Odour emissions from anaerobic piggery ponds. 2: Improving estimates of emission rate through recognition of spatial variability

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Abstract

Odour emission rates were measured for seven different anaerobic ponds treating piggery wastes at six to nine discrete locations across the surface of each pond on each sampling occasion over a thirteen month period. Significant variability in emission rates were observed for each pond. Measurement of a number of water quality variables in pond liquor samples collected at the same time and from the same locations as the odour samples indicated that the composition of the pond liquor was also variable. The results indicated that spatial variability was a real phenomenon and could have a significant impact on odour assessment practices. Considerably more odour samples would be required to characterise pond emissions than currently recommended by most practitioners, or regulatory agencies.

Keywords: Anaerobic; Pig; Swine; Pond; Spatial

1. Introduction

Odour emissions continue to be a major factor limiting the expansion of intensive livestock operations such as piggeries. Anaerobic ponds are extensively used for the storage and treatment of piggery wastes. These ponds were previously identified as the major source of odour from Australian piggeries (Dalton et al., 1997; Smith et al., 1999a,b). Strategies for reducing odour emissions from simple pond treatment systems are limited. There is little opportunity to optimise treatment by aerating, mixing, or storing the waste under specific oxygen-concentration conditions. These treatment strategies are widely used at municipal wastewater treatment facilities to optimise waste treatment and minimise off-site odour impacts. Impermeable pond covers effectively reduce emissions, but are too expensive for most piggeries. Permeable covers are also effective, but the long-term viability of this emerging technology is still unknown (Hudson et al., 2002, 2006). Odour emissions from anaerobic ponds have been reduced using various strategies, including removal of solid material prior to pond treatment (Dugba and Zhang, 1999) and dietary manipulation (Hobbs et al., 1996). The long-term efficacy of these approaches has not been demonstrated. In this context, pond treatment systems are likely to continue to be integral components of the waste treatment system and therefore significant potential sources of odour.

Traditionally, odour impacts from intensive livestock facilities have been managed by ensuring adequate separation from nearby residents. Various methods have been used to determine the buffer distance required, including formulae that consider the size of the operation, the demography of the surrounding area, the terrain and other site-specific factors (Skerman, 2000). Another approach is the use of dispersion modelling, which tries to estimate the dilution of odour between its source and the receptor. These models also use site-specific information such as the presence of vegetative buffers, the topography and the local meteorology. When determining a separation distance, information regarding the areal extent of an odour source is combined with an odour emission rate to estimate an odour flux, which is used
to estimate the likely odour impact. Whatever the approach, it is essential to reliably estimate the rate at which odours are emitted from the source.

In many instances, estimates of emission rates from anaerobic ponds are based on a limited number of samples. For example, Smith et al. (1999a) surveyed nine piggery ponds. One to seven discrete odour samples were collected from the pond surface using a wind tunnel or immediately downwind of the pond. The number of samples collected is usually limited by the high cost of analysis using dynamic olfactometry and the difficulty of collecting samples from ponds. The extent of much of the data currently used to define emission rate values was, therefore, determined more by financial constraints rather than scientific considerations.

Consideration of the entire assessment process and use of these data raises a number of issues. Odour samples are typically collected using a wind tunnel or an emission chamber (Jiang and Kaye, 1996; Sneath and Clarkson, 2000). While these devices provide stable and reproducible conditions, they cover a small portion of the total area of an emitting surface (Gholson et al., 1989), so the representativeness of the odour sample is questionable. Placement of the collection device also raises questions. Should it be operated near the bank of the storage basin for convenience but where the depth of the liquor is least, or should it be where the liquor depth is greatest? Should odour samples be collected close to where waste is discharged, or will this introduce bias? Should replicate samples be collected from a single point, or should single samples be collected from several points, or should replicate samples be collected from several points? The aim of this work was to demonstrate that spatial variability had been under-recognised in previous emission measurements, which implied that previous investigations may not have provided representative data.

2. Methods

The selection of study locations and techniques for odour sample collection and assessment were described in detail in Part 1 (Hudson et al., in press). Briefly, odour samples were collected from the surface of seven anaerobic ponds treating piggery wastes over a thirteen month period. These ponds were selected to represent waste treatment practices typical of south-eastern Queensland. Single odour samples were collected from the surface of the ponds from six to nine locations according to a regular array on each sampling occasion. A wind tunnel was used to collect all the odour samples. Each sample took approximately 15 min to collect. The interval between sample collections was approximately 30 min. The period of time for collection of all samples was therefore between about three and 5 h.

