

AIR POLLUTION FROM SWINE PRODUCTION FACILITIES DIFFERING IN WASTE MANAGEMENT PRACTICE

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ABSTRACT

Gaseous emissions from swine manure storage systems represent a concern to air quality due to the potential impacts of hydrogen sulfide, ammonia, methane, and volatile organic compounds on environmental quality, human health, and wellbeing. The lack of knowledge concerning functional aspects of swine manure management systems has been a major obstacle in the development and optimization of emission abatement technologies for these point sources. In this study, a classification system based on emission characteristics and solution-phase concentrations of phosphorus (P) and sulfur (S) was devised and tested on 29 swine manure management systems in Iowa, Oklahoma, and North Carolina in an effort to elucidate functional characteristics of swine manure management systems. Four swine manure management system classes were identified that differed in solution-phase concentrations of P and S, methane emission rate, odor intensity, and air concentration of volatile organic compounds (VOCs). Odor intensity and the air concentration of VOCs emitted from swine manure management systems were shown to be strongly correlated ($r^2 = 0.88$). The concentration of VOC in air samples from the 29 swine manure management systems was highest with high-load, outdoor manure management systems (Type 2). These swine manure management systems were also observed to have the highest odor intensity levels. Volatile organic compound (VOC) emission rate and odor intensity for swine manure management systems were found to be inversely correlated with methane and ammonia emission rates. Emission rate of methane, ammonia, and volatile organic compounds were found to be dependent upon manure loading rate and indirectly influenced by animal numbers. Data show that current swine production activities have the potential to produce up to 386 tons of air pollutants • site⁻¹ • year⁻¹.

KEYWORDS

Odor, Swine Production, Manure Management, Volatile Organic Compounds, Concentrated Animal Feeding Operations.

INTRODUCTION

In the United States, approximately 157,000 swine production facilities produce 103,000,000 hogs yr⁻¹ that are marketed in the U.S. and globally (ASAE, 1988; Harkin, 1997). Annually, these production facilities produce more than 116,652,300 tons yr⁻¹ of manure that is often stored for periods up to 13 months before land application (ASAE, 1988; Harkin, 1997). Air quality studies have indicated that emissions released from stored swine manure have the potential to decay local, regional, and global air quality through the discharge of ammonia (NH₃) (Harper and Sharpe, 1997; Asman, 1995), nitrous oxide (N₂O) (Eklund and LaCrosse, 1995; Sharpe and Harper, 1998), methane (CH₄) (Safley et al., 1992; Sharpe and Harper, 1997), hydrogen sulfide (H₂S) (Jacobson et al., 1997a), particulate matter (VanWicklen, 1997), and volatile organic compounds (VOCs) (Zahn et al., 1997). Much research has focused on the development of strategies to reduce or eliminate emissions and odors from stored animal manure. However, a major part of this research has not been applied by the swine industry due to economic restrictions or due to sporadic or ineffective performance of emission abatement approaches (Miner, 1982; Miner, 1995; Miner, 1999). Performance evaluations of emission abatement strategies often cite poorly understood microbiological processes or other poorly defined intrinsic properties of swine manure management systems as the reason for ineffective performance of a particular emission abatement method (Miner, 1995). However, the exact cause for many of these failures has remained speculative due to the lack knowledge concerning functional aspects of animal manure management systems.

The purpose of this research was to develop a method to functionally classify swine manure management systems based on solution-phase chemical properties and emission rates of CH₄, NH₃, H₂S, and VOC. A reliable method to functionally classify manure management systems would serve the agricultural industry as a management tool in evaluating best management practices for swine manure storage systems and would serve regulators as a rapid method to identify production sites that represent a potential air quality or nuisance concern.

METHODOLOGY

Physical and Chemical Characterization of Stored Manure

Three effluent samples (200 ml each) were taken at the surface of the manure management system at a minimum distance of 2.5 meters from the edge of the storage impoundment. This sampling strategy was justified based on a previous study by DiSpirito et al., (1995), that showed the absence of biological or chemical stratification throughout the solution column of a lagoon system during the summer and fall seasons. Total carbon (C), nitrogen (N), and hydrogen (H) was determined on oven (100° C) dried slurry samples using a Model 2100 Perkin Elmer CHN analyzer. Percent values were converted to g L⁻¹ values based on solids content determined by gravimetric methods.

Volatile solids concentration was determined by the difference in weight of oven-dried (100° C) and ashed (550° C) samples. Analysis of main-group elements and transition metal cations was performed on microwave digested (method SW 846-3015, CEM Corp., 1996) slurry samples according to EPA method SW 846-3015 (CEM Corp., 1996). Quantitative analysis of digested samples was performed using a Thermo Jarrel Ash Model ICAP 61E Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES). Other physical and chemical parameters evaluated in this study included pH, temperature, and bacterial chlorophyll *a* and *b* concentration. The pH and temperature values for slurry samples were an average from six individual pH measurements taken at different locations in the manure management system with a portable pH/temperature meter. Bacteriochlorophyll *a* and *b* was determined as previously described by Siefert et al. (1978) and DiSpirito et al. (1995). The bacteriochlorophyll *a* concentration was calculated spectrophotometrically using a molar absorptivity coefficient of $\epsilon_{777} = 75 \text{ cm}^{-1} \text{ mM}^{-1}$. Lagoons with bacteriochlorophyll *a* concentrations above 40 nmol/ml are subsequently referred to as “photosynthetic lagoons”.

Description of Swine Manure Storage Facilities, Placement of Air Monitoring Equipment, and Statistical Analyses

Loading criteria and individual site descriptions for 29 swine manure management systems located in Iowa (n = 24), Oklahoma (n = 2), and North Carolina (n = 3) that were sampled during the months of August and September 1997 are described in Table 1. Individual manure management systems were separated into four main categories (Type 1, Type 2, Type 3, and Type 4) based on the concentration of P and S present in liquid/slurry samples. Average physical and chemical properties, as well as management attributes for these systems are summarized in Table 1. Meteorological conditions (wind speed, relative humidity, irradiance, solution temperature at 10 cm, and air temperature) were monitored at 0.5 minute intervals during sample collection by an integrated weather station (Sauer and Hatfield, 1994) positioned near the center or on the downwind edge of the manure storage system.

Statistical evaluation of data and experimental designs were performed with JMP version 3 statistical discovery software (SAS Institute, Inc., Cary, NC).

Capture and Analysis of Air Pollutants from Swine Manure Management Systems

Volatile organic compounds (VOC) were captured on a multibed adsorbent tube containing a combination of Tenax TA and Carboxen-569 (Supelco, Bellefonte, PA), according to the low-volume sampling method developed by Zahn et al. (1997). For air sampling of VOC, flow rate through individual thermal desorption tubes was precisely regulated at 0.75 or 1.0 L min⁻¹ using thermal mass flow controllers (Series 810, Sierra Instruments, Inc., Monterey, CA) that were connected to a common, high-vacuum manifold. Desorption tubes were analyzed by gas chromatography using a flame ionization or mass selective detector as previously described by Zahn et al. (1997).

