Australian Government
Department of Agriculture

AUSTRALIAN Pork™

Assessing the Medium-Term Impact of Permeable Pond Covers on Pond Performance and Odour Management

Final Report
APL Project 2002/1829

January 2007

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Acknowledgements

This project is supported by funding from Australian Pork Limited and the Department of Agriculture.

Cooperation of the producers who made their facilities available for the field trials:

- Hyfarm (Erik Larssen & staff).
- University of Queensland Gatton piggery (Mark Bauer & colleagues).
- DPI&F Wacol Pig Research Centre (Steve Collingwood, Laurie Daley and Mike Magee).

Provision of olfactometry results of consistently high quality (Chris Clayton and the team of air quality assessors).

Converting vague ideas and poor drawings into practical and reliable field equipment (John McAlpine and Warren Mills , DPI&F Agricultural Engineering workshop, and
Les Zeller (Research Scientist), for all things electrical.

Queensland Health Scientific Services (specifically Gary Golding and Steve Tapper).

All the casual staff who transformed the idea for a supported straw cover into a functional object.

To all colleagues in Sustainable Intensive Systems, DPI&F, for their creativity, patience and good humour under some trying conditions while assisting with the field work.

DPI&F for financial support.

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Glossary and Abbreviations

Abbreviation	
APL	Australian Pork Limited
CIS	cooled inlet system
CO_2	carbon dioxide
COD	chemical oxygen demand
DPI&F	Department of Primary Industries & Fisheries, Queensland
ER	emission rate
GC	gas chromatograph
H_2S	hydrogen sulphide
ITD	ion-trap detector
L	litre
m	*meta*
MS	mass spectrometer
N	nitrogen
OER	odour emission rate
OU	odour units
p	*para*
PDMS	polydimethylsiloxane (silicone)
ppbV	parts per billion (volume/volume basis)
ppmV	parts per million (volume/volume basis)
PTR	proton-transfer reaction
SBSE	stirrer-bar sorbent extraction
SIM	selected ion monitoring
SIS	Sustainable Intensive Systems
SPME	solid-phase microextraction
SVOC	semi-volatile organic compound
TD	thermal desorption
TDU	thermal desorption unit
TKN	total Kjeldahl nitrogen
TS	total solids
UNSW	University of New South Wales
US EPA	US Environmental Protection Agency
UV	ultra-violet
VOC	volatile organic compound
VS	volatile solids

Non-Technical Summary

Assessment of the efficacy of permeable pond covers over a three-year period has confirmed that they are a cost-effective odour management tool. They have an anticipated life expectancy of at least ten years. Investigation of emissions of volatile chemicals and gases, as well as pond chemistry, has not provided any justification to avoid recommendation of this relatively low cost technology. Regulatory agencies are now in a position to accept this technology as one that has been adequately investigated, and as a consequence of which, predictable performance may be anticipated.

Adoption of this technology by the pig industry as an odour control tool should be limited only by site-specific circumstances and the costs and benefits of alternate technologies.

Selection of Cover Material
The efficacies of straw- and polypropylene and shadecloth composite covers at reducing odour emissions are quite similar.

It is recommended that polypropylene and shadecloth covers be used in preference to supported straw covers on the basis of cost and reduced maintenance over the life of the cover.
Maintenance of polypropylene and shadecloth covers appears to be largely driven by site-specific factors, provided the polypropylene is protected from UV damage.

Performance, Life Expectancy and Costs of Permeable Pond Cover
Efficacy of Reduction of Odour Emission Rates
When compared with the emission rate of the uncovered liquor of each pond, polypropylene and shadecloth covers reduced odour emission rates by about 74%, shadecloth-only covers reduced odour emission rates by about 70% while a supported straw cover reduced odour emission rates by about 66%.

When compared with the emission rate of an uncovered pond, a polypropylene and shadecloth cover reduced odour emission rates by 50%, while a shadecloth-only cover reduced odour emission rates by 41%.

The true efficacy of these covers is probably a lot higher – the nature of the odour released from the various cover surfaces is much less offensive than that emitted from the liquor. The apparently poor performance of the permeable covers is a reflection of the process of dynamic olfactometry - a presence/absence test, rather than a test of odour character or offensiveness.

