw flushed manure. The majority of this odor reduction occurred during biological N treatment. No single water quality parameter served as the sole indicator for the levels of all six odor compounds that we measured in wastewater. Except for phenol, the levels of ammonia N and electrical conductivity (EC) measurements were highly correlated with reduction of individual malodorous compounds in wastewater. Seven out of 15 parameters measured (soluble COD, soluble BOD, TKN, ammonia-N, nitrate-N, alkalinity, and EC) were found to be highly related to reduction of total measured malodorous compounds. These results suggest that selected water quality parameters in swine wastewater could assist to evaluate odor control measures when no sensory analysis or appropriate analytical equipment is available. They also indicate that treatment systems incorporating biological N removal can greatly reduce malodorous compounds in liquid swine manure.*

Keywords. *Biological oxygen demand, Chemical oxygen demand, Malodor, Manure, Odor, Swine, Volatile, Wastewater.*

Management of swine manure is a major environmental concern since the traditional treatment technology of anaerobic lagoon-spray field is effective only when sufficient cropland is available for application. When land and demographic conditions are limiting, malodors generated during lagoon storage and treatment and land application of manure may constitute potential health risks to farm workers and neighbors near swine facilities (Schiffman and Williams, 2005). Therefore, advances in manure treatment technologies may offer ways to reduce potential contamination of water and air by concentrated livestock wastes (Robbins, 2005). In particular, there is major interest in North Carolina in developing swine manure treatment systems that could reduce malodors generated by swine production. In July 1997, the state of North Carolina 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 environmentally superior technologies (EST). These EST would eliminate the discharge of waste to surface and ground waters, substantially reduce emission of ammonia and odors, eliminate the release of disease-transmitting vectors and air-borne pathogens, and reduce or eliminate nutrient and heavy metal contamination of soils and waters (Williams, 2001).

In July 2005, only one on-farm technology out of 18 diverse evaluated technologies was determined to meet the environmental performance criteria necessary for EST. This on-farm treatment technology treated the entire waste stream from a swine production unit using a three-stage system with consecutive solids separation, nitrification/denitrification, and soluble phosphorus removal (Williams, 2004; Vanotti et al., 2005a). Treated water was recycled into the animal housing for waste flushing, and excess water from the treatment system was stored in the old lagoon. Thus, the system effectively replaced anaerobic lagoon treatment by discontinuing loading of liquid raw manure into the lagoon. Performance criteria evaluated in the wastewater treatment system included the removal and/or recovery of nutrients, reduction in pathogens, and reduction in ammonia and odor emissions (Vanotti, 2004; Vanotti et al., 2006).

Evaluation of odor-abating waste handling methods consists of sensory analysis by olfactometry with human subjects or analytical methods. The olfactometry approach is cumbersome for routine analysis because rather large odor panels are needed to obtain reliable and reproducible results (Gralapp et al., 2001). Although an independent odor panel evaluation determined that the on-farm treatment system as

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a whole effectively reduced malodor emissions (Schiffman and Graham, 2004), further evaluation using analytical methods was performed in order to determine the relationship between water quality indicators and key odor compounds in successive stages of the wastewater treatment system. For odor evaluation, we used a simplified approach by measuring concentration of selected odor compounds in liquid manure (Loughrin et al., 2006). This approach allowed direct comparison of these compounds with water quality indicators commonly used in wastewater treatment. The use of water quality parameters as indicators of odor levels in wastewater may be useful to evaluate the success of odor control measures where no odor panel or appropriate analytical equipment are available (Williams, 1984). Therefore, our study had the following two objectives: i) evaluate the system's efficiency for odor control, and ii) determine those water quality parameters that serve as indicators for odor reduction.

Materials and Methods

Site Description

The study site was located on Goshen Ridge Farm, Duplin Co., North Carolina. The site had three finishing hog production units with 4400 animals each. Each unit consisted of six houses with one 1.0-ha anaerobic lagoon. The houses operated under a pit recharge system whereby the manure pits under the house flooring were drained by gravity once weekly, and the pits recharged with lagoon-treated liquid (Barker, 1996). As a demonstration project, one of the three production units was retrofitted with full-scale wastewater treatment system (Vanotti et al., 2005b) that was constructed and operated by Super Soil Systems USA (Clinton, N.C.). The system made use of three modules: solid-liquid separation, biological N treatment, and P removal (fig.1). The first module separated solids from raw flushed manure. Prior to entering the solid-liquid separation unit, the raw flushed manure was well mixed in a homogenization tank. Solids were separated using an Ecopurin solids-liquid separation module (Selco, Castellon, Spain) that included injection of a cationic polyacrylamide polymer flocculent, removal of solids in a rotary drum separator, dewatering solids in a belt press, and further separation of residual solids in a dissolved air flotation unit. The solid-liquid separation module produced 596 Mg of separated solids per year that were transported off-site and converted to organic plant fertilizer, soil amendments, or used for energy production (Vanotti, 2004).