Odour samples were analysed using dynamic olfactometry. Odour concentration data were combined with data describing wind tunnel conditions to generate odour emission rate values. Composite samples of liquor collected from a number of points on the surface of the pond were analysed for a range of water quality variables. During two sampling events, discrete samples of pond liquor were collected from the pond immediately adjacent to the wind tunnel while the odour samples were being collected. These liquor samples were submitted to the laboratory for analysis of the same variables as the pooled samples.

2.1. Statistical analysis

Data were analysed using the statistical package Genstat v8 for Windows (Lawes Agricultural Trust, 2005), which was also used to prepare a box and whisker plot (Fig. 1). The box represents the interquartile range of values for the variate, with the line within each box indicating the median value. The whiskers extend to the minimum and maximum values for each variate.

3. Results and discussion

Pond odour emission rates are summarised on a seasonal basis for all ponds in Table 1. Emission rates varied considerably between points on individual ponds, between different ponds and between sample days for individual ponds in the same week, or between seasons. Variation in odour emission rates was evident for each pond during each sampling day, during each sampling week and during each season. Mean odour emission rate decreased from day one to day two on nine occasions, while it increased on seven occasions. On one occasion, the mean odour emission rate on day one and day two was the same, while no conclusion could be made on the remaining day because equipment failure prevented sample collection.

A sample point observed to provide the highest odour emission rate on day one rarely corresponded with the point having highest odour emission rate on day two of the same sampling week. Results for pond B also indicated
that the mean odour emission rate could be quite different for a pond within the same sampling season, even when the time difference between sample dates was less than two months. These observations might be attributed to spatial and temporal variability. To confirm that spatial variability was a real phenomenon, however, other sources of variability needed to be excluded. These included random and systematic errors in the sample collection process, as well as errors arising from the actual odour assessment (dynamic olfactometry). While errors from these sources were minimised through strict adherence to standard operating practices and the Standard, variability arising from olfactometry was difficult to quantify. This arose from the sampling design, which required collection of discrete samples from all sample points. No replicate samples were collected and analysed. This limited our ability to distinguish between variability in measured values arising from either the sampling activity or from the measurement technique itself. Two methods were used to quantify errors arising from these potential sources of error and to then determine whether the variability observed reflected true differences in emission rate.

### 3.1. Indirect assessment of variability

This technique was described by Galvin et al. (2003), who noted that a one-way ANOVA test was unable to detect significant differences between emission rates measured for a given pond on two sampling days or between seasons. The statistical power of the test was very low (20%), and this was attributed to the absence of sample replication. Consideration of the repeatability criterion for an individual olfactometer provided an insight into the variability of the measurement technique. On-going measurement of the variability of the olfactometer indicated that the repeatability criterion was 0.37. This was considerably smaller than the value proposed by Australian Standard 4.323 for a competent facility (0.477). Use
of the measured repeatability criterion enabled confidence limits to be calculated and applied to the measured emission rate data. These confidence limits are shown in Table 1 together with average, minimum and maximum emission rate values for each pond by season. While these limits were shown as emission rate values, they were actually determined using the original odour concentration results, from which the emission rates were calculated.

These results implied that where the odour emission rate value for an individual point on a pond fell outside the olfactometry upper and lower bounds (95% percentile confidence interval), the difference observed was due to variability arising from the actual emission rate, sampling, or sample handling processes and not the olfactometry process. An assessment of the data summarised in Table 1 showed that a significant number of emission rate estimates fell outside these predicted limits. This implied that spatial variability was a real phenomenon.

3.2. Direct assessment of variability

The variability due to the measurement process was quantified using the response of the odour assessment panel to n-butanol presentations. Presentation of n-butanol at a number of known concentrations is used to standardise the panellist responses during each measurement session. The range of average concentration values at which the panel detects the reference gas provides a method to assess variability due to olfactometry (instrument plus panel member variability). n-Butanol concentration values corresponding to the time period over which the replicated samples were analysed were used to estimate olfactometry variability.

A direct assessment of the contribution of the olfactometry to the measured emission rates was made using replicated data derived from another research project (Hudson et al., 2006). A series of duplicate odour samples had been collected from sample point 5 of the pond at piggy B. The paired data derived from this point were separated and described as 5A and 5B respectively. Calculation and comparison of the variability between these two sets of data enabled a direct assessment of the likely variability due to the emission processes.

