5 Odour emissions and control

Odour refers to the aggregate effect of a mixture of gases on the sense of smell. For animal effluent and manure, it is the composite of over 170 trace compounds, including ammonia (NH_3), amines, hydrogen sulphide (H_2S), volatile fatty acids, mercaptans, alcohols, aldehydes, esters and carbonyls (Sweeten *et al.* 2006). Some of the compounds (e.g. H_2S and NH_3) have been monitored in detail individually owing to their impact on human and animal health (see chapter 6 'Occupational health and safety').

Odour is becoming an increasingly important issue as milking herds grow, notably in areas valued for rural residential blocks. The potential for odorous emissions to cause nuisance (inconvenience materially interfering with ordinary comfort) to neighbours cannot be dismissed. Although new developments may need to use odour assessment tools for decisions regarding siting, existing dairies must also understand odour generation and dispersion to implement effective odour control strategies.

Units of measurement—OU

Unfortunately, no individual component can be used as a marker to quantify livestock odour intensity; if so, the measurement and monitoring of odour would be a simpler matter than it is. Rather, the intensity of the odour must be measured by a trained human panel, a process referred to as olfactometry, which is described by AS 4323.3 'Stationary source emissions—Part 3: Determination of odour concentration by dynamic olfactometry' (Standards Australia 2001).

AS 4323.3 specifies the odour unit (OU) to report odour concentration. Odour concentration is measured by determining the dilution factor required to reach the detection threshold (the dilution at which the sample has a probability of 0.5 of being perceived). The odour concentration at the detection threshold is by definition 1 OU. Specific odour emission rates are expressed in units of $OU \cdot m^{-2} \cdot s^{-1}$.

Note that the European standard (CEN 1999), on which AS 4323.3 was based, uses units of $OU \cdot m^{-3}$ for concentration and therefore $OU \cdot m^{-2} \cdot s^{-1}$ for specific odour emission rate. Although both are correct, the units adopted by AS 4323.3 are more consistent with the definition of odour as a dilution factor.

Odour generation

Odour emissions are generated during the incomplete anaerobic decomposition of organic matter in manure. Area-based sources around the dairy include ponds, solids separation systems, manure stockpiles, feedpads, loafing paddocks and laneways. Silage, wet by-product storage and spilt feed are also significant sources of odour. The distribution of effluent and the desludging of ponds release odour, but the timing of such planned activities can be scheduled to minimise the impact on neighbours.

Anecdotal evidence suggests that, to date, most odour problems caused by dairies are a result of emissions from manure accumulated on laneways and feed areas (particularly after rain), spoilt grain and silage. The larger dairies more commonly have problems with odours from ponds than do smaller dairies.

Complaints about odours from the dairy itself may relate to a build-up of manure outside the washed areas (yard entry and exit, areas surrounding sump and solids trap) rather than the holding yard (as fresh manure is generally not considered to emit offensive odours). Where a dairy is close to neighbouring residences, the investigation of any complaint must consider whether noise (from plant and machinery, cows, radios etc.), dust or flies are at the root of the nuisance.

Odours could result from the reuse of treated effluent to wash yards, so options to improve the level of treatment before reuse must be considered (also see chapter 2.3 'Anaerobic, aerobic and facultative ponds').

Total odour emissions from a site are proportional to the surface area from which the odour is emitted (total odour emission equals the specific odour emission rate multiplied by the surface area). Therefore, for a given specific odour emission rate, the larger the area, the larger the total odour emissions. Intuitively, the volatile solids (VS) loading of the pond determines the specific odour emission rate, but limited data from the pig industry suggests that although higher loading rates may increase specific emission rates, the net result is that total odour emissions from the site may be reduced as a result of the smaller pond volume and surface area of the more heavily loaded pond (Skerman 2007). Hudson *et al.* (2004) determined that in piggery ponds with loading rates ranging from 53 to 454 g VS m^{-3}·day^{-1}, a 350% increase in loading rate produced a 39% increase in odour emission in winter. It is noteworthy that seasonal variations in emissions were at least as great as those due to loading rate.

Skerman (2007) used this result to develop odour emission versus loading rate curves for different desludging periods in an effort to identify the loading rate that minimises pond odour emissions. For a 10-year desludging period, a loading rate of 180 to 240 g VS m^{-3}·day^{-1} minimised pond odour emissions in piggeries. The optimum loading rate was higher with more frequent desludging.

Similar efforts are required for the dairy industry, but a lack of emission rate data is currently a limitation. Other advantages of more heavily loaded ponds include lower construction costs and a less expensive cover if additional odour or greenhouse gas (GHG) control is needed. These opportunities warrant research aimed at identifying odour emission rates from ponds under a range of loading rates.

Solid–liquid separation traps also generate odour but their overall contribution is usually small owing to their limited surface area. However, sedimentation basins may be a more significant source, depending on their surface area, design and management. Beef feedlot research has found that emissions from sedimentation basins can exceed emissions from ponds if not managed successfully (Sweeten *et al.* 1977). This finding is relevant for some larger dairies and freestall operations.

Any surface where manure accumulates will generate odour if the moisture content of the manure exceeds around 70% (the point at which anaerobic conditions begin to prevail). Within beef feedlots, odour emissions from wet pads are commonly 25 to 100 times those from dry pads and peak 1 to 5 days after rainfall (Lunney and Lott 1995). During dry times, stock traffic may pulverise accumulated manure, producing 'fines' that are removed by the wind. Although dust is a pollutant in its own right, it will also cause odour when it comes into contact with the olfactory nerve.