Cover Life Expectancy
The life expectancy of the straw component of a supported straw cover is about 12 months. Cover efficacy can be maintained by an annual application of good quality straw.

Polypropylene covers require careful protection to ensure an acceptable life expectancy. Direct sunlight causes severe deterioration of the non-woven cover material within a 12-month period.
Manufacture and deployment of a composite cover comprising a non-woven geofabric, shadecloth and flotation devices is likely to provide a cost-effective odour management device with an effective life of at least ten years.

Cover Costs

A polypropylene and shadecloth cover is likely to cost about $ 12.00/m^2 for the initial construction and deployment. Taking into account the costs of managing the cover over an effective life of 10 years, the total costs over this period are likely to be about $ 35,000.00 (about $ 3,500.00 per annum per 1000 m^2 area).

Ongoing management is probably limited to infrequent inspection of the cover and periodic management of vegetation around the pond margin. The presence of a cover will not unnecessarily complicate sludge removal provided a suitable method is used and some simple precautions are taken.

Impact of Permeable Pond Covers on Pond Characteristics and Performance

Impact on Pond Performance

No evidence of impairment of anaerobic waste treatment was observed. There was no sign of decrease in pond liquor pH at any of the ponds. Liquor from the covered pond at piggery C had lower volatile solids, chemical oxygen demand and total solids concentrations than the uncovered control pond. Values of these variables at all covered ponds were within the ranges previously observed across a number of uncovered ponds surveyed in southeast Queensland.

Impact on Pond Physico-Chemical Characteristics

Concentrations of volatile compounds appeared to increase in covered pond liquor. The average concentration of sulphide in the liquor of covered ponds was up to five times higher than in the uncovered control pond at piggery C. The lowest ammonia-N liquor concentrations occurred in the uncovered control pond; average ammonia-N concentrations were 20 to 550 mg/L higher in the liquor of the covered ponds.

There was considerable variability in the concentrations of a number of water quality variables prior to the installation of the pond covers. These differences arose from factors such as historical pond management and sources of fresh water inputs to the ponds. Not all of the variation can be attributed to the presence of the pond covers. Overall, there was no evidence that installing a pond cover caused changes in pond chemistry likely to compromise treatment processes or increase pond management requirements.

Impact on Pond Microbiological Characteristics

Limited data makes it difficult to draw strong conclusions. The presence of a pond cover appeared to alter the microfloral population in terms of algal species and numbers quite substantially. The major change was the reduction in numbers of blue-green algae. The total number of algae was reduced significantly. Effective removal of light explained these observations.

Impact on Gaseous Emissions

On-going difficulties associated with equipment made quantification of volatile organic compounds (VOCs) difficult. It was soon apparent that collection of measurable amounts of odorants was an onerous task, quite different to the analysis of the standard "Air-toxics" suite (as identified by US EPA methodology). While the University of New South Wales (UNSW)-style wind tunnel provides emission rate estimates that are more credible than those of other sampling devices, the operating conditions within the wind tunnel effectively dilute the odorants. Collection of volatile chemicals from large volumes of air onto Tenax® sorbent tubes appeared essential. This made access to a modern, sensitive gas chromatography-mass spectrometry (GC-MS) system mandatory. The sample inlet system should be reasonably flexible, allowing recovery of trapped odorants from sorbent tubes

using thermal desorption and other equilibrium-based sampling techniques such as solid-phase microextraction (SPME) and stir-bar sorptive extraction (SBSE).

Odour emissions from Australian piggery pond treatment systems appear to be dominated by phenols and nitrogen heterocycles such as indole and skatole. Volatile fatty acids appear to be present at concentrations lower than those measured in Europe and North America. Phenol emission rates were not reduced significantly by permeable pond covers, whereas rates of emission of 4-methylphenol, indole and skatole appeared to be reduced quite markedly.