The raw and log-transformed concentration data are summarised in Table 2 (n-butanol data) and Table 3 (replicate emission rate data). Variance ratio tests indicated greater variance in the pond odour sample results than in the n-butanol data. No significant difference existed between the variance values of the pairs of odour samples using either transformed or untransformed data. In contrast, however, there was a highly significant difference between the variance values of the log-transformed odour and n-butanol concentration data ($p = 0.00044$). These results indicated that additional variance could be attributed to the nine measurements of pond odour emission rates than could be explained by the variance of the olfactometry process alone. This confirmed that it was correct to attribute the observed apparent differences in pond emission rates to the emission process, and not the olfactometry. While this information excluded olfactometry as the source of the variability, it did not indicate the cause of variability observed for the pond emission rate data.

3.2.1. Assessment of variance components for each pond

Having confirmed that the variability observed for the pond emission rate data was not caused by olfactometry, the data were then assessed to identify the importance of other factors. The odour emission rate data were log transformed and analysed using Genstat procedures to identify the relative importance of factors such as sample point, season and day of sampling to the observed variance. The results in Table 4 showed that most of the variance was attributable to the residual variation (Point * Season * Day), with the next major contributor being season (Season * Day). With the exception of Pond C (sample point) and Pond E (season), there appeared to be little variation across the points after accounting for the other effects.

These results indicated that additional data were required if the cause of the variability in emission rate was to be determined with more certainty. Factors such as the physical and chemical status of the pond liquor,
environmental factors external to the pond, actions by the operators of the piggeries would all presumably require investigation. This information should be considered for future investigations of this nature.

### 3.2.2. Comparison of odour emission rates between individual sample points

As noted in Section 3.2, while point-to-point variability in odour emission rate was greater than variability in olfactometer assessment, little could be deduced regarding differences in emission rate between points on the same pond with the exception of pond C. Figs. 1 and 2 rate data for pond C by point or distance from waste discharge respectively. The box-and-whisker plot (Fig. 1) indicated obvious difference in emission rate between some points. Consideration of the shape of pond C provided some insight regarding the differences observed. As a long, narrow pond it was quite different to the other ponds studied. The length-to-width ratio for pond C was 3.8, while for the other ponds the ratio was 1.05–1.45. While Fig. 2 confirmed that there was no relationship between odour emission rate and distance from waste discharge point, it implied that the emission of odour from ponds was a complex process, influenced by a number of currently unknown variables.

### 3.3. Factors influencing odour emission rates

The theory describing the mass transfer of a volatile substance between a liquid and the overlying atmosphere suggests that a number of additional factors should be considered. The temperature of the liquid to some extent determines the kinetics of processes within the liquid, such as diffusion of odorants from the underlying liquor to the surface, from which transfer actually takes place (Schwarzenbach et al., 2003). It has also been established that emission increases with wind speed (Gillis and Miller, 2000). The wind speed above the liquid will determine the thickness of the surface layer through which an odorant must diffuse before other, more active processes occur, such as advection and dispersion. The concentration difference between the liquid and air above the liquid provides a chemical driving force, with direct implication for processes such as diffusion (Tchobanoglous et al., 2003). Finally, the chemical environment in the liquid has a direct bearing on the concentrations of substances that exist in ionised or electrically neutral form. The importance of pH in determining the relative proportions of NH₃ and NH₄⁺ and H₂S and HS⁻ or HS²⁻ in aqueous solution are examples in point. The importance of pH in determining the emission rate of individual components of odorous

![Fig. 2. Relationship between odour emission rate and distance from waste discharge point for pond C.](image-url)
air was confirmed for hydrogen sulphide (Paing et al., 2002) and ammonia (Aneja et al., 2001). Jiang and Kaye (1996) discussed the relationship between rates of emission of volatile substances and Henry Law constants.

In the current work, limited resources were available to consider the impact of these factors. For example, the temperatures of the liquor and the air passing through the wind tunnel were not measured at the time of sampling. Water quality samples were collected from the pond on each sample day, but these were composite samples derived from a number of pooled sub-samples collected randomly across the pond surface. These water quality samples were intended to provide information regarding the relationship between water quality and photosynthetic bacteria status, and not between water quality and odour emission rate.

Water quality samples were collected from the pond adjacent to the wind tunnel while each odour sample was being collected. Each of these samples was analysed individually for a range of determinants. The concentrations of a number of conservative and non-conservative determinants were quite variable for both sampling events. Concentration values for two water quality variables measured in liquor samples collected during the two sampling events are summarised in Figs. 3 and 4, together with the corresponding emission rate values. Similar results were observed for all the variables analysed with the exception of ammonia-N concentrations. This relationship is presented in Fig. 5, which indicates a weak relationship between odour emission rate and liquor ammonia-N concentrations.

