Identification of Risk Factors for Sub-Optimal Housing Conditions in Australian Piggeries: Part 4. Emission Factors and Study Recommendations

T. M. Banhazi, D. L. Rutley, W. S. Pitchford

Abstract. *The internal concentrations and emission rates of ammonia (NH_3), total bacteria, respirable endotoxins, and inhalable and respirable particles were monitored in 160 piggery buildings in four states of Australia (Queensland, Victoria, Western Australia, and South Australia) between autumn 1997 and autumn 1999. Emissions were calculated for individual buildings as a product of internal concentration and ventilation rate, which were estimated by a carbon dioxide balance method. Relative humidity and temperature were also measured. The overall mean emission rates of NH_3, total bacteria, respirable endotoxins, inhalable particles, and respirable particles per 500 kg live weight from Australian piggery buildings were 1442.5 mg h^{-1}, 82.2 × 10^6 cfu h^{-1}, 20.1× 10^3 EU h^{-1}, 1306.7 mg h^{-1}, and 254.7 mg h^{-1}, respectively. Internal concentrations of key airborne pollutants have been reported in companion articles. Building characteristics and management systems used in the piggeries were documented at the time of sampling and used in the subsequent statistical modeling of variations in pollutant emission rates. The emissions model used all statistically significant factors identified during prior modeling conducted for individual pollutant concentrations and ventilation airflow. The identification of highly significant factors affecting emission rates and internal concentrations should aid the development of strategies for the industry to reduce emission rates from individual buildings, thus improving the environmental performance of piggery operations. In the second part of the article, specific recommendations are made based on the overall study results.*

Keywords. *Environmental survey, Farm building, Pigs, Pollutant emission, Risk factors.*

A related publication revealed that considerable amounts of airborne pollutants can be found in the airspaces of Australian piggery buildings (Banhazi et al., 2008b). These concentrations, coupled with the relatively high ventilation rates measured (Banhazi et al., 2008c), could result in high rates of emission of these airborne pollutants. High emission rates of airborne pollutants could affect the environment surrounding piggery buildings. The potential health effects associated with particle and endotoxin emissions are well documented in the literature (e.g., Seedorf, 2004; Seedorf et al., 1998; Wathes et al., 1997). Damage to sensitive ecosystems and the formation of aero-

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The authors are **Thomas M. Banhazi, ASABE Member Engineer,** PhD, Senior Research Scientist, **David L. Rutley,** PhD, Research Scientist, and **Wayne S. Pitchford,** PhD, Senior Research Scientist, Livestock System Alliance, University of Adelaide, Roseworthy, Australia. **Corresponding author:** Thomas M. Banhazi, Livestock System Alliance, University of Adelaide, Roseworthy Campus, Roseworthy, SA 5371, Australia; phone: 618-8303-7781 fax: 618-8303-7975; e-mail: Banhazi.Thomas@saugov.sa.gov.au.

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sol particles associated with ammonia (NH_3) emissions are also major concerns in relation to pollutant emissions from livestock buildings (Groot Koerkamp et al., 1998). Transmission of pathogenic bacteria between buildings and farms (Seedorf et al., 1998; Takai et al., 1998) and the transportation of odorous components (Bottcher, 2001; Hammond et al., 1979; Hoff et al., 1997; Jacobson et al., 1999; Williams, 1989) are additional concerns related to particle and gaseous emission from farm buildings.

Understanding the key factors affecting airborne pollutant emissions is a vital step towards developing possible emission control strategies, thus reducing emission levels. However, emission rates can be influenced by a large number of factors. Therefore, the methodological identification and inclusion of important predictive factors and hence the proper modeling of emission rates are not easy to accomplish. Thus, our main objective was to develop statistical models to identify the statistically significant factors influencing the emission rates of different airborne pollutants by developing individual models for the emission of each of the main pollutants. We expect that the identification of significant factors influencing the emission rates of individual pollutants will facilitate the development of possible emission abatement methods.

Materials and Methods

Details of the techniques used for data collection and analysis have been described before (Banhazi et al., 2008a; Banhazi et al., 2008b; Banhazi et al., 2008c), and therefore only the outline of the methods used in the study is given here. A total of 160 piggery buildings were included in the study, and on each farm four piggery buildings were surveyed: dry sow, weaner, farrowing, or grower/finisher buildings, or deep-bedded shelters (DBS). More detailed descriptions of the buildings included in the study can be found in the first article of this series (Banhazi et al., 2008a). Data on each building were collected over a 60 h period (both in summer and winter), and a data collection form was developed to collect data relating to housing and management factors (Banhazi et al., 2008a). All environmental measurements were taken in a standardized time and location throughout the project, as detailed in the companion articles (Banhazi et al., 2008b; Banhazi et al., 2008c).

The concentration of airborne particles was determined gravimetrically using cyclone samplers for respirable (<5 μm) particles and seven-hole samplers for inhalable particles (Casella, Ltd., Kempston, U.K.), and then the endotoxin concentrations in the respirable dust samples were analyzed (Banhazi et al., 2008b). The sampling rate of the GilAir air pumps (Gilian Instrument Corp., West Caldwell, N.J.) was controlled at 1.90 L min^{-1} for respirable particles and at 2.00 L min^{-1} for inhalable particles. The sampling time was also standardized throughout the project (8 h). After the standardized field measurements were complete, the concentrations of airborne particles were determined by weighing the particle mass collected on filters. Subsequently, the contents of the exposed respirable filters were extracted, and a commercially available test kit (BioWhittaker, Inc., Walkersville, Md.) was used (based on the limulus amoebocyte lysate test) to determine endotoxin concentrations. The water-dust suspension was processed as described in a companion article (Banhazi et al., 2008b), and then a 500 μL aliquot was taken for subsequent analysis. The measurements were made using a QCL-1000 Chromogenic LAL test kit (BioWhittaker, Inc.) with a Kinetic-QCL Reader (BioWhittaker, Inc.,). Airborne bacteria were sampled by using a standard Anderson sampler (Bellin and Schillinger, 2001). Horse-blood agar (HBA) plates were used (Medvet Science Pty. Ltd., Stepney, Australia) to determine the total number of bacterial colonies (colony forming units, or cfu) after the plates were incubated at 37°C for 24 h under aerobic conditions. The flow rate during sampling was 1.9 L min^{-1} and the sampling time was 5 min.