Measurement of carbon dioxide emission rates using a UNSW-style wind tunnel was also difficult. The large flushing rates and relatively high background concentrations of carbon dioxide in the flushing air made measurement of the incremental change caused by the liquor beneath the permeable cover difficult. No statistically significant differences in rates of emission were observed between covered and uncovered ponds using wind tunnel sampling systems.

Using a US EPA dynamic emission chamber, net median and average carbon dioxide emissions were 17% and 24% higher from covered pond surfaces than from an uncovered control pond. These values were reasonably similar to those reported in the literature (increases in the range 33 to 38%, with one report of a 97% increase from a straw covered pond).

A distinct diurnal pattern in carbon dioxide emissions was observed – it is likely that biological activity in the surface of the cover may be responsible for the emission rate characteristics from the covered pond.

Despite the difficulties experienced with measurement equipment, both wind tunnel and flux chamber sampling devices indicated hydrogen sulphide concentrations were greater from the surface of the permeable cover than the liquor of the control pond. These results were consistent with the pond chemistry results, which indicated that average total sulphide concentrations were about five times greater in the covered pond liquor than the uncovered control.

Impact on Pond Liquor Chemistry

Differences in pond liquor quality between ponds appeared more significant than differences in pond chemistry caused by deployment of a permeable pond cover. Liquor concentrations of hydrogen sulphide and ammonia appeared to increase following cover deployment. No significant differences in concentrations of variables that might indicate pond treatment failure were observed. Liquor pH values, and volatile solids and chemical oxygen demand concentrations showed no signs of increasing or decreasing trend. The discharge from a covered pond did not appear to contain greater concentrations of under-treated waste material which could increase the loading rate on a secondary or facultative pond.

Mechanisms whereby Permeable Covers Reduce Pond Emissions

The reduction in odour emission rates observed over the period of this research indicate that both physical barrier and biofilter mechanisms are likely to contribute to the efficacy of the covers.

Relationship between Odorant Concentrations and Olfactometry

It was not possible to develop a model relating liquor odorant concentrations to the odour concentrations determined by dynamic olfactometry. The volume of data available describing the odorant signature of the odour samples was inadequate for the task.

It was possible however to demonstrate that a sensor-array was able to provide quantitative and qualitative information which was entirely consistent with the information derived from olfactometry. In view of the simplicity, lower capital and operating costs of sensor-based technology, together with demonstrated capability, this emerging technology is considered worthy of future investigation as an odour assessment tool.

Impact of Pond Covers on Emissions from Housing or Effluent Irrigation Areas

Use of a housing model indicated that odour emissions from housing flushed with covered pond liquor was likely to be about five times greater than that from liquor derived from an uncovered pond.

Actual measurements from housing showed that the differences in emission rate from a shed flushed with liquor derived from covered and uncovered ponds were unlikely to have an impact on downwind receptors. The exchange of odorants from the air space below the slats with the bulk air above the slats was probably less efficient than the exchange process that took place within the housing model, where a dynamic and turbulent interface was created between the air and liquid phases.

No statistically significant difference in emission rate was detected between grass covered surfaces irrigated with liquor derived from covered or uncovered ponds. The presence of an additional odorant load in liquor derived from a covered pond is likely to pose an odour risk only during the actual application period. This is an inherently odorous activity – the odour potential is best managed by timing the application appropriately, rather than desisting from effluent irrigation.

Assessment of the Impact of Permeable Covers on Odour Intensity and Offensiveness

Using an in-house method based on a published procedure, it was demonstrated that an inverse relationship existed between odour concentration and odour intensity score three ("distinct"). This trend coincided roughly with the different emitting surfaces. Highly concentrated (and generally more offensive odour samples) were classified as "distinct" at lower concentrations than samples derived from surfaces such as the pond covers. Practical application of these results is not obvious at present, however; additional information, such as a rating of offensiveness, may be required before this technique may be used in an improved regulatory framework.

Alternate Odour Assessment Tools

While GC-MS is a well-established and sensitive investigation tool, it does appear to have specific limitations in the context of odour assessment. Odorants elicit responses in receptors at very low concentrations. These may be near the limits of detection for the GC-MS technique.

