

ODOUR PRODUCTION, EVALUATION AND CONTROL

Project MLMMI 02-HERS-03

Final Report Submitted to

Manitoba Livestock Manure Management Initiative Inc.

October, 2002

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EXECUTIVE SUMMARY

An extensive literature review has been conducted to collect and analyze information on technologies and practices in odour measurement and mitigation. The review and analysis are focused on the following nine areas: (1) odour measurement and odour evaluation technologies; (2) odour production and odour release quantification; (3) feed additives and dietary manipulation for odour reduction; (4) manure additives; (5) in-barn manure handling systems; (6) manure storage design and management; (7) biofiltration; (8) dust control; and (9) emerging technologies for odour measurement and control. The suitabilities of odour management technologies to Manitoba are evaluated in terms of cost and climatic conditions.

Over 168 odour compounds have been identified in livestock odours. These individual odour compounds may be measured with analytical instrument such as GC or GC/MS, but there is no established correlation between the individual odour compounds and the human perception of odour. The most reliable way of measuring odour is using the human olfactory sense (nose). Dynamic-dilution olfactometers with trained human assessors are considered to be the industry standard for measuring odour concentration. However, there are considerable inconsistencies in the design and operation of olfactometers. A national standard should be developed, or existing standards, such as the European Union Standard, should be adopted, to provide guidelines for conducting olfactometry measurements of livestock odours. The human sniffing technique shows the potential of evaluating odour directly in the field. This technology is relatively inexpensive and may be adopted by various levels of regulatory agencies for evaluating odour complaints.

Research on the quantification of odour emissions from swine operations has been mainly focused on production buildings, with limited information available on manure storage, land application and mortality disposal. Odour emission rates vary widely among different facilities and within the same types of facilities. Reported odour emission rates range from 0.1 to 62 OU/s per m² of floor area for various swine production facilities. Limited data have shown that emission rates from earthen manure storage (EMS) are mostly below 10 OU/s per m² of manure surface area. An EMS normally exposes a much larger surface area than other storage types, and is therefore commonly associated with more odour complaints. Odour emission from land application could be minimized by proper injection. Adoption of manure injection by producers has appeared to shift odour complaints from land application to animal production facilities and manure storage units. Field measurements should be conducted to collect odour emission data from earthen manure storage under Manitoba climate conditions. Scientific methods should also be developed to assess the downwind impact of odour sources from swine operations and to establish setback requirements for Manitoba conditions.

Dietary manipulations have been shown to potentially reduce odour generation in swine operations. Although much of research to date has been done elsewhere, primarily in the Netherlands and the Midwestern region of the US, the results of the majority of the research can be translated to the Canadian situation either directly or with further refinement. However, differences in primary cereal crops used in feed and the associated differences in chemical composition warrant further research in Manitoba.

Many chemical and biological products are being marketed as manure additive for odour control. Research reported in the literature is mostly focused on the evaluation of manure

additives, with little on the mechanism of action or the development of products. Researchers have reported conflicting results on the effectiveness of using manure additives. This is partially due to the lack of universally accepted protocols for evaluating manure additives. Although some existing manure additive products have been shown to be effective in odour reduction under laboratory conditions, they may not perform well in actual production facilities. Many other factors, such as the building, ventilation, manure handling, feeding, and the overall management practice, may conceal the effect of manure additives in actual production facilities.

The in-barn manure handling system plays an important role in odour management. An effective manure handling system should promote quick separation of manure from animals to minimize odour generation. Properly designed slatted floor systems provide an effective way of separating manure from animals with minimum efforts. If manure is stored under the floors in the barn, well-designed ventilation systems are necessary to provide under-floor pit ventilation for minimizing odour problems. Solid manure systems usually result in less odour emission, but are more expensive and difficult to operate. Research should be conducted to evaluate solid manure handling systems for Manitoba conditions, in terms of their effectiveness in odour reduction, economic feasibility, and agronomic impacts of using solid manure as fertilizer.

Open-top manure storages such as earthen manure storage (EMS) are a main source of odour from swine operations. Covering the manure storage is an effective way of minimizing odour emission. Biocovers, such as straw, provide a cost-effective and farmer-friendly solution to odour problems associated with EMS, however they have not been adopted on a widespread basis by the swine industry. The straw cover is easy to apply, but will sink over time, and thus reapplication is required. Additional agitation and straw chopping are required for pump-out if straw covers are used. Straw covers also increase the volume of manure that must be transported. Synthetic plastic covers that provide complete year-round odour control in a cost-effective manner are commercially available. Research is needed to quantify the odour reduction by using various covers under Manitoba conditions.

Treating manure before or during storage may reduce odour emission from manure storage. Some technologies that have been studied are solid-liquid separation, anaerobic digestion, and composting (for solid manure). Most odorous compounds are contained in small manure particles. Therefore, removal of fine particles is necessary for effective odour reduction when using solid-liquid separation. Anaerobic digestion is performed in closed digesters and it reduces odour emission by converting odorous intermediate products of anaerobic decomposition into odourless end products of carbon dioxide and methane. Mesophilic and thermophilic anaerobic digestion seem hard to be accepted in Manitoba because of associated high heating cost during long and cold winter. Anaerobic digestion at lower temperatures of psychrotrophic or psychrophilic range holds some potential for Manitoba conditions.

Biofiltration is a potential technology for reducing odours from livestock facilities. Open-bed biofilters are the most common style for treating exhaust air from livestock facilities. The open-bed filters usually use compost and wood chips as filter medium and odour removal efficiencies of between 75% and 90% may be achieved. Biofilters associated with livestock operations generally do not need supplementary heat; the heat from the exhaust air and exothermic microbial activity in the filter bed is usually sufficient to keep the filter bed in the

right temperature range even under Manitoba climate conditions. Despite the success of open-bed biofilters, there is a need to continue research efforts to improve both the economics and aesthetics of biofiltration systems for livestock operations.

Dust may act as an important odour carrier. Odour compounds attached to small dust particles stays in the air longer, thus having a greater downwind impact. Furthermore, many of the respirable dust particles are odorous because of their fecal origin. Spraying oil or oil-water mixture inside the building seems to be effective in reducing dust and odour emissions. Other options, such as mechanical and electrical dust removal, are expensive.

One of the greatest obstacles to the advancement of odour management is the difficulty of measuring odour itself. Olfactometers are only capable of measuring the odour concentration. The electronic nose (e-nose) technology has the potential of measuring both quality and quantity of odour. Research is needed to correlate human perceptions of odours to e-nose measurements and to develop portable e-noses for field measurements of odour.

1. ODOUR MEASUREMENT AND ODOUR EVALUATION TECHNOLOGY

1.1 Composition of Swine Manure and Odour Compounds

Manure is managed in the liquid form in most swine production facilities across Canada (Tessier, 1999). The typical composition of liquid swine manure is 92% - 99% of water and 1% - 8% of solids (fig. 1). Fixed solids (FS) refer to the minerals that are undegradable by microorganisms. FS typically constitutes approximately 15% of the total solids (TS). Volatile solids (VS) refer to the organic matters, which is approximately 82% to 85% of TS (Taiganides et al. 1966; Evens et al. 1978). VS may potentially be decomposed by microorganisms and converted into stable end products. Odour compounds are produced if decomposition occurs under prevailing anaerobic conditions. Compounds that pose odour concerns include ammonia, hydrogen sulfide, volatile fatty acids, p-cresol, indole, skatole, and diacetyl, by either their relatively high concentration or their low detection thresholds (Priest et al., 1994). O'Neil and Philips (1992) summarized 168 odour compounds identified in livestock odours by various researchers. Among these compounds, thirty (30) had odour detection thresholds lower than or equal to 0.001 mg/m³ (Table 1). Six of the ten compounds with the lowest detection thresholds of all were sulfur-containing compounds.

Each odour compound (odourant) that constitutes a particular odour may be identified using analytical techniques such as gas chromatography (GC) and other gas analyzers. With the inclusion of a mass spectrometer (MS), for example, the amount (mass) of each odourant within an odour can be measured and used to determine the concentration of that gas in the odour (NCMAWM, 2001; Skoog et al., 1998). However, odour is the sensations that occur when a mixture of odourants stimulate receptors in the nasal cavity. In other words, odour is a complex psychophysical variable, not a simple physical or chemical variable. Researchers agree that the identification of any number of individual odourants within an odour and measurement of their concentrations are not sufficient to describe the strength (concentration or intensity) or quality (character) of that odour (Jones et al., 1994).

1.2 What Does Odour Measurement Entail?

Typically, livestock odour is evaluated relative to its potential nuisance-effect on humans. For instance, a person encountering an odour may file a nuisance-complaint to an official health or environmental conservation agency. The nature of the complaint relates to the affected person's perception of that odour. Often, this perception is associated with the **FIDO**, i.e., **F**requency, **I**ntensity or concentration (strength), **D**uration, and **O**ffensiveness of the odour (NCMAWM, 2001). The odour frequency is a measure of the number of perceivable odour events that occur in a given length of time, e.g., days, weeks, months, etc. The odour intensity or concentration is a measure of the strength of a perceived odour. The odour duration is a measure of the length of time an uninterrupted odour event occurs, e.g., seconds, minutes, hours, etc. The odour offensiveness is a measure of the unpleasantness/pleasantness of a perceived odour.

1.3 Measuring Odour Concentration

Odour concentration is the most commonly used parameter for signifying the strength of a livestock odour (NCMAWM, 2001; McGinley et al., 2000a). Although analytical techniques have been used to identify individual odourants in odour, there is no established correlation between the concentrations of these individual odourants or specific groups of odourants and the

human response to odour (Jones et al., 1994). Thus, non-analytical techniques employing the human olfactory sense are commonly used to measure the strength of odours (NCMAWM, 2001; Kephart and Mikesell, 2000).

1.3.1 Olfactometry

Olfactometry is a psychophysical technique that utilizes the human sense of smell, i.e., the olfactory senses, to determine odour concentrations (Jiang, 2000; McGinley et al., 2000b; CEN, 1999). In this technique, odour samples are diluted with different, known volumes of a neutral, odourless gas (diluent), e.g., nitrogen or filtered air. The different mixtures of odour and diluent are presented to a human panelist or group of panelists for sniffing and their responses are recorded. (NCMAWM, 2001; Jiang, 2000; CEN, 1999). It is typical to screen and select panelists based on their sensitivity and consistency. N-butanol is often used as a reference odour in the screening process (NCMAWM, 2001; CEN, 1999).

Generally, the first sample (mixture) presented to an odour panel is diluted with a very large volume of diluent. At this stage of the analysis, the diluted odour should be undetectable by the human nose. In subsequent presentations, the volume of diluent is decreased by a pre-determined factor. This process is continued until each panelist can barely, but positively detect an odour in the diluted mixture. When this occurs the panelist has reached the detection threshold for that odour (Schmidt, 2002; NCMAWM, 2001; Jiang, 2000; CEN, 1999). The dilution ratio or factor, i.e., the ratio of the volume of the diluted odour to volume of odour in the mixture is recorded at each panelist's detection threshold (NCMAWM, 2001; Jiang, 2000; Hamilton and Arogo, 1999).

Jones et al. (1994) briefly described two methods for determining odour concentration based on panelist responses. The first method, the "percent correct method", plots the percentage of correct responses at each dilution to the logarithm of the corresponding dilution ratio. A regression analysis is performed and the dilution ratio corresponding to 50% of the correct responses is regarded as the odour concentration. The other method, "individual threshold method", estimates the detection threshold of a panelist by taking the mean of replicated measurements. The odour concentration of the sample is then determined from the geometric mean of the panel's individual detection thresholds.

Odour concentration measured by olfactometry is expressed as "odour units" (OU) (mostly in North America) or "odour units per cubic meter" (OU/m³) (in Europe). Schmidt (2002) defines "odour units" as the volume of diluent required to dilute a unit volume of odour until the detection threshold of the odour is obtained. Alternatively, "odour units per cubic meter" is defined as the concentration of odour in one cubic meter of air at the panel detection threshold of the odour (NCMAWM, 2001; CEN, 1999). In the field of air pollution control, the pollutant concentration is commonly expressed as mass per unit volume (g/m³). Therefore, the unit OU/m³ seems logical to use for expressing odour concentration, but OU is not a mass measurement. The European standard (CEN, 1999) defines a European reference odour mass (EROM), which is equivalent to 123 µg n-butanol evaporated into 1 m³ of neutral gas (air). This leads to a definition of the European odour unit, denoted as OU_E by some researchers, which is the amount of odourant(s) that, when evaporated into 1 m³ of gas air at standard conditions, elicits a

physiological response from a panel (detection threshold) equivalent to that by one EROM. Therefore, the odour concentration is expressed as OU_E/m^3 , or simply OU/m^3 .

Odour Sampling

Olfactometric measurements of odour concentrations usually begin with sample collection from the odour source. Odour sampling may be dynamic or static (CEN, 1999). In the former, odorous air is transported directly from the source to the olfactometer for measurement. Whereas, in static sampling, the odorous air is collected and stored in a sample container or bag before it is transported to the olfactometer for measurement. It is important for the sampling equipment and the sample container to be clean and free of any residual odours. According to CEN (1999), materials used for olfactometry should: (1) not add odour to the sample (odourless); (2) react minimally, i.e., physically or chemically, with the odourants in the odour; (3) have low permeability to minimize losses through diffusion; and (4) have smooth surfaces. The following materials are defined as appropriate for odour sampling (CEN, 1999): (1) stainless steel; (2) PTFE (polytetrafluoroethylene); (3) FEP, Teflon™ (tetrafluoroethylene hexafluoropropylene copolymer); (4) PVF, Tedlar™ (polyvinylfluoride); (5) Nalophan, NA™ (polyterephthalic ester copolymer); and (6) glass.

Tedlar bags are most commonly used for collecting odour samples for analysis using olfactometers. However, several researchers have reported that the residual odour of Tedlar bags could seriously bias the odour measurement. Zhang et al. (2001b) found that odour intensity of clean Tedlar bags varied from 0.5 to 2.8 on a 5-point n-butanol odour intensity scale. Keener et al. (2002) showed that Tedlar bags emitted acetic acid and phenol, which might bias air samples collected for olfactory analysis.

Dynamic-Dilution Olfactometers

Dynamic-dilution olfactometers are considered to be the industry standard for measuring odour concentration. In dynamic olfactometry, the diluted odour is presented to the panelists by continuously injecting a stream of odorous air at a known flow rate and pressure into a stream of the filter air (diluent), also flowing at a predetermined rate (Watts, 2000; ASTM, 1997). Thus, the dilution ratio is the ratio of the volumetric flow rate of diluent to that of the odorous air.

Most dynamic-dilution olfactometers are based on the principle of the 3-port forced-choice method of sample presentation, which is also referred to as "Triangular Forced-Choice Dynamic Olfactometry" (NCMAWM, 2001; McGinley et al., 2000a; McGinley et al., 2000b; AWMA, 1995). In this method of dynamic olfactometry, the diluted odour is presented to the panelists through one of the three ports. The other two ports are used to present blank samples of the diluent to the panelists. Panelists are "forced" to identify which of the three ports the odour is presented from by sniffing and comparing the presentations from all the three ports. When a decision is made the panelists indicate which of the ports they think was used to present the odour sample. This is achieved by having the panelists select a "guess", "inkling" or definite "detection" (Schmidt, 2002; Jiang, 2000; Kephart and Mikesell, 2000; McGinley et al., 2000a; McGinley et al., 2000b; CEN, 1999; ASTM, 1997; AWMA, 1995; Jones et al., 1994). According to ASTM (1997), after a definite detection is made, the panelist is required to continue evaluating subsequent presentations (at lower dilution ratios) until it is certain that the initial definite detection was not obtained by chance.

There are considerable inconsistencies in the design and operation of olfactometers. Qu et al. (2002) compared odour measurements among four olfactometry laboratories in US and Canada. Odorous air samples collected from livestock facilities were delivered to the four laboratories and the odour concentration of each sample was measured by the four laboratories at the same time. They reported that large discrepancies existed among the laboratories. The greatest difference between the laboratories was 25 times (42 vs. 1045 OU/m³) in measured odour concentration.

Scentometer

A scentometer measures the odour concentration of ambient air directly in the field (NCMAWM, 2001; Kephart and Mikesell, 2000; Watts, 2000; Hamilton and Arogo, 1999). Odorous ambient air and filtered (odourless) ambient air are drawn into the scentometer and mixed each time the odour assessor sniffs from a sampling port inserted in his/her nostrils. The dilution ratio of the mixture is determined by the size of the openings the odorous air flows through as it enters the scentometer (Kephart and Mikesell, 2000; Watts, 2000; Miner and Barth, 1993; Hamilton and Arogo, 1999). Scentometers have limited levels of dilution and usually one sniffer operates the instrument. They are, therefore, less accurate than dynamic-dilution olfactometers. It is also difficult for the operator to avoid breathing odorous air before the scentometer is used. Therefore, the operator may experience odour fatigue when using the scentometer in the field.

1.4 Measuring Odour Intensity

Odour intensity is another measure of the strength of an odour. However, unlike odour concentration, it is a measure of the human response to an undiluted odour (Hamilton and Arogo, 1999). A common way of measuring odour intensity is comparing the intensity of an odour to the intensities of different but known concentrations of a reference odourant. ASTM (1999) recommends that successive concentrations of the reference odourant are greater than the preceding levels by a step factor of two. Odour intensity is obtained when a match is found between the intensity of the odour and the intensity of one of the concentrations of the reference odourant. At times it is difficult to match the intensity of an odour to the intensity of only one concentration of the reference odourant. In such cases, the odour intensity is considered as the intensity corresponding to the geometric mean of adjoining concentrations of the reference odourant (ASTM, 1999). Also, difficulties have been reported matching a livestock odour intensity with that of n-butanol gas. The two odours are quite different from each other.

Odour Intensity Referencing Scale (OIRS)

A common OIRS uses n-butanol as a standard reference odourant (Kephart and Mikesell, 2000; Schmidt, 2002; ASTM, 1999). ASTM (1999) describes two standard procedures for measuring odour intensity using n-butanol references. These include the, "dynamic-scale" and "static-scale" methods. In the dynamic-scale, an olfactometer, also referred to as n-butanol olfactometer (NCMAWM, 2001; Watts, 2000), may be used to obtain different concentrations of n-butanol by passing a diluent across the surface of a glass container of liquefied pure (99+mol%) n-butanol (ASTM, 1999). Panelists compare the intensity of livestock odours to different intensities of n-butanol presented using the olfactometer. With each presentation, the panelists decide if the intensity of the livestock odour is less, similar or greater than the intensity

of the diluted n-butanol sample (NCMAWM, 2001; Watts, 2000; ASTM, 1999). In the static scale, different n-butanol concentrations are obtained by mixing liquefied pure (99+ mol%) n-butanol with distilled, odourless water. The different n-butanol mixtures are stored in glass containers and presented to panelists. Panelists shake the glass containers before sniffing the n-butanol vapor in the container headspace. Reference is made to the concentration of n-butanol in water (BIW) (NCMAWM, 2001; ASTM, 1999) or, n-butanol in air (BIA) (St. Croix Sensory, 2000). The concentration of the vapor in the headspace is less than the BIW by a factor of ten (10) (St. Croix Sensory, 2000).

Category Estimation Technique

In this technique, human assessors estimate the intensity of an odour by ranking it according to their perception of its strength. The following is an example of the category intensity scale (NCMAWM, 2001; St. Croix Sensory, 2000; Misselbrook et al., 1993):

No Odour
Very Faint Odour
Faint Odour
Distinct Odour
Strong Odour
Very Strong Odour
Extremely Strong Odour

Odour intensity is determined from the geometric mean of the different levels (intervals) of the category scales as perceived by each panelist.

Zhang et al. (1999a) used a labeled magnitude scale (LMS) (Green et al., 1993) to rank the odour intensity of cloth swathes exposed to swine odour. The LMS is labeled with "barely detectable" at one end, and "strongest imaginable" near the other end and labels increased from short intervals at the weak end, to long intervals at the strong end. In a sensory session, each panelist was given a LMS graph and a set of instructions to rank the odour intensity on the scale that best matched their perception of the odour intensity of the sample. A ruler with linear scale markings from 0.0 at one end of the line, and 100.0 at the opposite end of the line, was placed against each panelist's score sheet. The numerical value was then noted according the following scale (Green et al., 1993):

95.5% strongest imaginable
50.1% very strong
33.1% strong
16.2% moderate
5.8% weak
1.4% barely detectable

This method allows for transferring the category ranking to numerical values.

1.5 Measuring Odour Offensiveness

Offensiveness is a subjective, qualitative, and comparative human classification of the nature of odour. The human perception of odour offensiveness is influenced by the character and intensity/concentration of the perceived odour (St. Croix Sensory, 2000; McGinley et al., 2000a; CEN, 1999). Parameters used to define odour offensiveness include the hedonic tone, odour description and annoyance level.

Hedonic tone

The hedonic tone is a measure of the pleasantness/unpleasantness of an odour (NCMAWM, 2001; St. Croix Sensory, 2000; McGinley et al., 2000a; CEN, 1999; Hamilton and Arogo, 1999). The hedonic tone of an odour is often evaluated and ranked using an 11 or 21-point scale ranging from +5 to 0 to -5 or +10 to 0 to -10, respectively. At +5 or +10 an odour is classified as very pleasant, very unpleasant at -5 or -10, and neutral at 0.

Odour Description

An odour may be qualified by relating its perceived character or smell to that of a known substance. Descriptors of various "smells" such as, fruity, chemical, rotten egg, medicinal, floral, sweet, etc., are listed on a "descriptor wheel" or in a table (St. Croix Sensory, 2000; McGinley et al., 2000a; Hamilton and Arogo, 1999).

Annoyance Level

Odour annoyance level or index is a measure of how humans "feel" about odours. The following scale is an example of annoyance measurement (St. Croix Sensory, 2000):

- Not Annoying
- Slightly Annoying
- Annoying
- Very Annoying
- Extremely Annoying

According to CEN (1999) and McGinley et al. (2000a), the annoyance level of an odour is often influenced by non-sensory factors such as personality traits, past experience, attitude, environment, etc.

1.6 Measuring Odour Frequency

Odour frequency is influenced by several variables interacting collectively. These variables include the wind direction and speed, atmospheric stability, location of and distance between receptor and source odour, and of course, the odour emission rate. The prevalent climatic conditions in an area determine the nature of odour dispersion in the locale of livestock operations (NCMAWM, 2001; Miner and Barth, 1993).

The Effect of Wind Direction and Speed

The frequency of any odour event at a given location downwind from a source of odour is dependent on how often the wind blows in that direction. Climatic data collected from weather stations can be used to determine the likelihood of odour events at specific sites located around

livestock operations (Miner and Barth, 1993). Furthermore, the wind speed determines the magnitude of the odour event. At low wind speeds, odour is diluted less and travels further than at high speeds. Jacobson et al. (2001b) reported an inverse relationship between the frequency of odour occurrences and wind velocity.

The Effect of Atmospheric Stability

The atmospheric stability relates to the level of air movement (turbulence) in the atmosphere, and it is commonly categorized by the stability classes (A – G) (Pasquill, 1961):

- A: Highly Unstable
- B: Moderately Unstable
- C: Slightly Unstable
- D: Neutral
- E: Slightly Stable
- F: Moderately Stable
- G: Highly Stable

Jacobson et al. (2001b) reported a majority of odour events occurred under stability classes E and F, with the most events occurring at lower wind speeds. In contrast, the least odour events occurred at stability class A, then B, then C, even at low wind speeds. Jacobson et al. (2001b) suggested that in the latter, the odours were sufficiently dispersed as the atmosphere became increasingly unstable in spite of the low wind speeds experienced.