Aside from moisture content, temperature is an important determinant of odour emission rates. That is, bacterial activity is more rapid under warm conditions than cool, with faster rates of decomposition and therefore odour generation.

Separation or buffer distance

The traditional regulatory approach to avoiding odour has been the imposition of separation or buffer distance requirements on new developments in an effort to allow the odour to disperse before reaching any potential receptor. Table 1 presents some commonly applied separation distances.

Table 1. Separation distances to nearest house (m).

	NSW	Vic	Tas	SA	WA
Pond	200	300	300	200	200
Solids trap				50	
Manure stockpile	200		300		
Land application	100	300 (slurry)	100[a]; 300[b]	100	100[a]; 300[b]

[a] Intermittent use only.
[b] Continuous use.

It could be argued that separation distance requirements should also be applied to the dairy and any feedpad. Both generate noise, light and, where manure is allowed to accumulate, odours. However, the determination of appropriate separation distance usually involves compromises; setback distances large enough to allow sufficient dispersion or attenuation under stable atmospheric conditions may unduly restrict new developments (or natural expansion), but small setback distances are insufficient to mitigate the frequency and severity of nuisance at some sites. It is unlikely that the separation distances from pond to receptor given in Table 1 are adequate for large operations, and farmers and regulators alike need additional tools to assist in planning. Fixed separation distances are not suitable for preventing nuisance impacts from odour as they are inflexible and unresponsive to site-specific issues (size and nature of operation, local weather patterns, topography).

Calculation of buffer distance

Some state guidelines for the pig and beef industries use empirical equations to calculate a suitable buffer distance according to the number of animals, site management practices, receptor type, local terrain and vegetation. The general nature of the equation is:

$$D = S \times \sqrt{N} \qquad (1)$$

where

D = separation distance

S = composite site factor ($S_1 \times S_2 \times S_3 \times \ldots \times S_n$)

N = number of standard animal units.

In the dairy industry, N is the number of dairy cattle units adjusted for live weight and time on feedpad. As dairy developments in Victoria (the first state to implement this approach for dairies) are assessed against the requirements of the Victorian Code for Cattle Feedlots (Department of Agriculture Energy & Minerals Victoria 1995), a dairy-specific stocking intensity factor (S_1) was developed for feedpads in the Goulburn–Broken catchment (Dairy Cattle Feedpad Working Group 2002) to be used in calculating Equation 1 and achieve compatibility with the code.

The Dairy Cattle Feedpad Working Group (2002) based S_1 on field-trial-derived relationships between odour emission rates, stocking intensity and management of beef feedlots using model-predicted odour concentrations calibrated by receptor impacts. As no research data from dairy farms was available for corroboration, this approach is indicative only. Where the calculated separation distance is less than the minimum fixed separation distance (300 m), this minimum distance applies.

Although this approach overcomes some of the limitations of the fixed separation distance, it has not been rigorously tested, and its use is limited to dairy farms with a feedpad. The use of a site factor based only on feedpad stocking rate and management does not enable different scenarios for potentially the largest odour source—the effluent management system—to be considered (e.g. single pond vs. two ponds, solids trap vs. sedimentation basin).

The remaining site factors are obtained from Dairy Cattle Feedpad Working Group (2002).

International approaches to calculating separation distances

Although models developed in the USA and Europe are not generally applicable owing to the intensive nature of their dairy farming systems and differences in climate, the approach used to develop the OFFSET model in Minnesota, USA, warrants consideration. In the OFFSET methodology, all potential odour sources are listed and assigned a representative specific odour emission rate (an average derived from a comprehensive odour monitoring program) (Guo *et al.* (2005). The specific emission rates can be adjusted to account for any odour control measures such as permeable or impermeable covers. The total odour emission from the site is then determined by summing the contribution from each source (specific odour emission rate multiplied by the respective surface area).

Once the total odour emission is calculated, the setback distance is determined using standard curves with an 'annoyance-free' frequency from 91% to 99%. The curves were generated by dispersion modelling and calibrated by on-ground surveys (emission rates and receptor impacts were measured over 4 years in 85 farms). For the purposes of OFFSET, annoyance-free odours are defined as those odours with an intensity of <2 (defined as weak or mild odours that are not likely to be annoying) on the *n*-butanol odour intensity reference scale (0–5).

The advantage of the OFFSET approach is that it can account for the size and nature of a range of odour sources, including adjustments for odour control measures, and the frequency of impacts on receptors without site-specific modelling. Unfortunately, the Australian dairy industry covers a much broader range of climatic and topographical conditions than in Minnesota, and has differing regulatory targets, and would require the generation of at least regional standard curves. (Note, however, that OFFSET assumes that the receptor is always located downwind of the odour source in the prevailing wind direction, which is the worst-case scenario.) More critically, the availability of representative odour emission rate data from Australian dairy farms is extremely limited (see 'Emissions data' below).

Dispersion of odours

Although the complete elimination of odour is not possible, potential conflict with neighbours may be avoided with an understanding of the conditions that are more likely to cause odour plumes to travel long distances. Odour is carried away from the dairy by the prevailing wind. As it moves downwind, dispersion causes the odour concentration to decrease with increasing distance from the site. The rate of dispersion depend on atmospheric stability: a hot, windy day (unstable atmosphere) results in faster dispersion than a cold, calm, cloudless evening (stable atmosphere).