Ammonia (NH₃) was collected from air using two glass impingers (210 ml internal volume) arranged in series, each containing 25 grams of 2 mm glass balls. Air samples were drawn by vacuum through a submerged fritted glass diffusion tube into 60 ml of 0.2M boric acid using a Buck IH sampling pump operated at 1.0 L min⁻¹. The boric acid solution was replaced in 30 to 120 minute intervals depending on proximity of the sampler to the emission source. Ammonium concentration was determined by the salicylate-nitroprusside technique according to U.S. EPA method 351.2 (U.S. EPA, 1979). Solutions of ammonium chloride in 0.2M boric acid were utilized as reference standards to determine ammonium ion concentration. Hydrogen sulfide (H₂S) and CH₄ were collected in 1.0 L Tedlar gas sampling bags and evaluated in the laboratory by previously described gas chromatographic methods using either a 0.32 mm x 30 m SPB-1 sulfur fused silica column with flame photometric detection (Bulletin 876, Supelco, Inc., Bellefonte, PA) or a 1/8" x 8' HayeSep-Q packed column with thermal conductivity detection (Chan et al., 1998), respectively. Air samples for H₂S and CH₄ analysis were collected in 1.0 L Tedlar gas sampling bags using a model 1062 grab sampler (Supelco, Bellefonte, PA) operated at 25 mL min⁻¹. Teflon surfaces were equilibrated with analytes (H₂S and CH₄) present in the air sample by performing four fill-purge cycles before collection of the final air sample. Lead acetate strips (Model #701, VICI Metronics Inc., Santa Clara, CA) were utilized at the point of air sample collection (by Tedlar bag methods) to confirm gas chromatographic results for the quantification of H₂S. The concentration of CH₄ in air was also determined in real-time at two of the 29 swine production facilities using a tunable-diode laser system operated in the infrared region at 2968.4034 cm⁻¹, as previously described by Simpson et al., (1995). A combination of the air sampling methods described above were used to validate the H₂S and CH₄ sampling techniques.

Flux Rate Measurements of Air Pollutants from Swine Manure Management Systems

Flux rate measurements for CH₄ emitted from outdoor manure management systems (lagoons, earthen basins, cement-lined basins, and steel-lined tanks) were determined using a flux chamber previously described by DiSpirito and Zahn (1998). Operational parameters were modified from a semi-static to dynamic mode by installation of a sweep gas manifold. Compressed air (containing 1.1 ppm CH₄) sweep gas was provided to the enclosure at a flow rate of 2.0 L min⁻¹ in a demand mode. Air pressure within the chamber was maintained at barometric pressure through the use of a silicone oil (impinger) purge valve, positioned on gas supply manifold. The static pressure differential was maintained at 0 ± 1.5 kPa throughout the collection period with the use of a mercury manometer. Gases were removed from the chamber through 0.635 cm ID Teflon tubing that was attached to a vacuum pump through an inline mass flow controller set at 2.0 L min⁻¹, following a 1 hr chamber equilibration period. The concentration of CH₄ in air samples was converted to trace gas flux density (f) through the equation:

$$f = (s/a) * (C_o - C_i) \text{ where:}$$

s = sweep flow rate (2.025 L min⁻¹), A = chamber basal area (2500 cm²), C_o = concentration of methane in the exit air (mg m⁻³), and C_i = concentration of CH₄ in the sweep gas (0.77 mg m⁻³).

The dynamic flux chamber method was found inappropriate for determining the flux rate of H₂S and VOC due to the low concentration, long equilibrium times, or potentially the condensation/reaction of these gases on chamber surfaces. The latter observation is supported by previous studies showing significant reduction of VOC collected from air if samples were drawn through glass or polymeric tubing (Zahn et al., 1997). Alternatively, meteorological techniques employing the Theoretical-Profile-Shape method for determining evaporative fluxes (Majewski, 1990) were used to evaluate VOC, H₂S, NH₃, and CH₄ emissions at four sites that were chosen to represent the four major system subtypes. Measurements were based on the concentration of airborne analytes present at a measurement height (z) and meteorological data, collected at the same point. Measurement height (z) was associated with system surface area and was calculated through trajectory-simulation models (Wilson et al., 1982). Additional air samples (2-5 samples) were collected upwind and laterally from the manure storage system to assess background air concentrations of target analytes and to confirm the source of these emissions.

Flux rate measurements for naturally-ventilated indoor manure management systems (animal confinements) were calculated by the sensible heat balance method. The sensible heat produced by pigs was estimated with the CIGR heat production equations (CIGR, 1992) that were based on pig weight and the ambient temperatures measured 0.5 m above the floor. Due to the similarities in construction of naturally-ventilated buildings sampled in this study, a single exposure factor was utilized in calculation of sensible heat balance (1390 W °C⁻¹). The equation utilized to calculate ventilation rate from temperature measurements was:

$$Q_v = (v/c_p) * (T_i - T_o) * (q_a - E(T_i - T_o)) \text{ where:}$$

Q_v = ventilation rate, m³ h⁻¹; v = specific volume of air, m³ kg⁻¹; c_p = specific heat of air, J kg⁻¹ * °C⁻¹; T_i = inside temperature, °C; T_o = outside temperature, °C; q_a = animal sensible heat, W; E = exposure factor of the building, 1390 W °C⁻¹. Alternatively, exhaust flow rate was determined experimentally in mechanically-ventilated animal confinements by monitoring exhaust flow rate at pit fan and ventilation fan orifices using an anemometer.

Evaluation of the Odor Intensity of Emissions from Swine Manure Management Systems

Odor intensity was measured by the method of direct scaling in reference to an odor standard of defined intensity using three to four trained panelists (Cain et al., 1998; Degel and Koster, 1998; Liden et al., 1998; Livermore and Laing, 1998). Direct scaling was based on estimation of the intensity of olfactory sensations associated with an odor source by assigning numerical values to sensory stimuli. Sensory responses were normalized against the artificial swine odor reference standard “Z-2” (Zahn and DiSpirito, 1999), that consisted of: 0.05 mM dimethyl disulfide, 8 mM acetic acid, 3.5 mM propionic acid, 0.5 mM isobutyric acid, 0.4 mM 2-butanol, 1.4 mM butyric acid, 0.2 mM isovaleric acid, 0.5 mM valeric acid, 0.1 mM isocaproic acid, 0.2 mM caproic acid, 0.2 mM heptanoic acid, 0.1 mM indole, 0.15 mM 3-methyl indole, 0.2 mM 4-methyl phenol, 0.12 mM 4-ethyl phenol, 0.15 mM phenol, 0.1 mM benzyl alcohol, 0.1 mM butylated hydroxytoluene, and 8 mM ammonium acetate. Chemical composition of the artificial swine odor Z-2 was optimized in a laboratory dynamic flux chamber to mimic emission parameters for VOCs emitted from a manure sample collected from a high-odor, Type 1 swine manure management system (Zahn and DiSpirito, 1999). Pure compounds were dissolved in warm (45° C) water while stirring and the solution pH was frequently adjusted to pH 6.8 with 2 M potassium hydroxide. Approximately 15 mL of the solution was transferred to an amber serum vial (30 ml nominal volume), was capped with a silicone/Teflon septum, and then degassed under repeated cycles of vacuum and argon to create an anaerobic headspace. Samples were stored in the dark at ambient temperatures until they were used. Panelists were provided the synthetic swine odor solution Z-2 in an uncapped 30 ml serum vial, a solution of 2 mM n-butanol in a 30 ml serum vial, and a site odor evaluation worksheet, previously described by Zahn (1997). Panelists then evaluated the n-butanol solution that was considered neutral (grade 3/10), and the Z-2 solution that was considered unpleasant (grade 6.5/10), at a neutral distance (>1000 m) from the waste management system. Panelists were then positioned in the emission plume from the waste management system (~ 1.5 m from the emitting source) and asked to compare the odor intensity to the reference standards. Numerical evaluations of the swine manure management systems ranged from neutral (3) to unbearable (10), and are reported as the sample mean. Air samples for VOC analysis were collected at the receptor throughout the evaluation.