Use of GC-MS for analysis of samples at these concentrations requires pre-concentration of the odorants. Such pre-concentration unavoidably introduces discrimination into the analysis process by under- or over-representing certain constituents.

Proton-transfer reaction mass spectrometry appears to offer very high sensitivity without the requirement for sample pre-concentration. The high cost of the technique is likely to limit widespread use for odour assessment in the foreseeable future.

Sensor-array (electronic nose) technology offers immediate opportunities for air quality assessment. It was able to discriminate between odour samples derived from closely related odour sources. It was also possible to quantify odour samples. There is however, a requirement to demonstrate the capability of this technology for real-time odour measurement under ambient conditions.

1 Introduction

Odour impact on nearby receptors continues to be a problem for intensive livestock industries. While compliance with regulatory requirements and high quality, dedicated management of an intensive livestock facility may reduce the potential for odour impacts, the combination of large numbers of animals, significant volumes of manure, spilt food and water and atmospheric dispersion processes makes elimination of odour impact impossible.

Encroachment of residential settlement into areas of rural land use is happening across Australia. This creates the potential for odour arising from intensive livestock facilities to impact on large numbers of people. There is therefore increasing interest by primary producers in identifying and implementing effective odour management strategies. A number of quite diverse techniques and products have been proposed as odour management tools for the pig industry. These include:

- Modification to diet (specifically protein composition) (Nahm, 2003; Clark et al., 2005);
- Incorporation of food additives to improve digestion and/or impair biochemical processes (McCrory and Hobbs, 2001);
- Implementation of specific waste management products, such as rods claimed to energise waste treatment (Dunlop et al., 2003);
- Implementation of advanced waste treatment processes primarily derived from municipal waste treatment systems, such as activated sludge processes and sequencing batch reactors (Tao et al., 1998; Chynoweth et al., 1998; Zhang et al., 2000).

A number of odour management strategies recognise that odour is produced from different areas of the pig production system – the odour emissions from these specific areas of production are then targeted for remediation.

Emissions from housing may be minimised by careful attention to cleaning and management of the housing. Careful design and construction may create conditions within the housing that encourage good dunging practices, reducing manure accumulation within pens or on the animals. Spraying oils into the shed environment has been demonstrated to reduce particulate emissions. This is thought to reduce odour emissions as well (Jacobsen et al., 1998).

Previous research has shown that both animal housing and waste treatment ponds are significant sources of odour. According to Zhang and Gaakeer (1998) and Smith et al. (1997; 1999) between 50 and 85 % of odour emissions arise from manure storage or pond treatment systems. As the dominant source of odour at conventional piggeries, it is therefore logical that pond treatment systems should be targeted for odour reduction.

While pond treatment systems have relatively low construction costs, and are relatively inexpensive to operate, the simplicity of such systems limits the level of intervention possible in order to modify the waste treatment process. The pond treatment systems installed at typical Australian piggeries do not allow for screening, stirring, recirculation or aeration, which are common practices at municipal or industrial wastewater treatment plants. Implementation of improved waste treatment processes such as sequencing batch reactors will impose increased capital and running costs on the piggery. It is also doubtful that most piggeries would have the human resources necessary to operate an advanced biological waste treatment system. Implementation of advanced treatment systems would also make existing pond treatment systems redundant, presumably an unattractive proposition to most producers.

The remaining options for reducing odour emissions from anaerobic treatment ponds using simple, low cost odour reduction techniques are quite limited. In an initial investigation undertaken on behalf of Australian Pork Limited (APL), permeable covers were identified as tools that might reduce odour emissions from anaerobic treatment ponds (Hudson et al., 2001). A potential benefit over other treatment systems was the fact that such a cover was a low-cost, add-on technology, with minimal redundancy. The literature review undertaken for this project provides a comprehensive background to this technology, including the evolution of permeable covers. This information was summarised as a peer-reviewed scientific publication (Hudson et al., 2006).

Laboratory and field scale trials undertaken on behalf of APL demonstrated that supported permeable covers had the potential to reduce odour emissions by at least 50%. Field measurements showed that both supported-straw and polypropylene covers were able to reduce odour emissions by up to 90% over a period of almost 12 months. Polypropylene-based covers offered cost advantages over straw covers. In addition, polypropylene covers appeared to require less maintenance than straw-based covers.