In some locations, odour plumes may travel long distances as a result of topographic features that confine plumes and limit their dispersion. Katabatic drift is the movement of cold air downslope within a valley, generally during times of stable atmospheric conditions. Farms in such situations are at additional risk of causing nuisance; new developments should avoid such sites.

Dispersion modelling

Computer-based odour concentration models can be used to determine the intensity and frequency of odours at specified locations around a source from local weather data. Ausplume is the dispersion model favoured by regulatory agencies around Australia; it should be used except where conditions make it unsuitable. Pacific Air and Environment (2003b) provides a guide to deciding which situations will be satisfactorily treated by Ausplume, and proposes that the following situations require a more advanced model:

- ‘Critical receptors are located at a distance from the source that is greater than the minimum distance travelled by the plume in one hour, and there is evidence of significant effects of non-steady-state meteorology.
- More than one [piggery] is being considered in the same model application.’

Pacific Air and Environment (2003b) states that there are:

‘significant limitations to Ausplume, which need to be recognised and which might mean that use of another, more advanced, model is appropriate for a given situation. Another commonly used type of model is the Gaussian puff dispersion model, of which CALPUFF is the best-known example. For low-level emission sources such as piggeries, the differences between predictions from steady state and puff models are expected to be greatest for stable, near-calm (low wind) conditions, which generally lead to the highest predicted short-term concentrations.’

Meteorological data

Generally, a minimum of 12 months of hourly data is required as input to a dispersion model for a thorough assessment. The 12-month period selected must be representative of the normal range of conditions in the area. Pacific Air and Environment (2003a) reviews data requirements and lists potential data sources.

Emissions data

Unfortunately, there is little data describing odour emission rates from dairy farms. One research project (Feitz 2002, Wang and Feitz 2004) and three commercial investigations (Geolyse 2007, Holmes Air Science 2000, The Odour Unit 2005) provide the only Australian data available (Table 2).

There is clearly a need for additional information to explain the magnitude of the difference between the data sets, particularly within the three data sets derived from samples collected with an isolation flux hood. All samples were analysed according to the current Australian Standard or, in the case of Holmes Air Science (2000), its basis, CEN (1999). Discussions with the owner of the property sampled by the Odour Unit (2005) suggest that the anaerobic pond was not functioning effectively—a conclusion supported by the high COD and BOD results. Similarly, after 8 years of operation and sludge accumulation, Geolyse (2007) suggested that the performance of the treatment ponds was curtailed by lower hydraulic residence times, leading to increased odour emission rates. Differences in the treatment system design, age and maintenance history of ponds logically produce significant variations in measured odour emissions.

The wind tunnel measured data of (Feitz 2002) yield numbers between the other data sets. Most research shows that isolation flux hoods under-predict odour emissions relative to wind tunnels (Galvin (2005). Unfortunately, there is no fixed correlation between emission rates as measured by the different apparatus, so corroboration between data sets is not possible (Jiang and Kaye (1996). The debate regarding the most appropriate apparatus for odour sampling continues.

Table 2. Available odour emissions data.

Source of odour	Specific odour emission rate ($OU \cdot m^{-2} \cdot s^{-1}$)			
Reference	Holmes Air Science (2000) [a]	Odour Unit (2005) [b]	Geolyse (2007) [c]	Feitz (2002) [d]
Collection apparatus	Isolation flux hood	Isolation flux hood	Isolation flux hood	Wind tunnel
Anaerobic pond	0.38	1.35 (on dry crust) 82.7 (on wet crust) 75.4 (no crust)	6.4	8.1 (2–34)
Storage pond	0.12	2.12	9.0	
Sump and manure separator	1.48			
Manure stockpile		9.42	0.08	
Freestall pen	0.35			
Freestall channel	0.58		0.07 (flushed clean) 0.14 (dirty)	
Silage	7.90	916	0.31	

a: Large freestall operation, data collected over 2 days during fine autumn weather; maximum of two measurements reported; no loading rate information collected.
b: Medium-sized operation with feedpad; data collected during one fine and hot (32 °C) day in autumn; COD at anaerobic outlet 9400 $mg \cdot L^{-1}$; BOD 1900 $mg \cdot L^{-1}$.
c: The same freestall operation monitored by Holmes Air Science (2000) after approximately 8 years of operation, sampled during winter.
d: Monitoring at 30 ponds (primary and secondary) over 12 months on farms in Queensland, NSW and Victoria.

Three international studies identified odour emission rates on dairy farms:

- Mean odour emission of 4.7 $OU \cdot m^{-2} \cdot s^{-1}$ (range 0–10.3) from a single-cell earthen basin holding manure slurry (2.2% TS); sampling by isolation flux hood; olfactometry standard not identified (Zhao *et al.* 2007).
- 27 $OU \cdot m^{-2} \cdot s^{-1}$ from 3 single-cell earthen basins; 6.3 $OU \cdot m^{-2} \cdot s^{-1}$ from 1st cell of 4 multiple-cell systems, and 5.1 $OU \cdot m^{-2} \cdot s^{-1}$ from 2nd cell; sampling by wind tunnel in accordance with ASTM Standard E679–91 (Gay *et al.* 2003).
- 7–10 $OU \cdot m^{-2} \cdot s$ from 2 single-cell earthen basins and 2–3 $OU \cdot m^{-2} \cdot s$ from 2 freestall barns; sampling by wind tunnel to CEN (1999) (Bicudo *et al.* 2003).