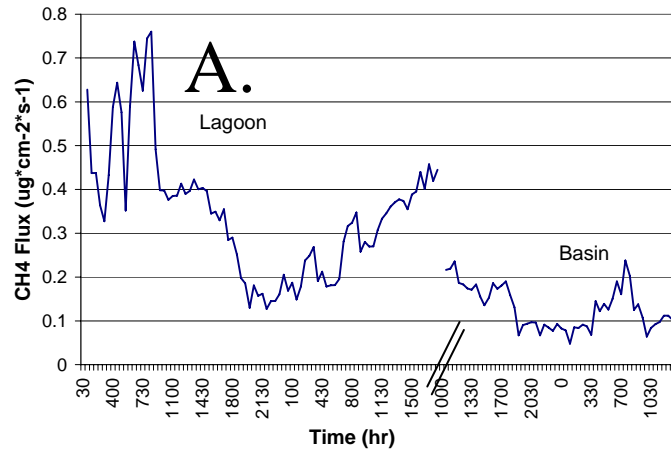
RESULTS AND DISCUSSION

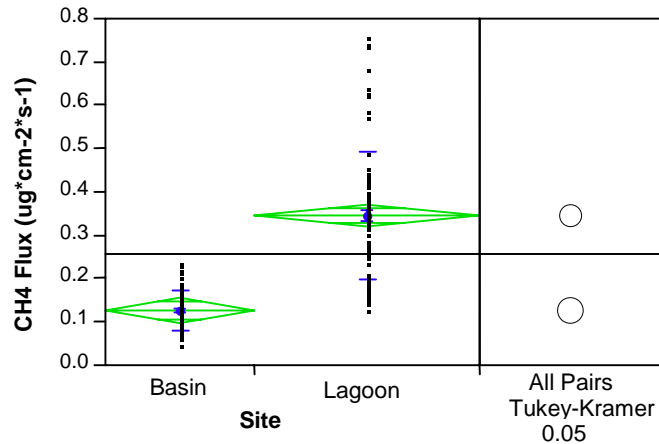
Influence of Loading Rate on Methane Emission From Stored Swine Manure

Studies were conducted on two types of manure management systems located on a feeder-to-finish swine production facility in central Iowa in August 1997 to assess differences in methane (CH₄) emission rate that could be attributed to differences in manure management system environment. Swine waste material entering the manure management system environments originated from animals of the same breeding population that were fed identical diets, were of similar weight, and were managed under similar management routines (feeding schedules and rates). Volatile solids loading rate, however, differed between the two systems by over 300-fold (37 *versus* 0.12 kg volatile solids*day⁻¹*m⁻³). For the basin system (37 kg volatile solids*day⁻¹*m⁻³), wastes were

emptied daily from the confinement into an outdoor concrete holding tank and for the lagoon system ($0.12 \text{ kg volatile solids} \cdot \text{day}^{-1} \cdot \text{m}^{-3}$), wastes were flushed into the earthen holding basin by an intermittent loop flush system. CH_4 flux measurements were performed on three separate occasions in August 1997 with a tunable-diode laser system over the center of the manure management systems using the theoretical-profile-shape method for measuring evaporative fluxes. While similar CH_4 flux values were observed for systems over the three separate sampling periods, only a single comparison is reported, since this sampling period demonstrated the greatest similarity between sites for environmental conditions known to influence CH_4 flux. Measured environmental conditions included wind speed (2.2 ± 0.14 versus $2.4 \pm 0.12 \text{ m s}^{-1}$ [mean and standard error mean]), irradiance (298 ± 35 versus $305 \pm 30 \text{ W cm}^{-2}$), relative humidity (RH) (85 ± 2 versus $78 \pm 2 \%$ RH), air temperature (18.6 ± 0.4 versus $22.6 \pm 0.5^\circ\text{C}$) and solution temperature at a 10 cm depth (27 ± 0.2 versus $23 \pm 0.3^\circ\text{C}$) for the lagoon and basin, respectively. Results from CH_4 measurements indicated that there were statistically-significant differences in both specific emission rate (0.35 ± 0.02 versus $0.13 \pm 0.01 \mu\text{g CH}_4 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ [mean and standard error mean]) and system emission rate (14.7 versus $0.5 \text{ g CH}_4 \cdot \text{system}^{-1} \cdot \text{s}^{-1}$) for the lagoon and basin, respectively (Fig. 1).

FIGURE 1. Flux rate of methane from swine waste management systems differing in volatile solids loading rate. The (A) methane flux over a 30 hr period from a swine waste lagoon ($0.12 \text{ kg volatile solids} \cdot \text{day}^{-1} \cdot \text{m}^{-3}$) and over a 25 hr period for a swine manure basin ($37 \text{ kg volatile solids} \cdot \text{day}^{-1} \cdot \text{m}^{-3}$). The time period between CH_4 measurements for sites was approximately 16 hours, which is indicated by the broken X-axis. Oneway Anova (B) for methane flux data and the Tukey-Kramer HSD means comparison table showing the absolute difference in the means minus the least significant difference.





B. Current literature values for CH₄ emissions from stored swine wastes have been reported over a range of nearly two orders of magnitude (Harper and Sharpe, 1997; Eklund and LaCosse, 1995). Harper and Sharpe (1997) proposed that the discrepancies between emission values might be explained by differences in measurement methods or due to atypical flux event periods. In addition to these explanations, results described in these experiments indicate that manure management environment, and specifically loading rate, may significantly influence the flux rate of CH₄. While these observations are not novel in the context of laboratory anaerobic digestion processes (Oleszkiewicz and Sharma, 1990; Hill and Bolte, 1989), they do represent the first report of such a phenomena occurring under production scale conditions in an animal manure management system. The proceeding experiments were focused on defining relationships between solution-phase chemical properties of various swine manure management systems and observed emission characteristics in order to further define the relationship between system loading rate and emission rate of CH₄, NH₃, H₂S, and VOCs.

Classification of 29 Swine Manure Management Systems Based on Solution-Phase Chemistry and Methane Emission Rate

The concentration range for elements found in the swine manure storage systems sampled in this study were found to be similar to those previously reported by Giusquiani et al (1998), Japenga and Harmsen (1990), and Zahn et al (1997) (Table 1). There was a general trend observed between volatile solids loading rate and concentration of elements for each of the samples evaluated (Table 1). Individual correlations between element concentration and volatile solids loading rate indicated that volatile solids loading rate could account for 48 to 76% of the variability observed with solution-phase concentration of elements. This inadequacy of volatile solids loading rate to account for differences in solution-phase elemental composition for various swine manure management systems, in addition to the technical difficulties associated with performing volatile solids measurements indicated that the solution concentration of elements may provide a more appropriate means to classify swine manure management systems.

In the search for useful solution-phase chemical classification criteria, 45 pairwise comparisons were made between the concentration of elements present in the 29 site samples. The nonparametric measure of association for each pairwise comparison is shown in Table 2. In general, poor correlations were observed for pairwise comparisons made between elements showing opposite partitioning behavior (Table 2). For example, transition metal ions have been shown to partition strongly into the sludge or particulate fraction of the manure, while sodium (Na), potassium (K), and to a lesser extent, phosphorus (P), magnesium (Mg), and sulfur (S), demonstrate neutral or preferential partitioning behavior into the supernatant fraction of the manure (Giusquiani et al., 1998; Zahn et al., 1997). Therefore, the concentration of transition metal ions in samples is highly dependent upon the concentration of suspended solids, while Na and K are nearly independent of the concentration of suspended solids. High correlation coefficients were observed for pairwise comparisons between several transition metals, for several transition metals and a small number of main group elements, and finally, for P and S concentrations in the 29 site samples. However, only one pairwise comparison (P and S) demonstrated clear functional clustering of manure management systems based on system CH₄ emission rate, air concentration of VOCs, or odor intensity (Fig. 2, Table 2).