The Effect of Distance from Odour Source

Distance from an odour source influences the frequency of specific odour events at that location. The specificity of each event is qualified by the odour intensity/concentration, direction of the receptor relative to the source and particular weather conditions, i.e., wind direction, speed and atmospheric stability under which the event prevails. In most situations, an inverse relationship exists between distance from the source and odour intensity as the odour disperses from its source. The wind speed and atmospheric stability prevailing at any time determine the rate at which the odour disperses into the atmosphere.

1.7 Measuring Duration of Odour Events

The odour duration relates to the length of time a specific odour event is experienced at a given location. Each event is characterized by an odour intensity/concentration of known magnitude. However, since the odour emission rates at the source may vary randomly, an odour event may relate to a range of odour intensities/concentrations rather than a single intensity/concentration. The duration of an odour event is also influenced by the persistence of the odour. If an odour is highly persistent it does not dissipate quickly, and therefore, its effect may be experienced for extended lengths of time.

1.8 Odour Measurement Standards

Measuring odour is complex process, and therefore standards must be followed to ensure the accuracy and consistence. A number of odour measurement standards exist, including:

- Australian/New Zealand standard (AS/NZS 4323.3:2001)
- Dutch standard (NVN 2820)
- European Union (EU) draft standard (prEN13725)
- French standard (AFNOR X-43-101)
- German standard (VDI 3881)
- US standard (ASTM E679-91 and ASTM E544-99)

These standards specify criteria, procedures and protocols to be followed when odour concentration or intensity are measured. They also specify the types of materials that may be used in equipment used for the analysis. Among these standards, the EU and ASTM standards are most commonly followed for measurements of livestock odours.

European Union Standard prEN13725

The European draft standard prEN13725, "Air Quality- Determination of Odour Concentration by Dynamic Olfactometry" (CEN, 1999) is anticipated to replace national standards of member countries of the EU (McGinley and McGinley, 2001; Mahin et al., 2000). The prEN13725 is a comprehensive document purported to be adopted by countries outside Europe and to become a global standard for measurement of odour concentration by olfactometry (McGinley and McGinley, 2001). As a matter of fact, the major olfactometry laboratories in North America follow (more or less) the EU standard in conducting livestock odour measurements. The EU standard details the following aspects of odour measurement (CEN, 1999):

1) Performance Quality Requirements for Dynamic Olfactometers

The standard specifies tests for accuracy and precision within and among laboratories in order to guarantee the repeatability and reproducibility of odour concentration measurements. It also stipulates tests for evaluating dilution and sampling apparatus on the basis of accuracy and instability (drift and dispersion).

2) Materials, Gases and Panel Members

Materials deemed appropriate for sampling and dilution apparatus are detailed (see section 1.3.1). The standard also specifies what neutral and reference gases can be used for olfactometry. In addition, the standard presents the design, operation and calibration criteria and procedures for determining performance limitations of olfactometers. It equally specifies environmental conditions that should prevail in laboratories or other facilities during odour analysis. Furthermore, prEN13725 stipulates conditions for recruiting panelists, panelist selection and panel size.

3) Sampling

The standard details the prescribed sampling methods, procedures, equipment, calibration methods, transportation, sample sizes and strategies for sampling from point sources (e.g.,

barn exhausts) and non-point sources with outward flow (e.g., biofilters) or no outward flow (e.g., manure storage facilities).

4) Presentation of odourants to assessors

The yes/no and forced choice methods of odour measurement are discussed earlier (section 1.3.1). A third method, the forced choice/probability method, is also specified by prEN13725. The standard also stipulates conditions for presentation and measurement of samples. These include time limitations for assessments and presentation intervals, number of replications per sample measurement and occupational safety requirements.

5) Data Recording, Calculation and Reporting

The standard specifies the minimum data recording requirements and the procedures for processing recorded data, e.g., calculation of odour concentration from a set of panel responses. The requirements for reporting and archiving results are also described.

ASTM Standards

ASTM E-679-91, "Standard Practice for Determination of Odour and Taste Thresholds by a Forced-choice Ascending Concentration Series Method of Limits" outlines olfactometry procedures, protocols and techniques for measuring, calculating and reporting odour concentration data (ASTM, 1997). ASTM E-544-99, "Standard Practices for Referencing Suprathreshold Odour Intensity" outlines procedures, protocols and techniques for measuring, calculating and reporting odour intensity using the dynamic scale and static-scale methods (details are discussed in section 1.4) (ASTM, 1999).

1.9 Measuring Downwind Odour

Dynamic-dilution olfactometers, commonly used for measurement of livestock odours, may not be suitable for measuring odours downwind from the source. Because of unstable atmospheric conditions, obtaining downwind odour samples that are representative to what is actually "felt" by the receptors becomes impractical. Typically, 10L Tedlar bags are used for collecting samples for olfactometer measurement and it takes up to several minutes to collect a sample (fill the bag). The collected sample, therefore, reflects the odour strength "averaged" over the sampling period. However, the instantaneous bursts of high odour strength may be of more concern than the average odour strength. Zhang et al. (2001b) reported that there was little correlation between the odour concentration of bagged samples measured with olfactometers and the odour intensity assessed by human sniffers in the field. In other words, the bagged samples could not capture instantaneous high odour levels in the field.

A potentially more satisfactory method of evaluating odour directly in the field is quantifying the instantaneous odour intensity by using human sniffers. The human sniffing technique has been used by several researchers in their studies of livestock odours. There is a German guideline which describes specific procedures of determining field odour plumes by human sniffers (VDI, 1993). Hartung and Jungbluth (1997) followed the German guideline to measure the odour plumes from dairy and cattle barns. Sniffers ranked odour intensity in the field based on a 6-point intensity scale suggested by German VDI Guideline 3882 (VDI 1992). Zhu et al. (2000b) used human sniffers to conduct on-site odour intensity measurement. The sniffers were trained to rank odour intensity on a scale of zero to five (0: no odour; 1: very faint;

2: faint; 3: distinctly noticeable; 4: strong; 5: very strong odour). Resident sniffers who received limited training were used by Guo et al. (2001b) in monitoring odour occurrences in a livestock production area. They used a relatively simple intensity scale of 0 to 3 (0: no odour; 1: faint odour; 2: moderate to strong odour, and 3: very strong odour). Zhang et al. (2001b) used trained human sniffers (Nasal Rangers™) to measure odour on four swine farms. Nasal Rangers™ ranked odour based on an eight-point u-butanol intensity scale. Their results showed the promise of using human sniffers for downwind odour evaluation.

Concluding Remarks

Many odour compounds have been identified in livestock odours. Although individual odour compounds may be measured with analytical instrument such as GC or GC/MS, there is no established correlation between the individual compounds and the human perception of odour. Human perception of odour is associated with the **F**requency, **I**ntensity or concentration, **D**uration, and **O**ffensiveness of the odour (**FIDO**). The most reliable way of measuring odour is using the human olfactory sense (nose). Dynamic-dilution olfactometers with trained human assessors are considered to be the industry standard for measuring odour concentration. However, there are considerable inconsistencies in the design and operation of olfactometers. Furthermore, dynamic-dilution olfactometers are not suitable for measuring downwind odour. Tedlar bags that are commonly used for collecting odour samples for olfactometer measurement may bias odour measurement because of their residual odour. A national standard should be developed, or existing standards such as the European Union standard should be adopted, to provide guidelines for conducting olfactometry measurements of livestock odours.

The human sniffing technique, such as trained Nasal Ranger™, provides a way of evaluating odour directly in the field. This technology is relatively inexpensive and allows for detection of instantaneous odour events in the field. With properly developed protocols, the human sniffing technique may be adopted by regulatory agencies at the Provincial level or even at the municipality level in Manitoba for assessing odour complaints.

2. ODOUR PRODUCTION AND ODOUR RELEASE QUANTIFICATION

The four main sources of odour release (emission) from swine operations are: (1) building exhaust, (2) manure storage, (3) land application, and (4) mortality disposal. The following sections discuss odour emissions reported in the literature from these four sources. The literature review has revealed that much research has been focused on odour emissions from the building sources and limited data are available on emissions from the other three sources.

2.1 Odour Emission from Swine Buildings

Odour release from swine buildings is quantified by the amount of odour (expressed as OU) being emitted per second (OU/s), which is commonly known as the odour emission rate. The odour concentration is often simply expressed as OU, instead of OU/m^3 (mostly in North America). This would result in a unit of $\text{OU}\cdot\text{m}^3/\text{s}$ for odour emission rate. For easy comparisons, the emission rate is also often described in terms of odour units emitted per unit floor area ($\text{OU}/\text{s}/\text{m}^2$) or per animal unit (OU/s per AU).

Odour emission rates from swine buildings are dependent on a number of factors, such as the type of operation (gestation, nursery, finishing, etc.), management practice, manure handling and storage, and ventilation. Several studies have also suggested that odour emission rates from animal facilities vary over the course of the day, and over the year (Zhu et al., 2000a; Schauberger et al., 1999). As well, indoor and outdoor temperatures seem to play a role in odour emission (Heber et al., 1998b). Generally, the operation type, manure storage method and ventilation are considered the most influential factors concerning odour emission, and are the easiest to report. As a result, most researchers have grouped odour emission rates according to these characteristics, while primarily grouping results by the facility type. A summary of odour emission rates reported in the literature is presented in Tables 2 – 5 for different swine operations (facilities).

As seen in Tables 2-5, different units have been used by researchers and it is difficult to compare the results. A common way of quantifying odour, which has been adopted by the majority of researchers, is using $\text{OU}/\text{s}/\text{m}^2$ (or $\text{OU}\cdot\text{m}^3/\text{s}/\text{m}^2$ in North America). Figure 2 summarizes the results reported by various researchers who measured odour emission in $\text{OU}/\text{s}/\text{m}^2$. It can be seen that odour emission rates vary widely among different facilities and within the same type of facilities. The emission rate is the highest ($62 \text{ OU}/\text{s}/\text{m}^2$) and varies most (from 0.4 to $62 \text{ OU}/\text{s}/\text{m}^2$) in farrowing facilities. The ranges of emission rates for gestation and finishing facilities are almost the same (fig. 2).

It should be noted that certain systems of manure storage and ventilation have more than one name. A shallow pit manure storage system may be also referred to as a pull plug system or potentially even a flush system. All these names are used to indicate a system where manure is stored in the animal facility for short periods of time – several days and up to a month. Some of these systems are emptied out every so often (hence pull-plug) or continually flushed out. Additionally, curtain wall ventilation is synonymous with natural ventilation. A curtain wall can usually be open or shut as desired, allowing air circulation.

It should be also noted that the reported odour emission rates were the average values for certain time periods. Wood et al. (2001) observed that the season (month of collection) significantly affected odour emission rates. Zhang et al. (2001a) reported that outdoor temperature had a significant effect on odour levels from barn exhaust, but not on odour emission rates. Zhou and Zhang (2001) reported that significant increases in odour emission rate were measured in the afternoon and evening in farrow and gestation barns. Hartung et al. (1998) found that the odour emissions from maiden sow and fatteners buildings increased at 11:00 am until 1:00 am in the course of the day, before they started to diminish until the next morning. Zhu et al. (2000a) observed a general trend of increasing odour emission rates for most animal facilities starting from 11:00 am. The researchers agree that the increase of ventilation rate with the outside temperature rise in the afternoon play a key role in determining the odour emission rates from animal buildings.

Another important issue associated with measuring odour emission rates from swine buildings is quantifying building ventilation rates (the odour emission rate is calculated as the product of the odour concentration and the ventilation rate). Ni et al. (1999) used a calibrated rotating impeller to measure ventilation rates in mechanically ventilated buildings. Naturally ventilated buildings or buildings with a combination of mechanical and natural ventilation require a more complicated method for calculating ventilation rates. One method is to measure temperatures and CO₂ concentrations for the heat balance and CO₂ balance, respectively (Heber et al., 2001b). The use of an artificial tracer gas such as SF₆ is considered to be much preferred over the heat balance or CO₂ method (Phillips et al., 2001).

2.2 Odour Emission from Manure Storage Facilities

The most common manure storage facility in Manitoba is the earthen manure storage (EMS) although concrete and steel structures have gained some popularity recently. Odour emission from earthen manure storage is seasonal - very little emission in the winter and more in the spring, summer and fall. Earthen manure storage is generally either anaerobic or facultative. This means that the organic matter in the manure undergoes anaerobic decomposition in earthen storage, thus generating offensive odours.

Odour emission from manure storage is quantified by the odour emission rate expressed as the amount of odour emitted per unit time and per unit surface area (OU/s/m²). Limited data are available in the literature on odour emission rates from manure storage. Table 6 summarizes results from two studies conducted in the United States.

The below ground tanks appeared to have higher odour emission rates (the highest was 51.3 OU/s/m²) than EMS (the highest 17.6 OU/s/m²). However, odour from below ground tanks would mostly be kept in the headspace if the tanks are covered. The odour emission rates from EMS were generally below 10 OU/s/m². The average emission rate of the 8 sites reported by Jacobson et al. (1999b) and Heber et al. (2000) was about 6 OU/s/m². Data in Table 6 do not indicate any trend in terms of the effects of barn-type and number of head on odour emission rate. Jacobson et al. (1999b) collected their data between April and October in Minnesota. They did not observe any significant variations in odour level during this time period. Heber et al. (2000) observed that the odour emission rate was proportional to the loading rate of volatile solids.

The sampling procedure may have dramatic effect on the measurement of emission rate from the manure surface. Wind tunnels (or flux hoods) are commonly used for sampling odour emission from manure surfaces. A wind tunnel is a portable open-ended, open-bottomed enclosure placed over an odour emitting surface. Filtered ambient air is blown through the tunnel to pick and mix with odour emitted from the surface. The mixture is sampled at the downstream end of the tunnel for determining the odour concentration. The odour emission rate is then determined as the measured odour concentration multiplied by the airflow rate. Smith and Watts (1994) evaluated the performance of two wind tunnels of different sizes in measuring odour emission from feedlots and reported that there was strong dependence of the measured emission rate on the air velocity inside the tunnel. They recommended that the air velocity should be specified whenever emission rates measured by wind tunnels are reported. This means that odour emission rates from manure storage reported in the literature are “nominal rates”, which are the emission rates at certain wind speeds used in wind tunnels but may not reflect the rates in the field where the wind speed changes instantaneously.

Researchers have attempted to correlate the odour emission rate to the wind speed. Schmidt et al. (1999a) investigated the effect of air velocity on the measurement of odour emission from manure storage. They found that measured emission rate increased exponentially with the bulk tunnel wind speed (fig. 3) and proposed the following equation to describe the relationship between the odour emission rate and the wind speed:

$$E/E_1 = u^{0.89} \quad (1)$$

where:

E = odour emission rate, OU/s/m²

E_1 = odour emission rate measured at wind speed of 1 m/s, OU/s/m²

u = wind speed, m/s

Heber (1999) made the following suggestions with regard to using wind tunnels for measuring odour emission rates from manure storage: (1) the swept surface area should be larger for anaerobic lagoons and other "low-load" storages, (2) concentrations of odours should be measured at both the inlet and outlet, and (3) the effect of wind on the operation of the wind tunnel should be considered, i.e., wind blowing against the air outlet of the tunnel could have a significant effect on the air flow inside the tunnel.

2.3 Odour Emission from Land Application of Manure

Odour emission during manure application is dependent on the exposure of manure to air and wind. Odour emission from land application occurs: (1) during application - odour is released while manure is traveling in the air, and (2) after application - odour is emitted from the manured soil. Quantifying odour emission during application is impractical, and may not be necessary nowadays because most producers are adopting the injection technology. A shift to injection-spreading of manure seems to result in more odour complaints traceable to animal production facilities and manure storage units than to the land application of manure (Jacobson et al., 1998). It should be cautioned, however, that odour emission during application might be extremely high if inappropriate equipment and procedures are used, such as the “big gun”

applicators. This was the reason why land application used to be the major cause of odour complaints when the incorporation and injection was not commonly practiced.

Odour emission rates from land application (the after-application-rate) are usually measured by using wind tunnels and expressed as the amount of odour emitted per unit time and per unit surface of manured soil (OU/s/m²). The operating principle of the wind tunnel is the same as that for measuring odour emission rates from manure storage. Zhang et al. (2001a) used a wind tunnel with an air speed about 3 m/s to measure odour emission after the injection of swine manure in arable fields. They observed that the emission rate measured from the manured soil was almost the same as that from the soil with no manure applied (4.0 vs. 3.6 OU/s/m²). They concluded that manure injection resulted in little odour emission from manured soil. Much higher odour emission rates were reported by Pain et al. (1994) for grasslands after land application of swine manure. Their measured emission rates ranged from 128 to 160 OU /s/m², obtained by using a wind tunnel at air speeds between 1 and 3 m/s.

In a series of experiments performed by Pain et al. (1991) in The Netherlands, livestock (pig and cattle) slurries were applied to grassland (Table 7) or arable land (Table 8), and odour levels were subsequently measured. Table 7 indicates that odour emission is affected by the total volatile fatty acid (VFA) in the manure – the higher the total VFA content, the higher the odour level. The table also shows that odour level decreased significantly in the first 6 hours of application. Results in Table 8 show that the effectiveness of incorporation in odour reduction depended on the incorporation tools.

Hanna et al. (2000) conducted field experiments in undisturbed (no-till) field to evaluate six liquid swine manure application/incorporation methods: (1) chisel; (2) sweep; (3) incorporation with tandem disk harrow after broadcast application; (4) broadcast application with no incorporation; (5) injection with a narrow-profile knife; and (6) surface application behind row cleaners. The row cleaner and all injection treatments used spoke-covering wheels. They found that incorporation techniques typically reduced odour level by a factor of three to ten as compared with a broadcast application. One day after application, odour was greatly reduced and often indistinguishable from that of unmanured soil.

Chen et al. (2001) compared four different techniques for applying liquid manure on grassland to examine the impact of each technique on the environment and agronomic responses. These techniques were manure injection, sub-canopy banding using a sleighfoot, incorporation using an aerator, and surface banding using a dribble bar. They found that among the four techniques, the injection resulted in lower ammonia and odour concentrations on the land surface immediately after manure application. Odour level was significantly higher than the background level when the manure pooled on the soil surface.

2.4 Odour Emission from Mortality Disposal Sites

The subject of odour emission from mortality disposal sites seems to be limited to anecdotal discussion. Little scientific research was found with regard to odour concentrations or emissions from mortality disposal sites. From this, one would conclude that mortality disposal sites are not usually considered odour sources.

The reasons behind this can be explained in a number of ways. Generally, it is required that mortalities be properly disposed of within 24-72 hours (Fulhage, 1994; MBAH, 1996). This does not commonly provide enough time for a carcass to decay significantly and produce offensive odours. Secondly, mortalities are rarely generated in significant quantities and thus are easily dealt with. Thirdly, unlike manure, mortalities are dealt with well within farm property boundaries. As well, people are less likely to complain about an odour if they cannot see the source, as their attention is less focused on the activities that may cause odours (BCMA, 1978).

While reports have been made that inadequate incineration or other improper mortality disposal may cause “bad” or “unpleasant” odours, no quantifiable data has been given (AAFRD, 2002). It should be noted that odour elimination is an objective of mortality disposal regulations, and that proper disposal should resolve any odour problems. Advice and tips for proper disposal are usually included in best management practice plans distributed by agricultural agencies.

2.5 Quantifying Downwind Odour and Setback Distances

Quantifying downwind odour is still difficult because of instantaneous changes in the atmospheric conditions (discussed in section 1.9). Dispersion modeling is often used to predict time-average odour levels downwind from odour sources. The human sniffing technique has also been used to measure the odour plumes downwind from livestock operations.

2.5.1 Odour Dispersion Modelling

Odour dispersion models are computerized mathematical tools used to predict the occurrence (frequency and duration) and concentrations of odours at any distance (location) from livestock odour sources. Two commonly used models are the Gaussian Plume and Gaussian Puff models (Ormerod, 2001; NCMAWM, 2001; Watts, 2000, Zhu et al., 2000b; Borg, 1997; Smith and Watts, 1994; Smith, 1993). Gaussian plume models assume that, over time, the average concentration distribution of the odour plume follows a Gaussian (bell-shaped) distribution. However, at any particular instant, the actual concentration may be very different and instantaneous concentrations may often occur which are greater than those predicted by Gaussian plume models (EPAV, 2000). Gaussian puff models, on the other hand, are non-steady state models that depend on high definition meteorological data (Ormerod, 2001) and recognize the fact that odour dispersion occurs intermittently and not in a steady continuous stream for any length of time, much less an hour (Zhu et al., 2000b). Gaussian plume models that have been widely used for odour dispersion modeling include AUSPLUME (EPAV, 2000), ISC3 (EPA, 1995), and STINK (Smith and Watts, 1994). Gaussian puff models that have been used for predicting odour dispersion include TAPM, CALPUFF, INPUFF-2, and RIMPUFF (Hatfield et al., 2000; EPA, 1995; Ormerod, 2001).

Dispersion models require inputs of odour emission rates from various sources on livestock operations and weather data. The adequacy of model predictions may be validated by comparing the model predictions to field measurements of odour intensity made by human assessors (Guo et al., 2001a; Guo et al., 2001b; Jacobson et al., 2001b; Zhang et al., 2001b; St. Croix Sensory, 2000; Zhu et al., 2000b).

2.5.2 Setback Distance

Odour is diluted as it is transported in the atmosphere. The dispersion theory indicates that if there is proper distance between the odour source and the neighboring residents, the odour nuisance may be minimized. The question is: What is the proper setback distance?

VanDevender (2000) conducted a study to investigate both odour strength and offensiveness around 36 randomly selected swine farms. His survey results, based on the analysis of 1,157 samples collected from 253 locations, are summarized in Table 9. The statistic analysis showed that if a swine facility was located 0.5 miles away from the neighbors, it would not cause odour complaint with a probability of 99%. This was a general observation on the setback requirement without considering the operation type and size, and other factors affecting odour generation and dispersion.

Heber (2001) established an Interactive Setback Model in which affecting factors, such as wind, ventilation, land use, etc., were taken into account. The model has the form of:

$$\text{Setback distance in feet} = 20 F * L * T * V * (AE * E + AS * S) * 0.5 \quad (2)$$

where:

F = wind frequency factor [0.75 to 1.00]

L = land use factor [0.5 to 1.00]

T = topography factor [0.8 to 1.00]

V = orientation and shape factor [1.00 to 1.15]

E = building odour emission, $N * P * B$, OU/s,

N = number of pigs

P = odour emission factor, OU/s-pig, [1 to 15]

B = building design and management factor, M-D

M = manure removal frequency [0.50 to 1.00]

D = manure dilution factor [0.00 to 0.20]

S = odour emission from outdoor storage, $C * G$, OU/s

C = odour emission factor for outside liquid manure storage, 50 OU/s-AU

G = animal unit, AU=1,100 lb of pig weight.

AE = odour abatement factor for buildings [0.30 to 1.00]

AS = odour abatement factor for outside liquid manure storage [0.30 to 1.00]

Heber's model suggested that two farms with the same type operation and same number of pigs might require different setback if the farms located at different geographic areas.

Jacobson et al. (2001a) developed an odour prediction method — Odour From Feedlots Setback Estimation Tool (OFFSET) to estimate average odour impacts from a variety of animal facilities and manure storages. The important input parameters to the model include odour sources and odour emission rate of each source, and control factors such as biofiltration and manure storage covers. Based on the values of these input parameters, the total odour emission factor (TOEF) is calculated and the setback distance is then plotted against the TOEF for different levels of annoyance (an example is shown in fig. 4). OFFSET is based on odour measurements from Minnesota farms and Minnesota climatic conditions, and therefore its application to other geographic areas should be done with caution.