Casey *et al.* (2006) compare emissions by animal types.

Hudson *et al.* (2004) identified significant spatial variability in emission rate (by as much as 10×) across the surface of piggery anaerobic ponds. They concluded that at least four odour samples are required to remove the uncertainty created by this spatial variability. Unfortunately, none of the sampling efforts listed in Table 2 meet that criterion.

The limited data available do not allow a representative range of odour emission rates to be selected. Therefore, the accuracy of any attempts at odour modelling for dairy developments must be considered questionable until additional information can be developed. A research program investigating emission rates from the range of sources around the dairy and the impacts of loading rates, age and maintenance regime on pond emissions is urgently needed.

Regulatory target criteria

The development of target odour criteria is complicated by the difficulties in odour sampling and measurement combined with a lack of suitable data on odour levels associated with annoyance and complaint (Galvin *et al.* 2007). In lieu of definitive information, state regulatory agencies have developed differing criteria (Table 3).

Table 3. Odour criteria summarised by Galvin et al. (2007) unless otherwise stated.

State	Percentile occurrence	Odour concentration	Averaging time	Assessment point
Queensland	99.5	0.5 OU point 2.5 OU non-point	1 h	Sensitive receptor (existing or future)
NSW	99.0	2 OU (pop. 2000+) to 7 OU (pop. 2)	1 s [b]	Sensitive receptor (existing or future)
Victoria	99.9	1 OU non-rural 5 OU rural + risk assessment	3 min	Property boundary
Tasmania [a]	99.5	2 OU	1 h	Property boundary
SA	99.9	2 OU (pop. 2000+) to 10 OU (pop. <12)	3 min	Sensitive receptor
WA [a]	99.5 99.9	2 OU 4 OU	3 min	Sensitive receptor (existing or future)

[a] Wang and Feitz (2004)
[b] A peak-to-mean factor (a conversion factor that adjusts mean dispersion-model predictions to the peak concentrations perceived by the human nose) must be applied to emissions before modelling .

If we take Victoria as an example, the 99.9th percentile 5-OU criterion means that the odour concentration at the point of interest has to be <5 OU for all but 9 h per year (0.1% of the time). The required buffer from site to receptor therefore increases with higher compliance frequencies and, where a population-based criterion is in place, with population density.

The different odour criteria adopted by states creates discrepancies across some regions. Wang and Feitz (2004) suggest that the Victorian odour criteria are significantly more restrictive than NSW, with a buffer distance 4.7 to 7 times larger. However, Galvin *et al.* (2007) suggest that although the criteria are different, modelling to Queensland, NSW and SA criteria produced similar buffer requirements for broiler farms in those three states.

Galvin *et al.* (2007) warn that the more stringent the percentile value is, the more likely that the modelled results fail to show the influence of terrain. That is, peak odour concentrations associated with atypical meteorological conditions dominate the results. Lower percentiles (99.5th to 98th) are more likely to filter out atypical conditions than the 99.9th percentile.

Wang and Feitz (2004) tried to define target criteria for the Australian dairy industry. They suggested 6.5 $OU \cdot m^{-3}$ (the recognition threshold for dairy odour), 1-h averaging and 99.5th percentile at receptor as appropriate criteria for the assessment of dairy farm odours, but based that conclusion on achieving an arbitrary separation distance of 500 m for the average emissions from the 9 farms modelled. Their work did not include any community survey or field panel assessment to verify the level of impact.

Odour control strategies

Proper siting, taking into account distances to neighbours, prevailing wind directions and topography, is the single most important factor in avoiding potential conflict. However, on existing farms, particularly those with sensitive receptors located close by, other strategies may be necessary to reduce emissions.

Attention to detail in general management and maintenance (good housekeeping) is an important factor in minimising complaints and maintaining good relationships with neighbours. Planning activities that are likely to release odours (desludging, solid and effluent application) for a time when odour impacts are less likely is also important.

Additional strategies such as chemically assisted solids separation, impermeable and permeable covers, partial aeration and odour control additives can control odours from ponds. Unfortunately, the costs of these strategies are significant and their efficacy varies. Fortunately, however, few operations currently need them.

Manure decomposing anaerobically (typically requiring a moisture content > 70%) is likely to emit odours. Management practices that eliminate any unnecessary accumulation of manure will help to reduce the potential for impacts on neighbours. Where it is not possible to eliminate those areas, regular and thorough maintenance is critical.

Feedpads, loafing pads and sacrifice paddocks

Feedpads should be designed to be cleaned regularly (preferably daily via flushing or scraping to minimise odours) and integrated with the effluent management system. However, the investment in large areas of concrete cannot be justified for all farms, and earthen feedpads and loafing areas are suitable provided they are designed properly (see chapter 4.2 'Feedpads, calving pads and loafing pads').

In minimising odour emissions from earthen pads, the critical aspects include:

- a minimum slope of 2% to 4% to promote good drainage (Lunney and Lott 1995)
- regular maintenance to fill holes and maintain free drainage
- attention to seemingly minor details such as cleaning under fences to maintain drainage and removing manure that settles in collection drains.