The second module treated the liquids after solid separation using a biological N removal system. The project used the Biogreen process (Hitachi Plant Engineering & Construction Co., Tokyo, Japan) that removed N via nitrification/denitrification processes. Nitrification transformed ammonia into nitrate and depleted about 80% of the alkalinity using nitrifying bacteria entrapped in polymer gel pellets in an aeration tank (Vanotti and Hunt, 2000). A pre-denitrification configuration transformed nitrates into N_2 gas where nitrified wastewater was continuously recycled to an anoxic tank (fig. 1). In this tank, suspended denitrifying bacteria used soluble manure carbon contained in the liquid to remove the nitrate (Vanotti et al., 2005b). Hydraulic retention time (HRT) was 31.2 h in the denitrification tank and 13.2 h in the nitrification tank. Thus, elimination of ammonia and reduction of carbonate buffering capacity during N biological removal treatment allowed the recovery of P from the liquid when small amounts of lime were added in the third treatment module.

In the third module, P was recovered as calcium phosphate, and pathogens were destroyed by the alkaline environment (Vanotti et al., 2005a). The effluent from the biological N treatment module was mixed with hydrated lime in a reaction chamber, and the pH of the process was kept at

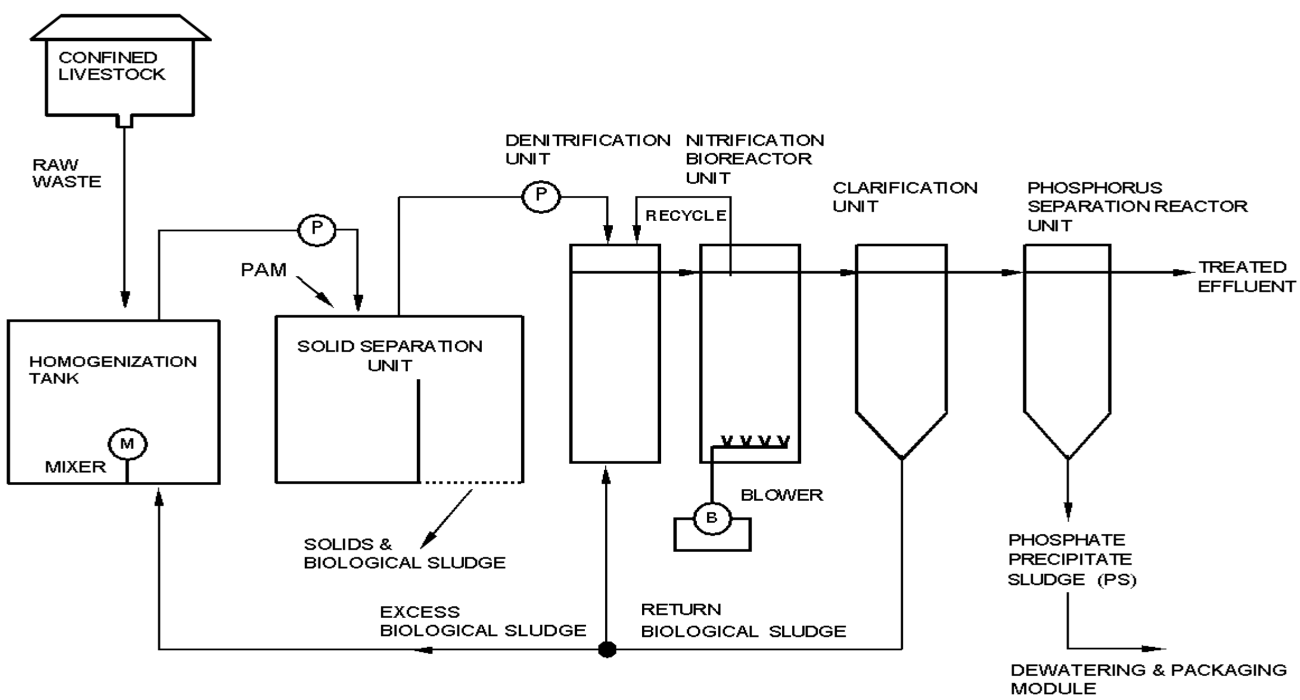

Figure 1. Schematic representation of advanced waste treatment plant.

10.5 to 11.0 by a programmable logic controller. The precipitate was separated in a settling tank. The precipitate was further dewatered in filter bags.