Gases such as NH_3 and carbon dioxide (CO_2) were monitored using a multi-gas monitoring (MGM) machine developed in-house. An electrochemical gas monitoring head (Bionics TX-FM/FN, Bionics Instruments Co., Tokyo, Japan) was used to detect internal concentrations of NH_3, and an infrared sensor (GMM12, Vaisala Oy, Helsinki, Finland) was used to detect CO_2 concentrations. An air delivery system transported air samples from the sampling points within and outside the buildings to the actual gas monitoring heads. The MGM machine was frequently calibrated using a custom-made 2500 ppm CO_2 mixture and a standard 50 ppm NH_3 calibration gas mixture (Calgaz, Air Liquide Australia, Ltd., Melbourne, Australia). Ventilation rates were estimated using a carbon dioxide (CO_2) balance method after the concentrations of CO_2 had been measured by a multi-gas monitoring machine (Banhazi et al., 2008b). ANIPRO software (developed from the early version of the Stalkl program) was used to compute the calculations required (Ouwerkerk and Pedersen, 1994). Total ventilation airflow rates (m^3 h^{-1}) were calculated over a 60 h period for each piggery building and expressed per livestock unit (LU, 500 kg live weight). Emission rates were calculated as factors of ventilation rates (m^3 h^{-1}) and internal concentrations of individual airborne pollutants and were also expressed per LU. Temperature and humidity readings were recorded in all buildings using Tinytalk temperature and humidity dataloggers (Tinytalk-2, Hastings Dataloggers Pty. Ltd., Port Macquarie, Australia).

At the time of data recording, the level of pen hygiene was assessed visually, as described by Banhazi et al. (2008b). Seasons were defined as "summer" from November to April and "winter" from May to October. Data were collected and forwarded to a central location for storage and analysis. In this instance, the dependent (response) variables of interest were airborne pollutant emission rates. As the distributions of all the variables (emission rates of different airborne pollutants) were skewed, the data were log-transformed before further analysis. The log-transformed data were then modeled to explain as much of the variation in the dependent variables as possible by using a general linear model (GLM) procedure (SAS, 1989). The GLM statistical method was selected to ensure that the unbalanced data obtained under field conditions were adequately handled (Banhazi et al., 2008a). We also aimed to identify those factors that had highly significant ($P < 0.01$) effects on the emission rates of all airborne pollutants considered in this study (SAS, 1989) to ensure that the likelihood of "chance fits" (associations identified between the dependent and explanatory variables by chance) were minimized. This was achieved by removing in stepwise manner the non-significant effects from the initial model until only effects at the 99% significance level remained for single pollutants, except for ammonia (Banhazi et al., 2008a; Banhazi et al., 2008b). We expect that the knowledge generated about the statistically identified risk factors influencing the emission rates of different air pollutants will allow us to generate recommendations on potential emission abatement techniques for producers. The results presented here are based on least squares medians (±confidence intervals) of the fixed effects.

Inclusion of Effects in the Emission Models

The effects considered in the model were essentially the summation of all important effects (table 1) identified separately for individual airborne pollutants and total ventilation airflow (Banhazi et al., 2008b; Banhazi et al., 2008c). As the ventilation model developed and described in a companion article (Banhazi et al., 2008c) proved to be a robust model, we integrated the factors identified for ventilation rates with factors identified for airborne pollutant concentrations (Banhazi et al., 2008b). Using the same group of factors to start with (including 13 main effects and covariates and a number of

Table 1. Main effects and covariates included in the combined model.

Main Effect, Covariate, or Interaction	Classification and Measurement
Building type/classification	Weaner, grower/finisher, dry sow, DBS, or farrowing
Hygiene level/cleanliness	Good, fair, and poor
Management type	Continuous flow or all-in/all-out management
Season	Winter or summer
Ventilation type	Mechanical, natural, tunnel/DBS
Weight of pigs per unit airspace	kg m^{-3}
Internal air temperature	°C
Internal relative humidity	%
Building width, height, and length[a]	m
Vertical height of wall ventilation opening	cm
Farm size	Number of sows

[a] Three different factors.

interactions), we developed statistical models for the emission of the five major airborne pollutants (NH_3, airborne bacteria, respirable endotoxins, and inhalable and respirable dust particles).

We assumed that our approach of developing detailed statistical models for concentrations of individual pollutants and ventilation rates (Banhazi et al., 2008b; Banhazi et al., 2008c) before attempting to model the emission rates of key airborne pollutants ensured (by definition) that all potentially important factors were considered in the statistical analysis. All main effects and interactions identified as significant with regard to pollutant concentrations have been explained individually in a companion article in this series (Banhazi et al., 2008b); therefore, in the following pages, we will discuss only the factors influencing emission rates.

Results

The raw emission data obtained from the study buildings are presented in table 2, together with the mean European emission rates for comparison. Emission rates were not measured successfully in all buildings due to logistical and instrumentation problems. The raw means of the emission rates are presented on a per-livestock unit (LU) basis (equivalent to 500 kg live weight).

Table 2. Rates of emission of the main airborne pollutants from Australian piggery buildings.

Emitted Pollutant	Mean	Median	No. of Buildings	Min.	Max.	European Emission Rate (Mean)[a]
Airborne bacteria (10^6 cfu h^{-1} LU^{-1})[b]	82.2	42.1	109	4.1	1433.2	34
Respirable endotoxins (10^3 EU h^{-1} LU^{-1})[c]	20.1	11.6	102	0.7	247.0	59
Respirable particles (mg h^{-1} LU^{-1})[d]	254.7	79.8	109	4.4	12150.0	85
Inhalable particles (mg h^{-1} LU^{-1})[d]	1306.7	855.1	109	20.3	26747.0	762
Ammonia (mg h^{-1} LU^{-1})[d]	1442.5	341.5	100	1.5	14006.4	1756

[a] Sources: Groot Koerkamp et al. (1998), Seedorf et al. (1998), and Takai et al. (1998).
[b] Colony forming units per hour per 500 kg live weight of animals.
[c] Endotoxin units per hour per 500 kg live weight of animals.
[d] Milligrams per hour per 500 kg live weight of animals.

Table 3. Summary of significant effects identified for the emission rates of the five major airborne pollutants.

Effect or Interaction Identified	Ammonia	Airborne Bacteria	Respirable Endotoxins	Inhalable Particles	Respirable Particles
Ventilation type		x	x	x	x
Wall ventilation air inlet height		x	x	x	x
Building height		x		x	x
Building type	x			x	x
Temperature	x			x	
Season	x				x
Humidity	x				x
Management	x			x	
Building width					x
Sow numbers	x				
Pen hygiene		x			
Building height × ventilation type		x		x	x
Temperature × building type	x			x	
Humidity × building type					x
Building height × season					x
Building width × season					x
Management × season	x				

Identification of Emission Factors

Table 3 summarizes the significant effects identified for the emission rates of airborne bacteria, respirable endotoxins, and inhalable and respirable particles at the 99% confidence level. For NH_3 emission rates, the model incorporating effects at the 95% confidence level was retained because of an unacceptable reduction in the predictive value of the model at the 99% confidence level. The reason for adopting this approach is explained in details in the first article of this series (Banhazi et al., 2008a; Banhazi et al., 2008b).