Concluding Remarks

Quantification of odour production and release is difficult because many odour compounds are contained in the manure, and the quantity and the proportion of these compounds in the manure vary greatly with the properties of the manure and the environmental conditions. The properties of the manure and the environmental conditions in turn vary with the type of operation and the management practice. Reliable measurements of emissions from large livestock buildings with inherently large spatial and temporal variations of pollutant concentrations are relatively difficult and expensive. Appropriate methodologies for such measurements are not readily apparent and techniques and strategies vary widely (Heber et al., 2001b).

Much research reported in the literature has been focused on the quantification of odour emissions from swine buildings, and limited information is available on odour emissions from manure storage, land application and mortality disposal. Odour emission rates vary widely among different swine facilities and within the same types of facilities. Reported odour emission rates range from 2.3 to 20 OU/s/m² for gestation facilities, from 0.4 to 62 OU/s/m² for farrowing facilities from 0.1 to 50 OU/s/m² for nursery facilities and from 2.5 to 21 OU/s/m² for growing/finishing facilities. Reported odour emission rates from earthen manure storage (EMS) were mostly below 10 OU/s/m². It should be cautioned that odour emission rates from manure storage are commonly measured with wind tunnel at certain wind speed. These rates may not reflect the rates in the field where the wind speed changes instantaneously.

Odour emission from land application could be minimized by proper injection. Adoption of manure injection by producers has seemed to shift odour complaints from land application to animal production facilities and manure storage units.

There are no well-established methods for quantifying downwind odour level. Dispersion modeling is often used to predict odour plumes (time-average odour level) downwind from odour sources.

Research is needed to study the effects of day-to-day barn conditions on odour emissions from swine buildings under Manitoba conditions. The specific factors that should be examined include: pen (floor) cleanness; washing frequency; dunging patterns; manure properties; feed ration, and any measures used for odour control (e.g., additives). Odour emissions from manure storage are dependent on climate conditions. Field measurements should to be conducted to collect odour emission data from earthen manure storage (EMS) under Manitoba climate conditions. Studies are also needed to establish the science-based setback requirements by taking into account Manitoba climatic and geographic conditions.

3. FEED ADDITIVES AND DIETARY MANIPULATION

3.1 Dietary Formulation Strategies

Matching Nutrient Supply with Requirements

The main compounds associated with swine odours are products of degradation of excess dietary protein intake. Furthermore, it has been estimated that about 65 to 70% of dietary nitrogen intake by growing pigs is excreted (Lenis and Jongbloed, 1999). This means that considerable reduction in nitrogen excretion can be achieved by carefully matching dietary nitrogen supply with requirements (Sutton et al., 1996, 1999; Jongbloed and Lenis, 1998). Sulfur excretion can also be reduced by carefully managing intake levels, either through the diet (sulfur amino acid levels) or controlling sulfate levels in drinking water. However, it should be noted that little research has been done to determine how such modifications can influence odour emission from swine barns and manure storage facilities. It, therefore, is essential to establish the effect of such modifications on odour emission from swine manure.

In order to closely match nutrient supply with requirements, it is critical to have two pieces of information: (1) the availability of nutrients in pig feed ingredients and (2) the requirements for specific nutrients for the main pig genotypes currently used in commercial pork production. Therefore, swine producers will need to have a good understanding of the nutrient requirements of their pigs under their unique conditions so as to better manage their nutrients. A number of factors including, genotype, capacity for lean tissue growth, environmental conditions, physiological status of the pig, etc affect nutrient requirements of swine (NRC, 1998). It is for this reason that it is important to know requirements for pigs within a herd.

Formulation of Low-Protein Amino Acid Supplemented Diets

A standard commercial pig diet is usually formulated to meet the minimum requirements for key amino acids to achieve the desired performance levels. Consequently, these diets are often too rich in protein and contain excessive amounts of other amino acids that contribute significantly to nitrogen excretion (Jean dit Bailleul et al., 2001). The excreted nitrogen is degraded and the resulting products are known to contribute to odour problems. Strategies to reduce the amount of nitrogen excreted in pig manure should, therefore, provide a means to minimize the generation nitrogen-derived odorous compounds in swine manure.

An approach that has been shown to reduce nitrogen excretion in pig manure is to feed low protein diets supplemented with synthetic amino acids (Sutton et al., 1996). According to Lenis and Jongbloed (1999), reducing dietary crude protein content by 2 percentage units will reduce nitrogen excretion by 20%, which is close to the estimate by Kerr (1995) that nitrogen excretion is reduced by 8.5% for every one-percentage unit reduction in dietary crude protein. Several studies have shown that feeding pigs low protein diets has no negative effect on pig performance provided such diets are well fortified with the key essential amino acids that are likely to be limiting (i.e. lysine, methionine, threonine, and tryptophan) (Oldenburg and Heinrichs, 1996; Tuitoek et al., 1997; Canh et al., 1998a, Grandhi, 2001a,b). The research completed at the Agriculture and Agri-Food Canada Research Centre in Brandon by Dr. Grandhi achieved a 28% reduction in total nitrogen excretion from pigs fed low-protein barley based diets with supplemental amino acids. These studies clearly indicate the potential to manage dietary

nitrogen utilization in pigs and consequently the reduction of odour emission from swine facilities. However, there is still a great need for research to apply this concept to pig feeds typical to the Western Canadian swine industry. This is particularly important considering that use of supplemental amino acids can add considerably to the diet cost (Table 10, de Lange et al., 1999).

Developing and using low-protein amino acid supplemented diets also has the potential to reduce ammonia emission from swine facilities. It has been shown that this strategy can reduce urinary excretion by as much as 30 % (Grandhi, 2001b). Urinary nitrogen is closely related to aerial ammonia levels, as it is easily volatilized (Canh et al., 1997; Grandhi, 2001a;b). In addition to developing similar diets based on non-traditional feedstuffs, there is a need to establish amino acid availabilities in alternative feedstuffs to facilitate formulation of diets that closely match supply of amino acids with requirements. A new simple technique for estimating amino acid availability in feedstuffs has been developed (Rutherford and Moughan, 1995) but its usefulness for routine evaluation of different feedstuffs should be established. Using true as opposed to apparent ileal amino acid digestibilities to formulate swine diets will increase precision in dietary amino acid supply since true ileal amino acids are additive in mixtures of feedstuffs (Nyachoti et al., 1997b; NRC, 1998). It is important to note that the true ileal amino acid digestibility coefficients in many of the alternative ingredients locally available in Manitoba are yet to be determined.

Ingredient Selection

In practical swine nutrition, a mixture of different feed ingredients is used to supply adequate dietary nutrients for optimal performance. Different ingredients have different levels of a given nutrient and the amount of each nutrient that is actually used for pig growth. This means that pigs are able to utilize dietary nutrients more efficiently from some feed ingredients than others. Furthermore, the type of feed ingredient influences the amount of endogenous nitrogen secreted by pigs and in general those feedstuffs that induce high levels of endogenous nitrogen secretion will also increase the amount of nitrogen excreted in pig manure (Nyachoti et al., 1997a).

Selecting feed ingredients that are highly digestible and/or that induce minimal endogenous nitrogen secretion in pigs offer a simple means to reduce nitrogen excretion in pig manure and its associated odour generation. This strategy was clearly demonstrated by the studies conducted by Dr. Grandhi at the Agriculture and Agri-Food Canada Research Centre in Brandon. In those studies, substituting hulled barley (induces high endogenous nitrogen secretion) with hullless barley (induces minimal endogenous nitrogen secretion) reduced total nitrogen excretion in pig manure by about 3% (Grandhi, 2001a,b). There is a need to further evaluate this strategy to optimize its usefulness to the swine industry in Manitoba as a tool for managing swine odours.

Ingredient Processing

It is well established that various technological processing of individual ingredients or complete rations can improve the digestibility of amino acids. Indeed, it has been established that for every 1% improvement in digestibility, the amount of nitrogen excreted per kg of pork produced decreases by 1.4% (van Kempen, 2000; cited by Han et al., 2001). Therefore, strategies

that can help improve feed digestion are also likely to reduce the amount of nitrogen excreted in pig manure. The true benefit of such strategies will only be realized if they are taken into consideration when formulating swine diets.

Finely ground and pelleted feeds are digested to a larger extent than those of coarser particle size. This was clearly demonstrated in a study by Wondra et al. (1995) whereby fine grinding (i.e. particle size reduction from 800 to 400 μm) reduced nitrogen excretion by 30%. As feeding finely ground feeds to swine has been associated with high stomach ulcerations (Wondra et al., 1995), the application of this technology to manage nutrient excretion and odour control from swine facilities should be considered carefully.

Current research at the University of Manitoba is investigating the impact of including micronized peas in grower diets at 45% on nitrogen excretion and manure volume. In this study nitrogen excretion in the feces was decreased by 31% (fig. 5, Nyachoti et al., 2002). As degradation of fecal nitrogen is a major source of odorous compounds, it is prudent to conclude that this technological treatment can be an effective strategy for odour mitigation from swine facilities. Considering that only one feed ingredient was micronized in the diets used in this experiment, it is likely to be an economically viable approach to minimizing nitrogen excretion and by extension, odour emission from swine facilities. Additional research, however, must be completed before the use of this technology can be optimized. Specific areas that should be addressed include the effect of micronizing other ingredients, determination of ammonia and odour generation from fresh and stored manure from pigs fed diets containing micronized ingredients, and an assessment of the economic implication of using this technology.

3.2 Practical Feeding Strategies

Phase Feeding

It is well established that as pigs mature, their requirements for dietary amino acids decline. This means that a diet suitable for growing pig, with high requirements for amino acids, will not be the same for a finishing pig whose need for amino acids is much less. It is for this reason that pigs should be fed diets with differing amino acid levels depending on their stage of growth or physiological status. In practical swine feeding, this has led to the use of more than one diet for pigs in the nursery or during the growing-finishing stage, with the main adjustment in the diet being reduction in protein content. This practice, commonly referred to as Phase Feeding, has been reported to result in 5% to 10% reduction in the total amount of nitrogen excreted in pig manure (fig. 6) (Lee et al., 2000; FASS, 2001). In a study by Peet-Schwering et al. (1996) in which pigs were fed decreasing proportions of a mixture of a high and low protein diet on a weekly basis, urinary nitrogen excretion and ammonia emission was reduced by 14.7% and 16.8%, respectively, compared to pigs on a phase feeding program. The concept of phase feeding can equally be applied to the breeding herd. Pregnant and lactating sows are in different physiological status and therefore their requirements for dietary nutrients differ substantially. Generally, requirements for gestating sows are lower than that for lactating sows. Research has shown that use of separate as opposed to one diets for the two stages can reduce nitrogen excretion by as much as 20% (Evert and Dekker, 1994).

Split Sex Feeding

There are well-established differences in amino acid requirements between gilts and barrows. Gilts have higher requirements for amino acids than barrows because of their higher capacity for lean tissue accretion (NRC, 1998). Therefore, penning gilts and barrows separately and feeding barrows protein-reduced diets offer a practical means of reducing nitrogen excretion in pig manure. It has been estimated that this strategy alone can reduce nitrogen excretion by 5 to 8% (FASS, 2001). This management strategy is now commonly used within the swine industry.

Minimizing Feed Wastage

As discussed in the above sections, odorous compounds from swine manure are a result of degradation of non-digested dietary nutrients. Any feed that is not consumed by the pig but ends up in the manure pit will be broken down and degradation of its protein component will add to the generation of odour-causing compounds. Instituting measures that minimize feed wastage will go a long way in reducing odour generation from swine manure. Such measures include proper feeder design, adjusting and cleaning feeders frequently, and using pelleted as opposed to mash diets (Gonyou and Lou, 1998; van Kempen, 2000). Based on a review of the literature, Han et al. (2001) proposed that feeders should be managed such that only 50% of the bottom part is covered as a general guideline for feeder adjustment to minimize feed wastage. Feed wastage as a result of poor feeder design has been estimated at 5% to 6% (Gonyou and Lou, 1998) but little research has been done to determine how this might impact odour generation from swine manure. As much as possible, the use of wet-dry feeders should be encouraged as they offer an effective means for reducing feed wastage. For instance, Han (1998) demonstrated a 60% reduction in feed wastage by pigs from 20 to 80 kg fed from wet-dry feeders compared to those consuming pelleted diets.

3.3 Impact of Dietary Additives on Swine Odours

The use of additives in swine diets for odour reduction has received considerable attention. In general, much of the current research has focused on the assessment of efficacy of individual additives in reducing or manipulating some measure of odour related to either barn air, fresh fecal samples, or the short-term storage of pig manure (urine and feces).

3.3.1 Manipulating Hindgut Microflora

As previously discussed, hundreds of compounds have been identified in swine manure as being potential contributors to swine odour. Several groups of these compounds, including sulfides, phenols, and indoles, are produced during microbial fermentation within the cecum and large intestine of the pig. Manipulation of the microbial ecosystem and nutrient supply has the potential to affect changes in the production of one or more classes of odour-causing compounds. To date, the approaches most often tried include (1) the feeding of enzyme-resistant carbohydrates to pigs to stimulate the production of less putrefactive bacteria, the so-called prebiotic approach, (2) the use of direct-fed microbials, or probiotics, to manipulate intestinal microflora, and (3) the use of antibiotic or antimicrobial agents.

Resistant Carbohydrates - Prebiotic Approach

The carbohydrate fraction of plant components can be broadly subdivided into sugars or non-sugars. Sugars represent the simplest form of carbohydrates, and range in complexity from simple monosaccharides (one sugar molecules; glucose, fructose) to oligosaccharides (numerous

sugar residues in chain; raffinose, stachyose). In general, the pig possesses sufficient enzymatic capacity within its small intestine to digest these sugars (Pekas, 1991), however more complex oligosaccharides may be somewhat resistant to enzymatic hydrolysis. With respect to the non-sugars, this carbohydrate fraction tends to include quite large molecules which serve an energy storage function, in plant and animal cells, or to provide structural support in plant cell walls. Again, this class of carbohydrate can be further subdivided, with the polysaccharide fraction being of particular interest to the current review. Polysaccharides include the common starches (amylose, amylopectin), large compounds consisting of repeating units of glucose, which are readily digested in the small intestinal tract of the pig. In addition, this group includes compounds such as inulin - a large polysaccharide consisting of repeating units of fructose. Inulin, as well as other non-starch polysaccharides (i.e., cellulose, pectins), are resistant to enzymatic hydrolysis within the small intestine of the pig and pass more readily into the large intestine and cecum, the primary sites for bacterial fermentation. Diets which result in the presentation of higher amounts of resistant carbohydrates to the hindgut have the potential to alter fermentation patterns and microbial populations. As such, the potential exists to manipulate the production of malodorous compounds by microbes in the hindgut.

The addition of 3% or 6% Jerusalem artichoke to diets for weanling pigs significantly ($P < 0.05$) reduced the intensity of sharp, pungent smells and skatole odour from manure, and produced a significantly ($P < 0.05$) “sweeter” smelling manure, as assessed by a sensory evaluation panel (Farnworth et al., 1995). Jerusalem artichoke contains fructans, a class that includes inulin. These fructans have been implicated in the manipulation of intestinal microflora, promoting the growth of bifidobacteria spp. Changes in intestinal microflora towards an enrichment of bifidobacteria spp. have been primarily studied as a means of out-competing pathogenic bacteria, such as *E. coli* and clostridia (i.e., Klein Gebbink et al., 2001), but an increase in fermentable substrates to the hindgut may also lead to changes in volatile fatty acid, amine, and sulfide production rates which can significantly influence the production of odour components. Farnworth et al. (1995) found increases in most of the volatile fatty acids when Jerusalem artichoke was supplemented, however they did not link these with the perception of odour by their sensory panel. In addition, the authors only studied fresh fecal samples and not manure per se. In a subsequent study (Kotchan, 1998), researchers examining the impact of 0, 2.5, or 5.0% Jerusalem artichoke to swine diets observed variable and inconsistent effects on the production of volatile fatty acids produced during the storage of manure for up to 111 days. Farnworth et al. (1995) did observe a significant decrease in the sensory perception of skatole smells with increasing Jerusalem artichoke inclusion, however they did not measure skatole, or other phenols or indoles directly. It may be that a shift away from indole- or phenol-producers in the hindgut is responsible for the observed improvement in manure odours. However, it remains to be determined the precise mechanisms whereby Jerusalem artichoke, and presumably other inulin- or oligosaccharide-containing compounds effect changes in swine-related odours.

Antibiotics/Antimicrobials

As discussed above, manipulating the hindgut microflora of the pig may lead to changes in the production of odour-causing metabolites, with the potential to lead to reduction in odour generation. Dietary antimicrobials continue to be used in North America swine rations due to the increases in performance that can be achieved through their use. As antimicrobials are removed from swine diets, due to increased international pressure, the potential exists for changes to

odour profiles from swine manure. In a study examining the impact of the dietary inclusion of 50 mg zinc bacitracin (antimicrobial) per kg, Hansen et al. (1997) demonstrated a significant reduction in skatole concentrations in blood and backfat of boars, indicating the potential to manipulate manure odours, as skatole is a major contributor to swine odours. Armstrong et al. (2000) examined the impact of high dietary concentrations of copper (225 ppm copper from copper sulphate or 100 ppm copper from copper citrate) and demonstrated a significant improvement ($P < 0.05$), using static olfactometry, in the odour characteristics of fresh fecal samples from swine. Copper has been used for decades in swine rations due to its reported antimicrobial effects, and the authors conclude that the antimicrobial effects of high dietary copper were responsible for the observed effects on odour levels. Additional research in this area is warranted in light of rapid changes in regulations and requirements pertaining to the use of dietary antimicrobial agents.

Probiotics

The interest in direct-fed microorganisms, or probiotics, has grown over the last 25 years. The probiotic concept involves the delivery of selected, beneficial organisms to the hindgut of the animal. However, several key factors must be in place in order to have a suitable probiotic: (1) the organism must survive the low pH and proteolytic activity within the gastric region and the proteases and bile salts within the small intestine; (2) there must be evidence provided of an enrichment or establishment of a significant microbial population; and (3) the probiotic must be effective in manipulating hindgut fermentation for the desired effect. It is the latter point that has received minimal attention relative to odour generation. To date, most trials with probiotics have focused on the potential health-promoting effects of these organisms (Kyriakis et al., 1999) with the goal of reducing reliance on antibiotics in feed. However, a few studies have documented shifts in microbial species that may be less putrefactive and lead to reduced emissions of malodorous compounds. Shu et al. (2001) provided a live culture of *Bifidobacterium lactis* in the diet of weanling pigs and observed reductions in *E. coli* numbers in fecal samples, suggesting a potential shift in hindgut microflora. However, the authors did not enumerate bifidobacteria in the intestinal microflora, but it was presumed. As discussed above, bifidobacteria are less putrefactive than *E. coli* or clostridia species. Despite the potential for probiotics, a lack of data to specifically address the impact that these additives might have on manure odours limits further insights.

3.3.2 Reducing Ammonia Emission

The bulk of studies examining the impact of diet on manure odour have focused on the impact that specific dietary regimens have on ammonia emissions from swine. Several dietary approaches have been taken, including (1) the use of low protein-amino acid supplemented diets (see above), (2) the increase of dietary non-starch polysaccharide levels to shift circulating urea towards microbial protein synthesis, (3) the use of binders or ion exchange compounds to sequester ammonia, and (4) dietary acidifiers to reduce ammonia volatilization.

Non-Starch Polysaccharides

Somewhat independent of the prebiotic approach (addition of specific carbohydrate classes through enriched products or purified sources) to changing swine odours is the consideration of the total non-starch polysaccharide (NSP; dietary fibre) fraction of the diet. Alteration in the NSP content of the swine ration can influence the partitioning of nitrogen

excretion between urinary and fecal losses. Increased urea nitrogen excretion invariably leads to higher ammonia concentrations, as urea can be converted to ammonia through the action of microbial urease enzymes present in the manure. The presentation of increased total resistant carbohydrates (NSP) to the hindgut promotes the shift in nitrogen excretion from urine to fecal nitrogen (Schulze et al. 1995; Canh et al. 1997, 1998b,c; Mroz et al. 2000a). Increasing NSP delivery to the hindgut microflora provides carbon substrates for the synthesis of microbial protein. The nitrogen required for the microbial protein is drawn from the total urea pool, derived from protein catabolism in the tissues of the pig or from microbial metabolism. Sequestration of urea into the microbial protein sink reduces the circulating urea concentrations, Figure 4. The effect of adding 30% sugar beet pulp, as a source of NSP, to swine diets on total nitrogen excretion and the ratio of nitrogen in urine relative to feces (Adapted from Canh et al. 1997) ultimately leading to a reduction in urea excretion by the kidneys into urine (fig. 7). Numerous sources of NSP have been used to reduce urinary nitrogen excretion, including tapioca, soybean hulls, and sugar beet pulp, however the question remains as the overall efficacy of this approach in reducing odours from swine. Ammonia represents a single component of air pollution and although it is poorly correlated to swine odour strength, it is still desirable to reduce ammonia emission from swine facilities (O'Neill and Phillips, 1991; Hobbs et al., 1996). However, to date, little information is available on the use of NSP to reduce odour, as assessed by olfactometry. As discussed above, the presentation of NSP can lead to an increase in volatile fatty acid production rates, which may lead to increased odour generation. Additionally, increasing the NSP content of the diet may also lead to a suppression of nutrient digestibility and increased total manure production, factors that can have significant economic impacts on producers.

The use of resistant carbohydrates to manipulate the production of odour-causing compounds in swine manure shows promise. The limitations of most studies to date include the consideration of odour-causing components in isolation. Measurement of relative changes in single parameters (ammonia or volatile fatty acids) provides only partial information. Future studies should focus on the use of objective measures of odour (olfactometry) in assessing the impact of resistant carbohydrates in swine diets. In addition, due to inherent variability in NSP content in plant sources such as Jerusalem artichoke and sugar beet pulp, attempts should be made to standardize their inclusion rates in swine diets to a specific level of NSP, or component thereof, instead of gross inclusion rates of the raw product. This should help to minimize variability between trials.

Feed Enzymes

Commercial feed enzymes are routinely used in feeds for swine and poultry to increase nutrient utilization. Fibre degrading enzymes have the potential to reduce endogenous gut nitrogen losses in monogastric animals, as fibre is one of the main factors that reduce nitrogen utilization by inducing high endogenous secretions (Nyachoti et al., 1997a). However, the impact of feed enzymes on odour producing compounds in pigs has not been evaluated.

Yucca Extract

Commercially available extracts of the desert plant *Yucca schidigera* have been promoted for their ability to reduce ammonia concentrations arising from swine manure. Several investigators have observed reduced ammonia emission rates through the addition of yucca

extracts to swine diets (Cole et al., 1998; Cromwell et al., 1999; Colina et al., 2001). Colina et al. (2001) observed a trend for a reduction in room ammonia levels from 3.6 ppm to 2.8 ppm (as measured with aspiration tubes), however the level of reductions are marginal and, as discussed above, ammonia is but a single component of air pollution. At present, the limited number of studies with this product provide no strong justification for its inclusion in swine rations, for the purposes of reducing odour.