TABLE 1. Physical properties, elemental composition, and methane flux rates from 29 swine manure management systems in Iowa, Oklahoma, and North Carolina during the months of August and September, 1997. System subcategories based on P and S concentrations as illustrated in Fig. 1. The range indicated for the parameters listed represents the standard error of the sample mean.

Parameter †	Site Classification ‡			
	Type 1 ‡	Type 2	Type 3	Type 4
Site number (n)	n = 6	n = 7	n = 6	n = 10
Description of waste management system	DP; n = 5 PP; n = 1	EB; n = 3 CLB; n = 3 ST; n = 1	L; n = 6	PL; n = 10
System methane flux rate (g CH ₄ system ⁻¹ hr ⁻¹)	636 ± 47	1830 ± 148	13900 ± 760	11990 ± 540
Volatile solids loading rate (kg VS day ⁻¹ m ⁻³)	79 ± 3.0	35 ± 2.6	0.3 ± 0.05	0.07 ± 0.02
pH	7.1 ± 0.04	7.3 ± 0.06	7.3 ± 0.06	7.1 ± 0.03
Solid content (mg/ml)	21.9 ± 0.9	13.4 ± 0.6	3.8 ± 0.4	2.8 ± 0.1
% Carbon (% dry mass)	37.2 ± 0.6	33.7 ± 0.5	16.6 ± 0.3	14.1 ± 0.3
% Hydrogen (% dry mass)	5.2 ± 0.3	4.9 ± 0.2	2.3 ± 0.2	1.8 ± 0.1
% Nitrogen (% dry mass)	3.0 ± 0.2	2.9 ± 0.2	1.8 ± 0.2	1.5 ± 0.1
Ca (mg/L)	301 ± 38	173 ± 24	58 ± 5	119 ± 10
Cu (mg/L)	18 ± 6.2	1.7 ± 0.2	0.2 ± 0.1	0.2 ± 0
Fe (mg/L)	47 ± 21.5	8.9 ± 1.2	1.2 ± 0.2	0.7 ± 0.4
K (mg/L)	1380 ± 400	1040 ± 134	624 ± 18	0.9 ± 0.3
Mg (mg/L)	128 ± 19	62 ± 10	20 ± 1.6	39 ± 4.0
Mn (mg/L)	3.2 ± 0.8	0.9 ± 0.2	0.1 ± 0	0.3 ± 0.2

Na (mg/L)	241 ± 86	225 ± 20.8	165 ± 4.6	18 ± 6.3
P (mg/L)	504 ± 26	153 ± 12.1	65 ± 4.5	0.2 ± 0
S (mg/L)	108 ± 8	39 ± 5.3	15 ± 0.4	8 ± 1.8
Zn (mg/L)	18.7 ± 8	2.7 ± 0.4	0.4 ± 0.1	0.1 ± 0

† Values represent the mean for samples listed in Fig. 1. Instrumental error was < 1% for CHN analysis and < 0.1% for ICP-AES analysis.

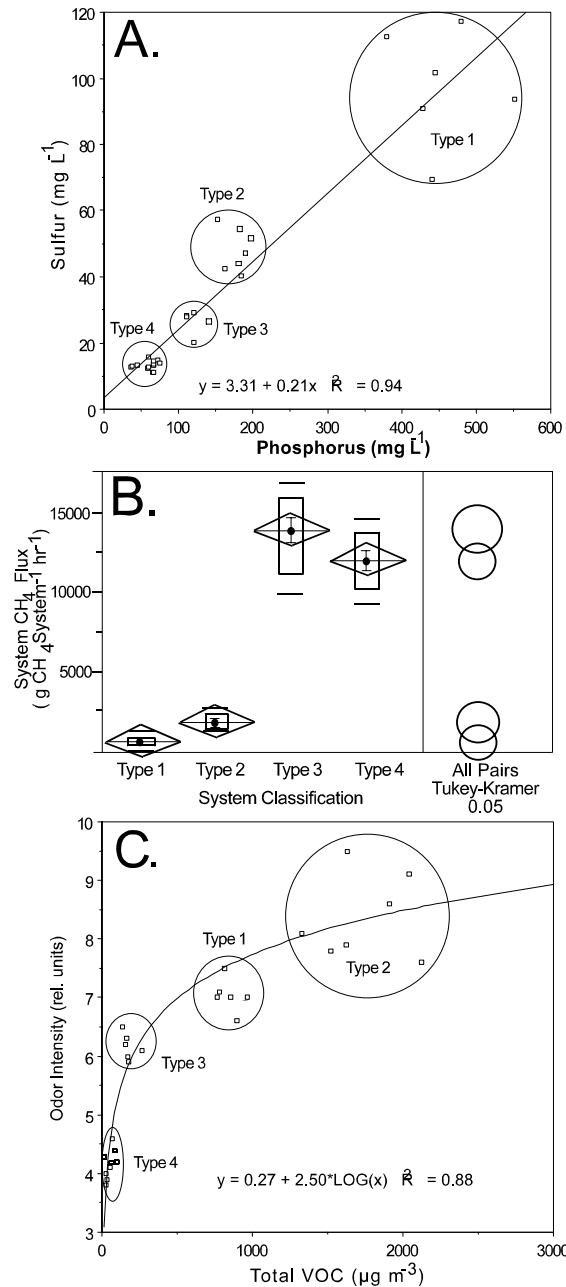
‡ Waste storage system designation as defined in Fig. 1. Type 4 and Type 3 systems represent lagoon systems with and without anoxic photosynthetic blooms, respectively. Type 2 systems represent earthen, concrete, or steel-lined manure storage basins. Type 1 systems represent confinement buildings with short and long term, under-slat storage (pull-plug and deep-pit systems). Subclassification designations: PL = phototrophic lagoon; L = lagoon; EB = earthen basin; CLB = concrete-lined basin (outdoor); ST = steel tank (outdoor); DP = deep pit; PP = pull-plug.

The 29 swine manure management systems were observed to cluster into four distinct system subtypes (Type 1, Type 2, Type 3, and Type 4) based on the concentration of S and P in the effluent fraction (Fig. 2, Table 1). No statistical differences were observed for CH₄ emission rates between Type 1 and 2 systems, nor between Type 3 and 4 systems. However, CH₄ emission rates for all other comparisons were statistically different (Fig. 2B). The mean odor intensity values for sampling sites showed a clustering behavior that was similar to the clustering of data points based on solution-phase P and S concentrations or system CH₄ emission rate. However, odor intensity showed nearly an inverse relationship to CH₄ emission rate, with the highest odor intensities occurring with manure management systems having the lowest CH₄ emission rates (Type 1 and 2 systems).