The system treated an average of 39 m^3 per day of raw manure flushed from the barns. The treated water was recycled to refill the barn's pit recharge system (13 m^3 d^{-1}), and excess water was stored (26 m^3 d^{-1}) in the lagoon and later used for crop irrigation. For a detailed description of the full-scale treatment system, see Vanotti et al. (2006).

Sampling

Liquid samples were obtained in five occasions from the wastewater treatment system operating at steady state during a period of two months (September - October 2003; Vanotti, 2004). Samples were taken from the following four points of the wastewater treatment system: 1) the homogenization tank, 2) after solid-liquid separation, 3) after biological N treatment, and 4) final effluent after P treatment (fig. 1). On each sampling date, duplicate 1.0-L composite samples were obtained by using two separate buckets to mix four sub-samples that were collected from tanks using a 500-mL polyethylene dipper with a 3.6-m-long handle. From each composite sample, two 40-mL aliquots were placed in headspace sampling vials and stored on ice until extraction. The remaining liquid of composite samples was used for water quality analysis.

Water Analyses

Volatile compounds were extracted using solid-phase extraction and quantified by gas chromatography as described in Loughrin et al. (2006) while all other water analyses were carried out according to Standard Methods (APHA, 1998). Total suspended solids (TSS) and volatile suspended solids (VSS) were determined according to Standard Methods 2540 D and E, respectively. The TSS were determined gravimetrically after filtration using glass microfiber filters (Whatman grade 934-AH, Whatman Inc., Clifton, N.J.) and drying to constant weight at 105°C, while VSS was that portion of TSS that was lost upon ignition in a muffle furnace at 500?C for 15 min. Chemical analyses consisted of alkalinity, chemical oxygen demand (COD), soluble COD (sCOD), 5-d biochemical oxygen demand (BOD), soluble BOD (sBOD), ammonia-N (NH_3 -N), total Kjeldahl N (TKN), total P, soluble P, pH, and electrical conductivity (EC). Soluble COD, BOD, NH_3 -N, and P were determined in filtrates obtained using 0.45-μm filter membranes. For COD and sCOD determination, we used the closed reflux, colorimetric method (Standard Method 5520 D), while BOD and sBOD were determined using the 5-day BOD test (Standard Method 5210 B). Ammonia-N was determined using the automated phenate method (Standard Method 4500-NH_3 G). TKN was determined by the same phenate method adapted to digested extracts (Technicon Instruments Corp., 1977). The pH was determined by Standard Method 4500-H^+ B and EC by Standard Method 2510 B.

System efficiencies were calculated as the average percentage reduction of water quality indicators and odor compound concentrations in the system's treated effluent (P treatment module) with respect to their initial concentrations in the influent (raw flushed manure). Total odor compound concentration in liquid manure was calculated as the sum of the concentration of the six selected odor compounds.

Summary statistics were performed using PROC Means (SAS, 1999). Significant relationships between water quality parameters and odor compounds were evaluated using linear correlation and regression analysis (Draper and Smith, 1981).

Results and Discussion

Water Quality

The wastewater treatment performance data obtained during the odor study period are presented in table 1 showing the values of various water quality indicators as the liquid passed through each treatment module and the overall efficiency of reduction for these parameters. Solid-liquid separation was effective in separating suspended solids and organic nutrients; most of the volatile and oxygen-demanding organic compounds (VSS, COD, and BOD) were also removed from the liquid by capturing the suspended solids. In the raw flushed manure, TSS and VSS averaged 7248 and 5536 mg L^{-1}, respectively. About 85% of TSS and almost 90% of VSS were removed by the solids separation module. Initial COD levels of 11,536 and BOD of 886 mg L^{-1} in raw flushed manure were reduced 78% and 52%, respectively, in this first treatment stage.

The liquid after solids separation still contained oxygen-demanding organic compounds (COD and BOD), significant amounts of N and P, mostly in soluble form (free ammonia and inorganic phosphate), as well as alkalinity (table 1). The biological N treatment module treated NH_3-N effectively. A pre-denitrification unit transformed NO_3-N into N_2 gas by continuously recycling nitrified wastewater into the denitrification tank (fig. 1). This pre-denitrification unit also consumed a large portion of the remaining total and soluble oxygen-demanding organic compounds (COD, sCOD, BOD, and sBOD). Instead of a relatively inefficient process of breaking down suspended organic compounds in a situation where no liquid-solids separation had been performed, the oxygen supplied during aeration in the nitrification tank was used to efficiently convert NH_3-N into NO_3-N and reduce alkalinity. On average, the biological N treatment reduced TKN, NH_3-N, and alkalinity by almost 90% with respect to their concentration in wastewater after solid-liquid separation. It produced a relatively clean effluent with 109 mg L^{-1} of NH_3-N, 300 mg L^{-1} of NO_3-N, and a slightly acidic pH of 6.8 (table 1).