The type of ventilation system used, the size/height of the wall ventilation inlets, and the building height were all associated with the emission rates of major airborne pollutants, with the exception of NH_3. Building type/classification affected NH_3 and inhalable and respirable particle emission rates. Temperature and management influenced both NH_3 and inhalable particle emission rates, and season and humidity had an effect on both NH_3 and respirable particle emission rates. Building width influenced only respirable particle emissions, whereas pen hygiene affected only airborne bacteria emission rates. Number of sows affected NH_3 emission rates at the 95% significance level.

Results confirmed that piggery buildings with poor pen hygiene emitted more bacteria than those with good pen hygiene (fig. 1).

Deep-bedded shelters (DBS) typically utilizing non-mechanical tunnel ventilation had higher rates of emission of respirable endotoxins compared with other types of buildings utilizing either natural or mechanical ventilation systems (fig. 2).

The emission rate of inhalable dust was higher from continuous-flow (CF) piggery buildings than from all-in/all-out (AIAO) buildings (fig. 3).

Building management interacted with season in regard to NH_3 emission, highlighting the risk of high NH_3 emissions from CF buildings in summer (fig. 4).

Table 4 lists the highly significant associations found between the emission rates of major airborne pollutants and various covariates considered in the model.

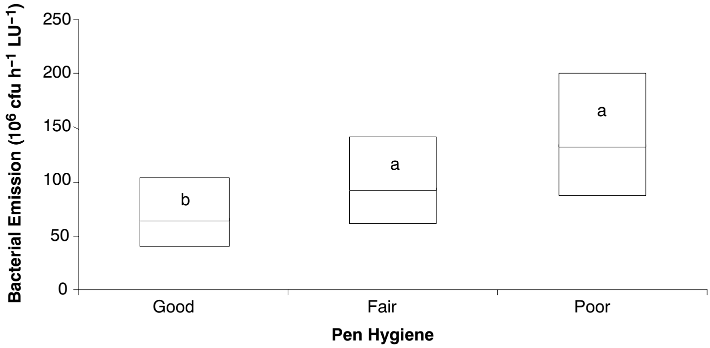

Figure 1. Effect of building pen hygiene on bacterial emission rates (10^6 cfu h^{-1} LU^{-1}) in Australian piggery buildings (medians with 95% confidence intervals; different letters indicate significant differences).

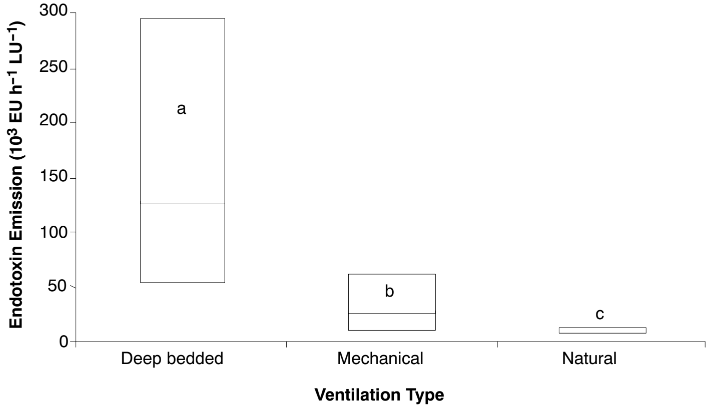

Figure 2. Effect of ventilation type on respirable endotoxin emission rates (10^3 EU h^{-1} LU^{-1}) in Australian piggery buildings (medians with 95% confidence intervals; different letters indicate significant differences).

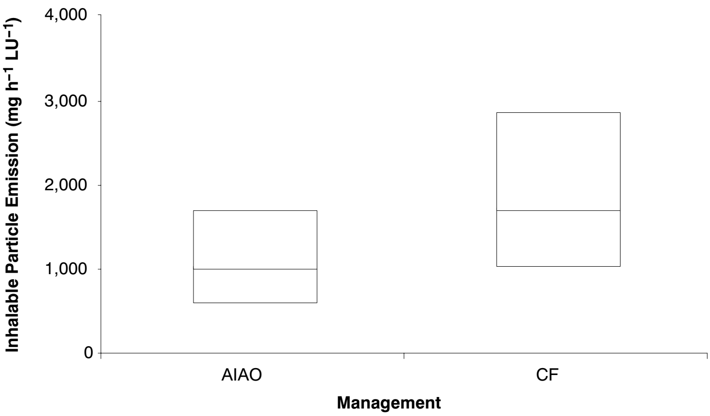

Figure 3. Effect of building management on inhalable particle emission rates (mg h^{-1} LU^{-1}) in Australian piggery buildings (medians with 95% confidence intervals).

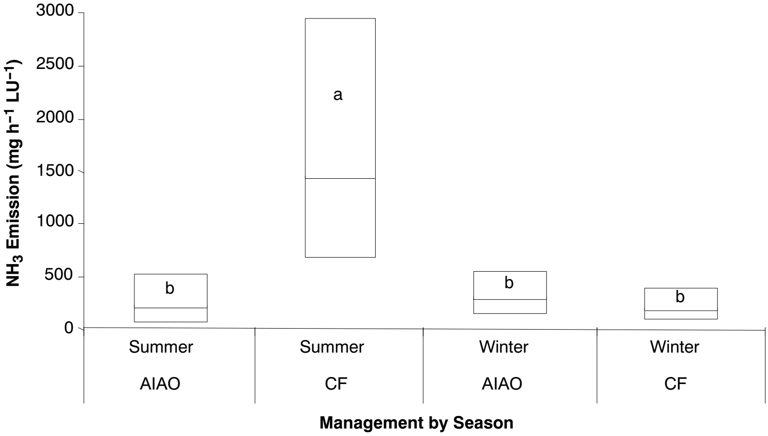

Figure 4. Effect of season and management interaction on ammonia emission rates (mg h^{-1} LU^{-1}) in Australian piggery buildings (medians with 95% confidence intervals; different letters indicate significant differences).

Table 4. Effects of different covariates on emissions rates of different airborne pollutants.