This reduction in odour emission rate significantly exceeded the performance hypothesized (50%) in the original proposal. The fairly consistent odour reduction observed over the trial period also indicated that implementation of this technology may offer ongoing and predictable performance. Initial estimates indicated that covers of this type might be affordable for most producers. It was estimated that supported straw covers could be installed for about A$ 12.00/m^2, while covers based on polypropylene might be installed for about A$ 7.50/m^2. These costs compared very favourably with those associated with impermeable covers. The cost for the materials, fabrication and installation of impermeable covers were estimated to be between A$ 30.00/m^2 and A$ 80.00/m^2. Additional plant is required to treat the biogas trapped under the cover. Typically biofiltration or gas flaring is used to eliminate odour from this biogas. Inclusion of these costs was estimated to raise the costs of an impermeable cover above A$ 130.00/m^2. Both biofilters and gas flaring treatments require ongoing maintenance and management – these costs would be additional to those identified earlier.

While permeable covers appeared to provide significant reduction of odour emissions from anaerobic treatment ponds, the initial trial provided "proof of concept", not a definitive guide to the industry regarding the long-term odour control performance, impact on waste treatment or likely capital and operating costs. A major weakness in the initial field-scale trials was the fact that the odour performance was determined on a series of trial covers that covered less than 5% of the total surface of the treatment pond. The impact of full coverage of the pond surface on odour control and waste treatment remained speculative. In addition, the laboratory-scale trials had demonstrated that volatile chemicals (specifically carbon dioxide and hydrogen sulphide) were retained in the covered liquor. This created the potential that odorants retained in the liquor might be released at other stages of the waste management process, such as during flushing (thereby increasing emissions from the housing), or during land application.

It was recognised that these weaknesses in the original research would limit the implementation of a potentially very useful odour management tool. Uptake of this research required full investigation of these issues. As a consequence, APL agreed to fund a second, more comprehensive research project to further investigate these issues and to verify the performance of permeable covers over a longer period.

1.1 Objectives of the Research Project

The research addressed seven specific objectives:

1. **Following trials over a minimum 30 month period, produce a comprehensive "how to" guide to enable the construction, deployment and maintenance of permeable pond covers by producers.**
   Selection of cover type, materials and manufacture would be described in detail.
   Suitable methods for deployment of cover support and application of straw would be described in detail.
   Maintenance schedule and methods of maintenance would be described.
   Diagnostic factors enabling sustainable pond management would be identified.
2. **Determine and report permeable pond cover life expectancy and costs.**
   Pond cover performance would be identified and reported in terms of odour reduction over time for all cover materials trialled.
   Material life expectancy would be defined under the environmental and operating conditions that prevailed at the test site(s).
   The factors that most influenced cover life expectancy would be identified.
   This information would be used to estimate the costs of permeable cover technology over a 10-15 year period to enable comparison of true costs with those of impermeable covers.
3. **Comprehensively report the impact permeable covers had on pond characteristics and performance over a three-year period.**
   The impact installation of a permeable cover had on the performance of an anaerobic pond, including supernatant chemical, physical and biological variables, would be clearly identified.
   The impact installation of a permeable cover had on gaseous emissions from ponds, including greenhouse and biogas components, as well as selected semi-volatile organic compounds (SVOC's) and volatile organic compounds (VOC's), known to be powerful odorants, would be clearly identified.
   Typical ranges for supernatant chemical and physical variables that might be expected if a permeable cover is in place for an extended period would be defined.
   If relevant, those factors that indicated that normal pond treatment processes were beginning to fail would be defined.
4. **Identify the basic processes whereby permeable covers reduce odour emissions.**
   The processes whereby odour emission was reduced, i.e. is the permeable cover a biofilter or a physical barrier, or do both mechanisms play a role in odour management, would be identified.
   The relative success or failure of covers in reducing odour emission would be explained as far as possible.
5. **Investigate the relationship between ambient air odorant concentrations and olfactometry**
   The relationship between air concentrations of individual odorants and olfactometry data would be quantified.
   The concentrations of odorants in supernatant would be compared with those in air above various cover types to improve predictive modelling of odour emission.
   Areas of future research whereby chemical, biochemical and physical processes could be manipulated at the molecular level (using permeable covers) to improve air quality management would be identified.