Zeolites

Zeolites are crystalline, hydrated aluminosilicates of the cations sodium, potassium, calcium and magnesium (Mumpton and Fishman, 1977). The zeolite family includes such compounds as clinoptilolite and mordenite, and they have received interest from the agricultural sector for their ion exchange and adsorption capacity. In particular, zeolites have been shown to be effective in the adsorption and binding of ammonium (NH₄⁺) ions (Mumpton and Fishman, 1977). However, the majority of these studies have focused on the *in vitro* ion exchange capacity of zeolites. When zeolites, such as clinoptilolite are fed to swine, data are less conclusive. Shurson et al. (1984) demonstrated lower plasma ammonia concentrations in pigs with increasing dietary concentrations of clinoptilolite up to 7.5%, and reductions in free p-cresol excretion of 70%. Another zeolite, Zeolite A, was without effect. A review of unpublished data (Theophilou, 2000) supports a marginal effect (although not tested statistically) of 2% clinoptilolite on reducing total non-protein nitrogen excretion by 30-50%. To date, however, the effect of these zeolites on odour production have not been rigorously evaluated. A concern with zeolites, from a feed formulation perspective, would relate to the energy dilution effect of having high concentrations of inorganic matter in diets. Furthermore, high levels of zeolites in manure may pose problems for manure handling equipment.

Dietary Acidifiers

As discussed above, the rate of ammonia volatilization from manure sources is dependent on a number of factors, including pH. A low, or acidic, pH maintains ammonia in the non-volatile form of ammonium ions (NH₄⁺). As such, air pollution potential related to airborne ammonia levels may be reduced by keeping low pH conditions. One option for achieving this is through the use of dietary acidifiers or through the manipulation of the buffering capacity of the diet. Several acidifiers have been investigated for their direct effect on urinary pH and ammonia volatilization, including calcium sulfate, calcium benzoate, and calcium chloride (Canh et al., 1998a; Mroz et al., 2000b; Colina et al., 2001). The addition of 2.4% calcium benzoate to swine diets was effective in reducing urinary pH by 1.6 units (Mroz et al., 2000b), and this research group had previously shown that a similar level of reduction in urine pH can significantly (44%) reduce ammonia emissions, as tested in small laboratory scale reaction vessels (Mroz et al., 1996). Colina et al. (2001) fed diets containing 1.95% calcium chloride to swine and observed no significant effect on ammonia levels in a nursery unit, however ammonia levels were low to begin with. Additionally, manure pH was not reduced. A study by van Kempen (2001) provides strong evidence of the benefit of dietary acidifiers. The author included 1% adipic acid (a product generally regarded as safe and used as a flavour enhancer) in grow-finish rations and demonstrated reduction *in vitro* ammonia release from urine samples and a 25% reduction in measured ammonia concentration in exhaust air from environmental chambers in which pigs were housed. In the latter experiment, the author used Fourier-transformed infrared spectrometry as an “electronic nose” to specifically measure ammonia levels in exhaust air samples. These

data support the contention that dietary acidification, sufficient to produce a urinary pH of approximately 5.5, relative to control urinary pH values in excess of 7, has the potential to reduce ammonia volatilization and, as a result, reduce associated odours. As mentioned above, the use of higher levels of dietary resistant carbohydrates has the potential to increase volatile fatty acid production in the hindgut, and reduce manure pH as well, with similar effects on ammonia volatilization rates (Canh et al., 1998b). However, the same limitations apply to these studies as for previously mentioned work, namely the lack of specific measurements of perceived odour, through the use of olfactometry measurements.

Concluding Remarks

Most of the research to date in the area of dietary manipulations for swine odour control has been done elsewhere, primarily in the Netherlands and the Midwestern region of the U.S. Limited Canadian or Manitoba research is available. Fortunately, however, the majority of the research can be translated to the Canadian situation either directly or with further refinement. However, differences in primary cereal crops used (corn vs. barley or wheat) and the associated differences in chemical composition (NSP content and types) warrants further consideration.

With respect to research performed to date, the majority of studies have employed a single indicator (sometimes more than one) of odour potential. These have generally involved a static measurement of ammonia, hydrogen sulfide, or indoles and phenols levels in exhaust air from animal rooms, in vitro apparatuses, or fresh fecal samples. Static concentration measurements provide valuable data but do not give a measurement of odour, per se. Better odour measurement methods, such as dynamic-olfactometry, should be employed in the assessment of the efficacy of dietary manipulations. With respect to manipulating diets or the use of dietary additives to reducing swine odours, consideration should be given to the following criteria:

- Is the inclusion rate of the ingredient or additive practical relative to its cost and to the provision of sufficient flexibility in the formulation of rations?
- Is the feed ingredient or additive readily available and in sufficient quantities for bulk purchase?
- Can the quality or composition of the ingredient or additive be assessed and what is the batch-to-batch variability?
- Does the dietary strategy lead to negative concerns unrelated to odour production? Some concerns are: impacts on the pig (nutrient digestibility, pig health status, overall, and performance); impacts on meat or carcass quality (residues, off-tastes or odours?, lean to fat ratio); impacts on humans handling product (safety concerns); impacts on feeding or manure handling equipment (corrosion, and ease of handling)

Research in the following areas will help to address these criteria and result in significant benefits to the swine industry in Manitoba:

- The development and testing of protein-reduced amino acid supplemented diets based on feed ingredients commonly used in western Canada, including alternative ingredients.

- The further exploration and demonstration of the benefits of ingredient processing in dietary nutrient management, including testing diets formulated based on specific ingredients
- The evaluation of new additives to provide unbiased, research-based assessments of their efficacy
- The evaluation of the long-term impact of these dietary strategies on stored manure characteristics
- The use of dynamic olfactometry in the evaluation of candidate dietary strategies, to provide an objective measurement of odour
- The assessment of the cost-effectiveness of candidate strategies in consideration of prevailing swine margins

4. MANURE ADDITIVES

4.1 Types of Manure Additive

Many chemical and biological products are being marketed as manure additives for odour control. Based on their mechanisms of action, these products may be grouped into the following categories (Ritter, 1981):

Masking Agents: mixtures of aromatic oils that have a strong characteristic odour of their own designed to cover up (mask) the manure odour with a more desirable one;

Counteractants: mixtures of aromatic oils that cancel or neutralize the manure odour such that the intensity of the mixture is less than that of the constituents;

Digestive Deodorant: bacteria or enzymes that eliminate undesirable odours through biochemical metabolic degradative processes;

Adsorbents: products with a large surface area that may be used to adsorb manure odours before they are released to the environment; and

Chemical Deodorants: strong oxidizing agents or germicides that alter or eliminate microbial action responsible for odour production or chemically oxidize compounds that make up the undesirable odour mixture.

4.2 Evaluation of Manure Additive Products

Research reported in the literature is mostly focused on the evaluation of manure additives and very little on the mechanism of action or the development of products. Professor Ritter at University of Delaware was among the first who studied manure additives. Ritter and Eastburn (1980) used liquid polyphosphate, zinc-nitrogen liquid fertilizer, potassium permanganate, a pesticide wetting agent, and a digestive deodorant as treatments in their study to control odours from liquid swine and dairy manure. They found that the liquid polyphosphate did not control odours if added shortly before surface application of the liquid manure. Potassium permanganate at concentrations of 300-500 ppm was the most effective chemical additive for odour reduction.

A research team led by Dr. Heber at Purdue University has been active in manure additive research. The team studied a commercially available manure additive (Alliance™) for reducing noxious gas emissions from swine buildings and gas levels inside the buildings (Heber et al. 1997). They reported that a 70% reduction in ammonia gas generation and concentration in their deep-pit finishing buildings could be expected by using Alliance™. The product, however, did not increase or decrease the hydrogen sulfide generation rate.

The Purdue team recently evaluated thirty-five (35) manure pit additive products, submitted voluntarily by vendors (Table 11) (Heber et al., 2001a). Each product was tested three times (42 days each replicate) in an enclosed 15-inch diameter by 48-inch tall manure storage reactor. They reported that none of the 35 products resulted in significant (at 95% certainty level) reduction in odour. Four (4) products decreased odour level at 75% certainty level.

A research team led by Dr. Bundy at Iowa State University has maintained a program of evaluating manure additives since 1995 (www.ae.iastate.edu/pitadd.htm). Their evaluations are mostly conducted in the laboratory with PVC columns to simulate manure storage systems. The odour concentrations of the headspace air from manure storage columns are measured by olfactometry. They defined the effectiveness of odour reduction as follows: <50% reduction as non-effective; 50%-69% reduction as marginally effective; 70% - 85% reduction as effective; and >85% reduction as very effective. A report by the Iowa team evaluated five (5) commercial manure additives for their effectiveness in reduction of odour and volatile compounds (Zhu et al. 1997). PVC columns of 38 cm diameter and 122 cm height were used to simulate manure pit storage in the tests. Each column was filled with manure to a depth of 92, leaving 30 cm headspace for air circulation. Columns were housed in an environmentally controlled room at 15 to 21°C. They found that all five products (MPC, Bio-Safe, Shac, X-Stink, and CPPD) reduced odour significantly (58% to 87%).

Another group that has been actively conducting manure additive research is the team led by Dr. Williams at North Carolina State. They established a protocol for evaluating odour control additives (Williams, 1995). The protocol outlined the procedures for manure collection, laboratory bench evaluation, pilot and commercial scale evaluation, and toxicity evaluation. Over the past six years, they have evaluated over 10 products.

A research team at University of Minnesota conducted in-barn tests to evaluate the effectiveness of 8 commercial manure additives (Bio Charge, Roebic Deodorizer, Pit Boss, Shac, BIO-409, MicroSpan MS-4, Pit Stop, and De-Odourase) (Johnson, 1997). Tests were conducted for at least nine months in two identical production facilities at the same site. Each evaluation was conducted in two barns, one treated with a product and the other one untreated as a control. Odour samples were taken in the center alley approximately three feet off the slatted floor and analyzed with a dynamic-dilution olfactometer. Results indicated that only one additive product showed a significant difference between the control and treated barns based on odour (fig. 7). All products, however, showed significant reductions in ammonia levels (fig. 8).

Researchers at University of Manitoba evaluated six pit additives in nursery barns (Zhang et al., 1999b). The barns had four similar rooms, with respect to dimensions, pig numbers and ventilation systems. One room was used as a control room and the other three were each treated with a different pit additive. Cloth swatches were used to take odour samples twice a week during experiments which lasted at least for one month and odour intensity was evaluated by human assessors (Zhang et al., 1999b). They reported that none of the six products appeared to be effective in altering odour intensity of barn air that could be detected by a human odour panel using cloth swatches.

Stinson et al. (2000) evaluated three manure pit additives in commercial scale channels and simulated outdoor storage with grower-finisher pig manure. The additives were American BioCatalysts, Pit Boss and Westbridge (H4-5O2). They reported that the performances of the additives were mixed. The degree of odour reduction ranged from zero to 11% in the indoor trial and zero to 66% reduction in the outdoor trial. Reductions in hydrogen sulfide from 57% to 76%

were achieved. They concluded that the tested pit additives would provide very limited odour and solids reductions with swine manure, but tend to increase the manure nutrient value.

Alkaline reagents have been found to reduce odour emission from earthen basins and concrete storage facilities. These reagents include various types of kiln dusts, fly ash, and lime products (Messenger, 1996). Field studies undertaken by the University of Iowa evaluated several alkaline reagents. The products were mixed with manure in a 3,000 gallon tank at a rate of 0.3 pounds of product per pound of manure solids. 80-90% reductions in manure odour level were reported (Messenger, 1996).

An important issue of using manure additives is the cost, which includes the materials and any equipment needed to apply them. Researchers at Iowa State University estimated that pit additives ranged from 30 cents to more than \$1 per pig marketed (60 cents to more than \$3 per head capacity).

Concluding Remarks

Different studies have resulted in conflicting results for the effectiveness of using manure additives. This is partially due to the lack of universally accepted protocols for evaluating manure additives. Although some existing manure additive products have been shown to be effective in odour reduction under the laboratory conditions, they may not perform well in actual production facilities. Odour control through manure additives in actual facilities is only a part of the system. Many other factors, such as the building, ventilation, manure handling, feeding, and the overall management practice, may conceal the effect of manure additives in actual facilities. Search for practically effective manure additives is still elusive.

5. IN-BARN MANURE HANDLING

5.1 Liquid Manure Handling Systems

Floor Systems

Odour production in swine facilities is strongly related to the cleanliness of animals present and the facilities. The simplest way to promote the cleanliness is the separation of manure from animals. This may be achieved effectively by using slatted floors. Partially slatted floors with approximately one-third slats and two-thirds solid floor are recommended (Alberta Pork and AAFRD, 2002). Slat spacing should be established to ensure that manure does not build-up on too narrow slots, and animal injury does not occur from slats that are too far apart.

Solid floors prevent the easy separation of manure and urine from animals, causing dirty animals and substantial odour (YCELP, 2002). The best way to reduce the odour associated with solid floors is more frequent cleaning. Manure that collects on the pen floor should be scraped into gutters daily (Alberta Pork and AAFRD, 2002). Solid floors should be sloped toward gutters to facilitate waste removal. Bedding could also be used on the solid floors for odour reduction (see section 5.2 on solid manure systems).

There is little quantitative information as to how odour production relates to the percentage of the floor being slatted. With totally slatted floors, usually more manure is stored in the barn. Also, the relative contribution of odour from the individual slats, stored manure, the building surfaces or the animals is not known. Proper pen design and selection of slats that clean easily with animal traffic can greatly reduce the pigs' contact with manure and reduce manure accumulation on the slats (Alberta Pork and AAFRD, 2002). Also, slats with adequate void to surface ratios are recommended. A step between the slats and solid flooring helps to define the dunging area (Alberta Pork and AAFRD, 2002).

Gravity Drainage and Flush System

Gravity drainage relies on the use of gravity and little-to-no water to remove manure from open-floor gutters into storage units (YCELP, 2002). This is used where minimal waste volume is desired (Meyer, 1990).

Flush systems collect manure from under-floor pits and open-floor gutters and discharge the waste into manure storage and/or treatment facilities (such as tanks, basins and lagoons). Manure can be removed on a daily or more frequent basis (Miner, 1995). Dickey et al. (1996) stated that flushing might occur 2-6 times per day. Floors of gestation barns cannot be flushed (due to slipperiness of the surface) but the open-floor gutter systems of these buildings can be flushed (YCELP, 2002). There are two types of tanks designed for flushing: the tipping bucket and the dosing siphon. Advantages of flushing open gutters are lower construction costs, quick manure removal, and lower odours within the building (Dickey et al., 1996). Pigs have easy access to gutters in a flush systems and this facilitates manure movement, as pigs establish dunging patterns. Disadvantages of this system are the dependency of success with cleanliness on proper design, and possible disease and drug transmission (Dickey et al., 1996). Gutter floors should slope at 1-2%, and a minimum flow of 3 feet per second and a discharge duration of ten seconds is adequate for most buildings (YCELP, 2002).

Mechanical Scraper

Mechanical removal of manure is used by some producers. Open channel scrapers as well as under-slat scrapers have both been proven reasonably successful and could be easily adapted to most existing buildings (Dickey et al., 1996). Open channel scrapers are less expensive to install, but have problems associated with pig injury and the transfer of disease and drugs between pens. Under-slat scrapers are more expensive but do not share the disadvantages that open channel scrapers have. However, ammonia within the building can be a problem with both scraper systems (Dickey et al., 1996). The system may also have high odour levels due to residual manure.

Under-Floor Manure Storage

Under-floor storage pits are commonly associated with slatted floors (Dickey et al., 1996). Slatted floors often cover a shallow collection pit where animal waste and wash water are collected. The reinforced concrete storage pit is generally sized for 1.0 cubic foot of storage per 1000 pounds of swine per day (Dickey et al., 1996). Less frequently, liquid manure is collected and stored in deep pits (8 feet) under slats (Alberta Pork and AAFRD, 2002). The deep pit systems typically produce less odour than shallow collection pits. Collection pits are usually the full width of the slotted area in the pens (Alberta Pork and AAFRD, 2002). Pits are usually filled by a combination of gravity flow and water flushing, as described above. Pit dividers and plugs lead to discharge pipes that take manure out of the barn. Under-floor storage pits have several advantages including ease of labor and minimizing the potential for water pollution, but at the same time pose a potential problem with respect to odour and gases. Well-designed ventilation systems, which incorporate under-floor pit ventilation, help reduce odour problems (Dickey et al., 1996). With mechanical aeration, the storages can be maintained with significantly less odour (Miner, 1995). Under-floor storage pits may also be combined with anaerobic lagoons or other outdoor storage for pit overflow (Dickey et al., 1996).

Reducing Exposed Surface Area of Manure

Reducing the surface area of exposed waste can reduce the emission of odor and other gases. A study by DGH Engineering (DGH, 2002) replicated a technology in use in the Netherlands that separates the feces and urine from spillage water in the gutters used in farrowing barns. The surface area of exposed manure was reduced by 67%, resulting in reductions in odour, ammonia and hydrogen sulphide of 17%, 25% and 27%, respectively.

5.2 Solid Manure Systems

Solid manure handling systems use bedding materials to absorb urine and feces (Alberta Pork and AAFRD, 2002). Solids manure systems are commonly used to house finishing pigs, however, gestating sows are also housed in bedded pens (Alberta Pork and AAFRD, 2002). It is important to use enough bedding material to absorb the majority of the liquid present, and the condition of the bedding should be examined on a daily basis to minimize potential odour. Housing systems that use bedding are normally cleaned after every batch of finished pigs, or on a regular schedule when they are used for sow housing (Alberta Pork and AAFRD, 2002).

A solid manure management system originated in Sweden is the deep-bedded system. In this system, the floor is padded with a layer of six to eight inches of straw, marsh grass or cornstalk bedding at the beginning of each production cycle. As pigs enter the room and the

bedding is soiled, fresh bedding materials is added two or three times a week (Moulton, 1998) or even daily (Halverson, 1998). The bedding-manure mixture is cleaned out at the end of each production cycle or periodically about four or five times annually. The bedding/manure mixture is stored or directly spread on agricultural land as fertilizer and soil amendatory. Moulton (1998) reported that deep-bedded system could reduce manure odour dramatically. There was no offensive smell in the buildings with deep-bedded system (Wilson, 1998).

The mechanism of deep-bedded system on odour reduction is that a small amount of manure is mixed with a large volume of absorbents (e.g., straw), an environment is created in which the bulk is sufficiently dry so that air permeates the manure-bedding mixture. As a result, anaerobic bacteria are inhibited, and aerobic bacteria, fungi, and more complex organisms thrive. This creates a condition for aerobic composting, which generates little odour (Miner, 1997).

Another recent development in solid manure handling system is the High-Rise™ building. A High-Rise™ building is a two-story, above-ground structure that utilizes a drying plenum and a special ventilation strategy to produce smaller manure volume and manure that can be handled as a solid, while using pens with conventional slatted floors (Stowell et al., 2000). Fleming and MacAlpine (2002) conducted a one year monitoring study on a swine barn of High-Rise™ type in Ontario. The barn had totally slatted floors and with a solid manure storage system beneath the slats. A bed of straw downstairs held the manure as it fell through the slats. All ventilation air was drawn downward through the slats and exhausted through wall fans in the manure storage area. In addition, aeration air is blown upwards through a sub-floor system to aid in drying out the manure. Odour was assessed with a scentometer and an odour panel of four people. They reported that odour level 30 m downwind of the barn was barely detected. The odour levels between 3.7 to 24.3 D/T (dilution to detection threshold) were measured at 10 m from ventilation fans. In terms of odour quality, they reported that exhaust air from the barn had only a slight odour of “liquid swine manure” and the smell seemed closer to spoiling feed or silage.

A low-cost straw bedding system, the hoop structure (e.g., Biotech Shelter), has gained some acceptance for grow-finish operations and for gestating sows in Manitoba and the Midwest region of US. A characteristic of this system is to use large amount of straw to provide a clean, comfortable physical environment for animals. The systems can be managed in different ways. One management style is to bring a large volume of straw into the facility initially, with no further additions of bedding material when animals are in the facility. This approach results in relatively low labour and bedding material requirements. But concerns have been raised with regard to animal welfare, air quality and the pollution potentials. Another management style is to use a small amount of straw for the initial bedding pack and add more straw regularly to maintain optimal bedding conditions for animals. This approach provides better environment for animals and enhances composting of manure pack. The average properties of the manure-bedding mixture are ideal for composting. Composting can be done with minimal management if the mixture is piled in windrows. The benefits of composting include volume reduction and nutrient stabilization, as well as odour reduction. No quantitative studies have been found in the literature on the odour reduction. Anecdotal evidences indicate that neighbors do not generally object to hoop structures because the odour during the growing period is low, but they generate odour during spreading (Harmon and Honeyman, 2002).

In comparison with liquid manure handling systems, the solid manure systems have the following advantages: (1) the potential of odour emission from the buildings, manure storage and land application is much less than liquid manure systems; (2) the water consumption is reduced by 80% to 90%; and (3) the cost of manure transportation is reduced because the weight of the straw-manure mixture is approximately 15% of liquid manure. Some disadvantages of solid manure systems are: (1) more intensive labor is required for bedding packing and cleaning out; (2) protected storage is needed to keep the straw dry; and (3) straw can be a source of dust and microorganisms.

Solid manure handling systems have not gained the popularity in Canada. According to Tessier and Marquis (1999), less than five percent of swine operations have adopted the solid manure systems and most of them are small operations. If a solid manure system is used in an intensive swine operation, the source and cost of straw, as well as the disposal of the straw-manure mixture, should be considered. It is estimated that the straw requirement for breeding and gestation facilities is typically 750 to 800 kg (2.5 bales) per sow place per year. The cost is estimated to be \$25 to \$30. For a finisher facility, the straw requirement is estimated to be 90 kg per pig marketed, or \$3.2.

5.3 Management Practices

Controlling the production of odorous gases in the barn helps to reduce the odour nuisance posed to the neighboring population. Ventilation rates in pig growing facilities range between maximum (0.5L/s/kg of live weight) during hot weather conditions to a minimum (10% of maximum) during cold weather conditions (CFBH, 1988). During periods of hot/warm weather, the low relative humidity will facilitate dry conditions in the barn whereas during cold weather, relative humidity values above 70% will result in moist surfaces and may facilitate an increase in odour generation. There appears to be no evidence in the literature that the odour emission rate (ventilation rate \times odour concentration) is different during the two weather conditions. However, poor dunging behavior of pigs during hot weather conditions may increase odour emission rates in partially slatted floor facilities. Pigs excrete on the solid floor and lie in these feces to provide additional cooling. Cooling sprinklers are effective during hot weather conditions to encourage pigs to stay clean. During cold weather conditions, the pigs excrete in the coldest area of the pen. If the air inlets direct the cold air to their designated sleeping area, dunging would occur in the sleeping area.

The effectiveness of the ventilation system during cold weather may be compromised if the heating capacity is under-designed. To maintain temperature under cold weather conditions, the minimum design ventilation rate can only be maintained with sufficient heating capacity. Livestock facilities with insufficient heating have excessive relative humidity and high ammonia levels due to wet surfaces.

There is little evidence in the literature as to the most effective way of dispersing the building air into the atmosphere. Today's swine facilities have both vertical and horizontal discharge of exhaust air. Some of the feeder barns are also vented from the pit airspace. Normally, pit ventilation does not exceed 30% of the total ventilation capacity (Borg, 2001).

Little research has been reported on relative building odours when barn air is exhausted beneath the slatted floor or above it or vertically through the roof.

Vented head spaces above the stored manure appear to generate more odour than a stagnant manure storage headspace. The odour transfer rate from the manure surface to the animal space is lower in a non-ventilated storage headspace. Research at the Michigan State University (von Bermuth, 2001) has led to the development of a new manure collection system that keeps feces separate from the swine. This results in reduced transportation costs for manure application and the manure phosphorous (P) is concentrated in the solids fraction. Manure separation immediately after being voided appears to have implications on odour emission rates along with hydrogen sulfide (H₂S) and ammonia emission rates.