Emitted Pollutant	Unit	Covariate	Interaction[a]	Slope
Airborne bacteria	$10^6 \times$ cfu h^{-1} LU^{-1}[b]	Building height (m)	Ventilation type (tunnel-ventilated DBS)	Positive
Airborne bacteria	$10^6 \times$ cfu h^{-1} LU^{-1}	Building height (m)	Ventilation type (natural ventilation)	Negative
Airborne bacteria	$10^6 \times$ cfu h^{-1} LU^{-1}	VH of air inlet (cm)[c]	N/A	Positive
Respirable endotoxins	$10^3 \times$ EU h^{-1} LU^{-1}[d]	VH of air inlet (cm)	N/A	Positive
Inhalable particles	mg h^{-1} LU^{-1}[e]	VH of air inlet (cm)	N/A	Positive
Inhalable particles	mg h^{-1} LU^{-1}	Temperature	Building type (weaner)	Positive
Inhalable particles	mg h^{-1} LU^{-1}	Building height (m)	Ventilation type (tunnel-ventilated DBS)	Positive
Inhalable particles	mg h^{-1} LU^{-1}	Building height (m)	Ventilation type (natural ventilation)	Negative
Respirable particles	mg h^{-1} LU^{-1}	VH of air inlet (cm)	N/A	Positive
Respirable particles	mg h^{-1} LU^{-1}	Building width (m)	Summer	Positive
Respirable particles	mg h^{-1} LU^{-1}	Building height (m)	Summer	Positive
Respirable particles	mg h^{-1} LU^{-1}	Building height (m)	Ventilation type (tunnel-ventilated DBS)	Positive
Respirable particles	mg h^{-1} LU^{-1}	Humidity (%)	Building type (DBS)	Negative
Ammonia	mg h^{-1} LU^{-1}	Humidity	N/A	Negative
Ammonia	mg h^{-1} LU^{-1}	Number of sows (farm size)	N/A	Negative
Ammonia	mg h^{-1} LU^{-1}	Temperature	Building type (dry sow)	Negative

[a] N/A = not applicable as there was no interaction for this covariate.
[b] Colony forming unit per hour per LU (one livestock unit equals 500 kg live weight).
[c] Vertical height (VH) of air inlet or ventilation openings on walls is an indication of the size of ventilation opening in predominantly naturally ventilated Australian piggery buildings.
[d] Endotoxin unit (EU) per hour per LU.
[e] Milligrams per hour per LU.

The vertical height of the ventilation wall openings (air inlets) was important in explaining variations in emissions of bacteria, endotoxins, and inhalable and respirable particles. The vertical dimension of the wall openings (indirectly indicating the sizes of the air inlets) had a similar effect on each of the previously mentioned pollutants (table 4). Ventilation type interacted with building height for emissions of bacteria and inhalable and respirable particles (table 4), whereas ventilation type as a main effect had a significant influence on endotoxin emission (fig. 2). However, the general trends were similar for all these pollutants. Essentially, DBS had high emissions of endotoxins, airborne bacteria, and inhalable and respirable particles, and emission rates from DBS increased with increasing building height. Temperature interacted with building type for inhalable dust emission, and emission rates from weaner buildings increased with increasing air temperature (table 4). Ammonia emission tended to decrease with increasing humidity (table 4) and also had a negative relationship with increasing sow numbers (table 4). A relationship between decreasing NH_3 emission rate and increasing temperature in dry sow buildings was found (table 4). Respirable dust particle emission from DBS decreased with increasing humidity, whereas the effect of humidity in all other types of buildings on the emission rates of respirable particles was not significant (data not shown). Respirable particle emission rates increased in summer as both the height and width of the buildings increased (table 4).

Discussion

Emission Rates

Evaluating the emission rates and assessing the measured mean values in terms of acceptability is difficult. Currently, there are no guidelines available for emission rates in Australia in relation to livestock buildings. As a basic emission assessment method, the raw means have been compared against the values obtained in a European air quality study (Groot Koerkamp et al., 1998; Seedorf et al., 1998; Takai et al., 1998) (table 1), which used a comparable methodology for measuring emission rates. The comparison indicates that the mean Australian airborne bacteria and particle emission rates were higher that the European rates, whereas NH_3 emission rates were comparable. Respirable endotoxin emission rates from Australian piggery buildings were lower than their European equivalents. Another possible way of evaluating the impact of measured emission rates is to assess the likely areas affected by particle and gas emissions from piggery buildings by using dispersion models. This approach has been used previously in European studies (Seedorf, 1997, 2004).

Identified Emission Factors

In terms of factors associated with emission rates, the general effects of building features associated with the different ventilation systems were dominant. For example, non-mechanical tunnel-ventilation systems (a feature of DBS) had greater emissions of airborne bacteria and inhalable and respirable particle in interaction with building height than other ventilation systems (table 4). High endotoxin emission rates from DBS were also observed. These high emission rates are probably also closely related to the presence of bedding material in these types of buildings. Because non-mechanical tunnel ventilation was used only in DBS within the survey population, the whole effect of the building type was manifested in the different ventilation systems. The open design of these structures facilitates high ventilation rates, which in turn manifested in high emission rates. The size of the ventilation air inlets was positively related to all viable and non-viable particle emissions (table 4). The majority of the surveyed buildings were naturally ventilated (Banhazi et al., 2008a), and in these types of buildings the size of the ventilation air inlet was very closely associated with ventilation rate and hence emission rate (Banhazi et al., 2008c). The fact that emission rates of all pollutants (except NH_3) were positively correlated with the size of the wall ventilation air inlets confirms that pollutant emission is very closely related to the amount of air moved through the buildings.

The inhalable dust emission rate from CF buildings was significantly higher than that from AIAO buildings (fig. 3), indicating that AIAO systems improve management and thus reduce rates of emission of inhalable particles. Management interacted with season for NH_3 emission and highlighted the risk of high NH_3 emissions from CF buildings in summer (fig. 4). This was not surprising, as NH_3 concentrations were also significantly elevated in summer in CF buildings (Banhazi et al., 2008b). When such high concentrations are coupled with the tendency to use numerically higher ventilation rates in summer (Banhazi et al., 2008c), we can expect that high NH_3 emission rates will result (fig. 4).