The poor relationship between OER and concentrations of individual chemical variables was not unexpected. With the exception of hydrogen sulphide and to a far lesser extent ammonia, these variables did not contribute to odour emissions. The contribution of ammonia and hydrogen sulphide to piggery pond odour is not particularly strong either (Zhu, 2000). These data confirmed that surface pond liquor composition was not spatially homogeneous, and surface pond liquor composition was subject to quite significant change over relatively short periods of time.

Variation in emission rate over time might also be an issue because the samples were collected at different times. As mentioned in the Methodology, samples were not collected concurrently from all sample locations. Samples were collected from each location in turn. This meant that the samples did not represent the pond surface at the same moment in time. The impact of short duration ebullition of biogas on biogas emission rates were investigated by McGrath & Mason (2004). Major biogas-induced perturbations at the pond surface were classified as either type 1 or 2 events, and other observed biogas activities as small bubble events. Preliminary estimates of biogas production rates, obtained using the observational method, ranged from 0.002 to 0.015 m$^3$ m$^{-2}$ day$^{-1}$ for major eruptions.

3.4. Role of pond liquor composition in determining odour emission rates

The potential for water quality to influence emission rates was only recognised on completion of the initial emission rate survey. To address this specific gap in information, two series of odour samples were collected from pond B. A discrete water quality sample was collected from the pond adjacent to the wind tunnel while each odour sample was being collected. Each of these samples was analysed individually for a range of determinants. The concentrations of a number of conservative and non-conservative determinants were quite variable for both sampling events. Concentration values for two water quality variables measured in liquor samples collected during the two sampling events are summarised in Figs. 3 and 4, together with the corresponding emission rate values. Similar results were observed for all the variables analysed with the exception of ammonia-N concentrations. This relationship is presented in Fig. 5, which indicates a weak relationship between odour emission rate and liquor ammonia-N concentrations.

While not stated explicitly, information derived during review of publications regarding odour and VOC sampling infers that the surface liquor of anaerobic ponds is well mixed and spatially homogenous. Evidence for this included absence of recommendations for collecting replicate odour samples (Fleer, 2002). An exception was work related to use of the US EPA flux chamber, where collection of a minimum of six samples was recommended to estimate spatial variability (Gholson et al., 1989). The observed variability in odour emission rates showed that an assumption of spatial homogeneity was not valid.

![Fig. 3. Variability in liquor sulphide and ammonia-N concentration and odour emission rate with sample location, June 2002.](image-url)
0.0004 to 0.024 m$^3$ m$^{-2}$ day$^{-1}$ for small bubble events. These results indicated that specific, short-duration events could influence emission rates considerably. The existence of temporal variability should not, therefore, be ignored. The experimental requirements to quantify such temporal variability were quite specific however, and were not addressed in this study.

3.5. Number of samples required to estimate pond emission rates adequately

Having identified that considerable variability in odour emission rate existed, it was necessary to calculate the number of samples that should be analysed to estimate pond odour emissions adequately. The data obtained for each day was used to estimate the number of samples using the Genstat v8 procedure STTEST (sample size calculations – $t$-tests). The variance values derived from daily pond emission rate data were used in this process. The test allowed the significance level and power of the estimate to be selected by the user. One of the options was a “non-inferiority” selection. For the data selected, the criterion to be satisfied was that the number of samples should provide an estimate that fell within the 95% confidence interval of the measured mean. The number of samples required to satisfy this criterion for each sampling event were summarised in Table 5.

The number of samples suggested in Table 5 were significantly larger than those collected in the current study, or any other investigation of pond emission rates. On the basis of cost, it would be unlikely that the collection and analysis of these numbers of samples could be justified. As a minimum, however, it could be recommended that practitioners, regulators and the general community should recognise the uncertainty associated with measuring odour emission rates. During future investigations it would be

![Fig. 4. Variability in liquor sulphide and ammonia-N concentration and odour emission rate with sample location, September 2002.](image)

![Fig. 5. Relationship between liquor ammonia-N concentration and OER during two sampling events.](image)
What could be the causes of variability in odour emission rate? This information was new, the basic question, "What could be the causes of variability in odour emission rate?" remained largely unanswered. Odorants are derived from the metabolic activities of anaerobic bacteria. Were there localised areas where specific bacterial species predominated, leading to localised areas of increased odour emission?