Dunging areas are major odour sources inside the swine buildings. Lemay et al. (2000) and Feddes et al. (2001) investigated a concept of creating two independent airspaces within a room, i.e., the main airspace and an enclosed dunging area (EDA). In swine barns with partially-slatted floors, for example, enclosed dunging areas can be constructed over the slats to confine the area in which the pigs drink, urinate and defecate. These enclosed areas are individually ventilated and the exhaust air may be treated by biofiltration (Lemay et al., 2000). There are some extra costs associated with constructing, maintaining and ventilating these partitioned spaces in the barn. The result, however, is that the rest of the barn air is kept cleaner, smells less offensive and may be vented without treatment.

The emptying procedure of manure from the barn affects the rate of odours and gas emission rates, especially H₂S. Some of the larger, newer swine facilities have reported high levels of H₂S during the process of draining the manure storage pits. During the emptying process, manure drops up to 2 m vertically into a main discharge pipe. The manure in the horizontal pipe does not flow fast enough initially resulting in other manure plugs dislodging and manure gas being introduced into adjacent rooms. Perhaps sizing the horizontal drainage pipe to accommodate open channel flow, rather than pipe flow may prevent adjacent manure plugs from leaking during emptying of the storage pits.

Excessive stocking density also leads to pen fouling. Open pen partitions may be used to encourage animal socializing in the dunging area. Feeder management can also affect odour production. Wasted feed adds to the organic load of the stored manure.

Concluding Remarks

An effective manure handling system should promote quick separation of manure from animals to minimize odour generation. Properly designed slatted floor systems provide an effective way of separating manure from animals with minimum efforts. However, there is a lack of quantitative information as to how odour production relates to the percentage of the floor being slatted. If manure is stored under the floors in the barn, well-designed ventilation systems are needed to provide under-floor pit ventilation for reducing odour problems.

Odour level may be extremely high when liquid manure is being discharged from the barns. The discharge systems should be designed to achieve adequate flow rate for preventing adjacent manure plugs from leaking during emptying of the storage pits.

Solid manure systems usually result in less odour emission, but are more expensive and difficult to operate. Several solid manure systems have been tested and used and they have shown the promises in odour reduction. Research should be conducted to evaluate solid manure handling systems such as High-Rise™ for Manitoba conditions, in terms of their effectiveness in odour reduction, economic feasibility, and agronomic impacts of using solid manure as fertilizer.

Properly maintained barn environment is also a key in odour control no matter what types of manure handling systems are used. Adequate temperature and relative humidity should be maintained in the barns to prevent “dirty pens”. Furthermore, the barn should be adequately ventilated to remove airborne dust, gases, and bioaerosols from the building. The feasibility of using multiple ventilated spaces (e.g., enclosed dunging area, or EDA) for odour control should be explored.

6. MANURE STORAGE DESIGN AND MANAGEMENT

6.1 Earthen Manure Storage (EMS)

From the point view of odour control, manure storages may be categorized as covered storages or open-top storages. Manure storages with solid structural covers, such as concrete or steel tanks with lids, emit little odour except when they are emptied (Table 12). Odour emission rates from the manure storages are discussed in Section 2 for various storage systems. This section focuses on odour management for earthen manure storage, which is most commonly used in Manitoba for storing swine manure. Discussion is also extended to various manure treatment processes.

An earthen manure storage do not necessarily function as a lagoon. A lagoon is designed and managed to *store and biologically* treat liquid manure. If an earthen manure storage is designed to only store manure, it is not a lagoon. A lagoon may contain one of three types of waste-stabilizing bacteria — anaerobic (inhibited by oxygen), aerobic (requiring oxygen) or facultative (maintained with or without oxygen). These bacteria convert volatile solids in the manure into liquids and gases such as methane and carbon dioxide (Miner, 1995). Anaerobic lagoons are commonly used for storing and treating livestock manure because their ability of handling high loading rates and low maintenance requirement. Anaerobic lagoons may be single or multi-stage, with latter being more beneficial to odour control. The first stage lagoon is the primary treatment unit where organic materials are allowed to stabilize. The second and subsequent stages contain relatively clean water, which can easily be pumped for use in flush systems or applied to cropland. Multi-stage systems make the removal of sludge and effluent easier (YCELP, 2002).

Aerobic lagoons are either equipped with mechanical aerators or encompass a large surface area so that there is enough free oxygen to sustain aerobic bacteria (YCELP, 2002). This means that aerobic lagoons are more costly, but produce less odour than anaerobic lagoons. When a mechanical aeration process is selected, a portion of the organic load is usually removed by a pre-treatment process, liquid-solids separation (Miner, 1995). Because the aerated lagoon does not depend on wind or algal growth for the oxygen supply, the depth can be more than five feet, typically 8-20 feet (Lorimor et al., 2001).

Odour from a well-designed and well-managed lagoon should be only slightly musty; foul odour indicates a malfunction (Tyson, 1996). A common cause of malfunction is too high of a loading rate: an overloaded lagoon is odourous. Miner (1995) recommended loading rates between 1.5-3.0 ft³/lb of pig, depending on location. The loading rate can be increased as the outside temperature increases because bacteria are more active in warmer temperatures. During spring warm-up, bacteria have excessive amount of organic matter to stabilize, resulting in large amounts of biogas being produced and creating serious odour problems (Heber and Ni, 1999). To minimize spring warm-up odour problems, a lower loading rate should be maintained. Some strategies are: adding small amount of waste frequently (less than 7 days); separating solids from liquids; or hauling away some manure if fields can accept it (Heber et al., 1999). It is also beneficial to agitate and remove sludge from lagoons every 3 to 4 years to reduce build-ups. A higher pH may increase the activity of methane bacteria (Tyson, 1996). Addition of hydrated lime increases the pH if it is too low (less than 6.5) in the lagoon.

6.2 Covers for Manure Storage

Covering outdoor manure storage facilities is an effective way of reducing odour emission from manure storage. Manure storage covers limit solar heating and wind-induced volatilization. They also provide an aerobic zone within the cover material with high surface area for filtering and aerobic degradation of odour compounds emitted from manure (Heber et al., 1999). Manure storage covers may be categorized as natural crusts, solid covers, impermeable covers, and biocovers. Table 12 shows a general comparison of various covers for odour control. A natural crust, which occurs with a high-fiber diet (such as barley-based diets), may reduce odours by 50% (Heber et al., 1999). Solid covers can almost completely eliminate odour emission, but are very expensive. Impermeable floating plastic covers may provide more than 99% odour reduction (Heber et al., 1999), and are economically viable and commercially available. The estimated cost is \$0.35 to \$0.45 per head marketed (Petersen, 1998).

Biocovers (floating organic covers) may provide an effective way of reducing odour emission from outdoor, open manure storage units (Clanton et al., 2001; Mannebeck, 1985; Miner, 1995). A biocover is usually composed of organic material (e.g. wheat straw, barley straw, chopped cornstalks, sawdust, wood shavings, rice hulls, etc.) that is blown onto the surface of the storage in a layer about 250 mm thick (Bicudo, 1999). Gas concentrations build up under the cover, keeping most of the gases in solution (Bicudo, 1999). More effective covers, such as straw, also act as biofilters and reduce the concentration of odours and gases in air which diffuse through the cover. Straw can be wetted with manure to make it more biologically active and promote biofiltration (Zhang et al., 1999c). Such a cover can float for several months, depending on rainfall, depth of manure, surface area of the storage unit, winds, manure characteristics, etc. (Jacobson et al., 1997).

Biocovers are relatively inexpensive, as the raw materials are readily available. Heber et al. (1999) reported that 8" to 12" chopped straw (barley, wheat, oats or brome) could provide 50% to 80% odour reduction at a cost of about \$0.01-0.02 per square foot. This cost estimate may vary depending on the local price of straw. Jacobson et al. (1999c) estimated the cost of a 12" straw cover as being \$0.08 per square foot (\$0.80/m²), not including the application cost. Zhang et al. (1999c) estimated the cost of a straw cover to be between \$0.10 to and \$0.50/m². Bicudo (1999) reported the cost of a straw cover on an open manure storage unit to be between \$1.07 and \$1.61 per m² (assuming 6 months of useful operation).

Although straw covers have been available for approximately ten years, the swine industry has been reluctant to adopt this technology on a widespread basis. In spite of government programs to promote this technology, only a small number of storages are covered with straw annually. Shortcomings of this cover system include sinking of the straw with time. Normally, two applications are required in a season. Additional agitation and straw chopping are required for pump-out. Furthermore, a straw cover inhibits evaporation but permits all precipitation to enter the manure. The extra costs to transport this additional liquid during pump-out can be significant. Covered manure also has higher nitrogen and volatile organic compound concentrations, resulting in more odours when pumping (Bicudo, 1999).

Straw may be mixed with vegetable oil to keep the cover afloat longer (Barrington, 1997; Schmidt, 1997). The lifespan of a biocover can also be extended by combining it with geotextile

fabric or floatation devices, such as the polystyrene pellets. Again, this adds to the cost and maintenance requirements. Some examples of the cost of synthetic covers are: clay balls - \$21.50 to \$53.80/m²; geotextile - \$1.07 to \$4.30; and plastic sheeting - \$10.76 to \$21.52/m² (Jacobson et al., 1997c).

Synthetic plastic covers have historically been relatively expensive. In order to ensure the cover is robust enough to withstand wind forces, these systems became too heavy and expensive to be attractive to the livestock industry. Recently, this problem has been overcome by the development of a technology that utilizes negative air pressure to anchor lightweight plastic covers (Small and Danesh, 1999). Based on a capital cost of \$6.00 to \$8.00 per square meter, the cover is economically attractive, since the cover has a service life of up to ten years. Additional benefits include isolation of precipitation and the retention of manure nitrogen, factors that offset the cost of the cover. Several covers are in use across Canada and the northern United States.

6.3 Aerating Manure Storage

Maintaining an aerobic condition in manure storage minimizes odour emission. Aeration is a means of providing oxygen to manure.

Extend Aeration

Aerating manure for a relatively long period may bring about the decomposition of microbiomass, referring as stabilization of organic matters. The required retention time for stabilization is usually more than ten days. To effectively reduce odour generation by means of stabilization of organic matter in manure, the aeration rate must be twice the BOD (biological oxygen demand) loading. Using the data reported by Cumby (1987) and Westerman and Zhang (1997), the aeration rate was estimated as 0.43 kg O₂/pig/day.

Surface Aeration

Surface or subsurface aeration has been reported as an efficient way to reduce odour emission from manure storage (Iowa State University, 1998). The aeration process maintains a certain level of dissolved oxygen in the surface layer of manure. When odourous compounds formed by anaerobic digestion in the manure moves to the aerobic surface layer, they are oxidized into odourless gases (CO₂) or other odourless products. For example, hydrogen sulfide is converted into solid sulfur settling down to the bottom of the storage.

The oxygen requirement for surface aeration was recommended as 1/3 to 1/2 the BOD loading (NZAEL, 1984), which is only 1/6 to 1/4 of that for extend aeration. The annual operation costs reported by Iowa State University (1998) and Westerman and Zhang (1997) were \$3.5 to \$3.6 per finishing pig. The prices of aerators range from \$4,500 to \$9,000. Usually, more than one aerators are needed for a storage facility. Assuming the lifespan of an aerator is 10 years. The total cost of surface aeration is approximately \$4.6 to \$6.4 per finishing pig place per year, or \$1.8 to \$2.5 per pig marketed.

The aeration depth of 80 to 400 mm was reported as effective for odour control (Ginnivan, 1983). Recent studies conducted by Zhang et al. (1997) showed that continuous low rate aeration to maintain the dissolved oxygen (DO) in the surface layer of 150 to 450 mm at 0.5

mg/L was effective in controlling odour emission from swine manure (96% reduction in odour concentration).

All available information of surface aeration for odour control obtained either from bench scale studies or from areas of warmer climates. In Manitoba, the surface of manure storage may be frozen for five months in a year (from November to March). The surface aeration may be needed only from April to October. After five months low temperature storage, the organic (odour generating) matter accumulated in the storage with little decomposition. DGH (2001) reported that the volatile fatty acid (VFA) concentration in earthen manure storage could be as high as 13,000 mg/L at the end of February. It is not certain whether surface aeration would be effective in odour control under Manitoba conditions. Further research should be conducted.

6.4 Other Manure Treatment Technologies

Manure may be treated before or during storage for odour control. This subsection discusses several common manure treatment processes.

6.4.1 Solid-Liquid Separation

Fresh swine manure contains high levels of suspended solids that are predominantly organic matter. It is the anaerobic decomposition of organic matter that produces odour compounds. Removing solids from the manure means reducing organic matter in manure storage, and therefore the process should reduce odour emission from manure storage. However, the quantitative effects of solid removal (solid-liquid separation) on odour reduction have been seldom reported. Some researchers (e.g., Heber et al. 1999) believed that solid-liquid separation for liquid manure was somewhat effective in reducing odour, but others observed that the effect was insignificant (Zhu et al., 2001). The discrepancies are probably attributed to the effect of particle sizes of manure solids.

A study conducted by Zhang and Westerman (1997) showed that most of odour-generating compounds are contained in fine solid particles. Also, in a study related to the particle sizes distribution in swine manure, Jett et al. (1974) reported that approximately 83% of the crude protein and 93% of fat in the original manure samples were contained in the material which passed the 0.25 mm sieve. The results of a study conducted by Hill and Tollner (1980) showed that 40% of VS, 47% of COD, and 70% TKN passed the 0.105 mm sieve. All of the above mentioned parameters are odour related. Research on the relationship between the solid particle size in manure and major odourous compounds conducted by Zhu et al. (2001) showed that most odourous compounds (VFA and BOD) were contained in manure particles smaller than 0.075 mm. For odour reduction, removal of fine particles (smaller than 0.075 mm) seemed necessary. Unfortunately, little information could be found on how fine particles could be separated to satisfy the purpose of odour reduction.

Most solid separation technologies that are currently used are not efficient in removing fine particles. Therefore, instantaneous odour reduction cannot be expected from the solid-liquid separation. The significance of solid-liquid separation process is, however, that it is a necessary pre-treatment for some other treatment techniques, such as drying and composting. Removing solids lowers the organic strength in the liquid portion, and this in turn would reduce the energy requirement for the further treatment of the liquid portion of manure.

Gravity Separation

In gravity separation, manure flows through a settling tank (or basin), solid particles are separated from liquid by sedimentation if solids are heavier than liquid or floatation if solids are lighter than liquid. Liquid flows out of the tank and solids are retained in the tank. The settled solids need to be removed periodically.

Studies have shown that the gravity separation is more efficient than mechanical separation in removing fine solids from swine manure (Uiuc, 2002). It was reported that two-hour sedimentation accounting for the removal of 80% of Total Suspended Solids (TSS) and, on average, 55% of Total Chemical Oxygen Demand (TCOD), 35% of Total Biological Oxygen Demand (TBOD) (Oleszkiewicz, 1979). It was found that swine waste sedimentation was virtually completed after 2-hour quiescent laboratory conditions, and additional settling time resulted in only an insignificant decrease in TSS concentration of order of 1% to 3% (Oleszkiewicz, 1986). Based on a two-year monitoring study on the performance of concrete sedimentation basin at a swine feedlot, Lorimore et al. (1995) reported that the efficiency of total solids removal was 64.2%.

Mechanical Separation

Commonly used mechanical solid separation techniques are screens and centrifuge. The performance of various screening systems was reviewed by Zhang and Westerman (1997) (Table 13). The highest removal of organic matters were reported as 70% in terms of VS with 0.104 mm vibrating screen and 69% in terms of COD with 1.0 mm stationary screen. In general, the removal of organic by means of separation was below 50%.

The costs of mechanical solid-liquid separation were estimated on the information reported by Bicudo (2002a). The operation cost of mechanical solid-liquid separator was estimated to be \$0.26/finishing pig place/year, about \$0.10/finisher marketed. Fixed cost for a screen separator was estimated between \$7,500 and \$22,500.

The effectiveness of solid-liquid separation is also depending on at what time solid-liquid separation is conducted. Fresh swine manure contains high levels of suspended solids (SS) and low levels of dissolved solids (DS) (Evans et al., 1978). While the manure stored in pits or in storage, it undergoes microbiological decomposition. The microbiological activity breaks down SS particles into small sized colloidal particles and DS particles that are hard to be separated from liquid because of their small sizes and stability or resolvability in a suspension system. In order to make an effective use of solid-liquid separation technology, manure separation should be conducted as soon as manure excretion. The result of a laboratory study conducted by Zhu (2000) showed that the solid-liquid separation technique, if applied to the treatment of liquid swine manure with solid particle sizes equal to or greater than 1.0 mm, should be performed within the first ten days after the manure is excreted in order to improve separation efficiency. The use of separation techniques to treat manure that is older than 25 days may not be a cost effective practice in terms of removing organic solids that have potential for producing odours during storage (Zhu, 2000). These conclusions were drawn at a condition of storage temperature from 18 to 22°C. The storage period before the separation is performed should be shorter if the storage temperature is higher.

6.4.2 Anaerobic Digestion

In comparison with open anaerobic lagoons, closed anaerobic digestion systems (digesters) provide a more efficient way of degrading organic matter in the manure, and produce less odour because odourous intermediate products of anaerobic decomposition are converted into odourless end products: carbon dioxide and methane. Another advantage of anaerobic digestion is nearly complete retention in the effluent of the fertilizer nutrients N, P and K that were in the raw manure entering the digester (Field et al., 1984).

Under anaerobic conditions (i.e. no free oxygen present), two groups of heterotrophic bacteria, in a two-step liquefaction/gasification process, convert over 90% of the organic matter in the manure, initially to intermediates (partially stabilized end products including organic acids and alcohols), and then to methane and carbon dioxide. Welsh et al. (1977) reported that anaerobic digestion reduced the presence and offensiveness of swine manure odours. The effect lasted for nearly three months after storage. Dague and Pidaparti (1992) conducted a bench-scale experiment using three 12-L anaerobic sequencing batch reactor (SBR). They claimed that anaerobic SBR could almost totally eliminate odours from swine manure. Massé et al. (1997) conducted an anaerobic digestion experiment with four 25-litre sequencing batch reactors. The odour reduction was reported as that the digester effluents had little odour when compared to the raw manure. Lorimor (2000) determined the quantitative effect of a heated, complete mix anaerobic digester on odour reduction. The digester was built in a 5,000 sow gestation-farrowing facility. The odour concentration was reported as approximately 4,710 OU from raw manure and 520 OU from the digested manure. The first farm-based anaerobic digester in the US was constructed in 1972 solely for odour control purpose (Miller, 1999). Other industrial scale units for demonstration were also reported (Iowa State University, 1998; Miller, 1999; Lotimor, 2000).

Temperature Requirement by Anaerobic Digestion

Anaerobic decomposition generally takes place at two temperature ranges: thermophilic range from 49 to 57°C, and mesophilic range from 30 to 38°C (Metcalf & Eddy, 1997). The thermophilic digestion carries on three to four times faster than mesophilic digestion since biological reaction rate is roughly doubled for every 10°C in temperature increase. The operating cost of thermophilic digestion is much higher than mesophilic digestion because of the higher temperature requirement, especially for the cold climatic conditions. The energy is usually required to maintain the digester temperature and to raise the manure temperature as it enters the digester. Under the Manitoba climate conditions, the total operation costs are estimated to be \$7.1 per pig place per year for mesophilic digestion, and \$14.1 per pig place per year for thermophilic digestion.

High heating costs have prohibited swine producers from using anaerobic digestion in cold regions. Researchers are looking onto the possibility of operating anaerobic digestion at lower temperatures of psychrotrophic range with an optimum temperature range between 20 and 30°C, and even at psychrophilic range with an optimum temperature around 15°C. (O'Rourke, 1968; Ke-Xin and Nian-Gua, 1980; Chandler et al., 1983; Cullimore et al., 1985; Lo and Liao, 1986; Sutter and Wellinger, 1987; Balsari and Bozza, 1988; Safley and Westerman, 1992; Safley and Westerman, 1994; Massé et al., 1996; and Massé and Droste 1999). Studies have shown that the same treatment effect could be obtained by low temperature anaerobic digestion, but a longer solids retention time (SRT) in the low temperature are required.

A study conducted in Manitoba showed that the temperatures in covered EMS were in the range of psychrophile, from 1°C (surface) to 4°C (bottom) in winter, and from 23°C (surface) to 17°C (bottom) in summer (DGH, 2001). Anaerobic digestion at temperatures of psychrotrophic and psychrophilic ranges holds some potential for Manitoba conditions.

Types of Anaerobic Digestion Operation

Conventional digesters for manure treatment include continuously stirred-tank reactors (CSTR) and plug flow reactors (PFR). In these two types of digester, the hydraulic retention time (HRT) equals to the solid retention time (SRT) and active biomass is removed from the digester in the effluent on a daily basis (Zhang et al., 2000). The Anaerobic Sequencing Batch Reactor (ASBR) is a suspended-growth, biomass-retaining reactor that has been found more cost-effective for treating dilute manure than conventional digesters (Zhang et al., 2000). Dague and Pidaparti (1992) and Massé et al. (1997) reported that ASBR was effective in odour reduction. Cheng and Liu (2002) tested an attached-growth anaerobic digester (AGAD) for treating swine manure. Plastic Ballast rings were used in the digester as the medium for bacteria to attach to. The system was shown to be able to minimize clogging problems.

Iowa State University (1998) estimated that the construction cost of ASBR for a 3,000-head finish operation, including the cost for a biogas recovery system, was \$473,000 (\$293,000 for the reactor, \$180,000 for the generator system). Assuming a life span of 20 years, amortized annual cost would be \$7.9 per pig place, or \$3.0 per marketed pig. The fixed cost for a complete-mix anaerobic reactor (continuously stirred-tank reactor) for a 5,000 sow gestation-farrowing facility was reported as \$750,000, or \$7.5/sow place/per year (20 year design life) (Lorimor, 2000).

Biogas Generation

Biogas produced in anaerobic digestion contains approximately 40% to 70% of methane, which has a heat value of approximately 37 MJ/m³. Methane produced by SBRs in a 3,000 head-finish operation could generate about \$9,000 (\$0.07/kW-h) worth of electricity annually, or \$3 per finisher place per year and \$1.15 per marketed pig (based on 2.6 pigs marketed per finisher place per year) (Iowa State University, 1998). With a complete-mix reactor, the annual electricity generated in a 5,000-sow gestation to farrowing was estimated to be worthy of \$35,000 (\$0.07/kW-h), or \$7 per sow place per year (Lorimor, 2000). Other demonstration projects in the US have showed that the electricity and heat recovered from digestion systems may not only sustain the digestion requirement but also offset part of electricity cost. It has been reported that the economic efficiency of anaerobic digestion depends on the scale of the operation. The break-even point was reported as 10,000 pigs (Reid, 2001). For operations with less 10,000 pigs, anaerobic digestion is probably not economically beneficial because of the high fixed cost.

The rate of biogas generation in an anaerobic digester is also an indicator of the effectiveness of odour reduction. The precursors of biogas are VFAs, which are the most significant odourous compounds in manure (Schaeffer, 1977; Williams, 1984; Chen et al., 1994). High biogas productivity results from the thoroughness of the conversion from odourous VFA to odourless methane and carbon dioxide.

6.4.3 Composting

Many researchers have reported that composting could be effective in odour reduction (COG Handbook, 2002; Iowa State University, 1998). The compost, the end product from composting, has a non-offensive soil-like smell. However, the composting process itself may generate odours (NRAES, 1992). Three sources of odours from the composting process are: (1) raw materials, (2) ammonia lost from high-nitrogen containing materials, and (3) anaerobic decomposition of organic matter within windrows or piles (NRAES, 1992). Schmidt et al. (1999b) reported that high emissions of odour and ammonia were found during composting. ASAE Standards (ASAE, 2000) indicates that ammonia volatilization might be high during the early stage of composting.