The slightly acidic conditions prevailed until the liquid reached the P-removal treatment module. There, the pH of the system's effluent was raised above 10.0. This rise in pH has been shown to destroy over 99% of pathogen indicators present in the wastewater and simultaneously precipitate P as a high calcium phosphate content material (Vanotti et al., 2005a). In the P-module, soluble P concentration was reduced by 98% with respect to raw flushed manure (table 1).

Overall, the treatment system was at steady-state and performed efficiently during the odor-monitoring period with respect to elimination of solids, COD, BOD, TKN, NH_3-N, TP, SP, and alkalinity (table 1). The high treatment efficiencies (83% to 100%) during the odor study were similar to those reported for this same system during a 10.5-month (April 2003 to March 2004) monitoring period (Vanotti et al., 2006).

Table 1. Wastewater treatment plant system performance and system efficiency at Goshen Ridge Farm. Data are means during the odor monitoring period (Sept.-Oct. 2003, n = 5).

Water Quality Parameter[a]	Raw Flushed Manure (mg L-1)[c]	Treatment Step: After Solid-Liquid Separation (mg L-1)[c]	After Biological N Treatment (mg L-1)[c]	After Phosphorus Treatment (mg L-1)[c]	System Efficiency[b] (%)
TSS	7248 ± 414[d]	1025 ± 240	103 ± 6	537 ± 112	93
VSS	5536 ± 458	708 ± 147	71 ± 6	155 ± 27	97
COD	11536 ± 248	2505 ± 197	508 ± 9	408 ± 5	96
sCOD	1876 ± 113	1285 ± 95	461 ± 7	290 ± 24	85
BOD	886 ± 225	426 ± 41	26 ± 8	7 ± 3	99
sBOD	299 ± 60	179 ± 32	7 ± 2	4 ± 1	99
TKN	1447 ± 32	960 ± 20	109 ± 8	72 ± 11	93
TP	449 ± 11	153 ± 12	127 ± 2	53 ± 12	88
NH_3−N	852 ± 20	837 ± 18	109 ± 7	50 ± 6	94
NO_3−N	3.1± 0.8	0.5 ± 0.5	337 ± 26	360 ± 19	−−−
NO_2−N	0	0.5 ± 0.5	2.3 ± 1.0	20 ± 6	−−−
SP	104 ± 3	98 ± 4	122 ± 1	1.6 ± 0.1	98
Alkalinity	4641 ± 102	4143 ± 158	300 ± 62	778 ± 60	83
pH	7.73 ± 0.04	7.98 ± 0.02	6.79 ± 0.25	10.15 ± 0.13	−−−
EC	10.2 ± 0.2	10.3 ± 0.3	5.8 ± 0.1	5.0 ± 0.2	−−−

[a] TSS = Total Suspended Solids; VSS = Volatile Suspended Solids; COD = Chemical Oxygen Demand; sCOD = Soluble COD; BOD = Biochemical Oxygen Demand; sBOD = Soluble BOD; TKN = Total Kjeldahl N; TP = Total P; NH_3−N = ammonia−N; NO_3−N = Nitrate+Nitrite−N; NO_2−N = Nitrite−N; SP=Soluble Inorganic P; EC=Electrical Conductivity.
[b] System efficiency compares reduction in concentration of water quality indicator in treated effluent (P treatment module) with respect to influent (raw flushed manure).
[c] Except for pH and EC (mS/cm).
[d] Data represent the mean of 5 determinations ± standard error of the mean.

Reduction of Selected Odor Compounds in Wastewater

Data on selected malodorous compounds from the wastewater are presented in table 2. All measured compounds make important contributions to manure malodor due to their characteristic odors and low detection thresholds (Spoelstra, 1980; Nagata and Takeuchi, 1990; Schiffman et al., 2001). Although volatile fatty acids (VFA) are often cited as important contributors to fecal malodors (Spoelstra, 1980; Williams, 1984; Zahn et al., 2001), we decided not to measure them in our study. This decision was based on two early observations that made VFA determination not reliable to assess changes of malodor compound concentrations in the liquid of the treatment system evaluated. The first one is the dependence of VFA solubilities on pH. Alkaline pH of the wastewater stream (table 1) would make VFA less volatile and therefore lessen their contribution to malodor (Spoelstra, 1980; Miller and Berry, 2005). The second observation is that VFA tend to accumulate during long-term storage of manures and are found in lower amounts in fresh wastes (Miller and Varel, 2003), which is a problem for our study because we assessed a wastewater treatment that treated fresh manure. We concluded, therefore, that the six selected compounds – phenol, *p*-cresol, *p*-ethylphenol, *p*-propylphenol, indole, and skatole – served as good indicators for overall odor quality in this wastewater stream. The monitored compounds averaged about 207 ng mL^{-1} in raw flushed manure, with skatole and *p*-cresol comprising almost 80% of this total (table 2). Because of their low detection thresholds and relatively high concentration, skatole and *p*-cresol are likely to be largely responsible for the objectionable odor of this raw flushed manure.