Odor intensities and VOC concentrations in Type 2 systems were consistently higher than measurements performed on Type 1 systems. This result was not entirely consistent with solution-phase P and S concentrations or with system CH₄ emission rates, which predicted Type 1 systems to have the highest odor intensities and air concentrations of VOCs. Gas transfer velocities for CH₄ and VOCs are known to differ by several hundred-fold (MacIntyre et al., 1995). In addition to large differences in gas transfer velocities for CH₄ and VOCs, surface exchange rate for some VOCs is known to be influenced by solution-phase chemical events that include ionization (pH), hydrogen bonding, and surface slicks (MacIntyre et al., 1995). For these reasons, CH₄ is not an appropriate criterion for predicting VOC volatilization potential between swine manure management systems. Wind, temperature, and irradiance are known to be major factors in the emission rate of sparingly soluble gases (VOCs) from liquid or semi-solid surfaces (MacIntyre et al., 1995; Zahn et al., 1997). Based on the VOC transfer velocity calculations of MacIntyre et al. (1995), the difference due to wind and temperature exposures between outdoor and indoor manure management systems can account for between 51% to 93% of the observed differences in VOC emissions. This analysis provides evidence that exposure factors can account for differences observed in VOC flux rates, VOC air concentrations, and odor intensity between Type 1 and 2 systems.

Swine waste management systems are often designed to release gases produced in anaerobic decomposition processes into the atmosphere. Within these systems, a complex consortium of microorganisms (anaerobic food chain) decompose complex biological waste material to end products including CH₄, H₂S, CO₂, and NH₃ (Gottschalk, 1988; Lana et al., 1998; Mackie et al., 1998; Wolfe, 1996). The anaerobic food chain is often functionally separated into microorganisms catalyzing acid-producing reactions from complex organic substrates and *Archaea*, that catalyze CH₄-producing reactions from products formed in the breakdown of complex organic substrates (Wolfe, 1996). The emission rate of CH₄ and partially decomposed microbial substrates (volatile fatty acids) has been previously employed as an indicator to assess functional coupling between processes in the anaerobic food chain in anaerobic digesters (Hill and Bolte, 1989). “Overloaded” anaerobic digestion processes have been correlated with high emission rates of VOCs (volatile fatty acids) and low emission rates of CH₄, while optimum loading rates promote high bioconversion efficiencies of complex organic matter into CH₄ (Hill and Bolte, 1989).

FIGURE 2. Cluster analysis for the (A) concentration of total phosphorous versus total sulfur in liquid samples from 29 swine production sites utilizing anaerobic liquid/slurry swine waste storage systems. The (B) Anova (compare all pairs) for methane emission rate for swine manure management systems categorized according to phosphorus and sulfur concentrations and the Tukey-Kramer HSD means comparison table (Alpha level = 0.05). The (C) correlation between concentration of volatile organic compounds present in air from waste management systems versus the mean odor intensity.



Data in Figure 2 and Table 1 provide evidence that the biological processing events occurring in high-load systems (Type 1 and Type 2) may result from the functional decoupling of the anaerobic food chain. This observation is further supported by the fact that these same systems show an accumulation of organic (particulate C, H, N) material (Table 1) and high air concentrations of VOCs (Fig. 3; Table 3). In contrast, the high emission rates for CH_4 and low liquid-phase organic content (particulate C, H, N) associated with Type 3 and 4 systems (Table 1) indicates that the environment in these systems provides for relatively more efficient bioconversion of complex organic substrates into CH_4 .

TABLE 2. Results for the pairwise comparison of element concentrations present in effluent samples from 29 swine manure management systems. Values indicate the nonparametric measure of association between pairwise comparisons of elements.

Element	Nonparametric measure of association (Spearman's rho value)									
	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn
Ca	1	0.65	0.80	0.92	0.82	0.37	0.66	0.66	0.66	0.66
Cu		1	0.92	0.70	0.66	0.83	0.65	0.96	0.92	0.96
Fe			1	0.64	0.78	0.95	0.59	0.93	0.89	0.91
K				1	0.36	0.56	0.96	0.74	0.74	0.67
Mg					1	0.83	0.30	0.69	0.68	0.66
Mn						1	0.50	0.87	0.85	0.84
Na							1	0.67	0.66	0.62
P								1	0.94	0.96
S									1	0.93
Zn										1

Data reported in this study were collected in three geographical regions of the U.S. over a six week period in the late summer (August and September, 1997). This experimental design was chosen based on previous reports that bacterial photosynthetic and SO_4 reduction activities in swine waste management systems located in northern U.S. climates reach a near steady-state condition during this time period (Do et al., 1998; Do et al., 1999; Jacobson et al., 1997b). A second objective of this design was to identify differences in emission or solution-phase properties of swine waste management systems that could be attributed to geographical location (Iowa, n = 24; Oklahoma, n = 2; and North Carolina, n = 3). However, no significant differences were observed in any of the parameters measured in this study when “like” manure management systems (i.e., photosynthetic lagoons *versus* photosynthetic lagoons) were compared on the basis of geographic location. While the certainty of this finding is diminished by the low sample number, it was not entirely surprising that effects of geographic location played a minor role in the emission characteristics of (steady-state) manure management systems when contrasted to the effects due to loading rate. While the effects of geographic location on emission parameters appeared to be insignificant, geographic location was found to influence the rate at which the apparent steady-state condition was achieved. Based on the population dynamics of purple non-sulfur photosynthetic populations, it has been noted that that the apparent steady-state condition occurs at least 1.2 months earlier in North Carolina lagoons when compared to comparable lagoon systems in Iowa (Do et al., 1998). The seasonal transition in P and S concentrations for photosynthetic lagoons in Iowa progress from “basin-like” characteristics in early spring (100 mg L^{-1} P and 30 mg L^{-1} S) to intermediate concentrations (“lagoon-like”) in late spring (60 mg L^{-1} P and 16

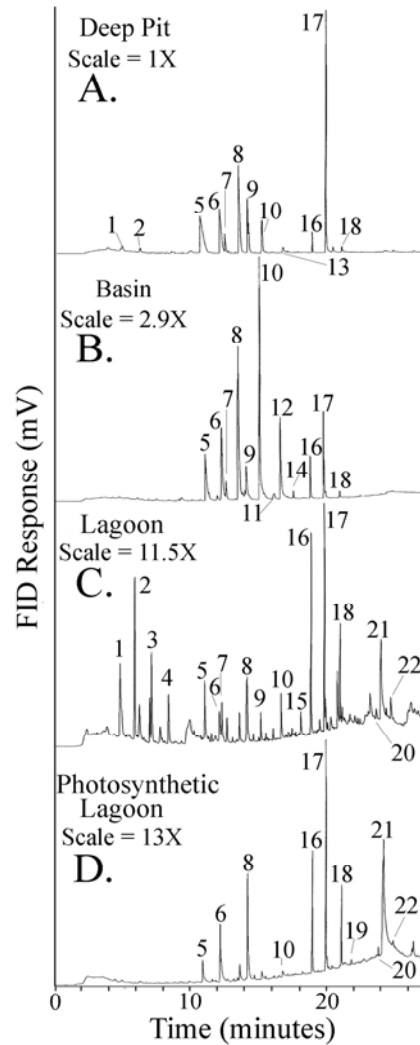
TABLE 3. The average concentration of trace gases and organic compounds present in air samples from swine manure management systems representing the four system classes. Values reported represent the sample mean for a 24 hr sampling period.