Scrape earthen pads if more than 50 mm of manure has built up to reduce the manure load present during wet periods. Clean any earthen drains as often as needed to remove settled manure. If vegetation is established in drain beds, it will reduce flow velocity and trap manure; therefore, regular spraying with a broad-spectrum herbicide is necessary.

Spilt feed is particularly odorous if it becomes wet and spoils. Any feed accumulating behind feed bunks or around feedpads must be removed before it spoils.

Feed-out or sacrifice paddocks can be a significant source of odour following rainfall owing to the accumulation of manure and waste feed. Areas to be used for such practices should be selected to avoid affecting neighbours (consider buffer distance and prevailing winds) and rotated regularly to avoid an excessive (>50 mm) build-up of putrescible material.

Manure stockpiles

Water draining from stockpiled solids must be prevented from ponding around the pile, where it will maintain anaerobic conditions at the base of the pile. A compacted pad with a 2% to 3% slope to the effluent collection system is required for adequate drainage. Fill and compact any depressions made during manure removal.

If the manure stockpile is large or emitting odours, it may need to be windrowed and turned regularly until it dries enough to maintain aerobic conditions required for composting (see chapter 2.9 'Composting'). Such turning is likely to release significant odours and must be timed to avoid worsening the situation (see 'Planned activities' below).

Feed storage

Although the nature of odours from silage is different (often described as sweet or grassy) and usually less offensive than from manure, it may be of an intensity that causes complaints. The Odour Unit (2005) reported that odour emissions from the face of a particular silage bunker produced the one of the highest odour emission rates ever recorded (Table 2). Placing a cover over the disturbed face of the bunker may be necessary where neighbours experience effects. All leachate from the bunker must be captured and directed to the effluent collection system.

Operations that feed food-processing by-products (e.g. brewer's grain, cannery pulp) have an additional odour source. Although such odours may not be unpleasant, feed volumes stored on-site should be minimised as much as possible. Anecdotal reports of leachate from some cannery wastes inhibiting pond function (and increasing odour emissions) suggest that the waste's properties (moisture content, pH, EC) must be investigated; if they prove problematic, separate leachate storage may be required.

Spoiling grain can be a potent source of offensive odour and spills should be removed as frequently as they happen.

Dietary modification

Powell (2006) states that 'manure management should start at the front, rather than the back end of the animal.' Carbohydrates and proteins in manure are the two major energy sources for bacterial growth and odour production (Zhu *et al.* 1999), so strategies that reduce the amount of these constituents may reduce odour emissions from both the ponds and the other areas around the farm.

The principle odorous compounds resulting from manure decomposition include volatile fatty acids (VFAs), ammonia, amines, indoles, phenolics and volatile sulphur-containing compounds (Mackie *et al.* 1998). Zhu *et al*. (1999) confirmed that the most pungent odorous compounds (in pig effluent) originate from the decomposition of proteins. Sutton *et al.* (2006), however, suggest that reducing N output (and, by association, proteins) from cattle is challenging and limited by the ability to accurately formulate diets with the required nutrient availability (particularly where pasture comprises the major proportion of intake). In trying to reduce odours, take care not to diminish milk production and animal performance.

Miller and Varel (2001) suggest that VFAs from feedlot cattle are predominantly produced by the fermentation of carbohydrates, particularly starch. Improving the digestibility of grain supplements is one means of reducing waste starch output and therefore odour. Archibeque *et al*. (2006) established that feeding high-moisture ensiled maize plants reduced starch output in manure and the production of odorous compounds relative to dry rolled maize. In addition, Burkholder (2004) found that feeding steam-flaked maize to dairy cows increased N digestibility, reduced N output and reduce the rate of ammonia loss from manure and urine compared with dry rolled maize.

Although the variability in pasture-based systems precludes much of the opportunity for ration modification afforded to cows fed in freestall sheds and, to some extent, on feedpads, the formulation of supplementary feeds should be based on nutritional requirements to avoid overfeeding and reduce the excretion of undigested components.

Planned activities

Planned activities (cleaning solids traps, effluent irrigation, desludging, manure spreading etc.) should be timed to avoid effects on neighbours. Although these procedures will generate odour, the manager can select the timing of the activity to minimise emission impacts (Lunney and Lott 1995) by:

- avoiding timed activities if other emissions from other sources are high (for example, following rainfall), as odours are largely additive
- scheduling activities from Monday to Thursday to avoid operations immediately before the weekend
- performing operations in the morning to take advantage of warming conditions, which enhance dispersion, and to allow odour emissions to reduce before stable atmospheric conditions return with nightfall

- favouring days with unstable atmospheric conditions—warm, windy, little cloud cover and no rain forecast
- avoiding activities when the wind is blowing towards sensitive receptors.

Lunney and Lott (1995) report that odour emissions following manure spreading decay to negligible levels (~10% of initial emission rates) within 2 days. Excessive rates of application or uneven spreading may cause odour emissions to remain high for longer. Incorporation of manure as soon as possible after spreading not only reduces odour emissions, but also maximises the nutrient value of the manure by limiting N loss. If manure is not incorporated, follow-up rain may cause odour emissions to spike and result in nutrient loss in runoff.