Table 2. Reduction of odor compounds contained in the liquid by the treatment system at Goshen Ridge Farm, (Duplin Co., N.C.) measured by solid phase extraction.[a]

Odor Compound	Raw Flushed Manure (ng mL^{-1} water)	Treatment Step: After Solid-Liquid Separation (ng mL^{-1} water)	After Biological N Treatment (ng mL^{-1} water)	After Phosphorus Treatment (ng mL^{-1} water)	System Efficiency[b] (%)
Phenol	11.8 ± 2.0	5.4 ± 1.4	3.5 ± 1.4	2.2 ± 1.2	81.3
p-Cresol	34.9 ± 7.6	53.5 ± 39.5	0.08 ± 0.03	0.06 ± 0.01	99.8
p-Ethylphenol	21.6 ± 12.2	13.9 ± 8.2	0.07 ± 0.03	0.05 ± 0.01	99.8
p-Propylphenol	5.2 ± 1.0	3.8 ± 1.1	0.08 ± 0.03	0.06 ± 0.01	98.9
Indole	3.5 ± 1.9	4.8 ± 0.4	0.84 ± 0.5	0.23 ± 0.16	93.5
Skatole	130 ± 28.0	100 ± 27.5	0.07 ± 0.03	1.72 ± 1.02	98.7
TOTAL	207 ± 52.6	182 ± 78.0	4.61 ± 2.0	4.3 ± 2.4	97.9

[a] Data represent the mean of five determinations ± standard error of the mean.
[b] System efficiency compares reduction in odor compound concentration in effluent (P treatment module) with the odor concentration in the influent (raw flushed manure).

Very small reduction of odor compounds was found between raw flushed manure and after solid-liquid separation. This was because solid phase extracts of water mostly contained odor compounds dissolved in the aqueous phase but very few odor compounds that were associated with suspended solids (ter Laak et al., 2005). Therefore, it seemed unlikely that much difference in the levels of malodorous compounds would be seen between raw flushed manure and after solid-liquid separation even though a great deal of the solids was removed in the first stage of the solids separation process.

It appears that major reduction of malodorous compounds in waste treatment systems may occur due to anoxic treatment with nitrate serving as the terminal electron acceptor (Bories et al., 2005). After biological N treatment, we found a marked reduction in malodorous compounds (table 2). Most probably, the dramatic reduction in odor compounds after biological N treatment occurred in the denitrification module where over 80% of the NO_3-N in the wastewater was removed by utilization of soluble carbon remaining in the wastewater after solids separation. Recycling into the nitrification tank may have further removed remaining odor compounds by oxidation supplied with aerators (fig. 1). Reduction of malodor compounds was minimal after P-removal; minor amounts of phenol, indole, and skatole were detected in the P-removal module (table 2).

Although compounds were undoubtedly lost by volatilization, we do not feel that this was a major route to reduction of malodorous compounds in the wastewater stream. An independent study using a trained odor panel and dispersion modeling evaluated the odorous emissions from swine houses, raw flushed manure, homogenization tank, denitrification/nitrification tanks, treated effluent, and at varying distances downwind from the production unit (Schiffman and Graham, 2004). That study indicated that odor emission from the wastewater treatment system was almost negligible when odor emissions from the animal housing were subtracted from the total odor contribution of the production unit. Our analytical study arrived to a similar conclusion since monitored malodorous compounds in water were reduced by about 98% by the wastewater treatment system (table 2). Most of this percent reduction in the wastewater treatment system occurred after the biological N treatment module.

Water Quality Parameters as Odor Reduction Indicators

The use of certain water quality parameters as indicators of probable odor compound levels in wastewater may assist research in evaluating liquid swine waste treatment systems for odor control when techniques such as gas chromatography or olfactometry are not available. A study made to relate chemical characteristics to the odor of liquid swine waste indicated that the offensiveness of swine waste odor correlated linearly with the logarithm of BOD in aerobic systems (Williams, 1984). In another study, Loughrin et al. (2006) found that BOD was linearly related to total odor compound concentration in liquid of anaerobic and aerobic swine lagoons. Table 3 shows the correlation coefficients between 15 water quality parameters versus individual and total odor compounds; several commonly used water quality indicators, such as NH_3-N, EC, and alkalinity, correlated well with concentration in liquid of odor compounds during wastewater treatment.