To control the odour emission from composting piles or windrows, the aeration rate, turning frequency and other sophisticated management skills are needed. The requirements for aeration rate and turning frequency vary with the ambient environment and the degree of composting process.

Swine manure is nitrogen-rich, and therefore some carbonaceous raw (bulking) materials need to be added to achieve the desired carbon to nitrogen ratio of approximately 30 for successful composting. In case straw is used as the bulking material, the required amount is approximately one lb per gallon of swine manure, or 7,000 lb (about nine bales) of straw per sow per year in a farrow to finish operation.

Concluding Remarks

Open-top manure storages such as earthen manure storage (EMS) are a major source of odour from swine operations. Covering the manure storage is an effective way of minimizing odour emission. Biocovers or floating organic covers, such as straw, provide a cost-effective and farmer-friendly solution to odour problems associated with manure storage. The straw cover is easy to apply but will sink over time, and thus reapplication is required. Additional agitation and straw chopping is required for pump-out if straw covers are used. Impermeable floating plastic covers may provide over 99% odour reduction, and are economically viable and commercially available. Surface aeration has also been reported as an effective way of reducing odour emission from manure storage. However, it is not certain whether surface aeration would be suitable for Manitoba conditions and further research should be conducted.

Treating manure before or during storage may reduce odour emission from manure storage. Some technologies that have been studied are solid-liquid separation, anaerobic digestion, and composting. Most odourous compounds are contained in small manure particles. Therefore, removal of fine particles is necessary for effective odour reduction when using the solid-liquid separation technologies. Furthermore, solid-liquid separation should be performed within the first ten days after the manure is excreted to maximize the separation efficiency.

Anaerobic digestion, performed in closed digesters, reduces odour emission by converting odourous intermediate products of anaerobic decomposition into odourless end products of carbon dioxide and methane. Mesophilic and thermophilic anaerobic digestion may not be suitable for Manitoba because of associated high heating cost during long and cold winter. Anaerobic digestion at lower temperatures of psychrotrophic or psychrophilic range holds some

potential for Manitoba conditions. Further research should be conducted to develop the low temperature anaerobic digestion systems.

Composting produces a non-offensive soil-like smell end product. However, the composting process itself may generate odours. Further research is needed to examine the possibility of composting manure from conventional confined swine production facilities.

7. BIO-FILTRATION

Biofiltration, in the context of exhaust air treatment, is a technology in which air is passed through a packed bed of warm, moist, nutrient-rich, porous filter medium prior to emission into the atmosphere. The filter medium provides a suitable environment for the growth of microbial films. Any volatile compounds, organic and some others, that are carried in the air stream diffuse into these films and are metabolized (Alonso et al., 1997). The principle metabolites are carbon dioxide and other non-odorous gases, water, and mineral salts (Williams, 1993). The degradation of contaminant compounds in biofilters occurs at normal temperatures and pressures, so biofiltration is economically competitive with other emission control technologies (Alonso et al., 1997). Biofilters are especially effective when used to treat large volumes of air containing low concentrations of contaminant compounds (Otten and Gibson, 1994). Biofiltration, therefore, is an appropriate technology for reducing offensive odours in air emitted from livestock facilities (Janni and Nicolai, 2000; Goodrich and Mold, 1999; Nicolai and Janni, 1997; Noren, 1986).

7.1 Operating Conditions

Since the microbial activity is the primary mechanism by which odorous air is cleansed in biofiltration, the effectiveness of a biofilter is maximized by maintaining preferential conditions for the growth of appropriate microbes. These conditions include temperature, nutrient availability, moisture, and acidity. The required conditions vary depending on the kind of microorganisms which are intended to colonize the filter medium.

The appropriate operating conditions for good microbial growth take time to stabilize in a new biofilter. During the start-up of a new biofilter, there is usually an acclimation period of up to several weeks in which the odour removal efficiencies start low and gradually improve (Nicolai, 1998). Once established, however, microbial activity is usually sustained with minimal inputs except an appropriate waste air stream and perhaps some supplemental moisture (Striebig et al., 2001). Since microbial activity is exothermic, a biofilter bed of reasonable size can maintain operating temperatures even in cold climates (Mann et al., 2002).

In the compost or soil biofilters common in livestock operations, the accumulation of microbial biomass will eventually clog pore spaces in the filter medium. Clogging limits airflow, as well as nutrient and water transport to the microbes, reducing the efficiency of the biofilter (Sadowsky et al., 1999). Such biofilters are therefore considered to have an effective operating life of about three to five years because operating conditions degrade at about this time, and the filter medium must therefore be replaced (Schmidt et al., 2000).

Odour Compounds

Biofilters have been found to be effective in reducing concentrations of ammonia, hydrogen sulfide, methyl mercaptan, dimethyl disulphide, and other reduced sulphur-based and nitrogen-based organic compounds found in livestock odours (Easter and Okonak, 2000). The presence or absence and relative concentrations of these contaminants might influence the type of filter media that are considered and the design of the ancillary systems such as water application and leachate collection.

Microbes

In some industrial applications, biofilters may be inoculated with particular strains that metabolize specific contaminants (Chung et al., 1997a; 1997b; 1997c). In livestock applications, however, the open-bed compost or soil biofilters that are commonly used are dependent on colonization by naturally-occurring strains of bacteria. Sadowsky et al. (1999) tried to identify pure strains and consortia of microbes from various biofilters attached to swine and cattle facilities, and identify the particular substrates which each metabolized. They encountered difficulty in isolating microbes that effectively degrade odour compounds, and came to the conclusion that the microorganisms which inhabit biofilter media exist in a complex community that degrades odours through, perhaps, the communal exchange of substrates. Hence, selective isolation of specific organisms from these kinds of biofilters is not likely to be a good means of characterizing the active microbes or of isolating strains useful as inoculants.

There has been some work in which mesothermic bacteria are replaced by fungi as the active organism type in biofiltration (van Groenestijn et al., 2001). Unlike bacteria-based biofiltration, inoculation of the filter medium is required to establish the desired fungal growth. The resulting microbial community, however, is more resistant to drying and acidification than are bacteria. Also, the aerial mycelia of the fungi form large surface areas which affect good absorption of contaminant compounds. Challenges in the operation of such a biofilter include the low pH that is prerequisite for good fungal growth, and clogging of the filter by fungal biomass. Fungal biofilters appear to be a cost-effective approach for treating waste air streams contaminated with aromatics, alkenes, other hydrophobic compounds (van Groenestijn et al., 2001).

Temperature

The naturally-occurring microorganisms that most effectively degrade odour compounds are mesothermic bacteria. The temperature range for biofiltration, therefore, is from 15 to 40°C (Burrowes et al., 2001), with the optimum temperature between 30 and 40°C (Janni and Nicolai, 2000; Leson and Winer, 1991). Odour removal efficiency decreases at higher temperatures, in part because the adsorption and solubility of odour compounds decreases with increasing temperatures (Burrowes et al., 2001). Yang and Allen (1994) found that hydrogen sulfide was also effectively removed in laboratory-scale, closed-bed biofilters filled with compost when they were operated at temperatures between 25 and 50°C, with the greatest removal occurring between 30 and 40°C.

Biofilters associated with livestock operations generally do not need supplementary heat; the heat from the exhaust air and exothermic microbial activity in the filter bed is usually sufficient to keep the filter bed in the right temperature range. For instance, Janni (2000) has found that during Minnesota winters the ventilation air and biofilter heat is sufficient to keep an open-bed biofilter at an appropriate operating temperature. Mann et al. (2002) showed that similar biofilters operated reasonably well even in the more extreme winter conditions of Manitoba, maintaining temperatures of about +16°C when ambient temperatures varied between +9.2 and -34.2°C. Moreover, open-bed biofilters usually release enough heat to melt any snow that falls on them, providing moisture.

Nutrient Availability

Leson and Winer (1991) suggested that most commonly-available organic biofilter media would provide sufficient nutrients for the degradation of odour compounds. Numerous authors report, however, that the degradation of persistent hydrocarbons such as toluene (Bibeau et al., 1997; Kiared et al., 1997; Don, 1985), styrene (Jorio et al., 2000; Arnold et al., 1997), hydrogen sulfide (Coleman et al., 1995) and combinations of other aromatic hydrocarbons (Corsi and Seed, 1995; Edwards and Nirmalakhandan, 1996) is enhanced by the addition of supplemental inorganic nutrients to the filter bed.

Oxygen Level

The presence of oxygen is necessary, by definition, for aerobic microbial activity. A filter medium must therefore be chosen that has sufficient porosity, so that it affords good airflow throughout the filter bed (Nicolai, 1998). Even distribution of airflow is also important to prevent other operational problems, such as uneven drying of the filter medium and channeling.

Moisture

The support of microbial populations sufficient to reduce odours requires that moisture levels in the filter medium be maintained between 40 and 70% (mass of water: mass of dry medium) (von Bernuth et al., 1999), with 60% being ideal (Eweis et al., 1998). On one hand, too much moisture plugs pores in the filter, causing channeling and limiting oxygen availability (Nicolai, 1998). As well, if the filter is too wet, there is the risk of compaction of the filter medium, resulting in low porosity, high back pressure, and compromised air flow. Excess volumes of acidic leachate could also result (Swanson and Loehr, 1997). On the other hand, if the filter is too dry there will be insufficient microbial activity. Too little moisture also creates cracks or channels in the filter bed that reduce odour-removal efficiency (Nicolai, 1998). Dry air is especially problematic if the inlet airflow is cold and water capacity is therefore low. If the airflow is not humidified to near 100%, moisture will be stripped from the medium and, if precipitation (in an open-bed system) is inadequate, then supplemental water must be applied.

Acidity

There is little doubt that the pH of the biofilter medium has an effect on the microorganisms and microbial enzymes that metabolize odour compounds, and might also indirectly influences the availability of required nutrients (Atlas and Bartha, 1993). Low pH has traditionally been considered to be detrimental to odour removal efficiency. A number of researchers have found that a near-neutral pH provides the widest spectrum of aerobic bacterial activity, and that deviation from near-neutral pH compromises biofilter effectiveness (Deviny et al. 1999; Yang and Allen 1994; Leson and Winers 1991). Webster et al. (1996) found, however, that biofilter performance was relatively constant throughout a gradual decline in pH from neutral to less than 2. This stability may have been due to acclimation of the microbes or compensating shifts in the microbial community structure. As mentioned, pH less than neutral has been shown to be more suitable for the growth of fungi in biofilter media (van Groenestijn et al. 2001).

Since exhaust air from swine facilities can contain ammonia and hydrogen sulfide, the pH value in biofilters used for odour control over prolonged periods can decrease because of

nitrification and the oxidation of hydrogen sulfide (Atlas and Bartha 1993). To prevent acidification from occurring in situations where there are problematic concentrations of ammonia or hydrogen sulfide in the treated air stream, buffer compounds can be added to the filter medium, or prescrubbers may be used to remove the offending compounds (Le Cloirec 2001; Dong et al. 1997; Amirhor and Gould 1997; Scholtens et al. 1991).

7.2 Design Considerations

7.2.1 Types of Biofilters

Open-bed: The most popular style of biofilter for treating exhaust air from livestock facilities is an in-ground or on-ground, open-bed filter of compost and wood chips (Janni and Nicolai 2000). Exhaust air from a mechanically ventilated animal housing unit is forced into a plenum under the filter bed and moves upward through the filter medium. This is the least expensive type of biofilter to construct both in terms of initial investment and operating costs. It may be situated in a lined earthen berm, an open concrete tank, or may simply be composed of filter medium piled over a plenum formed by shipping pallets laid on the ground.

Closed-bed: Closed-bed biofilters are generally more expensive to construct, operate and maintain than open-bed systems (Burrowes et al., 2001). Such filters can provide more effective removal of odour and contaminants, however, because they afford more effective control over operating parameters such as filter bed moisture, temperature, and humidity. They are best suited to treating smaller air flow rates than generally occur in the swine industry, and so are frequently used for specialized industrial purposes where the removal of persistent organic compounds is necessary (e.g. benzene, toluene, xylene, styrene, etc.).

7.2.2 Components

The main structural requirements of the open-bed biofiltration systems most commonly used with mechanically ventilated animal housing include: exhaust fans and an air duct system to deliver exhaust air from the source to the filter, an airflow distribution system (usually some kind of plenum beneath the filter medium), a support structure for the filter medium, and the filter bed itself. A moisture control system may be required to prevent drying of the filter bed and, finally, it may be necessary to contain and dispose of leachate.

7.2.3 Influencing Factors

Factors to consider when designing biofilter are outlined below. For a detailed design procedure, refer to the Extension Program of the Department of Biosystems and Agricultural Engineering, University of Minnesota. This agency has published information and procedures for designing an on-ground, open-bed biofilter, intended for use with a livestock facility, based on estimated ventilation requirements and the properties of available filter materials (Nicolai, 1998). Swanson and Loehr (1997) have also published a general guide to understanding biofilter applications and design practice.

Dimensions

Where space is limited, the required area per unit airflow, or footprint, of the biofilter may be an important consideration. A typical footprint is about 10 to 17 m²/(1000 L/s) (50 to 85 ft²/1000 cfm) (Schmidt et al., 2000; Janni, 2000). The deeper the filter, the smaller the footprint

required for a given volume of filter medium. Increasing depth, however, also increases the possibility of compaction of the filter medium and a resulting restriction in airflow and loss of odour removal efficiency. Filter thickness should be at least 250 to 450 mm (10 to 18 in.) (Janni, 2000). Finding the inverse of these recommendations gives surface loading rates of roughly 60 to 100 L/s/m². Burrowes et al. (2001) recommend surface loading rates of 5 to 10 L/s/m² for soil media biofilters; 7.5 to 15 L/s/m² for organic media in open systems; and 25 to 75 L/s/m² for closed-bed systems. Observing surface loading rate recommendations such as these helps to confine the geometry of the biofilter to a manageable depth for a given airflow rate, avoiding operational difficulties such as compaction, poor airflow distribution, and drying of the filter bed.

Pressure Drop

The pressure drop through the filter medium (i.e. resistance to airflow) influences the size and operating cost of the required ventilation equipment; a lower pressure drop results in lower costs. Pressure drop depends on the nature and depth of the filter medium and the airflow rate. Usually, filter media contain a bulking agent which increases the porosity and lower the unit pressure drop. Pressure drops for typical filter media and airflow ranges have been reported in the literature. For instance, Nicolai and Janni (2001) determined the pressure drop for compost/wood chip mixtures with percent void spaces of 40, 50 and 60%. The expected values range from 10 Pa/m at 5 L/s/m² for a mixture with 40% void volume, to 500 Pa/m at 3300 L/s/m² for a mixture with 60% void volume. Some empirical equations are also available for estimating pressure drop across beds of granular materials based on measured values such as particle size, bulk density, and particle density (ASAE, 2000).

Cost

Because of the small profit margins in the livestock industry, biofilters must be low-cost (Nicolai and Janni, 1997). Materials used in the construction of the biofilter, principally the filter medium, should be readily available. Operation and maintenance costs must also be minimal.

Jacobson et al. (1998) estimated the construction, operating, and maintenance costs for an on-ground, open-bed, compost biofilter for a swine production unit, amortized over three years, to be between \$0.50 and \$0.80 per finished market pig. In terms of operating costs per unit airflow, Burrowes et al. (2001) found that a similar system costs somewhere from \$8.80 per 1000 L/s to \$29.40 per 1000L/s. Closed systems, on the other hand, cost about \$11.75 per 1000 L/s to \$59 per 1000 L/s (Burrowes et al. 2001). Easter and Okonak (2000) reported operating costs for both open and closed biofilters as being \$53 per 1000 L/s and \$70 per 1000 L/s, respectively. Janni (2000) estimated the cost of this kind of biofilter as \$0.22 per piglet on a 750-sow gestation/farrowing facility, assuming a three-year operating life. He also calculated that rodent control, a moisture application system, and higher operating costs for barn ventilation amount to an estimated \$450/year.

Effectiveness

The effectiveness of biofiltration is usually evaluated on the basis of removal efficiency. Work has been done to test low-cost, open-bed biofilters at swine production facilities (Nicolai and Janni, 1997); odour removal efficiencies of between 75% and 90% were achieved. Janni et al. (1998) also tested compost and brush chip biofilters over a ten-month period. Using EBCT of

8 and 4 s, they achieved odour removal efficiency of 91% and 87%, respectively, hydrogen sulfide removal efficiency of 97 and 96%, and ammonia removal efficiency of 74% and 82%.

Particulate Removal

Exhaust air streams from poultry units are often carry a substantial amount of dust, which can compromise the effectiveness of a biofilter by clogging the pore spaces. Dust filtration of the air stream, therefore, is recommended for poultry units, but usually is unnecessary for most swine or dairy operations (Nicolai and Janni, 1999).

7.2.4 Airflow Distribution and Support Structure

Airflow through an open biofilter is usually bottom-up. The airflow distribution system is intended to provide even distribution of the exhaust air across the filter bed, and the system should be carefully designed to accommodate this objective. Examples of effective distribution systems are: a network of perforated plastic piping below the filter bed and surrounded by crushed stone (Burrowes et al., 2001); a layer of shipping palettes laid on the ground (Nicolai and Janni, 1997); a concrete bed with inlaid plastic piping; a concrete bed with slotted openings (Burrowes et al., 2001); and a perforated plate, screen, or grating. In the latter case, a minimum total opening area of at least 20% to 35% (ASAE, 2000; Nicolai, 1998) through the support structure is recommended to prevent excessive back pressure.

7.2.5 Filter Media

A good filter medium must provide optimum conditions for the growth of a large, diverse microbial population and permit even distribution and relatively unhindered passage of the required airflow (Burrowes et al., 2001). Specifically, in order to harbour the appropriate bacterial populations, biofilter media must provide microbial colonization sites, retain moisture, supply inorganic nutrients, buffer pH, and help maintain a mesothermic temperature range. The characteristics of the filter medium should also include physical stability and good bearing strength, so that it will degrade slowly, yield relatively clear leachate, and compact little with time. It should also be very porous so that the pressure drop is low.

The required characteristics are often realized by mixing two or more materials to form the filter medium. Popular and effective materials that are appropriate for most Canadian locations are biologically active components such as soil and compost and bulking agents like wood chips or bark (Table 14). When choosing a biofilter medium, factors to consider are the proposed cross-sectional depth of the biofilter, the surface loading rate per square meter, the cost and availability of the ingredients, their particle size distribution, porosity, and service life (Burrowes et al., 2001). Some of these factors may be influenced by the characteristics of the air stream to be treated.

Compost : Compost is a popular filter material first used as a biofilter medium in Germany in about 1967 (Burrowes et al., 2001). Compost biofilters have an operating life of about 2 to 5 years (Burrowes et al., 2001). They host high concentrations of microorganisms, have large particulate surface areas, high permeability, good water retention, and good pH buffering capacity. Adding wood chips provides structural stability and resistance to decay and compaction (Burrowes et al., 2001). Blending with bark also enhances many of the favourable characteristics of compost (Burrowes et al., 2001). Due to these strengths, the required size of a

compost biofilter for a given application is smaller than that of a soil biofilter, for example. Drawbacks of compost include odour emissions from unaerated or immature compost. If the bearing capacity of the compost is low, then compaction of the filter bed can result in short-circuiting. Varying moisture content can shrink and swell a compost biofilter bed and result in cracking and crusting (Burrowes et al., 2001). Stirring or fluffing every few months mediates this. Finally, very dry compost is hydrophobic and adding moisture may require working the entire bed (Burrowes et al., 2001).

Soil: Soil is more physically and chemically stable than compost, and is also an excellent pH buffer. Soil usually has good bearing strength, which precludes much compaction of the filter bed. The operating life of a biofilter with a soil medium has been shown to be more than 10 years in Europe and more than 30 years in Washington State (Burrowes et al., 2001). The permeability of some native soils, however, is low, resulting in high pressure drops and low allowable surface loading rates. Sandy loams are generally more suitable for biofiltration (Burrowes et al., 2001; Nicolai and Janni, 1997). Another drawback of soils is that they are often more difficult than compost to keep out of the air distribution system or to amend, should the need arise.

Bark and wood chips: Chipped wood or bark provide high structural stability and bearing strength, and good porosity. They are a moderate source of nutrients and may retain some moisture. These properties depend on the particle size and to some extent on the type of wood used. The primary role of wood products in a biofilter is to maintain the porosity and structure of the filter bed.

Synthetic materials: Numerous kinds of synthetic filter materials have been tried as biofilter media (Burrowes et al., 2001). For instance, plastic packing material, ceramics, and activated carbon pellets may be used. Unlike biological materials, however, these do not provide a natural source of microorganisms and must be inoculated with, for example, soil, compost, or sewage sludge. Moreover, synthetic materials tend to be low in nutrients. Hence, they usually are used in the same role as wood chips, as only a fraction of the biofilter medium to improve the structure and permeability. To their advantage, synthetics can have a very uniform particle size and even pore size distribution and, as well, can be hydrophilic and easily wettable.

7.3 Maintenance

The warm, moist, nutrient rich biofilter material provides an ideal habitat for many kinds of pests. The maintenance of a biofilter includes, therefore, the removal of excess vegetation, control of noxious weeds, and control of rodent infestations.

Moisture Control

Moisture from the biofilter bed is lost through evaporation and must be replaced either by moisture from the inlet air stream, precipitation, or irrigation from a control system. Types of water application apparatus that can be used include spray nozzles, soaker hoses, and prehumidifiers. Surface irrigation is suitable to environments where evapotranspiration rates are high. The surface of the biofilter must be frequently irrigated at low application rates to prevent settling, compaction, and the saturation of medium. Impact sprinklers are often used for this purpose, because fine mist sprayers are prone to plugging (Burrowes et al., 2001). Surface irrigation alone, however, is not recommended because of the tendency to wet only the top of the

filter bed (Burrowes et al. 2001). Since most drying in upflow filters occurs from the bottom up, soaker hoses can be located in the middle of the filter bed to provide supplemental moisture. The inlet air can also be prehumidified by placing spray nozzles in the inlet air ducts, or using spray chambers or packed tower scrubbers (Lannon, 2000). With the use of timers, controllers, and moisture sensors, an effective automated control system can be devised.

Drainage and Leachate Collection

An on-ground or in-ground, open-bed biofilter must be sloped or located on a well-drained site to prevent the accumulation of water in plenum (Nicolai, 1998). In any case, the excess moisture that drains out of the bottom of biofilters can be acidic if inorganic compounds in the air stream are being degraded. If the leachate is acidic, it might be necessary to contain, collect and treat it before disposal to prevent groundwater contamination (Burrowes et al., 2001). Plastic liners can be used for this purpose in open-top systems, in conjunction with a drainage pipe sized for the maximum expected storm load (e.g. 100-year storm) (Burrowes et al., 2001). The drainage system must also be able to handle the water flow from a broken soaker hose or possible other malfunction (Burrowes et al., 2001). In more advanced systems, the drainage water might be reapplied to maintain the moisture content of the filter bed (Swanson and Loehr, 1997).

Clogging

Due to the accumulation of microbial biomass, the odour removal effectiveness of biofilter medium may decrease with time (Alonso et al., 1997). In the compost or soil biofilters commonly used in agriculture, there is no convenient way of removing this excess biomass from the filter medium short of reworking or replacing the entire filter bed. For this reason, soil or compost biofilters are increasingly viewed as installations that must be renewed or replaced after a limited operating life.