Odours during irrigation of effluent may result from either the release of gaseous compounds or aerosol drift. If the latter is the cause, the nozzle and pressure combination of the irrigation equipment needs to be reviewed (low pressure, large nozzle size and low application height will minimise aerosol drift). The following measures may also help:

- Diluting the effluent with clean water may reduce odours during irrigation. Additionally, a short irrigation with clean water following the effluent may flush effluent from the large surface area of the vegetation.
- Pump effluent from the final pond within the treatment and storage system if possible. If there is only one pond, set the on a float to draw from under the surface and avoid sludge (but low enough to avoid air entrainment and floating material).
- Avoid application rates that lead to surface ponding.

Public relations

The importance of maintaining good public relations in reducing the perception of odours cannot be overstated. Informing neighbours before planned activities will not only avoid coinciding with any social events, but also help to retain goodwill through what should be only short-term impacts. If neighbours are experiencing an increase in odours, keeping the lines of communication open will allow the farmer to review the possible reasons and rectify problems before the neighbours feel their only option is a formal complaint to authorities.

Aesthetics and image are also important—a clean and well maintained farm will generate fewer odour complaints than a weed-covered, debris-laden farm. Plants may also help by providing a visual screen around the site (out of site is out of mind). Note, however, that although trees provide a windbreak that creates turbulence and vertical dispersion, they offer limited benefit during calm conditions, when odour plumes are most problematic (Lunney and Lott 1995).

Odour control strategies for ponds

Sweeten *et al*. (2006) suggest that problems caused by odours from ponds generally stem from overoptimism in design, performance, ease of maintenance and public tolerance of off-site impacts. They suggest that many problems could be avoided by not making the following mistakes:

- Designing to meet minimum guidelines (no capacity for natural expansion).
- Underestimation of organic loading rate (e.g. time on yard or feedpad, manure output per head).
- Inappropriate site selection.
- Attempting to accomplish both treatment and storage with one single-stage pond rather than multistage ponds (on larger farms).

- Insufficient sludge clean-out interval or failure to plan for sludge removal and use.

Where an effluent pond is established as being the cause of offensive odours, the following control strategies may help.

Chemically assisted solid–liquid separation

Solid–liquid separation may remove a portion of the VS before the anaerobic pond, but as most of the precursors to odour generation are contained in the finer particle fraction (typically <0.25 mm), which is not removed in solid–liquid separation, it has a limited capacity to reduce odour generation (Zhang and Lei 1998). If odour control and nutrient removal are the goals, chemically assisted solid–liquid separation may be required.

Chemical treatment involves the addition of coagulants and flocculants to alter the physical state of smaller suspended and colloidal solids and facilitate their removal by physical separation. Inorganic coagulants destabilise the net negative surface charge on the colloidal particles and promote the formation of flocs. Commonly used coagulants include calcium hydroxide (lime), ferric chloride and aluminium sulphate (alum). These metal ions also react with phosphate ions to form a precipitate and increase the removal of phosphorus from effluent.

Polymers promote flocculation or agglomeration of the flocs. Among commercially available natural and synthetic polymers, polyacrylamide (PAM) is the most common synthetic polymer, and chitosan is an example of a natural polymer with similar efficacy to PAM (Garcia *et al.* 2007). Timby *et al*. (2004) and Krumpelman *et al*. (2005) both confirmed that high-charge-density cationic PAM is suitable for dairy effluent. Polymers can be added separately or in combination with metal salts.

Garcia *et al.* (2007) recorded removal rates of up to 95% of total suspended solids (TSS) and 54% of total phosphorus (TP) from dairy effluent (3.2% TS) after flocculant (PAM) treatment and passage through a 0.25-mm screen. Zhang *et al*. (2006) found that gravity settlement of dairy effluent (3% TS) after the addition of the polyethylenimine (PEI) reduced TS by up to 58% and TP by 77%. Chastain *et al.* (2001) found that mechanical screening (1.6-mm) followed by treatment with PAM and 60 min settling time reduced TS, VS, N and P by similar amounts as solid–liquid separation followed by treatment lagoon.

Researchers investigating coagulants generally list ferric chloride and alum as more effective than lime (note, however, that lime is significantly less expensive). Barrow *et al*. (1997) identified removal rates of 89% of TS and 88% of TP from 1% TS dairy effluent following treatment with ferric chloride and 20 min of settling. Karthikeyan *et al.* (2002) noted that the removal of total solids from 1.6% TS dairy effluent following 30 min gravity settlement improved from 30% without coagulants to 65% with alum and 70% with ferric chloride. Kirk *et al*. (2003) also demonstrated significant improvement following the addition of coagulants and favoured the use of alum over ferric chloride owing to its slightly better performance and price.

Generally, combinations of inorganic coagulants and PAM remove more TS and P than either alone (Krumpelman *et al.* 2005, Timby *et al.* 2004, Zhang *et al.* 2006).

Although the referenced papers identify the dosage rates used, these must be followed cautiously as the required dosage rates increase with increasing TS concentration of the effluent. Apart from wasting chemicals, adding excessive amounts can actually impede solid–liquid separation owing to destabilisation of flocs (Zhang *et al.* 2006). A bench-scale test using a sample of the effluent is required first to identify the most suitable chemical and optimum dosage rate.