The ammonia emission rate tended to increase with decreasing humidity (table 4). This is in line with the observed trend of higher NH_3 concentrations in summer reported in overseas publications (Groot Koerkamp et al., 1998) and with the results discussed previously. Higher temperatures usually mean lower relative humidity in piggery buildings. However, the reduction observed in NH_3 emission rates in dry sow buildings as the air temperature increased was an unexpected finding of the study and thus requires more explanation (table 4). This observed reduction might be related to the nature of the typical manure management systems used in dry sow buildings. Unlike pigs at other life stages, dry sows in Australia typically have their movements restricted by the use of dry sow crates. These crates are used to prevent fighting between animals, which frequently happens in group housing situations. Animals kept in crates are prevented from smearing their droppings on the pen floor, and the droppings are usually deposited behind them on a small slatted area. The manure then either falls through the slats (and is carried away by the effluent system) or alternatively remains intact and dry on the slats. The major source of NH_3 volatilization would be the manure left behind on the slats, as urine tends to promptly drain through the slats. However, it could be argued that at higher temperatures these potential sources of emission (intact manure deposits on the slats) dry out quickly, forming a dry crust and therefore preventing further volatilization of NH_3. Essentially, quicker drying of the manure (the emission source) may lead to the reduction in NH_3 emissions observed at higher temperatures from dry sow buildings. This phenomenon was not observed in other buildings, as animals walking through their own droppings break up the manure deposits, constantly creating an emission source. However, the dry sow crates create a situation whereby the formation of a crust on the manure deposits actually reduces emission rates. Similar preventive effects of crust formation on NH_3 emissions from manure lagoons have been reported before (Bicudo et al., 2001).

Humidity and building type were associated with respirable particle emission rates, and increased humidity appeared to decrease emissions from DBS. Again, this is in line with previous observations of concentrations (Banhazi et al., 2008b). The humidity increase in DBS would make the bedding material more adhesive, trapping smaller particles within the larger fibers of the bedding material, reducing both internal concentrations and therefore emissions of respirable particles from these structures. Increases in building widths and heights increased respirable particle emission rates in summer (table 4), indicating that the absolute throughput increase demonstrated for ventilation airflow in relation to these building features is a real effect (Banhazi et al., 2008c). We demonstrated that ventilation airflow increases with increasing building size, and that this was manifested in higher respirable particle emission rates in summer (Banhazi et al., 2008c).

Temperature interacted with building type for inhalable particle emissions, and in weaner buildings there was a positive correlation between the rate of emission of inhalable particles and temperature increase (table 4). Weaner buildings tended to have increased ventilation rates in summer, as these types of buildings tend to be the only ones in Australia that are fully insulated and mechanically ventilated, giving piggery managers a real opportunity to control ventilation rates. The majority of other types of buildings tended to be naturally ventilated (perhaps with the only other exception being farrowing buildings), and their ventilation rates cannot be closely controlled. Therefore, in these types of buildings, ventilation rates and therefore emission rates were not as temperature-sensitive as in weaner buildings. In addition, with increasing temperature, there was also a marked increase in particle concentrations in weaner buildings (Banhazi et al., 2008b). When these two effects are combined, it is not surprising that a marked increase in inhalable particle emission rates was observed.

Pen hygiene was associated with emission rates of airborne bacteria (fig. 1). It is clear from the results that rates of emission of airborne bacteria can be reduced by keeping buildings (and more importantly pigpens) in a good state of hygiene. These results again support the findings of the concentration modeling component of this current study as related to bacterial concentrations (Banhazi et al., 2008b). Bacterial concentrations increased as the cleanliness of pens decreased, creating more opportunities for higher emission rates (Banhazi et al., 2008b). Sow numbers (indicative of farm size) were negatively correlated with NH_3 emission rates at the 5% significance level, and the explanation for this effect is not simple (table 4). However, it could be hypothesized that the negative correlation observed between NH_3 emission rate and farm size (as expressed by sow numbers) is a function of the higher stocking rates utilized on larger farms. Further investigations would be required to verify this hypothesis.

In summary, DBS systems generally have high emission rates of both viable and non-viable particles. In these buildings, increasing the humidity might decrease emission rates but would not be advised as a management tool, as it could compromise thermal comfort of the animals in both summer and winter. Therefore, the implementation of treatments that will increase not the humidity but the adhesion of the bedding material should be considered in DBS. Summer and higher temperatures will result in higher rates of emission of respirable and inhalable particles. Farms that utilize AIAO management and are therefore more likely to keep their pens clean will have reduced rates of emission of NH_3, bacteria, and inhalable particles (figs. 1, 3, and 4). Although higher and wider buildings might have higher total ventilation airflow rates (Banhazi et al., 2008c), increasing building dimensions will adversely affect emission rates.

Recommended Control Procedures Based on Overall Study Results

The associations identified between air quality, and management and the engineering features of the buildings have enabled us to develop key recommendations based on the combined results of this study (Banhazi et al., 2008a; Banhazi et al., 2008b; Banhazi et al., 2008c). The implementation of these in-principle abatement techniques will help producers to minimize the concentration of airborne pollutants in piggery buildings and emission from those buildings. This has the potential to increase the environmental sustainability of the piggery enterprise, enhance the efficiency of pig production, and reduce the occupational health and safety risk for farm workers. The identified main causes of airborne pollution, their likely associations, and resulting recommendations are depicted in figure 5.

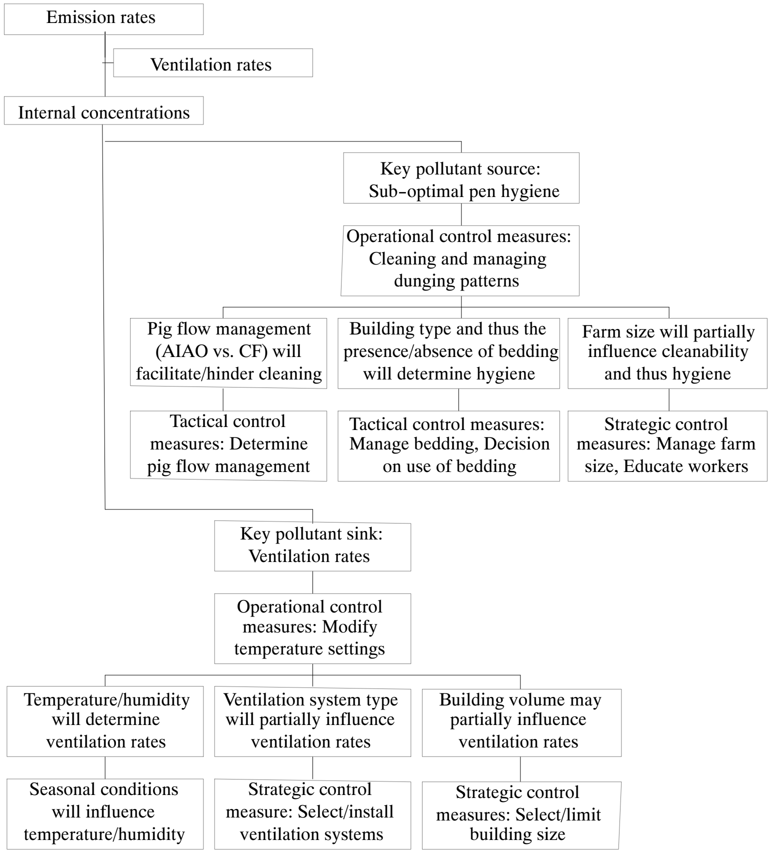

Figure 5. Likely relationships between identified individual risk factors for sub-optimal air quality.