Disposal of Medium

If the biofilter medium is to be replaced every two to five years, then disposal of the old medium must be considered. The medium from a compost biofilter may be land applied. The material may be screened to remove any bulking agents, such as wood chips, for reuse. Attention may have to be given to the accumulation of nutrients in the medium because, over the life span of the filter, nitrogen and sulfur are sequestered in the filter as ammonia and hydrogen sulfide are removed from the waste air stream. A limited amount of research has been done to quantify the nutrients that are sequestered (Sun et al., 2000), and so nutrient analysis is advisable when first deciding whether or not to land apply the material.

Concluding Remarks

Biofiltration has been proven an appropriate technology for reducing offensive odours in air emitted from livestock facilities. Open-bed biofilters are the most common style for treating exhaust air from livestock facilities. The open-bed filters usually use compost and wood chips as filter medium. Odour removal efficiencies of between 75% and 90% may be achieved. Biofilters associated with livestock operations generally do not need supplementary heat; the heat from the exhaust air and exothermic microbial activity in the filter bed is usually sufficient to keep the filter bed in the right temperature range even under cold Manitoba climate conditions (DeBruyn et al., 2000).

During the start-up of a new biofilter, there is usually an acclimation period of up to several weeks in which the odour removal efficiencies start low and gradually improve. Once established, however, microbial activity is usually sustained with minimal inputs except an appropriate waste air stream and perhaps some supplemental moisture. In biofilters that use compost or soil as filter medium, the accumulation of microbial biomass may eventually clog pore spaces in the filter medium. These types of biofilters may have an effective operating life of about three to five years because operating conditions degrade at about this time, and the filter medium needs therefore be replaced.

Despite the success of open-bed biofilters, there is a need to continue research efforts with regard to biofiltration of exhaust air from livestock facilities. The open-bed biofilter is typically constructed as an add-on to an existing livestock facility; often resulting in inefficiencies in the overall system. For example, additional booster fans are typically needed to supplement the existing exhaust fans. A simpler, more efficient system would result if a single fan could be used to both ventilate the barn and move air through the biofilter. Perhaps the structure of the biofilter could be integrated into the structure of the barn itself. Such innovation would likely improve both the economics and aesthetics of biofiltration.

8. DUST CONTROL

8.1 Dust and Odour

A significant source of odour emissions from confined feeding operations is from the animal production buildings. Pedersen and Takai (1997) and Feddes et al. (1999) showed that dust is an important carrier of odour from production facilities. A confounding factor in determining the dispersion of odour is the role of respirable dust in concentrating and transporting these odours (Parbst, 1998; Hartung, 1985). Bottcher et al. (2000) reported that odours attached to airborne particulate might increase the persistence of the odour as it dispersed away from the source. They measured odour in two production units, and found a linear relationship between the odour intensity and the odour dilution ratio, with a slope of about -0.5 in one unit and -0.84 in the other unit. The steeper slope means that odour dissipate quicker in the air as it is dispersed. The odour samples with a slope of -0.5 are more persistent than the steeper slope of -0.84. Bottcher et al. (2000) attributed the difference in odour persistence to different dust concentrations.

Hoff et al. (1997a) cited literature that indicates that odour is amplified by the presence of dust particles. Odour in the absence of dust particles reduces in intensity much faster with dilution when compared to odour in the presence of airborne dust particles. Heber et al. (1988) found that in eleven monitored swine barns, particle counting indicated that 93% of the airborne particles were smaller than 5.2 microns. Small dust particles have a low settling velocity and a high proportion of the surface area. This suggests a longer contact time between the particles and odours in the air. Furthermore, many of the respirable dust particles are thought to be of fecal origin since they breakdown readily and have a high protein content relative to feed particles.

Wang et al. (1998) found that a synthetic dust particle, Tenox, was a superior adsorber of volatile fatty acids and p-cresol when compared to the feed/fecal particles. This suggests that the particle types that are airborne have a different affinity for the odourous gases. Indolic compounds were not adsorbed by the synthetic or the feed/fecal airborne particles.

Payeur et al. (2002a) found no relationship between dust concentrations and odour emissions in the experiment where they applied canola oil at a rate of 0 and 10 mL/m²/day for dust reduction. They also found that there was no relationship between odour emissions and protein content in the diet.

Pedersen (1993) found a correlation of 0.66 between animal activity and airborne dust concentration. His results suggested that the correlation would strengthen as the level of activity is better defined. Carbon dioxide and heat production and dust release show similar diurnal variation (Pedersen 1993; Pedersen and Takai 1997). During the non-active periods, ventilation of the animal house would be lowest, while during the day activity levels are highest and ventilation rates are the highest. Based on these results, Schauburger et al. (1999) concluded that odour release rates are not constant over the day. The diurnal variation of odour concentrations of the exhausted air can range up to a factor of 6 with the maximum value during the night and the minimum during the day. If dust is an important carrier of odour, then the diurnal

fluctuations in dust concentrations are an important part of predicting odour concentration and emission rate over a 24-h period.

8.2 Dust Control

Jacobson et al. (1999d) evaluated odour and gas reduction potential of soybean oil sprinkling for airborne dust control in a pig nursery. They used the dosage recommended by Zhang et al. (1996), which applied 40 mL/m² for the first 2 days, 20 mL/m² for the next 2 days and a 5 mL/m² “daily maintenance” level for the remaining days. The oil was sprinkled in the barn with a hand-held commercial paint sprayer. In their two trials, there was a significant reduction in their first trial. In the second trial, the outdoor temperature increased, causing higher ventilation rates. There appears to be less odour reduction during higher ventilation rates, which may have coincided with poor dunging behavior.

Feddes et al. (1999) used a similar oil dosage whereby one dosage was 60 mL/m²/week and the other dosage was 30 mL/m²/week. With the 60 mL/m²/week application, odour concentration was reduced by 20%, whereas the 30 mL/m²/week resulted in no reduction in odour emission rate. They also suggested that sprinkling oil on the floor surfaces only removes the odorous dust particles originating from the solid surface of the floor. Since 75% of the respirable dust was removed, a large amount of odours appear to be generated by the slatted area where little dust is generated due to the moist surfaces.

Godbout et al. (2000) described their experiment to reduce odour emissions by sprinkling canola oil. They applied 31 mL/m²/day that resulted in a 90% reduction in respirable dust, but did not report any odour emission data. Takai et al. (1993) used a mixture of water and rapeseed oil (5 – 30 mL/pig/day). Respirable dust levels were reduced by 76%, 54% and 52% for buildings housing piglets, young pigs and fattening pigs, respectively.

Bottcher et al. (2000) evaluated windbreak walls for tunnel ventilated livestock buildings. Windbreak walls were placed near exhaust fans to divert the exhaust air upwards. This effect promotes larger plumes of dust and odour at the source. Hoff et al. (1997b) evaluated biomass filters for reducing odorous dust emissions. Exhausted odorous air was forced through panels of biomass. They did obtain high dust and odour reductions.

Auvermann et al. (2001) reviewed the state of knowledge concerning the sources, emissions and control of particulate matter (PM) from confined animal feeding operations. An increase in slatted floor area may reduce PM emissions, especially with increased stocking density. The increased hoof action pushes the manure accumulations into the pits or flush gutters below rather than leaving it on the surface to dry and be re-suspended (Auvermann et al., 2001).

Suppressing the dust generation (source) appears to be the most effective option in reducing airborne dust concentrations. Many of the oil application techniques reduce airborne dust concentrations up to 80%. Other technologies deal with the dust particles while airborne. Mechanical cleaning systems include fibre filters and water or oil scrubbers. These units require large quantities of airflow, frequent maintenance and replacement of filters (Zhang, 1999). To remove the concentration by 50%, the equivalent ventilation rate of the building would need to be cleaned mechanically at 100% efficiency. For this reason, mechanically removal of airborne

dust is not an option. Electrical cleaning of the airspace is another option for dust removal. This might include ionization, electrostatic precipitation and ozonation (Zhang, 1999). Again, an effective system requires high initial and maintenance costs along with the inconvenience of static electricity charges on the housing equipment.

Concluding Remarks

Dust may act as an important odour carrier. Odour compounds attached to small dust particles stays longer in the air, thus having a greater downwind impact. Furthermore, many of the respirable dust particles are odourous because of their fecal origin.

Mechanical and electrical cleaning of the airspace is an expensive option. Suppressing the dust emissions at the source by some form of oil application is the most cost effective. The effectiveness of removing dust to removal of odour is not well known. Reducing odour intensity by 40% has a negligible impact on the human receptor. When assuming that 40% of the odour can be reduced (very optimistic), this reduction results in a minor change in the odour level perceived by the person smelling the odour. Reducing odour from 100 to 60 (40%) odour units is perceived as a 2 to 1.77 or an 11% change. Odour reduction must be substantial before the effectiveness can be sensed by the nose.

Technologies other than oil sprinkling have not been adopted by the industry due to input costs or effectiveness in large ventilated air spaces.

9. EMERGING TECHNOLOGIES IN SWINE ODOUR RESEARCH

9.1 Odour Measurement and Quantification

One of the greatest obstacles to the advancement of odour management is the difficulty of measuring odour itself. Several parameters are required to characterize an odour, as discussed in Section 1.. Olfactometers, the standard odour measurement instrument, are only capable of measuring the odour concentration. The electronic nose (e-nose) technology has the potential of measuring both quality and quantity of odour. An e-nose provides odour analysis through the use of multiple sensor arrays (more commonly known as electronic nose systems). The e-nose technology combines the principles of human olfaction with the ability to analyze and fingerprint odours. However, while the human nose has millions of sensors or receptors (Kephart and Mikesell, 2000) capable of detecting odour concentrations in the range of parts per trillion (Fenner and Stuetz, 1999), electronic noses are designed with between 4 and 50 sensors (Kephart and Mikesell, 2000; Gardner, 2002; Lewis, 2000; Hedderich, 1995) and in most devices, with sensitivities 100 to 1000 times less than the human nose (Kephart and Mikesell, 2000). Lewis (2000) reported a new type of electronic nose that can detect biogenic amines at concentrations as low as 10 parts per trillion within a few seconds.

Electronic noses have been developed to recognize and distinguish between odours from a variety of sources or, odours from similar sources (CLAQC, 2000; Kephart and Mikesell, 2000; Lewis, 2000; Matzger et al., 2000; Fenner and Stuetz, 1999; Misselbrook et al., 1997; Hedderich, R. 1995; Hamilton and Arogo, 1999). Most applications of these devices have been found in the food and beverage industry (Fenner and Stuetz, 1999; Misselbrook et al., 1997). E-noses have been used for the measurement of odour intensity and concentration of livestock odours by some researchers (Kephart and Mikesell, 2000; Matzger et al., 2000; Fenner and Stuetz, 1999; Misselbrook et al., 1997), but its application to field livestock odour measurement is at the research stage,

Misselbrook et al. (1997) reported a linear relationship between odour concentration of cattle slurry measured by olfactometry and the average response of sensors in an electronic nose. Qu et al. (2001) conducted a study to develop a correlation between the odour measurements of a commercially available electronic nose and odour concentrations measured with an olfactometer. Odour air samples were collected from four pig production sites. They reported that that well-trained electronic nose (with artificial neural network) could measure odour concentrations with about 20% mean error. Gralapp et al. (2001) compared odour measurements by an olfactometer, a GC/MS and an electronic nose. Odour samples were collected from swine finishing facilities. They found that electronic nose evaluation of odour was not strongly correlated to olfactometry measures ($r < 0.2$). However, the equation developed from the GC/MS analyses was capable of predicting the electronic nose response to odour. The results suggested that human panelist responses might be based on detection of compounds that were not well detected by the electronic nose.

A research team led by Dr. Nagle at North Carolina State University is developing an electronic nose for measuring livestock odours. A panel of human assessors characterizes the perception of swine odour and the results are used calibrate the electronic nose sensors. Dr. Nagle's e-nose is still in bench-top testing stages.

9.2 Technologies for Odour Control

Electrical Treatment of Manure

Bunce (2001) reported that electrolysis could oxidize odour-causing components of swine manure. He claimed that electrochemical remediation technologies offer several advantages in neutralizing the smell of manure compared to aeration, including relatively simple equipment and operation at ambient temperature and pressure.

Goodrich et al. (1996) reported a study on employing high-voltage electric pulses to modify the population of microorganisms which degrade stored manure. The objective of their study was to develop a pulsed electromagnetic device that would suppress the growth of microorganisms that produce noxious odours in swine manure. They reported that high-voltage electric pulses for short duration could inactivate more than 99.9% of microorganisms. In their laboratory study, they successfully inactivate the indicator microorganism by 4-log decrease of viable organisms. However, no direct effect on odour reduction was reported.

Oligolysis is an electro-chemical process that uses electrical power to help precipitate sulfide ions in swine slurry (Feddes et al., 1998). Electrodes are placed in the slurry and a voltage is applied across the electrodes, releasing ferrous ions into the slurry (Feddes et al., 1998). The ferrous ions then combine with sulfide ions to form an insoluble precipitate, reducing the amount of sulfide that could potentially form odourous hydrogen sulfide (Feddes et al., 1998). A recent study by Feddes et al. (1998) found that hydrogen sulfide levels were noticeably reduced (97% of free dissolved sulfide), but odour levels were not impacted significantly.

Ultrasound

The technology is primarily focuses on hydrogen sulfide reduction. Acoustic waves penetrate manure and break chemical bonds, as well as triggering chemical reactions (Anonymous, 2002). The technology was developed by researchers from the University of Iowa, and is currently being tested in a large swine barn.

Ozonation

Ozonation has been used to disinfect drinking water. In the ozonation process, ozone deactivates organisms by oxidizing their cell walls and cytoplasmic membranes (Wu et al., 1999). In manure treatment, ozone oxidizes metabolites produced during anaerobic storage, thus reducing odour (Wu et al., 1999). In a study by Wu et al. (1999), ozone-enriched oxygen was bubbled into stirred swine slurry. Odour was tested by panelists using a three-point scale (acceptable, unacceptable and extremely unacceptable). It was found that ozonation was effective in reducing odour.

Non-Thermal Plasma

Non-thermal plasma is based on a concept similar to that of ozonation. With non-thermal plasma, gaseous molecules are converted into non-toxic molecules through reaction with reactive species (UMOT, 2002). The reactive species are formed by discharging electrical energy into gases, which creates electrons that react with background gases (UMOT, 2002). Non-thermal

plasma appears to reduce individual gas components of odour, rather than the entire odourous mixture. This technology is still at the research stage.

Land Application Additives

It is well-known that the method of land application can have a significant impact on odour emission. Researchers are experimenting with additives to reduce the odour from land application. Rosenfeld and Henry (2000) did a study comparing land application of sewage sludge to land application of a mixture of wood ash and sewage sludge. The study was performed on a lab-scale basis, and it was determined that the mixture of wood ash and sewage sludge produced significantly less odour than sewage sludge alone. Although the initial results were promising, a full-scale study is needed to get an accurate measure of the usefulness of this technology.

Thermochemical Conversion

He et al. (2000a and 2000b) developed a technique — thermochemical conversion (TCC), for treating manure. Manure slurry is treated in an air-tight reactor under high temperatures (275 to 350°C) and high pressures (5.5 to 18 MPa). Under this high-temperature and high-pressure condition, no microorganism in the manure survives and the organic matter in the manure is converted into oil that can be used as fuel with an estimated heating value of 34,940 kJ/kg. The reaction can be completed within two minutes. Carbon dioxide (CO₂) was reported the only gaseous by-product of the process. TCC may completely eliminate the original manure odour, but it releases an odour smelled like tar (He, 2002). The strength and offenses of tar-like odour is unavailable. This technology is currently at the bench scale stage.

Freezing

Alberta Agriculture, Food and Rural Development (AAFRD) (2000) reported a Canadian technology for swine manure treatment — freezing manure, known as the snowfluent technique. Manure is treated by spraying it into cold air under high pressure and freezing it into ice crystals. The ice crystals fall on the ground as artificial snowfall. As snowpack melts, small volume of highly concentrated meltwater, large volume of relatively dilute meltwater, and a highly concentrated, light weight, solid residue are obtained. The concentrated meltwater and solid residues can be applied to the agricultural land, with significant reduction in transportation and spreading cost. The large volume of dilute meltwater can be re-used in the barns for manure flushing. It was reported that odours from the snowpack were much less than from the manure lagoon and were minimal in the meltwater. The solid residue left after runoff had noticeably less odour than conventionally treated liquid or solid manure. The mechanism of action is that freezing ruptures the cell-wall of odour causing microorganisms.

The cost of the snowfluent treatment was reported as \$26,705 for 2.8 million gallons of manure (AAFRD, 2000). Based on this figure, the cost of treating manure in finish operations is estimated as between \$1.3 and \$1.6 per marketed pig.

9.3 Researchers Working on Odour Management Technologies in Canada and US

University of Alberta and AAFRD

Principal Researchers: J. Feddes, I. Edeogu, G. Clark
Research areas: Olfactometry measurement of odour; electronic noses for odour measurement; biofiltration; dispersion modeling of odour; dust control; barn ventilation.

University of Manitoba

Principal Researchers: Q. Zhang, D.D. Mann; Y. Chen, R. York, J. House, M. Nyachoti
Research areas: Olfactometry measurement of odour; electronic noses for odour measurement; biofiltration; dispersion modeling of odour; swatch technique for odour sampling; pit additive evaluation; feeding strategies; manure injection.

McGill University

Principal Researchers: S. Barrington
Research areas: Olfactometry measurement of odour; manure additives; building ventilation.

Prairie Swine Center and University of Saskatchewan

Principal Researchers: S. Lemay
Research areas: Building ventilation; pit additive evaluation; ammonia emission.

University of Minnesota

Principal Researchers: L. Jacobson; K. Janni, D. Schmidt, R. Nicolai, J. Zhu
Research areas: Olfactometry measurement of odour; odour emissions, biofilters, non-thermal plasma treatment of manure; manure additives; solids separation; set-back distance; manure storage covers; dispersion of odour.

Purdue University

Principal Researchers: A. Heber, J. Ni
Research areas: Olfactometry measurement of odour; odour emissions, manure additives; set-back distance.

Oregon State University

Principal Researchers: J.R. Miner
Research areas: Odour control strategies for animal production facilities; covers for manure storage; odour measurement.

Iowa State University

Principal Researchers: D. Bundy, J. Lorimor, S. Hoff
Research areas: Olfactometry measurement of odour; manure additives; odour dispersion.

University of Illinois

Principal Researchers:

Y. Zhang

Research areas:

Odour measurement; odour reduction (diet, animal housing); manure treatment; odour source reduction from manure storage; odour reduction from land application activity; site selection; odour transport.

North Carolina State University/Animal and Poultry Waste Management Center

Principal Researchers:

C. M. Williams, R.W. Bottcher, T. Nagle, J. J. Classen

Research areas:

Manure additives; odour measurement; electronic noses

Duke University/Taste and Smell Lab

Principal Researchers:

S.S. Schiffman

Research areas:

Sensory evaluation of odours, electronic noses; effects of odour on humans

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of Manitoba Livestock Manure Management Initiative Inc (MLMMI). The technical assistance of X. Zhou, B. Knopp, and M. Nakonechny was invaluable to this study.

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Table 1. Odour compounds with low detection threshold identified in animal waste (O’Neil and Philips, 1992)

Compounds	Lowest Detection Threshold, mg/m ³
methanethiol	0.000003
2-propanethiol	0.000025
3-propene-1-thiol	0.000005
2,3-butanedione	0.000007
phenylethanoic (phenylacetic) acid	0.00003
ethanethiol	0.000043
4-methylphenol (p-cresol)	0.00005
Hydrogen sulfide	0.0001
1-octene-3-one	0.0001
benzenethiol	0.00014
2,4-decadienal	0.00018
3-methylbutanoic acid	0.0002
2,6-dimethylphenol	0.0002
3-methylphenol	0.00022
2,4-nonadienal	0.00025
decanal	0.00025
trimethylamine	0.00026
actonoic acid	0.0003
nonanal	0.0003
methylthioethen	0.0003
ethyldithioethanol	0.0003
2-phenylethanol	0.00035
3-methylindole (skatole)	0.00035
butanoic acid	0.0004
2-methylphenol	0.0004
2-butene-1-thiol	0.00043
2-nonenal	0.0005
indole	0.0006
Pentanoic acid	0.0008
butanal	0.00084

Table 2. Summary of odour emission rates from gestation facilities

Manure Collection	Ventilation	Odour Emission	Rreference
deep pit	mechanical	3-20 OU.m ³ /s/ m ²	Zhu et. al., 2000a
deep pit	curtain wall, mechanical	2.3 OU/s/m ² (avg.)	Jacobson et. al., 1999b
pull plug, deep pit	natural and mechanical	12.6 OU.m ³ /s/ m ² (avg.)	Wood et. al., 2001
pull plug	mechanical	3.6 OU/s/m ² (avg.)	Jacobson et. al., 1999b
shallow pit (pull plug)	mechanical	6-18 OU/s/m ²	Zhang et. al., 2001a

Table 3. Summary of odour emission rates from farrowing facilities

Manure Collection	Ventilation	Odour Emission	Rreference
deep pit	mechanical	5-12 OU.m ³ /s/ m ²	Zhu et. al., 2000a
pull plug, deep pit	mechanical	4.80 OU.m ³ /s/ m ² (avg.)	Wood et. al., 2001
pull plug	mechanical	0.4 OU/s/m ² (avg.)	Jacobson et. al., 1999b
shallow pit (pull plug)	mechanical	7-62 OU/s/m ²	Zhang et. al., 2001a
pull plug	mechanical	1.3 OU/s/m ² (avg.)	Jacobson et. al., 1999b
pull plug	natural	5.6 - 44.0 OU.m ³ /s per SPU	Smith et. al., 1999
scrape	mechanical	29.8 OU/s/m ² (avg.)	Jacobson et. al., 1999b
unknown	mechanical	35.27 OU.m ³ /s per pig (avg.)	Verdoes and Ogink, 1997

Table 4. Summary of odour emission rates from nursery facilities

Manure Collection	Ventilation	Odour Emission	Rreference
deep pit	mechanical	1.8 OU/s/m ² (avg.)	Jacobson et. al., 1999b
deep pit	mechanical	2.1 OU/s-m ² (avg.)	Lim et. al., 1999
deep pit	mechanical	7-50 OU.m ³ /s/ m ²	Zhu et. al., 2000a
pull plug, deep pit	natural and mechanical	8.66 OU.m ³ /s/m ² (avg.)	Wood et. al., 2001
shallow pit	mechanical	11-36 OU/s/m ²	Zhang et. al., 2001a
pull plug	mechanical	0.1 OU/s/m ² (avg.)	Jacobson et. al., 1999b
deep litter	mechanical	162-5734 OU/m ³	Pattison, 1999
unknown	mechanical	4.95 OU.m ³ /s per pig (avg.)	Verdoes and Ogink, 1997

Table 5. Summary of odour emission rates from swine finishing facilities

Manure Collection	Ventilation	Odour Emission	Rreference
deep pit	mechanical	13.9 OU/s/m ² (avg.)	Jacobson et. al., 1999b
deep pit	mechanical	3 – 15 OU.m ³ /s/ m ²	Zhu et. al., 2000a
deep pit	curtain, mechanical	2.5 OU/s/m ² (avg.)	Jacobson et. al., 1999b
deep pit	natural and mechanical	3990 OU/m ³ (geo. mean)	Heber et. al., 1998a
deep pit	natural	3-11 OU.m ³ /s/ m ²	Zhu et. al., 2000a
shallow pit	mechanical	11-21 OU/s/m ²	Zhang et. al., 2001a
pull plug	natural	1.3 – 45.5 OU.m ³ /s per SPU	Smith et. al., 1999
deep litter	natural	7 – 42 OU.m ³ /s per pig	Payne, 1997
unknown	mechanical	16- 495 OU/s/LU (LU= 500 kg)	Hartung et. al., 1998
flush, pull plug, scrape, deep pit	natural and mechanical	6.86 OU.m ³ /s/ m ² (avg.)	Wood et. al., 2001
unknown	mechanical	14.21 OU/s (avg.)	Verdoes and Ogink, 1997
unknown	mechanical	10.1 OU/s (avg.)	Verdoes and Ogink, 1997