No single water quality parameter served as the sole indicator for the levels of all six odor compounds that we measured in wastewater (table 3). However, for all compounds except phenol, the levels of NH_3-N and EC were highly correlated with reduction in malodor. Interestingly, NO_3-N levels were inversely correlated with the levels of most malodor compounds. This finding makes sense in that the influent was characterized by high levels of NH_3-N and low levels of NO_3-N, while this situation was reversed in system-treated effluent after biological N treatment (table 1).

Table 3. Linear correlation coefficient (r) between water quality indicators and odor compounds in the liquid of the treatment system at Goshen Ridge Farm (Duplin Co., N.C.).

Water Quality Indicator[a]	Odor Compound in Liquid						
	Phenol	*p*-Cresol	*p*-Ethylphenol	*p*-Propylphenol	Indole	Skatole	Total
TSS	0.97*[b]	0.41ns	0.85ns	0.80ns	0.45ns	0.78ns	0.72ns
VSS	0.97*	0.42ns	0.85ns	0.81ns	0.46ns	0.79ns	0.73ns
COD	0.99*	0.49ns	0.89ns	0.85ns	0.53ns	0.83ns	0.78ns
sCOD	0.94ns	0.80ns	0.99*	0.99*	0.84ns	0.98*	0.97*
BOD	0.97*	0.72ns	0.98*	0.97*	0.75ns	0.96*	0.93ns
sBOD	0.94ns	0.80ns	0.99*	0.99*	0.83ns	0.99*	0.97*
TKN	0.93ns	0.83ns	0.99*	0.99*	0.85ns	0.99*	0.98*
TP	0.99*	0.47ns	0.87ns	0.84ns	0.53ns	0.81ns	0.76ns
NH_3-N	0.79ns	0.95*	0.96*	0.98*	0.97*	0.98*	0.99*
NO_3-N	-0.78ns	-0.96ns	-0.95*	-0.97*	-0.97*	-0.98*	-0.99*
NO_2-N	-0.62ns	-0.62ns	-0.63ns	-0.65ns	-0.71ns	-0.64ns	-0.66ns
SP	0.47ns	0.39ns	0.41ns	0.42ns	0.50ns	0.41ns	0.42ns
Alkalinity	0.82ns	0.92*	0.98*	0.99*	0.93ns	0.99*	0.99*
pH	0.36ns	0.22ns	0.26ns	0.26ns	0.37ns	0.25ns	0.26ns
EC	0.78ns	0.96*	0.95*	0.97*	0.97*	0.97*	0.99*

[a] TSS = Total Suspended Solids; VSS = Volatile Suspended Solids; COD = Chemical Oxygen Demand; sCOD = Soluble COD; BOD = Biochemical Oxygen Demand; sBOD = soluble BOD; TKN = Total Kjeldahl N; TP = Total P; NH_3–N = ammonia–N; NO_3–N = Nitrate–N; NO_2–N = nitrite–N; SP = Soluble Inorganic P; EC = Electrical Conductivity.

[b] * indicates probability (P < 0.05) that r = 0; ns indicates r is not significantly different from 0.

For total measured malodorous compounds, seven water quality parameters (sCOD, sBOD, TKN, NH_3-N, NO_3-N, alkalinity, and EC) were found to be significantly related to reductions in malodor (table 3). These relationships are summarized by treatment stage in figure 2. As a result of the biological N module, NO_3-N is the only water quality indicator that increased markedly in the system effluent as compared to raw flushed manure. Thus, it was the only parameter that showed negative correlation and regression line coefficients. While the utility of water quality parameters as a measure of odor reduction indicators needs further investigation, our results indicate that commonly measured water quality parameters, such as NH_3-N, NO_3-N, or EC, can be used as semi-quantitative yardsticks for probable levels of malodor. Therefore, this approach could be used to evaluate odor control measures where no odor panel or appropriate analytical equipment is available.

Conclusions

Results from this study demonstrate that the full-scale wastewater treatment system using consecutive solids separation, biological N, and soluble P removal treatment stages effectively produced a clean effluent and eliminated 98% of selected malodorous compounds from raw flushed manure. Most of this percent reduction in the wastewater treatment system occurred after the biological N treatment module.