Eliminating an Important Source of Pollution by Improving Pen Hygiene

This study clearly demonstrated that one of the main drivers of air quality in piggery buildings is pen hygiene (essentially pen cleanliness), as this factor influenced the concentrations of airborne bacteria, NH_3, and respirable particles (Banhazi et al., 2008b) and the emission of airborne particles. It was evident that pollutants are readily generated from dried fecal material on pen floors and on the animals' skins. Therefore, regular cleaning of pigpens as well as the maintenance of adequate hygiene standards is very important task for pig producers. Dunging patterns in traditional buildings also need to be controlled, as one of the main benefits of using slatted dunging areas in pigpens is to be able to separate the pigs from the excreta, thus reducing the opportunities for the manure to dry and become airborne via air turbulence created by the ventilation system or by the movement of the pigs. In order to minimize the risk for sub-optimal pen hygiene, piggery managers need to (1) keep pens dry, (2) implement pig flow management that will facilitate regular pen cleaning, (3) control building temperatures, and (4) maintain adequate stocking rates to facilitate the maintenance of correct dunging patterns. These risk factors (predisposing piggeries for sub-optimal pen hygiene) are briefly discussed below.

It has been demonstrated that wet flooring is a risk factor for triggering incorrect dunging, as pigs are attracted by wet areas to be used as toilet areas (Banhazi et al., 2002a). Thus, avoiding unnecessarily wetting of pen floors, repairing leaking taps, and drying of freshly cleaned pigpens before restocking are ways of eliminating risk factors for incorrect dunging. In previous studies, all-in/all-out (AIAO) management systems combined with improved cleaning have successfully reduced airborne pollutant concentrations in weaner and grower buildings (Banhazi and Cargill, 1998). The study reported in this series of articles demonstrated that AIAO management was also beneficial in reducing concentrations and emission of NH_3 and inhalable particles (Banhazi et al., 2008b). Therefore, implementing AIAO management practices with cleaning between batches is recommended to improve air quality.

The present findings also confirmed previous results reporting on the strong influence of temperature (season) on incorrect dunging behavior (Aarnink et al., 1997; Huynh et al., 2005) by pigs. At higher temperatures, pigs tend to break correct dunging behavior; therefore, during summer, more NH_3 could evaporate from the contaminated pen floors (Aarnink et al., 2000). During summer, pigs will be attracted to slatted areas to use as cool resting places. This will make the slatted areas unavailable to be used as toilet areas. Appropriate management of ventilation systems and the utilization of additional management tools (such as spray cooling) to cool pigs are very important aspects of good piggery management (Huynh et al., 2006). In addition, discouraging the crowding of slatted areas by pigs is also important, as it was suggested that crowding of the slatted area by other pigs will result in fouling of the solid pen surface (Bate et al., 1988; Fritschen, 1975; Hacker et al., 1994).

Managing Different Classes of Buildings

Piggery managers also need to be aware of the inherent differences between traditional (slatted) and deep-bedded systems. Users of bedded systems (deep-bedded shelters) should be aware that air quality in these buildings is probably going to be sub-optimal. The type/classification of buildings (dry sow, farrowing, weaner, grower/finisher, or DBS) had a large affect on the concentrations of total bacteria, respirable endotoxins, and inhalable and respirable particles (Banhazi et al., 2008b). Overall, DBS recorded the highest concentrations of all four pollutants, which suggests that the presence of bedding material is a risk factor for the high pollutant concentrations under dry Australian climatic conditions. Similar findings have been reported in cattle buildings by European researchers (Takai et al., 1998). The classification of ventilation systems (natural, mechanical, and tunnel-ventilated DBS) also had a very significant influence on emission rates, as presented in this article. The high emission rates from DBS observed for respirable endotoxins, airborne bacteria, and inhalable and respirable particles were partly related to the high internal concentrations of these pollutants typically measured in these buildings (Banhazi et al., 2008b). To overcome the negative effects of bedding on air quality (but retain the positive influence of bedded systems on animal welfare), it was suggested that spraying a mixture of oil and water directly onto pen floors inside piggery buildings could significantly reduce airborne particle concentrations in both traditional and DBS housing systems (Banhazi et al., 1999a; Banhazi et al., 1999b; Nonnenmann et al., 2004; Perkins and Feddes, 1996; Senthilselvan et al., 1997; Takai et al., 1995; Zhang et al., 1996). Impregnation of bedding material with oil is another viable method of particle reduction in poultry buildings, weaner kennels, horse stables, and DBS (Banhazi et al., 2001; Banhazi et al., 2002b; Ellen et al., 2000; Feddes et al., 1999; Feddes et al., 1995; McGovern et al., 1999).

The risks associated with building characteristics, the likely consequences of the risks, and potential reduction methods are summarized in table 5.

Table 5. Summary of identified risks, consequences, and suggested control strategies to prevent sub-optimal air quality in piggery buildings.

Identified Risk	Source of Risk
Presence of bedding material in buildings or shelters	Bedding particles becoming airborne
Reduction in pen hygiene (soiling of pen floor)	Poor hygiene level
Poor pig flow management	Reduced opportunity for cleaning
Large piggery size	Increasing intervals between cleaning
Sub-optimal temperature, humidity, and ventilation rates	Inadequate ventilation management
Outcome	Likelihood
High concentration of airborne pollutants in the airspace of piggery buildings	Highly likely
Consequences of Risk	Significance
Possible reduction in production efficiency in pigs	Moderate
Possible occupational health and safety risk for workers and associated legal consequences	Major
Environmental risk as a result of airborne emission	Moderate
Potential clash with planning authorities	Major
Difficulty with attracting stable workforce	Major
Control Strategies	Rating
Implement AIAO management of buildings	Highly effective
Impregnation or spraying of bedding material with oil/water mixture	Highly effective
Dry pens before re-stocking with a new batch of pigs and avoid wetting of pen floors	Effective
Hose down (wet) slatted areas of slatted areas	Moderately effective
Use sawdust to mark resting areas	Moderately effective
Reduce stocking rate	Moderately effective
Reduce the effects of high temperature on dunging patterns	Effective
Pay extra attention to hygiene in large piggeries	Moderately effective
Careful hygiene management of buildings in summer	Highly effective
Reduce excessive heat to avoid the development of incorrect dunging patterns	Effective

Conclusion

Two possible theoretical ways of achieving reductions in airborne pollutant emissions from piggery buildings are to reduce internal concentrations and ventilation rates. However, in reality, ventilation rates are manipulated to achieve an optimal thermal environment and minimize internal pollutant concentrations. Therefore, the best practical way of achieving a reduction in airborne pollutant concentrations within buildings is to control the source of pollution problem, i.e., identified risk factors. However, it is clear from our results that ventilation rates have a strong association with emission rates. Therefore, while all effort should be made to reduce internal concentrations and therefore emission rates, the limitations to achieving drastic reductions in emission rates by only manipulating internal concentrations have to be recognized.