6. **Investigate whether emissions from housing and effluent irrigation areas are increased following the deployment of a permeable cover on a pond**
   Rates of odour emission from standard pig housing before and after permeable covers were installed on an anaerobic pond used as a source of flushing liquid would be determined.
   Rates of odour emission would be determined from soils irrigated with effluent derived from covered and non-covered anaerobic ponds.
   The impact pond covers may have on whole of farm odour emission rates would be quantified.
7. **Assessment of impact of permeable covers on odour intensity and offensiveness**
   Various techniques would be assessed to determine the impact of the covers on odour intensity and offensiveness.

2 Introductory Technical Information

Review of the scientific literature published since the original report was released provided some additional information regarding the performance of permeable cover materials.

2.1 Straw-Based Covers

Relatively few field trials have been conducted to assess the efficacy of straw-based permeable pond covers in reducing odour emission rate. Clanton et al. (1999) performed large scale laboratory trials of unsupported straw covers over a 60 day period. The straw cover reduced the odour emission immediately by 60% and by up to 78% three weeks later. The trial could not be continued because the unsupported cover sank.

In a subsequent trial, Clanton et al. (2001) used straw as a surface layer on a geotextile fabric base. Over a 10-week study period, odour emissions were reduced by 47% and 79% for 100 mm and 300 mm thick layers of straw respectively. The small "anaerobic waste volume" to "cover thickness" ratio caused by the experimental facilities selected for the trial may have caused under-loading of the cover with regard to odour.

Cicek et al. (2004) undertook a short-duration assessment of the efficacy of an unsupported straw cover. An entire pond was covered with a straw layer (thickness unspecified). Odour samples were collected from the surface of this pond and a similar uncovered pond on a neighbouring farm. Three sets of samples were collected over a 10-day period using a wind tunnel of the type developed at the University of New South Wales (Jiang et al., 1995). These were analysed using dynamic olfactometry. Although emission rates were not calculated, it was possible to compare the odour concentration of the samples because the wind tunnel was operated under standardised conditions. The straw cover reduced the odour concentration by an average 31% over the three sample days.

2.2 Geofabric Based Covers

Little information has been published regarding the performance of geofabric-based covers. Clanton et al. (1999) evaluated a 0.3 mm geotextile cover on a series of 7,500 L tanks containing pig manure. Following an assessment period of approximately three weeks, it was concluded that a geotextile cover reduced odour by about 59%.

In a subsequent investigation, Clanton et al. (2001) investigated the efficacy of three thicknesses of geofabric in reducing odour emissions. Over a ten-week assessment period, 0.3 mm, 1.1 mm and 2.4 mm thick geofabrics provided -22%, -4% and 39% odour reduction respectively.

Dobson et al. (2002) assessed the efficacy of a composite permeable cover based on geofabric. The cover was a commercial product called Biocap™. Odour reduction was assessed using field odour assessment techniques, so actual odour emission rates were not reported. The number of field observations reported as "below the detection threshold" was 84% for the covered pond, while it was 30% for an uncovered control pond. The frequency of detection of objectionable odour near the covered pond was 16%, while it was 70% at the uncovered control.

Bicudo et al. (2004) conducted a two year evaluation of a commercial permeable cover (Biocap™). The trial took place at full scale at three pig farms. At each farm, one treatment pond was covered completely, while another pond was left uncovered as a control. About 200 odour samples were collected from either the pond or cover surfaces over the trial period using a UNSW-style wind tunnel. Olfactometry was performed according to the CEN standard (1999), upon which the Australian olfactometry standard is based (Standards Australia and Standards New Zealand, 2001). Odour emission rates from the covered ponds were reduced by between 15% and 76% over the trial period, with an overall average reduction of 51%. It was observed that the performance of the cover deteriorated in the second year of the trial relative to the first year. Deterioration in cover performance was speculatively attributed to "environmental factors and chemical reactions occurring within the geotextile".