Peak # and Retention time (min.)	Compound	Swine waste storage system classification type (Analyte air concentration ($\mu\text{g m}^{-3}$) and Percent total peak area (%))			
		Type 1	Type 2	Type 3	Type 4
SCA†	Ammonia	9623	7923	9362	10843
SCA	Methane	5002	8406	18703	24406
SCA	Hydrogen Sulfide †	54	48	27	29
1 (4.8)	Dimethyl disulfide	12 (1.3)	nd	17 (6.8)	nd
2 (6.1)	2-Butanol	8 (0.8)	nd	19 (7.5)	nd
3 (7.5)	Dimethyl trisulfide	nd	nd	13 (5.2)	nd
4 (8.6)	Unknown	nd	nd	- (2.9)	nd
5 (10.6)	Acetic acid	281 (15.2)	262 (7.6)	11 (2.7)	2 (2.3)
6 (11.9)	Propionic acid	126 (11.1)	50 (2.3)	5 (1.9)	4 (8.2)
7 (12.4)	Isobutyric acid	23 (2.5)	107 (11.4)	6 (2.2)	nd
8 (13.3)	Butyric acid	142 (15)	586 (32)	13 (5.1)	5 (12.9)
9 (14.0)	Isovaleric acid	73 (8.3)	98 (6)	3 (1.2)	nd
10 (15.0)	n-Valeric acid	43 (4.9)	360 (27)	5 (2.0)	1 (0.7)
11 (15.7)	Isocaproic acid	nd	10 (0.5)	nd	nd
12 (16.0)	n-Caproic acid	nd	105 (7.4)	nd	nd
13 (16.1)	Unknown	- (1.2)	nd	nd	nd
14 (16.6)	Heptanoic acid	nd	8 (0.3)	nd	nd
15 (17.2)	Benzyl alcohol	nd	nd	2 (1.2)	nd
16 (18.8)	Phenol	9 (1.5)	24 (1.6)	8 (6.9)	3 (9.9)
17 (19.7)	4-Methyl phenol †	85 (19.6)	32 (2.7)	9 (7.5)	3 (17.8)
18 (20.9)	4-Ethyl phenol †	3 (0.7)	2 (0.2)	4 (3.3)	1 (6)
19 (21.9)	2-Amino acetophenone †	nd	nd	nd	0.2 (0.4)
20 (23.4)	Indole	nd	1.1 (0.2)	0.8 (0.6)	0.1 (0.5)
21 (23.7)	Hexadecanoic acid	nd	nd	9 (7.8)	5 (33)
22 (24.2)	3-Methyl indole	0.5 (0.2)	1.4 (0.3)	1.3 (1.1)	0.2 (0.7)
Total concentration of non-methane VOCs identified in air ($\mu\text{g m}^{-3}$)		806	1647	126	25
Percent of total peak area (%)		82.3	99.5	65.9	92.4

† U.S.-EPA priority pollutants identified in air samples: cresols (isomers and mixtures), H_2S , phenol, and acetophenones. nd = analyte not detected.

$\text{mg L}^{-1} \text{S}$), to low concentrations during the photosynthetic bloom event in late June ($1 \text{ mg L}^{-1} \text{P}$ and $8 \text{ mg L}^{-1} \text{S}$) (Do et al., 1998). Maximum methane flux during these transition events was observed to occur shortly (2-9 days) before the photosynthetic bloom (Do et al., 1998). These studies indicate that the P and S concentrations may provide valuable swine manure management classification information regardless of the season or geographical location.

FIGURE 3. GC-FID chromatograms of volatile organic emissions from four swine manure storage systems that represent the four swine manure management subtypes. From top to bottom: Air sample collected in a deep pit (Site A), air sample collected over a concrete-lined basin (Site B), air sample collected over a lagoon (Site C), and air sample collected over a photosynthetic lagoon (Site D). Peak reference numbers correspond to organic compounds listed in Table 3.



The Relationship between Emission Chemistry and Odor Intensity

Several recent investigations have attempted to define relationships between chemical concentration of specific gases and odor concentration or intensity (Hobbs et al. 1995, Jacobson et al. 1997a, Jacobson et al. 1997b, Obrock-Hegel 1997, Pain et al. 1990). Obrock-Hegel (1997), found that nutritional manipulation of amino acid intake reduced NH_3 , cresols, and indoles measured in air samples from production environments. However, no reduction in odor concentration was observed between control and treatment samples. Schulte et al. (1985) and Hobbs et al. (1995), linked high levels of ammonia (NH_3) to odor. Unfortunately, the latter authors noted that the relationship between NH_3 and odor could not be universally applied to all farms, especially when they differed in the type of manure management system utilized. The use of hydrogen sulfide (H_2S) as a surrogate of livestock waste odor has also proven to be a formidable challenge. Jacobson et al., (1997a) evaluated odor and H_2S concentration in air from approximately 60 different pig, dairy, beef, and poultry manure storage units on farms in Minnesota. Low correlation was observed between H_2S and odor concentration for manure storages based on a species comparison and for production systems grouped according to manure management system type (pit, basin, and lagoon). The study further suggested the possibility that chemical odorants other than H_2S (i.e., VOCs) were responsible for swine odor. In support of this conclusion, Powers et al., (1999) recently demonstrated that solution-phase concentrations several VOCs, present in anaerobic digester effluent were correlated with odor intensity. However, solution-phase concentration of VOC did not predict odor intensities well enough to suggest that human panels should be eliminated. Data quality in this study was likely influenced by the fact that correlations were not performed in a similar matrix (air *versus* liquid). Previous studies (Zahn et al., 1997) have established that solution-phase measurements often provide an inaccurate representation of malodor potential and therefore, represent an inappropriate comparison (MacIntyre et al., 1995).

To test the potential relationship between airborne VOCs and swine manure odor, odor intensity and air concentration of VOCs were determined simultaneously at the 29 swine production facilities. Figure 2C shows the relationship between average odor intensity, assessed through direct scaling techniques using a defined odor intensity, and the total air concentration of VOCs present at the receptor. The relationship between mean odor intensity and air concentration of VOCs was observed to obey Michaelis-Menten kinetics, with a Michaelis constant (K_m) of $95 \mu\text{g m}^{-3}$ VOCs and receptor saturation occurring at $1250 \mu\text{g m}^{-3}$ VOCs (Fig. 2). The saturation properties showed typical second-order kinetics and were characteristic of a receptor-ligand process. A qualitative analysis of VOCs present at sites representing the four classes of swine manure management systems is shown Figure 3 and Table 3. The gas chromatography-flame ionization detector (GC-FID) chromatograms from swine production sites with high odor intensities gave relatively intense signal responses but were chemically-simplistic in nature when compared to chromatograms from lagoon systems (Fig. 3; Table 3). These results suggest that chemical concentration rather than diversity is the largest determinate in the odor intensity response associated with swine waste odor. This observation is

important since the ability to define odorant synergisms and antagonisms has been suggested to be the most significant obstacle in applying chemical methods in odor measurement (Mackie et al., 1998). Data presented in Figure 2C provide evidence that the total air concentration of non-methane VOCs predict the odor intensity associated with a swine manure management systems evaluated in this study.

TABLE 4. Average horizontal flux rate and average system flux rate for air pollutants collected over a 24 hr period from swine manure management systems described in Table 2.