The use of chemically assisted solid–liquid separation is limited for the following reasons:

- Coagulants require specialised equipment (and significant capital cost) to achieve the rapid mixing necessary for maximum performance (Metcalf & Eddy Inc. 2003).
- Monitoring short-term changes in effluent concentrations and responding with changes in dosage rate is difficult (Worley *et al.* 2005).
- Chemical costs are significant, ranging from US$56–80 per cow y^{-1} (Sherman *et al.* 2000) to US$104 per cow y^{-1} (Barrow *et al.* 1997).
- Higher dosage rates of coagulants and flocculants reduce pH, in turn affecting other treatment processes (e.g. anaerobic digestion).
- Some flocs are too delicate to be removed by screening (Barrow *et al.* 1997) and require sedimentation for removal.

As separated solids typically have a moisture content > 80%, stored solids will quickly become anaerobic and produce an additional odour source (negating some the improvement sought) unless handled properly (see 'Manure stockpiles' above). Screw presses and centrifuges are among the few devices able to achieve the <70% moisture content necessary to avoid anaerobic conditions in separated solids (see chapter 2.1 'Solid liquid separation systems').

Impermeable covers with gas collection

Impermeable covers are designed to trap all gases produced during decomposition. In addition to removing a significant areal odour source, they allow the captured gas to be flared or used as an energy source, both resulting in combustion of any odorous compounds (see chapter 8.1 'Production and beneficial use of methane'). Flares typically destroy >95% of volatile organic compounds, which is generally sufficient for odour control, but high-temperature catalytic or thermal incineration may be required for complete odour destruction.

An alternative to combustion is to pass the collected gases through a biofilter, in which microorganisms reduce the organic compounds to less offensive forms. A basic biofilter comprising a 300-mm-deep mix of straw and compost over a chamber formed by shipping pallets reduced odour emissions from ventilated pig sheds by 82% and hydrogen sulphide by 80% (Nicolai and Janni 2001).

Permeable covers

Permeable covers reduce emissions by acting as both a partial barrier (resistance to mass transfer) and as a biofilter providing surface area for biological treatment (Regmi and Surampalli 2007). Biofilters provide a suitable environment for aerobic microorganisms to oxidise odorous gases and reduce odour emissions.

Permeable covers may be made from materials such as supported straw, geotextile, vegetable oil or clay balls. Fortunately, these covers are often unnecessary for dairy anaerobic ponds, as the nature of the effluent commonly results in the natural formation of a crust (see chapter 2.3 'Anaerobic, aerobic and facultative ponds'). Bicudo *et al.* (2001) measured odour emissions from a crusted swine manure storage over 5 months and determined a mean emission rate of 7.3 $OU{\cdot}m^{-2}{\cdot}s^{-1}$ with crust (in early spring and autumn) and 13.6 $OU{\cdot}m^{-2}{\cdot}s^{-1}$ without crust (in summer). Misselbrook *et al.* (2005) suggest that crusts reduce ammonia emissions from dairy slurry stores by approximately 50% but did not measure the impact on odour. Monitoring at an Australian dairy by the Odour Unit (2005) showed a 98% reduction in odour emissions from a dry crust relative to the liquid surface (Table 2).

Crusts, therefore, are beneficial as an odour control strategy and should be left intact if they are not causing problems (see chapter 2.3 'Anaerobic, aerobic and facultative ponds'). However, two issues that may affect odour emissions require further research:

- Wet, recently formed crusts appear to increase odour emission rates (Bicudo *et al.* 2001). Does rainfall cause a similar outcome and, if so, over what period?
- Some gas concentrations appear to increase in the liquid (Bicudo *et al.* 2001). What impact will this have on emissions from storage ponds or during effluent distribution?

In ponds where a natural crust cannot be generated, artificial permeable covers may be necessary to control odours. In their literature review, Hudson *et al*. (2006a) provide a comprehensive summary of research into cover efficacy, and including laboratory-scale reductions in odour emission rates of 71% to 84% from piggery effluent. Subsequent field trials (Hudson *et al.* 2006b) found reductions of 87% to 90% by both supported straw covers and a supported geotextile (a double layer of polypropylene weed mat). Installation costs ranged from A$7.50 m^{-2} for the geotextile cover to A$12.00 m^{-2} for supported straw covers.

In US-based research, Clanton *et al*. (2001) suggested that unsupported straw covers require a thickness of up to 300 mm to keep straw afloat and dry enough to act as a biofilter. Husdon *et al*. (2006b), however, suggested that supported straw covers were effective even when the straw had undergone significant decomposition and the thickness had decreased to 20 mm.

Hudson et al. (2007) reported on the long-term efficacy of three cover types over 3 years at piggeries in Queensland. Average odour emission rates were reduced by 76% by a polypropylene cover overlain by shadecloth (for UV protection), 69% by shadecloth only, and 66% by a supported straw cover. Research by Regmi and Surampalli (2007) supports the suggestion that geotextile fabric covers are as effective as straw covers.

Partial aeration

Owing to the different biological pathways involved, aerobic treatment emits little odour compared with anaerobic treatment. As naturally aerobic ponds are not a practical option for agricultural effluent treatment, mechanical aeration is sometimes used to achieve aerobic conditions in a much smaller pond than would otherwise be necessary. However, complete stabilisation via mechanical aeration is not normally economically justifiable, as the power requirement for maintaining a completely mixed state is very high—15 to 30 $kW{\cdot}ML^{-1}$ for mechanical aerators and 10 to 30 $m^3{\cdot}ML^{-1}{\cdot}min^{-1}$ for diffused-air devices (Metcalf & Eddy Inc. 2003).