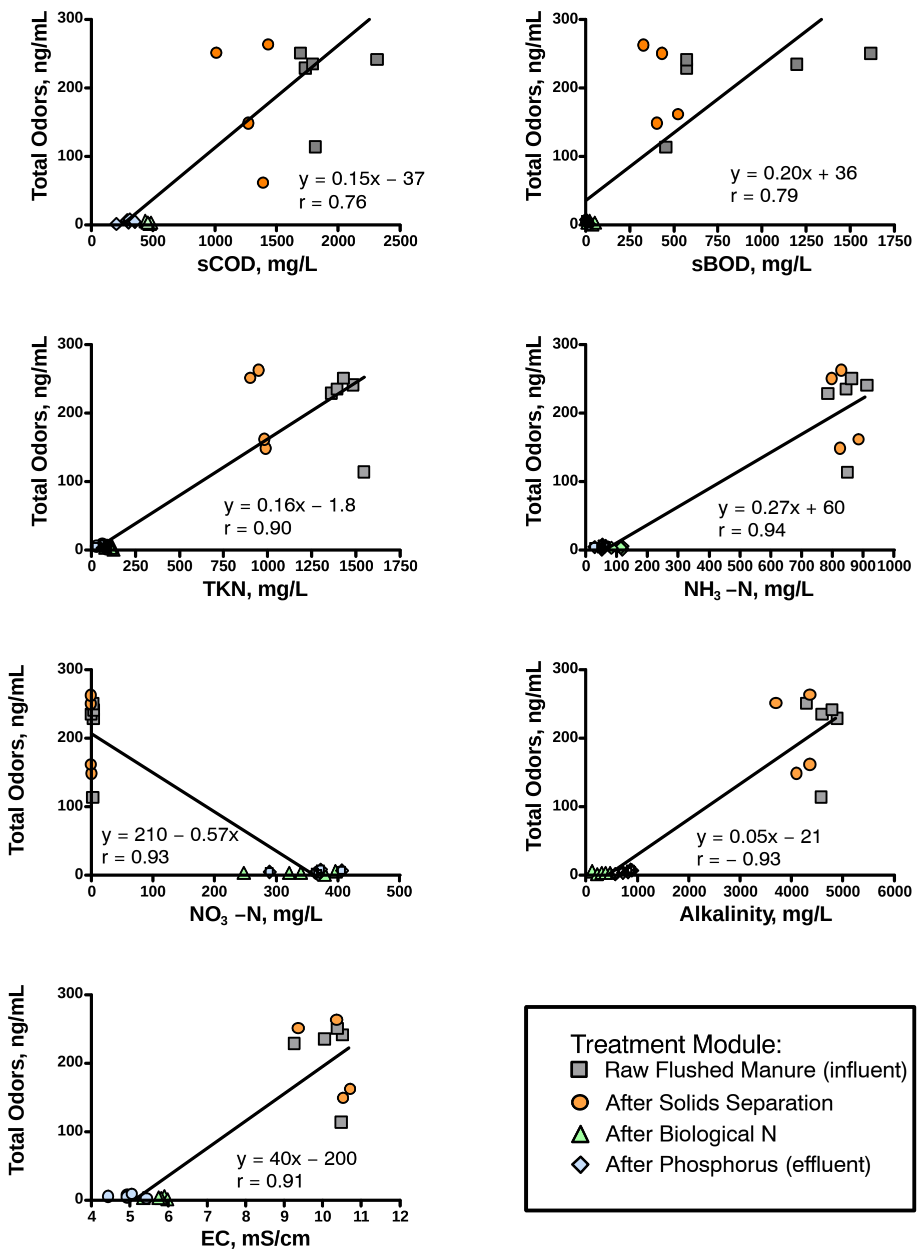

Figure 2. Relationship of mean concentration of total measured malodorous compounds vs. mean sCOD, sBOD, TKN, NH_3-N, NO_3-N, EC, and alkalinity measured in successive stages of the wastewater treatment system Goshen Ridge Farm (Duplin Co., N.C.). Each data point is the mean of duplicate sample analyses. All regression coefficients differ statistically from 0 with P < 0.01.

No single water quality parameter served as the sole indicator for the levels of all six odor compounds that we measured in wastewater. Except for phenol, the levels of NH_3-N and EC were highly correlated with reduction of individual malodor concentrations. Seven out of 15 parameters measured (sCOD, sBOD, TKN, NH_3-N, NO_3-N, alkalinity, and EC) were found to be highly related to reduction of total measured malodorous compounds. These results suggest that use of selected water quality parameters as indicators of probable odor levels in wastewater may assist to evaluate odor control measures when no odor panel or appropriate analytical equipment are available.

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References

APHA. 1998. *Standard Methods for the Examination of Water and Wastewater*, 20th ed. Washington, D.C.: American Public Health Association, American Water Works Association, and Water Environment Federation.

Barker, J. C. 1996. Effects of manure management practices on air quality and animal performance in swine production buildings. N.C. Cooperative Extension Service Pub. No. EBAE 180-03. Raleigh, N.C.