Parameter	Flux rate of analytes for individual swine waste storage systems			
	Type 1	Type 2	Type 3	Type 4
Mean wind velocity ^a (cm s ⁻¹) or ventilation rate ^b (m ³ hr ⁻¹) during sampling period	110,000 ^b	190 ^a	128 ^a	90 ^a
Ammonia flux rate (ng NH ₃ cm ⁻² s ⁻¹)	66 †	167	109	89
System Ammonia flux rate (g NH ₃ system ⁻¹ hr ⁻¹)	1060	1900	7700	6270
Methane flux rate (ng CH ₄ cm ⁻² s ⁻¹)	34 †	178	218	200
System methane flux rate (g CH ₄ system ⁻¹ hr ⁻¹)	550	2010	15410	14120
Hydrogen sulfide flux rate (ng H ₂ S cm ⁻² s ⁻¹)	0.37 †	1.10	0.32	0.24
System hydrogen sulfide flux rate (g H ₂ S system ⁻¹ hr ⁻¹)	5.9	12.5	22.7	16.9
Priority pollutant (PP) flux rate (ng PP cm ⁻² s ⁻¹) ‡	1.04 †	2.30	0.56	0.30
System priority pollutant flux rate (g PP system ⁻¹ hr ⁻¹) ‡	16.6	26.1	39.6	20.9
Combined VOC flux rate (ng VOC cm ⁻² s ⁻¹)	5.60 †	35.0	1.60	0.21
System combined VOC flux rate (g VOC system ⁻¹ hr ⁻¹)	89.9	394.0	113.1	14.5
System total air pollutant flux rate (g TAP system ⁻¹ hr ⁻¹)	1720	2420	15550	14150

† System flux rate calculated using an active surface area of 4,459,000 cm² and assume a homogenous emitting source for active surfaces.

‡ U.S.-EPA priority pollutants identified in air samples: cresols (isomers and mixtures), hydrogen sulfide, phenol, and acetophenones.

Odor measurement methods using human olfactory senses are based on the use of psychophysical theory. As the name implies, psychophysical methods are based on relationships between psychological and physical attributes of sensory stimuli. The intensity of olfactory stimuli reported by an individual is related to stimulus magnitude. For many odorants used in the food and fragrance industry, there is a linear relationship between log olfactory intensity reported by the individual and the air concentration of the odorant(s) present in air (Turk and Hyman, 1991). This relationship between perceived olfactory stimuli and intensity of sensation is referred to as the fundamental psychophysical law (Stevens, 1957; Stevens, 1962). Data reported in Figure 2C show that the total air concentration of VOCs correlate well to the log stimulus intensity ($r^2 = 0.88$) and therefore, conforms to the fundamental psychophysical law. In agreement with other olfactory studies, we observed that data quality was influenced by variables associated with the subjective nature of intensity scales, fatigue, sex, age, race, and visual cues (Cain et al., 1998; Degel and Koster, 1998; Liden et al., 1998; Livermore and Laing, 1998; Turk and Hyman, 1991). However, the use of the defined odor standard Z-2 was found to reduce most of the sampling variability associated with intensity scales. Evidence for this conclusion was provided by the low average standard deviation reported by panelists for site evaluations (avg. std. dev. = 0.14 odor units). A prerequisite that underlies all olfactory methods is the ability to define and properly sample chemical odorants that constitute a particular odor. Accomplishing this objective has been a formidable challenge, since it requires the use of both olfactory and analytical methods to validate sampling methods. The results of this study demonstrate utility of chemical methods in odor analysis and in the validation of air sample collection methods (i.e., Teflon bag sampling).

Emission Rate of Air Pollutants from Swine Manure Management Systems

Analysis of CH₄ emission rates, airborne VOC concentration, and odor intensity for the 29 swine manure management systems evaluated in this study indicated that manure management systems could be functionally classified according to phosphorus and sulfur concentrations. This analysis, however, provided limited insight into the differences in microbial processes associated with these systems. In an effort to further elucidate chemical and biological differences associated with the system classification, a detailed evaluation of solution-phase characteristics and gases (H₂S, NH₃, CH₄, VOCs) was conducted at four swine manure management systems which represented each of the four system classes. Results for CH₄ fluxes determined by meteorological methods in these experiments were consistent with previous methane flux observations performed using dynamic flux chamber techniques and also supported earlier conclusions that bioconversion efficiency is influenced by manure management loading parameters. In systems with relatively low emission rates of CH₄ and NH₃ (Type 1 and 2 systems (Tables 3, 4, and 5)), high concentrations of organic carbon and nitrogen (particulate C, H, N) were found to accumulate in the solution phase (Table 1). These systems were also observed to have the highest odor intensities. In contrast, Type 3 and 4 systems showed a lower tendency to accumulate solution-phase organic material (Fig. 3; Tables 1 and 3) and a much higher emission rate of CH₄ (Fig. 2; Table 1).

The emission rate of hydrogen sulfide (H₂S) appeared to be independent of the waste management system classification developed in this study (Table 5). This observation was unexpected since the emission rate of CH₄, NH₃, and VOCs were dependent upon the type of manure management system utilized (Fig. 2.; Table 5). Common precursors of H₂S in anaerobic swine manure management systems may include cysteine (cystine), methionine (indirect biotransformation), sulfur (S₀), thiosulfate (S₂O₃), or sulfate (SO₄). Sulfate (SO₄) is known to play a major role in mammalian physiology and is released (~0.1 to 1.4 g of SO₄ day⁻¹) in urinary excretions as SO₄-organic conjugates or SO₄ salts (Lehninger, 1988). Based on a daily SO₄ excretion rate of 0.13 g SO₄ pig⁻¹ day⁻¹ and a complete conversion to H₂S, a production facility with 4560 pigs (Site A, Table 5) is estimated to emit 593 g H₂S day⁻¹ through dissimilatory SO₄ reduction processes (Gottschalk, 1988; Postgate, 1984).

TABLE 5. Production site emission rates for air pollutants collected over a 24 hr period from swine production systems consisting of manure management systems described in Tables 3 and 4.

Parameter	Flux rate of analytes for individual swine waste storage systems			
	Type 1 ‡	Type 2	Type 3	Type 4
Annual production number and type	Feeder to finish 13680 pigs yr ⁻¹	Farrow to finish 8200 pigs yr ⁻¹	Feeder to finish 14170 pigs yr ⁻¹	Farrow to feeder 18500 pigs yr ⁻¹
Site waste management system description †	4 - DP	2 - CLB 2 - PP	1 - L PFS ‡	2 - PL PFS ‡
Daily ammonia emission (kg NH ₃ site ⁻¹ day ⁻¹)	101.7	141.7	232.8	369.2
Methane flux rate (kg CH ₄ site ⁻¹ day ⁻¹)	52.8	122.7	466.1	831.0
Hydrogen sulfide flux rate (kg H ₂ S site ⁻¹ day ⁻¹)	0.6	0.9	0.7	1.0
Priority pollutant (PP) flux rate (kg PP site ⁻¹ day ⁻¹)	1.6	2.1	1.2	1.2
Combined VOC flux rate (kg VOC site ⁻¹ day ⁻¹)	8.6	23.2	3.4	0.9
System total air pollutant flux rate (kg TAP site ⁻¹ day ⁻¹)	165	291	704	1203

† Waste storage system description: PL = phototrophic lagoon; PFS = continuous pit flush system; L = lagoon; EB = earthen basin; CLB = concrete-lined basin (outdoor); DP = deep pit; PP = pull-plug.

‡ The emission rate for analytes released from the continuous pit flush systems was calculated based the system-specific horizontal flux density for individual analytes (Table 4) and the total pit surface area actively flushed with recycled lagoon liquid. The active surface area for PFS systems at site C and D was 510 m² and 890 m², respectively.