Table 6. Odour emission rates from manure storage units

Type of operation	Number of Animals	Storage Type	Odour Emission (OU/s/m ²)	Reference
gestation, farrow and nursery	100	earthen basin	3.1	Jacobson et al., 1999b
nursery and finishing	1920	earthen basin	17.6	Jacobson et al., 1999b
gestation and farrow	286	below ground tank	12.8	Jacobson et al., 1999b
gestation, farrow and nursery	160	below ground tank	51.3	Jacobson et al., 1999b
farrow to finish	430	earthen basin	4.4	Jacobson et al., 1999b
finish	600	above ground tank	19.4	Jacobson et al., 1999b
farrow to finish	684	earthen basin	6.8	Jacobson et al., 1999b
nursery	5500	above ground tank	0.1	Jacobson et al., 1999b
nursery and finishing	6000	earthen basin	3.8	Jacobson et al., 1999b
gestation, farrow and nursery	4250	earthen basin	2.2	Jacobson et al., 1999b
Farrow to nursery	20000	earthen basin	6.2	Heber et al. 2000
Farrow to nursery	2900	earthen basin	2.9	Heber et al. 2000

Table 7. Odour concentration at different times after the application of swine manure to grassland (Pain et al., 1991)

Application Rate, m ³ /ha	14.0	15.6
Total solids, %	15.7	13.6
Total VFA, mg/L	4356	3354
Time after Application	Odour Concentration, OU/m ³	
1 hr	1076 (311.1)	299 (52.5)
6 hr	91 (30.9)	148 (28.8)
12 hr	97 (16.7)	177 (44.0)
24 hr	106 (30.2)	115 (13.5)
36 hr	64 (17.3)	126 (20.9)
48 hr	60 (5.8)	-
60 hr	34 (17.8)	-

() standard error

Table 8. Odour concentration at different times after the application of swine manure to arable (Pain et al., 1991)

Application rate, m ³ /ha	Total Solids	Time after Incorporation	Odour Concentration, OU/m ³			
			Plough	Rotary Harrow	Tines	Control
64	8.9%	Immediate	681	1133	1586	1049
64	10.9%	3 hrs	994	1178	1026	1027
61	8.8%	6 hrs	583	513	578	626

Table 9. Frequency of odour rank measurements (VanDevender, 1999)

Distance, miles	Non-detectable	Detectable but Non-Offensive	Mildly Offensive	Strongly Offensive
0 to 0.1	41%	35%	21%	3%
0.1 to 0.2	52%	36%	11%	1%
0.2 to 0.3	78%	19%	3%	0%
0.3 to 0.4	100%	0%	0%	0%
0.4 to 0.5	89%	5%	1%	1%
0.5 to 1	14%	86%	0%	0%

Table 10. Estimated reduction in nitrogen excretion by growing-finishing pigs fed protein-reduced corn-soybean meal-based diets balance for amino acids using synthetic amino acids (de Lange et al., 1999)

Ingredients (%)	Corn-soybean No Added Amino acid	Corn-soybean + Lysine	Corn-soybean + Lysine, Threonine, and Tryptophan
Corn	75.85	79.38	83.28
Soybean meal	21.15	17.50	13.40
Premix	3.00	3.00	3.00
Lysine. HCl	-	0.12	0.25
Threonine	-	-	0.06
Tryptophan	-	-	0.02
Total protein in diet (%)	16.5	15.2	13.7
Reduction in N excretion (%)*		-11	-24
Estimated ingredient cost (\$/tonne)	220.6	218.7	239.1

* relative to the corn-soybean meal diet with no added amino acids.

Table 11. The degree of certainty that manure additive products were successful in decreasing odour, H₂S, and NH₃ (Heber et al., 2001).

Product Name	Odour Reduction (Certainty)	Hydrogen Sulfide Reduction (Certainty)	Ammonia Reduction (Certainty)
Agri-Clean			
Agricycle™			3% (75%)
AgriKlenz Plus			6% (95%)
Alken Clear-Flo®	27% (75%)	47% (95%)	
AWL-80			10% (95%)
Biocharge Dry		37% (95%)	7% (95%)
Biological Manure Treatment	25% (75%)		5% (95%)
BIO-MAX Biosystem			
Conserve-N			
Digest 54 Plus			2% (75%)
EM Waste Treatment			15% (95%)
GT-1000OC & BC-2000AF		34% (95%)	
INHIBODOUR®		36% (95%)	
KOPROS®			
Krystal Air™			7% (95%)
Lagoon Aid			
Manure Management Plus™			6% (95%)
MBA-S		19% (75%)	3% (75%)
MICROBE-LIFT			
MUNOX®			
M2 Acid Buffer			
Nature's Key Pit & Lagoon			
N-P50			3% (75%)
OdorKlenz BMT			
Peroxy Odor Control			3% (95%)
Pit Remedy			
PS1		14% (75%)	
Roebic Manure Liquefier			
Roebic Odour Eliminator		23% (75%)	
SEPTI-SOL			
Solmar AW-509			
Super Microbial Odour Control	32% (75%)	37% (95%)	
UC-40™ Microbe Formula		15% (75%)	
X12			
Zymplex	28% (75%)	27% (95%)	

Table 12. Comparison of covers for manure storage (Cetac-West, 2002)

Type	Material	Strength	Weakness	Cost
Solid Emission Covers	Steel, concrete or wood	Almost complete odour control Long lasting	Expensive	Concrete cover: \$50,000
Flexible Emission Covers	A tarp and anchoring devices Dome style covers also require a low pressure blower	Excellent odour control – 95% Long lasting – 10 to 15 years Easy to remove	Expensive Some maintenance required	\$10,000 plus \$200/year in operating costs
Biocovers (Straw)	Quality barley straw works the best Blown over storage using a forage harvester Peat moss can be added to improve nutrient intake in the field	Inexpensive Effective odour control	Straw tends to sink requiring multiple applications Straw may interfere with pumping equipment	150 mm barley straw @ \$1.00/square bale = \$0.23/m ² per application
Supported Biocovers	Polystyrene pellets may be applied prior to the barley Oil can be added to the straw as well	Effective odour control Floatation measures may reduce straw applications Polystyrene pellets can be collected and reused	Recovery of floatation devices can be difficult More expensive alternative	25 mm polystyrene + 125 mm barley straw = \$2.45/m ²

Table 13. Performance of mechanical separators on swine manure separation (modified from Zhang and Westerman, 1997)

Separation Equipment	Screen Opening (mm)	TS in raw Manure (%)	Separation efficiency (%)					TS in Separated Solids (%)
			TS	VS	COD	TKN	TP	
Stationary screen	1.5	0.2-0.7	9	—	24	—	—	6
	1.0	0.2-0.7	35	—	69	—	—	9
	1.0	1.0-4.5	6-31	5-38	0-32	3-6	2-12	5
Vibrating screen	1.7	1.5	3	—	6	—	—	17
	0.841	1.5-2.9	10	—	1-14	—	—	18-19
	0.516	1.8	27	—	24	—	—	20
	0.516	3.6	21-52	25-55	17-49	5-32	17-34	9-17
	0.39	0.2-0.7	22	28	16	—	—	16
	0.44	1-4.5	15-25	18-38	13-26	2-5	1-15	13
	0.104	3.6	50-67	54-70	48-59	33-51	34-59	2-8
Rotating screen	0.75	2.5-4.12	4-8	—	4	—	—	16-17
	0.8	1-4.5	5-24	9-31	2-19	5-11	3-19	12
Belt press	0.1	3-8	47-59	—	39-40	32-35	18-21	14-18
Centrifuge	—	1-7.5	15-61	18-65	7.8-44	3.4-32	58-68	16-27

Table 14. Comparison of general biofilter media types (Easter and Okonak, 1999, except from Nicolai 1998 where noted*)

Parameter	Peat	Soil	Wood Chips (coarse)	Wood Bark and Compost	Straw	Activated Carbon	Ceramic, Plastic
Bearing strength		High		Low		Med	High
Air permeability	Med*	Low	High*	Med	High*	Med	High
Backpressure (kPa/m depth)		1.6 to 4.9		0.8		0.4	0.4
PH buffering		High		Low		None	None
Nutrient supply	High*	High	Med*	High	Low*	None	None
Hydrophilic (dry)		Yes		No		No	Yes
Moisture capacity	High*	High*	Med*	High*	Med*		
Footprint required (m ² /L/s)		0.12		0.06		0.04	0.02
Bed lifetime (year)		10 to 30		2 to 5		5	10 to 30

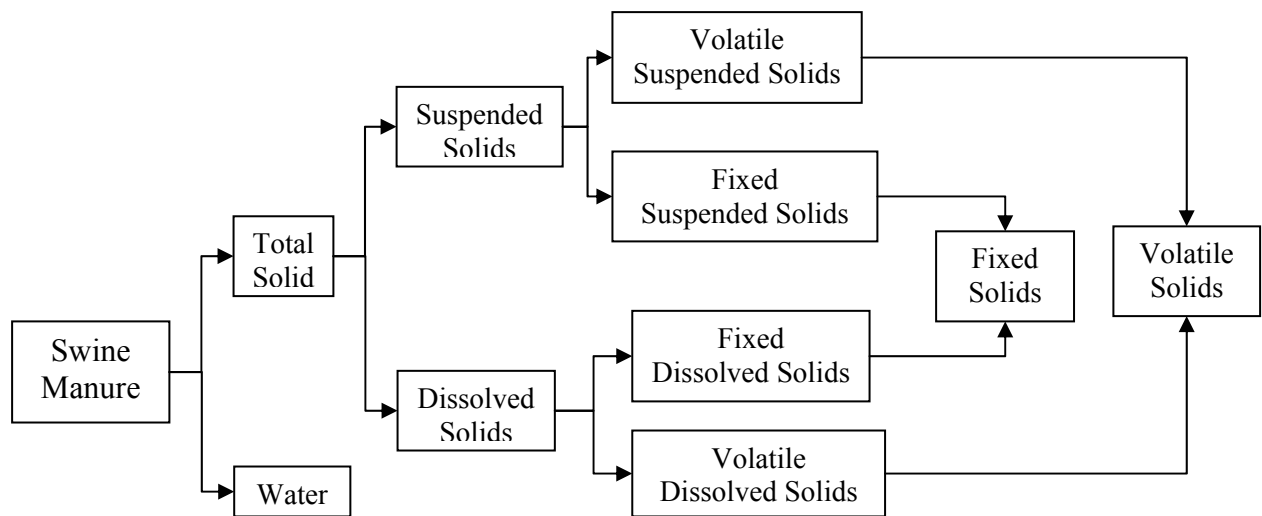


Figure 1. Composition of liquid swine manure

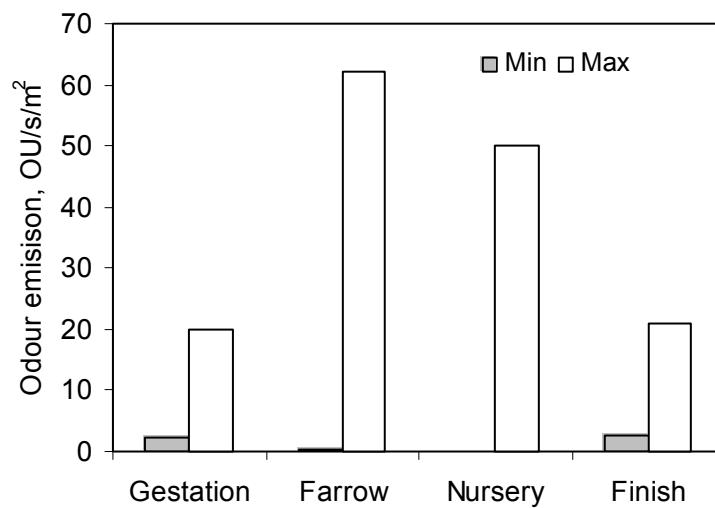


Figure 2. Summary of odour emission rates from swine buildings

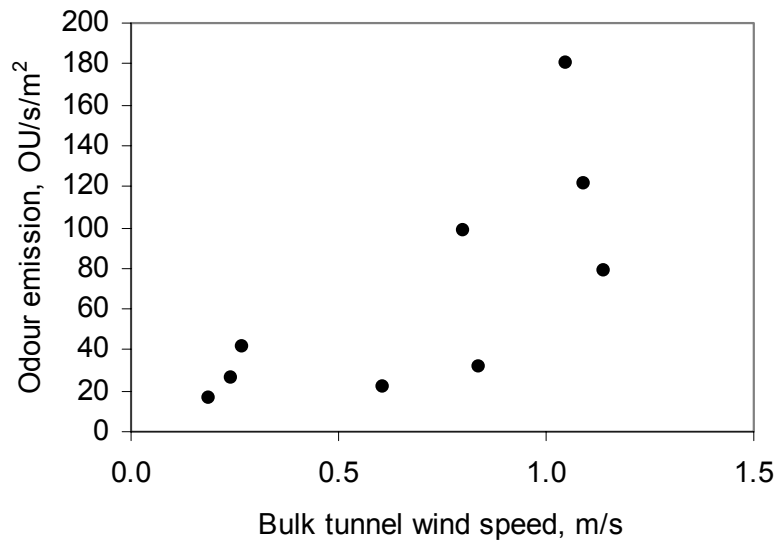


Figure 3. Effect of air velocity (wind speed) in wind tunnel on measurement of emission rates from manure surface (based on data from Schmidt et al., 1999a)

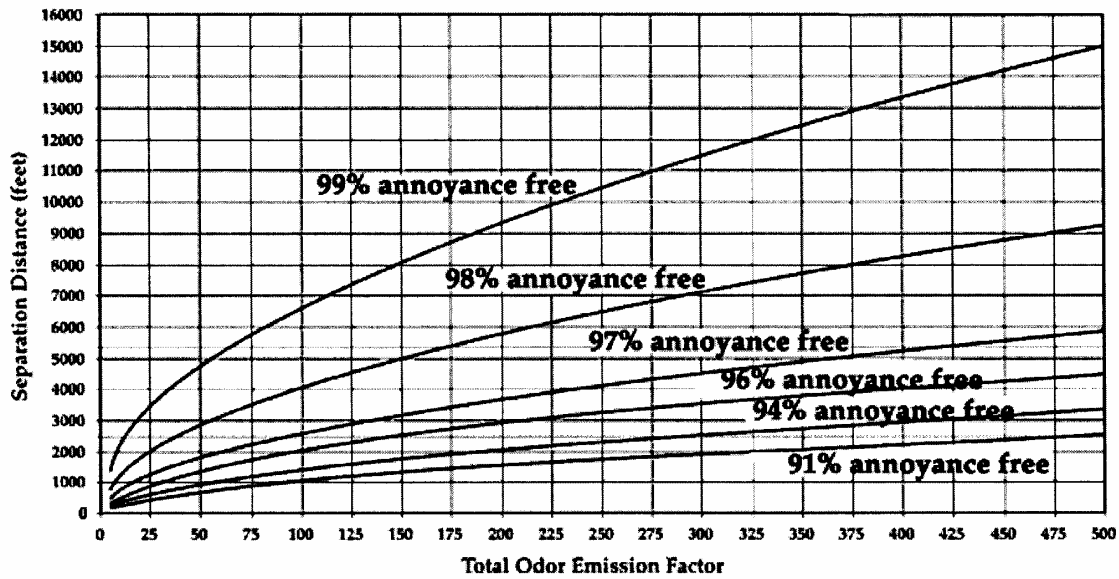


Figure 4. Estimated setback distances from farms at different odour annoyance-free frequency requirements, leeward of the prevailing wind from animal operations (Jacobson et al., 2001)

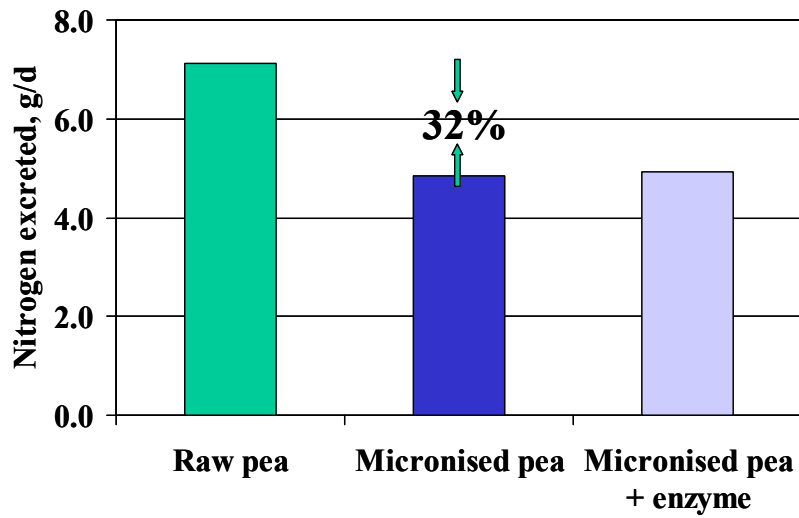


Figure 5. Effect of incorporating micronized peas with or without enzyme supplementation in grower diets on fecal nitrogen excretion (Nyachoti et al., 2002)

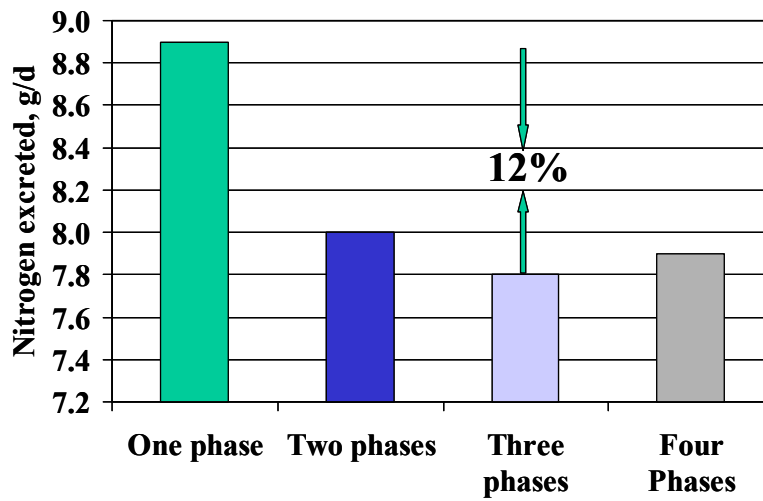


Figure 6. Effect of phase feeding on nitrogen excretion in finishing pigs (Lee et al., 2000a)

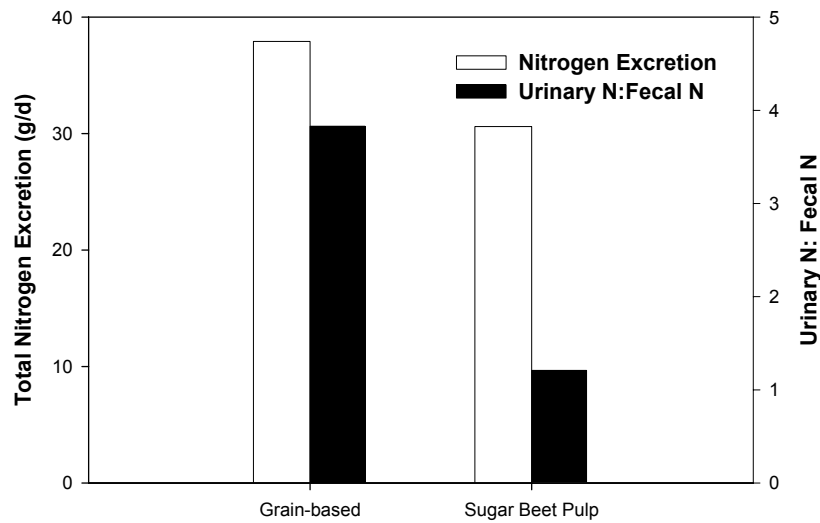


Figure 7. The effect of adding 30% sugar beet pulp, as a source of NSP, to swine diets on total nitrogen excretion and the ratio of nitrogen in urine relative to feces (Canh et al. 1997)

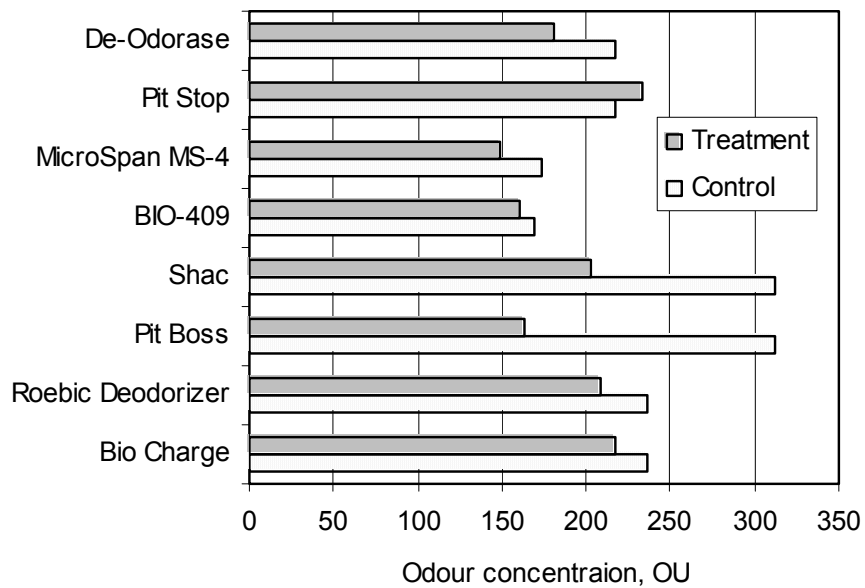


Figure 8. Odour level changes comparing treated and untreated barns. Odour samples were taken in the center alley approximately three feet off the slatted floor (Johnson, 1997).

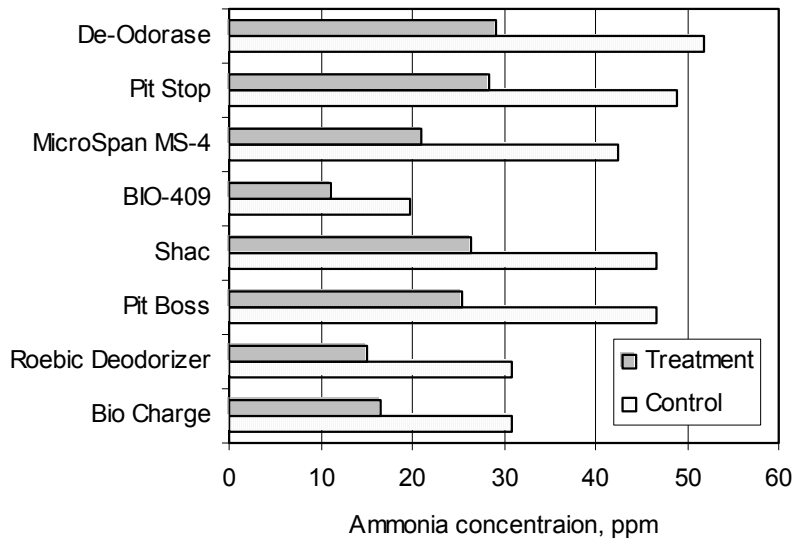


Figure 9. Ammonia level changes comparing treated and untreated barns. Air samples were taken in the center alley approximately three feet off the slatted floor (Johnson, 1997).