Therefore, in addition to controlling the underlining risk factors influencing air quality in piggery buildings, techniques that will effectively capture emitted pollutants should also be investigated. The utilization of wet air scrubbers in mechanically ventilated buildings and the establishment of vegetation belts around naturally ventilated piggery buildings are two potentially useful techniques that need to be studied. The knowledge generated by this study via the identification of statistically significant factors associated with emission rates could improve the management of piggery buildings by alerting producers to potential management problems. Such improved awareness could contribute to the protection of the natural environment surrounding piggery facilities.

Future Research Directions

The air quality project described in this series of articles (Banhazi et al., 2008a; Banhazi et al., 2008b; Banhazi et al., 2008c) has opened up other avenues for future investigations in three main areas, including (1) economical evaluation of sub-optimal air quality, (2) special investigation of DBS, and (3) further development of reduction techniques. These potential research areas are briefly discussed below.

To satisfy the requirements of pork producers, environmental protection authorities, the concerns of animal welfare groups, and occupational health and safety planners, it remains an important task to evaluate the effects of air quality on (1) the production efficiency of pigs under farm conditions, (2) the health of farm workers, and (3) the health of the surrounding environment in the vicinity of piggery buildings. As data accumulate, analysis of air quality and associated production-related data will enable all interested parties to undertake a balanced and rational debate on the environmental conditions required for optimum levels of pork production. The objective quantification of health, welfare, and production effects of air quality in piggery buildings can be best achieved by conducting studies under farm conditions. Substantial quantities of on-farm data should be collected and analyzed by using a modeling approach to account for variations caused by other effects than air quality within datasets. If counteracting factors are appropriately dealt with, the effect of air quality can be appropriately evaluated under field conditions. When all potential benefits of optimal air quality management, such as reduced environmental pollution, decreased human health risks, improved production efficiency, and improved animal welfare, are appropriately accounted for and rewarded by the marketplace, there will be real motivation to incorporate air quality management into routine farm management practices.

Further studies on the relationship between the quality/management of bedding and airborne particle concentrations would be useful. Specifically, investigation of potential treatments for bedding materials could help to develop methods of reducing the concentrations and emission of viable and non-viable particles in DBS and could reduce endotoxin emissions from these buildings. Subsequent improvements in air quality could lead to additional production efficiency improvements in pigs housed in DBS. More importantly, an increased understanding of the possible physiological or immunological reasons behind pigs' ability to tolerate relatively high airborne pollutant concentrations in DBS could also help us to improve the production results in both DBS and traditional piggery buildings.

Investigation of methods of improving pen hygiene and managing dunging patterns would likely lead to improvements in air quality in piggery buildings. In addition, techniques such as air scrubbers and vegetation belts around buildings need to be investigated to find safe and reliable emission abatement techniques to be used routinely by livestock producers.

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References

Aarnink, A. J. A., D. Swierstra, A. J. van den Berg, and L. Speelman. 1997. Effect of type of slatted floor and degree of fouling of solid floor on ammonia emission rates from fattening piggeries. *J. Agric. Eng. Res.* 66(2): 93-102.

Aarnink, A. J. A., J. W. Schrama, R. J. E. Verheijen, and J. Stefanowska. 2000. Effect of ambient temperature on pen fouling by pigs. In *Proc. 10th Intl. Congress on Animal Hygiene*, 933-937. Boxtel, The Netherlands: International Society for Animal Hygiene.

Banhazi, T., and C. Cargill. 1998. An assessment of the benefits of age-segregated rearing and all-in/all-out management in respiratory disease free herds. In *Proc. 15th IPVS Congress*, 387. C. Cargill and S. McOrist, eds. Birmingham, U.K.: University of Birmingham.

Banhazi, T., C. Cargill, N. Masterman, and J. Wegiel. 1999a. The effects of oil spraying on air quality in a straw-based shelter. In *Manipulating Pig Production VII*, 28. P. D. Cranwell, ed. Werribee, Victoria, Australia: Australasian Pig Science Association.

Banhazi, T., M. O'Grady, C. Cargill, J. Wegiel, and N. Masterman. 1999b. The effects of oil spraying on air quality in traditional weaner accommodation. In *Manipulating Pig Production VII*, 27. P. D. Cranwell, ed. Werribee, Victoria, Australia: Australasian Pig Science Association.

Banhazi, T., J. Wegiel, M. Kloppers, and C. Cargill. 2001. Improving air quality in weaner kennels. In *Manipulating Pig Production VIII*, 47. P. D. Cranwell, ed. Werribee, Victoria, Australia: Australasian Pig Science Association.

Banhazi, T., K. Hillyard, T. Murphy, and M. Kloppers. 2002a. The effects of floor wetting on established dunging patterns. In *Animal Production in Australia*, 373. D. K. Revell and D. Taplin, eds. Adelaide, South Australia: Australian Society of Animal Production.

Banhazi, T., R. Woodward and P. Hynd. 2002b. Improving air quality in bedded systems. In *Animal Production in Australia*, 375. D. K. Revell and D. Taplin, eds. Adelaide, South Australia: Australian Society of Animal Production.

Banhazi, T. M., J. Seedorf, D. L. Rutley, and W. S. Pitchford. 2008a. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 1. Study justification and design. *J. Agric. Safety Health* 14(1): 5–20.

Banhazi, T. M., J. Seedorf, D. L. Rutley, and W. S. Pitchford. 2008b. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 2. Airborne pollutants. *J. Agric. Safety Health* 14(1): 21–39.

Banhazi, T. M., J. Seedorf, D. L. Rutley, and W. S. Pitchford. 2008c. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 3. Environmental parameters. *J. Agric. Safety Health* 14(1): 41–52.

Bate, L. A., R. R. Hacker, and P. A. Phillips. 1988. Effect of growth on porcine defecation patterns. *Canadian Agric. Eng.* 30(tech. note): 191-192.