The limited additional material published since the publication of the results from APL project 1473 provided the following general information regarding the performance of permeable covers for odour reduction:

1. Straw covers reduced odour emissions by between 31% and 90%;
2. The performance of straw covers was dependent on the cover remaining above the liquor surface;
3. Buoyancy or support was essential if long-term odour reduction or consistent performance was required;
4. The performance of geotextile-based permeable covers appeared quite variable (-22% to 90% odour reduction), with no clear identification of causative factors.

Other practical issues required investigation before this technology could be offered to the industry as attractive or dependable. These are stated as a series of questions that might be asked by a producer or regulator:

- How long will the various permeable covers last under operating conditions typical of my piggery?
- Which type of cover will best suit my operation and where do I obtain the materials?
- How do I manufacture and deploy a large cover, or can I outsource these tasks?
- How will I maintain my waste treatment system once the cover is in place?
- Is it necessary to remove the cover during desludging and how will it be done?

Other, more scientific issues had been raised following completion of APL projects 1473 and 1628. These issues would most likely be of particular interest to regulatory agencies, who would be anxious to avoid the adoption of relatively untested technology. Failure to answer these questions might lead to compromises of waste treatment processes or untimely failure of the odour reduction technology, leading to unexpected odour impacts:

- Will a permeable cover compromise waste stabilisation?
- Will odorants accumulate in the pond supernatant?
- Will housing odour emissions increase during flushing if pond chemistry is altered?

- How well will these covers reduce odour emissions over daily, seasonal, annual or longer timescales?
- What are the processes whereby permeable covers reduce odour emission?
- Are reductions in odour emissions sustainable?
- Can measured concentrations of odorants be related to olfactometry results?

3 Research Methodology

3.1 Estimation of Waste Loading Rates

The spreadsheet model PIGBAL (Casey et al. 1999) was used to estimate pond loading rates. Utilising typical metabolic factors for pigs, feed composition and measured feed and water usage values, the model provided realistic estimates of waste production for typical Australian piggeries (McGahan et al., 2000). Waste outputs are typically reported as mass of volatile solids per m^3 active pond treatment volume per day (mass VS/m^3/day).

3.2 Field Trial Facilities

Trials were undertaken at three different piggeries:

Piggery A was a small piggery housing approximately 80 boars, producing semen for the artificial insemination market. The animals were housed in a single, slat-floored building. Waste was flushed from the building weekly using pond liquor sourced from a second, wet weather storage pond located on the property. Hosing of the pens and laneways occurred every second day. The waste was discharged directly into a small primary pond, measuring approximately 17 m x 9 m with a storage volume of 210 m^3. The waste loading rate was estimated to be about 130 g VS/m^3/day.

Piggery B was operated as a grow-out facility. Weaners were received at eight weeks of age from piggery C and exited at about 23 weeks of age. The average herd size of about 1,300 animals was housed in three separate buildings. The liquor used for flushing the sheds was derived from a single 9,200 m^3 anaerobic pond, into which the waste derived from the sheds was discharged approximately daily. The waste loading rate was estimated to be about 80 g VS/m^3/day.

Piggery C was operated as a breeder-grow out unit, with one third of the pigs born on site raised until sent to market and the remainder sent off-site for finishing. Animals were housed in nine fully slatted sheds. All flushing and hosing water was derived from municipal supply. Hosing occurred every second day, while flushing took place weekly. Approximately 2,400 animals were housed on site at any time. Waste was discharged to a pipeline that contained a splitter box. This diverted approximately half of the waste load and volume to each of two similarly sized anaerobic ponds (40 m x 35 m). Excess liquor discharged from each pond into a single secondary pond. Each primary pond experienced a waste loading rate of about 50 g VS/m^3/day. The parallel configuration of the two anaerobic ponds was very fortuitous – it allowed one pond to be covered and the other to be left uncovered as a control.