Partially aerated or 'stratified' ponds (where only the surface layer is aerated) have been investigated for odour control (Westerman and Zhang 1997). The aeration level recommended varies from 33% to 50% of the daily BOD load (Vanderholm 1984) and up to 50% of the daily COD load (Barker *et al.* 1980). For dairy effluent with a COD:BOD ratio of 6.9 (ASAE 1999), the latter recommendation is 7 to 10 times the former. As Vanderholm's recommendation was based on domestic effluent (where the 5-day BOD test represents a greater proportion of the ultimate BOD than in dairy effluent), the more conservative recommendation of Barker *et al*. (1980) should be used for design purposes.

At a rate of oxygen transfer by a typical mechanical aerator of no more than 1.0 kg O_2 kWh^{-1} (Cumby 1987, Metcalf & Eddy Inc. 2003), the energy consumption required to meet 50% of the daily COD load would be at least 120 kWh per cow per year, assuming that 10% of the 0.65 kg per cow COD output is collected (see chapter 1.2 'Characteristics of effluent and manure').

Zhang *et al.* (1997) suggest that continuously supplying sufficient oxygen to maintain a dissolved oxygen (DO) concentration of 0.5 $mg{\cdot}L^{-1}$ in a surface layer of 0.15–0.3 m depth appears to offer acceptable odour control. A deeper aerated layer (or higher DO concentration) is necessary where aeration ceases for more than 9 h. Ginnivan (1983) recommended similarly shallow depths (0.08–0.4 m), and Barker *et al*. (1980) recommended a slightly deeper layer of 0.6 m. Practical constraints in aerator design and function may limit how shallow the depth of the aerated layer can be (Westerman and Zhang 1997).

Odour control additives

Commercial products marketed as a solution to odour problems continue to attract interest despite a lack of scientific evidence of their efficacy. However, some operators believe them to be somewhat effective.

The many odour control additives available can be grouped according to their method of action:

- Digestive agents—additives that presumably alter the microbial community to enhance the degradation of odorous compounds or reduce their production.
- Masking agents—volatile oils with a stronger but more acceptable odour than the nuisance odour.
- Counteractants—aromatic oils that neutralise an odour. However, owing to the complex nature of odour, it is unlikely that a single counteractant could be effective (Lunney and Lott 1995).
- Disinfectants—germicides that alter or eliminate bacterial action. Such chemicals are often toxic and therefore impractical, as well as expensive.
- Oxidising agents—chemicals that oxidise odorous compounds (and may also provide some disinfection), including ozone.
- Bio-catalysts—bacteria and enzymes that encourage the formation of non-odorous end products such as methane rather than the by-products of incomplete digestion.
- pH modifiers (particularly for ammonia control).
- Adsorbents—commonly zeolite or sphagnum peat, which perform a similar function to biofilters (see 'Impermeable covers with gas collection' above).

McCrory and Hobbs (2001) provide a comprehensive review of additives, their various modes of action and their efficacy. FSA Environmental (1999) include a comprehensive listing of research papers with detailed information on odour control additives.

Research shows that bio-catalysts may offer some scope for reducing the time needed for establishing a suitable population of bacteria in anaerobic ponds during startup (Dugba and Schneider 2000). However, anecdotal evidence suggests that seeding a new pond with sludge from an operational pond will have a similar effect (see chapter 2.3 'Anaerobic, aerobic and facultative ponds').

The pH modifiers also demonstrate reliable efficacy. In this case, the pathway for the emission of ammonia is well understood and predictable. As pH controls the equilibrium between ammonia (NH_3) and ammonium (NH_4^+) in solution, pH modification may reduce ammonia volatilisation. Of the pH modifiers, acids have been shown to be consistently effective (but can be expensive or hazardous and corrosive), but base-precipitating salts offer only a short-term effect and must be reapplied frequently (McCrory and Hobbs 2001). Unfortunately, ammonia is not well correlated with odour, so the impact may not be significant.

Commercial additives containing saponins appear to offer some scope for conserving ammonium, but the mechanism by which this is achieved is unclear. Further, research results have not been consistent; for example, Andersson (1994) found that the cost of additive outweighed the value of the N retained in slurry.

Sweeten *et al*. (2006) summarise work by Purdue University to evaluate 35 digestive agents claimed to reduce odour. Each additive was tested in a simulated manure pit over three 42-day periods and compared with four untreated controls. At the 95%

confidence level, 7 of the 35 additives reduced hydrogen sulphide levels but none reduced odour emissions as measured by olfactometry.

In local research, Nick Bullock & Associates (2007) report on four concurrent demonstration trials using probiotics in conjunction with low-energy aeration of dairy effluent ponds. Unfortunately, the results were not conclusive, as BOD, VS and nutrient levels were not significantly reduced by the treatment. Occasional increases in odour levels were observed when aeration disturbed the settled sludge. Problems with blocked air stones were a continuing problem in most of the ponds. At the field scale, it is difficult to reconcile that tens of litres of additive can have a significant impact on a pond containing (typically) millions of litres of effluent and billons of bacteria. In addition, as odorous compounds are produced via many different, and as yet largely unresearched, pathways, one product is not likely to work in all situations. Researchers have been unable to establish reliable guidance on which odour control additives are effective under what conditions. The most common conclusion is that the use of additives is an unreliable and potentially expensive option for odour control.

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