Bellin, P., and J. Schillinger. 2001. Comparison of field performance of the Anderson N6 single stage and the SAS sampler for airborne fungal propagules. *Indoor Air* 11(1): 65-68.

Bicudo, J. R., D. R. Schmidt, C. L. Tengman, W. Powers, L. D. Jacobson, and C. J. Clanton. 2001. Odor and gas emissions from a naturally crusted swine manure storage. ASAE Paper No. 014092. St. Joseph, Mich.: ASAE.

Bottcher, R. W. 2001. An environmental nuisance: Odor concentrated and transported by dust. *Chem. Senses* 26(3): 327-331.

Ellen, H. H., R. W. Bottcher, E. von Wachenfelt, and H. Takai. 2000. Dust levels and control methods in poultry houses. *J. Agric. Safety Health* 6(4): 275-282.

Feddes, J. J. R., K. Taschuk, F. E. Robinson, and C. Riddell. 1995. Effect of litter oiling and ventilation rate on air quality, health, and performance of turkeys. *Canadian Agric. Eng.* 37(1): 57-62.

Feddes, J., G. Qu, J. Leonard, and R. Coleman. 1999. Control of dust and odour emissions using sprinkled canola oil in pig barns. In *Dust Control in Animal Production Facilities*, 265-270. S. Pedersen, ed. Aarhus, Denmark: Danish Institute of Agricultural Science.

Fritschen, B. 1975. Toilet training pigs on partly slotted floors. Lincoln, Neb.: University of Nebraska, Institute of Agriculture and Natural Resources, Cooperative Extension Service.

Groot Koerkamp, P. W. G., and J. H. M. Metz, et al. 1998. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *J. Agric. Eng. Res.* 70(1): 79-95.

Hacker, R. R., J. R. Ogilvie, W. D. Morrison, and F. Kains. 1994. Factors affecting excretory behavior of pigs. *J. Animal Sci.* 72(6): 1455-1460.

Hammond, E. G., C. Fedler, and G. Junk. 1979. Identification of dust-borne odors in swine confinement facilities. *Trans. ASAE* 22(5): 1186-1189, 1192.

Hoff, S. J., D. S. Bundy, and X. W. Li. 1997. Dust effects on odour and odour compounds. In *Ammonia and Odour Emissions from Animal Production Facilities*, 101-109. J. A. M. Voermans and G. J. Monteny, eds. Rosmalen, The Netherlands: PV Rosmalen.

Huynh, T. T. T., A. J. A. Aarnink, W. J. J. Gerrits, M. J. H. Heetkamp, T. T. Canh, H. A. M. Spoolder, B. Kemp, and M. W. A. Verstegen. 2005. Thermal behaviour of growing pigs in response to high temperature and humidity. *Applied Animal Behaviour Sci.* 91(1-2): 1-16.

Huynh, T. T. T., A. J. A. Aarnink, C. T. Truong, B. Kemp, and M. W. A. Verstegen. 2006. Effects of tropical climate and water cooling methods on growing pigs' responses. *Livestock Sci.* 104(3): 278-291.

Jacobson, L., L. Johnston, B. Hetchler, and K. Janni. 1999. Odor emissions control by sprinkling oil for dust reduction in pig buildings. In *Dust Control in Animal Production Facilities*, 223-230. S. Pedersen, ed. Aarhus, Denmark: Danish Institute of Agricultural Science.

McGovern, R. H., J. J. R. Feddes, F. E. Robinson, and J. A. Hanson. 1999. Growth performance, carcass characteristics, and the incidence of ascites in broilers in response to feed restriction and litter oiling. *Poultry Sci.* 78(4): 522-528.

Nonnenmann, M. W., K. J. Donham, R. H. Rautiainen, P. T. O'Shaughnessy, L. F. Burmeister, and S. J. Reynolds. 2004. Vegetable oil sprinkling as a dust reduction method in swine confinement. *J. Agric. Safety Health* 10(1): 7-15.

Ouwerkerk, E. N. J., and S. Pedersen. 1994. Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. In *Proc. XII World Congress on Agricultural Engineering*, 516-529. Milano, Italy: CIGR.

Perkins, S. L., and J. J. R. Feddes. 1996. The effect of timing of floor-application of mineral oil on dust concentrations in a swine farrowing unit. *Canadian Agric. Eng.* 38(2): 1-5.

SAS. 1989. *SAS/STAT User's Guide.* Version 6, 4th ed., Vol. 2. Cary, N.C.: SAS Institute, Inc.

Seedorf, J. 1997. Emissions of respirable dust fractions from livestock buildings. In *Proc. Intl. Symposium: Ammonia and Odour Emissions from Animal Production Facilities*, 1: 641-644. J. A. M. Voermans and G. J. Monteny, eds. Rosmalen, The Netherlands: PV Rosmalen.

Seedorf, J. 2004. An emission inventory of livestock-related bioaerosols for Lower Saxony, Germany. *Atmospheric Environ.* 38(38): 6565-6581.

Seedorf, J., and J. Hartung, et al. 1998. Concentrations and emissions of airborne endotoxins and microorganisms in livestock buildings in northern Europe. *J. Agric. Eng. Res.* 70(1): 97-109.

Senthilselvan, A., Y. Zhang, J. A. Dosman, E. M. Barber, L. E. Holfeld, S. P. Kirychuk, Y. Cormier, T. S. Hurst, and C. S. Rhodes. 1997. Positive human health effects of dust suppression with canola oil in swine barns. *American J. Respiratory and Critical Care Med.* 156(2): 410-417.

Takai, H., F. Moller, M. Iversen, S. E. Jorsal, and V. Bille-Hansen. 1995. Dust control in pig houses by spraying rapeseed oil. *Trans. ASAE* 38(5): 1513-1518.

Takai, H., and S. Pedersen, et al. 1998. Concentrations and emissions of airborne dust in livestock buildings in northern Europe. *J. Agric. Eng. Res.* 70(1): 59-77.

Wathes, C., M. Holden, R. Sneath, R. White, and V. Phillips. 1997. Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust, and endotoxin in U.K. broiler and layer houses. *British Poultry Sci.* 38(1): 14-28.

Williams, A. G. 1989. Dust and odour relationships in broiler house air. *J. Agric. Eng. Res.* 44: 175-190.

Zhang, Y., A. Tanaka, E. M. Barber, and J. R. R. Feddes. 1996. Effects of frequency and quantity of sprinkling canola oil on dust reductions in swine buildings. *Trans. ASAE* 39(3): 1077-1081.