Bories A., Y. Sire, and T. Colin. 2005. Odorous compounds treatment of winery and distillery effluents during natural evaporation in ponds. *Water Sci. Technol.* 51(1): 129-136.

Draper, N. R., and H. Smith. 1981. *Applied Regression Analysis*. New York: John Wiley & Sons.

Gralapp, A. K., W. J. Powesand, and D. S. Bundy. 2001. Comparison of olfactometry, gas chromatography, and electronic nose technology for measurement of indoor air from swine facilities. *Transactions of the ASAE* 44(5): 1283-1290.

Loughrin, J. H., A. A. Szogi, and M. B. Vanotti, 2006. Reduction of malodorous compounds from a treated swine anaerobic lagoon. *J. Environ. Qual.* 35(1): 194-199.

Miller, D., and V. Varel. 2003. Swine manure composition affects the biochemical origins, composition, and accumulation of odorous compounds. *J. Anim. Sci.* 81(9): 2131-2138.

Miller, D., and E. Berry. 2005. Cattle feedlot soil moisture and manure content: I. Impacts on greenhouse gases, odor compounds, nitrogen losses, and dust. *J. Environ. Qual.* 34(2): 644-655.

Nagata, Y., and N. Takeuchi. 1990. Measurement of odor threshold by triangle odor bag method. *Bull. Japan Environ. Sanitation Center* 17: 77-89.

Robbins, J. H. 2005. *Understanding Alternative Technologies for Animal Waste Treatment.* Washington, D.C.: Water Keeper Alliance.

SAS. 1999. SAS Version 8.00. Cary, N.C.: SAS Institute, Inc.

Schiffman, S. S., J. L. Bennett, and J. H. Raymer. 2001. Quantification of odors and odorants from swine operations in North Carolina. *Agric. Forest Meteorol.* 108(3): 213-240.

Schiffman, S. S., and B. G. Graham. 2004. Comparison of odor dispersion at swine facilities and a waste processing center using a Eulerian-Lagrangian model. Raleigh, NC: North Carolina State Univ. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase1report04/A.10odorpdf. Accessed 13 April 2006.

Schiffman, S. S., and C. M. Williams. 2005. Science of odor as a potential health issue. *J. Environ. Qual.* 34(1): 129-138.

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(3): 241-260.

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

ter Laak, T., P. Mayer, F.Busser, H. Klamer, and J. Hermens. 2005. Sediment dilution method to determine sorption coefficients of hydrophobic organic chemicals. *Environ. Sci. Technol.* 39(11): 4220-4225.

Vanotti, M. B., and P. G. Hunt. 2000. Nitrification treatment of swine wastewater with acclimated nitrifying sludge immobilized in polymer pellets. *Transactions of the ASAE* 43(2): 405-413.

Vanotti, M. B. 2004. Evaluation of environmentally superior technology: Swine waste treatment system for elimination of lagoons, reduced environmental impact, and improved water quality. Raleigh, N.C.: North Carolina State Univ. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase1report04/A.9Super%20Soil%20final.pdf. Accessed 13 April 2006.

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. *Bioresource Technol.* 96(2): 209-214.

Vanotti, M. B., A. A. Szogi, and P. G. Hunt. 2005b. Wastewater treatment system. U.S. Patent 6,893,567. Washington, D.C.: U.S. Patent Office.

Vanotti M. B., A. A. Szogi, P. G. Hunt, P. D. Millner, and F. J. Humenik. 2006. Development of environmentally superior technology to replace anaerobic swine lagoons in the USA. *Bioresource Technol.* (in press).

Williams, A. G. 1984. Indicators of piggery slurry odour offensiveness. *Agric. Wastes* 10(1): 15-35.

Williams, C. M. 2001. Smithfield and Premium Standard Farms program implementation. In *International Symposium Addressing Animal Production and Environmental Issues*, ed. G. B. Havenstein, 18-21. Raleigh, N.C.: North Carolina State University, College of Agriculture and Life Sciences.

Williams, C. M. 2004. Development of Environmentally Superior Technologies. Phase I Report for Technology Determination per Agreements Between the Attorney General of North Carolina and Smithfield Foods, Premium Standard Farms and Frontline Farmers. Raleigh, N.C.: North Carolina State Univ. Available at http://www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase1report04/front.pdf. Accessed 13 April 2006.

Zahn, J. A., A. A. DiSpirito, Y. S. Do, B. E. Brooks, E. E. Cooper, and J. L. Hatfield. 2001. Correlation of human olfactory responses to airborne concentrations of malodorous volatile organic compounds emitted from swine effluent. *J. Environ. Qual.* 30(2): 624-634.