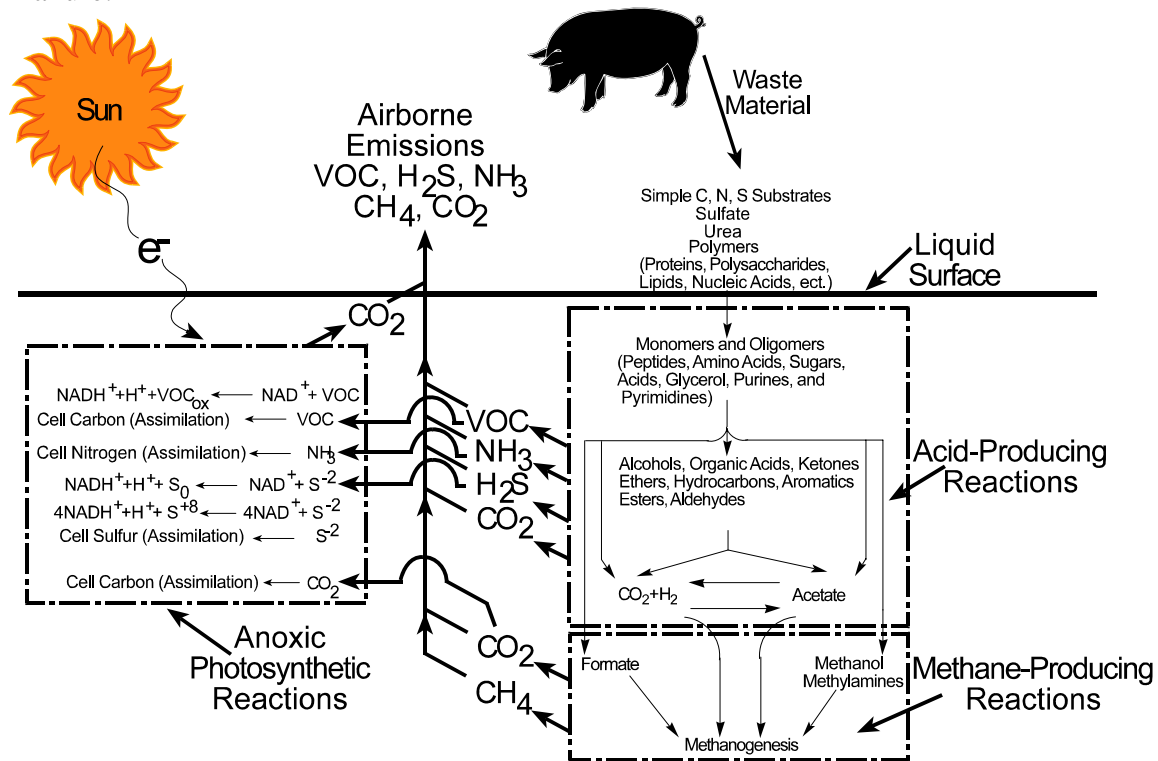
This calculated value is similar to the observed daily H₂S emission rate (Table 5, Site A), indicating that urinary SO₄ excretions may account for a significant proportion of the sulfur (S)-precursors contributing to the H₂S emissions measured in this study. The finding that SO₄ may be the major S-precursor contributing to H₂S emissions provides microbiological insight into why H₂S emissions might be independent of waste management system classification. All complex forms of sulfur require energy expenditure (by the bacterial cell) before S-gases can be released (i.e., formation of methyl mercaptan or dimethyl disulfide from methionine). Energy consuming microbial processes have been shown to be highly sensitive to solution-phase environmental parameters such as metal ion concentration and concentration of organic matter (Oleszkiewicz and Sharma, 1990; Hill and Bolte, 1989). In contrast, SO₄ reduction is an energy-yielding process that is highly favorable under environmental conditions observed in all manure management systems evaluated in this study. These results suggest that future mass-balance studies should aim at characterization of the S-cycle in swine waste management systems with special emphasis on sources and fate of SO₄.

Manure management systems with high loading rates and relatively low CH₄-producing activity showed up to a 26-fold increase in total VOC emissions when compared to low-odor photosynthetic lagoons (Fig. 2 and Table 5). The data indicate that VOCs are more likely to be of concern with systems employing high loading rates, while CH₄ and NH₃ are likely to be more problematic with systems employing lower loading rates. In addition to nuisance concerns, elevated VOC concentrations may present a concern to human health. A small number of regulated industrial pollutants are present in airborne emission streams from swine production facilities (Table 3). The air concentrations for these compounds at the source were found to be at least one order of magnitude below exposure levels established for safe work environments by occupational health organizations (Plog, 1988). However, the use of industrial exposure indices may not be appropriate for assessing exposure to animal waste emissions due to the following considerations: First, several agricultural waste pollutants are unique to agricultural systems and thus, have no established exposure indices. Second, bioactive airborne pollutants, such as microbial secondary metabolites, remain largely uncharacterized from swine production systems. Bioactive compounds have been identified as a serious human health risk, since many of these compounds have been shown to influence mammalian cell physiology in the part per billion and sub-part per billion range (Andersson et al., 1998). Third, there is a lack of information on the acute and chronic toxicological impacts of VOCs derived from swine manure on children and individuals of compromised health. This concern is reflected in recent epidemiological studies that have shown a higher incidence of psychological dysfunction and health-related problems in individuals residing near large-scale swine production facilities (Thu et al., 1997; Schiffman et al., 1995).

Lagoons with established anoxic bacterial photosynthetic populations (Type 4 systems; bacteriochlorophyll *a* concentrations above 40 nmol/ml) showed lower odor intensities, lower air concentrations of VOCs, and lower emission rates of VOCs when compared to other swine waste management systems (Fig. 3; Tables 3 and 4). Photosynthetic bacteria

carry out the process of photosynthesis under anaerobic conditions. These requirements for photosynthesis differ greatly from algae and plant species that use water as an electron source for photosystem II and evolve oxygen in this reaction (Kobayashi and Kobayashi, 1995). Instead of utilizing water as a reductant, anoxic photosynthesis is dependent on substrates such as H_2S , hydrogen (H_2), and VOCs to provide reducing equivalents, while light from the sun provides the energy source (Gottschalk, 1988). Bacteria capable of anoxic photosynthesis are categorized into one of four major groups (purple sulfur, purple non-sulfur, green sulfur, and green-gliding) based on the presence of specific types of bacteriochlorophyll, phylogenetic characteristics, and metabolic capabilities (Gottschalk, 1988; Siefert et al., 1978). All four groups of photosynthetic bacteria are able to utilize organic substrates (VOCs) as a source of carbon and the green-gliding and purple bacteria are able to use organic substrates as proton donors. However, a novel species of *Rhodobacter* (*Rhodobacter* sp. PS9) dominates the photosynthetic population (~20% of the total microbial community structure) in all photosynthetic swine lagoon systems examined in this study (Do et al., 1998; Do et al., 1999). The physiological characteristics of this purple non-sulfur photosynthetic bacterium provides evidence for the observed degradation of VOCs and decreased odor emissions from photosynthetic swine waste lagoons (Fig. 4).

FIGURE 4. Model for the biotransformation of stored swine manure. The figure depicts major substrates and products from biological reactions occurring in stored anaerobic manure.



CONCLUSIONS

The lack of knowledge concerning functional aspects of swine manure management systems has complicated present efforts to develop or improve emission abatement technologies to meet the stringent air quality and nuisance regulations presently imposed by several States. The task of elucidating functional aspects of swine waste management systems is often convoluted by the plethora of manure management strategies presently used in the swine industry. In the absence of appropriate compatibility or functional measures, emission abatement strategies are often paired with swine manure management systems based only on empirical observations. As a result, the performance of these abatement methods is difficult to predict and often impossible to improve through scientific methods. Solution-phase concentrations of P and S are shown in this study to be a useful tool in the classification of swine manure management systems according to functional aspects of the system. The methods described in this study provide an inexpensive means to rapidly assess best management practices for swine manure management systems and also provide a means by which to identify swine production systems that represent a potential air quality or nuisance concern.

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