Stratification of the active volume, and currents within the active volume could contribute to variations in composition of the pond surface liquor layer. Upwellings of gases trapped within the sludge layer are frequently observed on most ponds. While it is well known that aeration of certain zones in wastewater treatment processes leads to localised increases in OER due to stripping of VOCs (Gwynne et al., 2002), the importance of localised ebullition (upwelling) events on OER has not been investigated for piggery anaerobic ponds.

Currents created by thermal stratification and de-stratification, or wind action could also cause variability in odour emission rates. These currents could cause upwellings from which odour emission rates would be higher than from areas where the surface liquor is forced deeper into the pond. Stratification in the pond may create barriers trapping odorous gases during certain periods. Breakdown in stratification during odour sampling may contribute to the highly variable odour emission rates observed. All of these factors require investigation. Whilst these factors could play some role in explaining the variability in observed odour emission rate, they are unlikely to explain all of the variability. Some of these processes operate over relatively short time periods (e.g., upwelling), while others may occur over longer periods but in a less obvious manner (e.g., wind mixing).

Another range of factors that could have a bearing on pond odour emission rates are those arising from the management of the piggery itself. What effects do practices such as washing down piggery housing with antimicrobials have on odour emission? Four of the six piggery ponds surveyed were identified as farrow-to-finish operations. Disinfectants are more heavily used in breeding operations to minimise disease risks to piglets. It is likely that these compounds could have some impact on the pond bacterial populations, even if only transiently. The combination of a discharge of antimicrobial material and cooler pond temperatures might selectively inhibit certain bacteria. This could explain some of the seasonal variability.

A factor that was not considered was the relationship between time of discharge of waste to the pond and time of odour sample collection. The timing and frequency of discharge of waste from the housing to the pond varies from piggery to piggery. It also varies from time to time at any given piggery. It has been observed that when waste is discharged to an anaerobic pond, fine, almost colloidal material in the discharge may rapidly spread across the entire pond surface. The coarser material presumably sinks more rapidly to the sludge. It was reported that the fine material may be important as a source of "immediately available" odour (Ndewga et al., 2002). The period of time between waste discharge and odour sample collection could therefore be important in determining the extent of variability in odour emission rate.

The frequency at which waste is discharged to the pond may also be important. If waste is discharged relatively infrequently, it could be more of a shock load to the treatment pond. Anaerobic processes are sensitive to shock loading. In addition to being a shock load, material that has been held in under-floor storage, or in a sump for some time prior to discharge to the pond, may contain higher concentrations of odorants than waste that is discharged after limited storage time.

The collection and analysis of air samples is expensive and labour intensive. It is, therefore, important to obtain a representative OER that does not over- or under-predict the odour emission rate. Sneath and Clarkson (2000) highlighted the importance of representative sampling. Given the general lack of information pertaining to the spatial
variability of odour emitted from anaerobic lagoons, it could be concluded that previous studies did not evaluate the odour emissions from lagoons in the context of spatial variability of emissions. Heber et al. (2000), Lim et al. (2003) and Smith et al. (1999b) calculated odour emission rates from a minimal number of locations on discrete emission sources, using a limited number of samples. In these studies, samples were commonly collected from the edge of anaerobic lagoons, which might not truly represent the pond odour emission characteristics. The methods employed were possibly used to simplify the sampling process when using the reasonably bulky wind tunnels, or to reduce sampling costs.

Significant variation in OERs was observed for each of the lagoons studied, which showed serious doubt over the results of previous research that did not undertake a more intensive sampling regime. The work by Schulz and Lim (1993) and Smith et al. (1999) sought to identify the primary odour sources at piggeries. The data from these investigations were used to produce generic buffer distances, or used as standard OER values. The unquestioned use of these results in the future as standard OER is no longer possible as doubts have been raised as to whether the data was adequately representative of OER of anaerobic waste treatment ponds.

4. Conclusions

An important outcome of this research was the identification that an interaction of numerous factors, which determined the rate at which odour was emitted from piggery ponds. From the results it could be demonstrated that the variability in odour emission observed could not be explained by the variability arising from the olfactometry process alone. Future sampling programs should have regard for issues such as the impact of producer-controlled activities (flushing regime, use of antimicrobials, stock numbers, etc.) on pond processes, the impact of time on the emission rate, seasonal effects on odour emission rate and having a clearer grasp of physical conditions that prevailed in the pond prior to and during the sample collection. While this research might not have answered questions regarding these factors, it identified them as potentially significant in determining odour emission rates.

It could also be concluded that previous estimates of odour emission might be inaccurate. Regulatory agencies and consultants to the pig industry should consider the results of odour impact modelling obtained with currently available data against the data presented here.

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References