3.3 Permeable Pond Covers

Two types of permeable pond cover were trialled – polypropylene geofabric and supported straw. The polypropylene geofabric cover was manufactured from a non-woven, spun-fibre, needle punched polypropylene material. Typical specifications for the felt-like material were 55 g/m^2 density, 4.4 mm thickness and a specific gravity of about 0.9. The fabric was supplied commercially as a 4 m x 60 m roll. Lengths of fabric were sewn together to create a series of discrete pond cover units. Experience indicated that units larger than 400 m^2 were too heavy to manoeuvre with available

resources. Each cover unit was manufactured to provide "pockets" running the length of the cover at about 2 m centres and across the breadth of the cover at about 4 m centres. Polystyrene blocks wrapped in waterproof material were inserted into these pockets to provide buoyancy. Previous experience with smaller cover units showed that this buoyancy was essential to ensure that the covers would not sink. This was especially important along the cover margins.

In a typical installation, the individual cover units were unrolled along the pond margin, the buoyancy was inserted into the pockets, and the cover unit moved out on to the pond. The process was repeated for each unit in succession. Once all the units were deployed, the fabric was attached to steel pickets around the pond perimeter. Deployment of a polypropylene cover at pond A is shown in Figure 1 and Figure 2 :

Figure 1: Polypropylene cover ready for deployment

Figure 2: Polypropylene cover deployed on pond

Deployment of a polypropylene cover at pond C is shown in Figure 3 and Figure 4:

Figure 3: Polypropylene cover ready for deployment

Figure 4: Polypropylene cover deployed on pond

The supported straw cover was manufactured using similar materials to those described previously (Hudson et al., 2006). In the initial deployment, the barley straw was manually applied to the supporting surface. Figure 5 and Figure 6 show application of straw in progress. Subsequent replenishment of the straw layer made use of a mechanical shredder coupled to a blower unit. Bales

of straw were manually fed into the shredder and the resulting chopped straw was blown onto the cover. This technique could cover a pond about 60 m wide under calm conditions.

The pond at piggery A (pond A) was covered completely using a polypropylene geofabric cover. Approximately one-third of the surface of the pond at piggery B (pond B) was covered with a supported straw cover, while the remaining two thirds of the surface was covered with a polypropylene cover. One of the ponds at piggery C (pond C, covered) was completely covered with a polypropylene cover. The other pond at piggery C (pond C, control), was left uncovered as a control.

A comprehensive guide to covering a pond is provided as Appendix 1.

Figure 5: Commencement of straw application to support

Figure 6: Straw applied to about ¼ of straw-covered surface

3.4 Modification in Response to Ultraviolet Radiation Damage to Covers

Continuous exposure to intense sunlight caused obvious damage to the polypropylene geofabric within 12 months following deployment. Where the cover was damp, damage did not occur. This was attributed to the biomass that accumulated on the surface of the cover, providing protection from ultraviolet radiation. In areas where the cover fabric was dry (e.g. along the ribs created by the buoyancy material), thinning of the fabric occurred, followed by the appearance of holes and finally, complete disintegration and disappearance of the fabric. To overcome this problem, the entire polypropylene cover was overlain by a polyethylene shadecloth (95% + shade factor). The shadecloth was deployed in the same manner as the polypropylene fabric. Additional buoyancy was not required however – the shadecloth was fully supported by the polypropylene layer. This arrested further deterioration of the polypropylene cover.

3.5 Odour Sample Collection

To assess the impact of the various covers on odour emission, it was necessary to determine the odour emission rate for each surface. A wind tunnel constructed according to Jiang et al. (1995; 2001) was used for this purpose. This is the same device that was used to collect samples for APL projects 1473 and 1628 (Hudson et al., 2001; Hudson et al., 2004). The operation of the wind tunnel was previously described in these reports and in the literature (Hudson et al., 2006; Hudson et al., 2007).

In our previous trials, it was possible to suspend a wind tunnel from a gantry floating on two pontoons (Hudson et al., 2006). This gantry was manoeuvred above the supported cover, the wind

tunnel remotely lowered onto the pond cover and the samples collected. With the surface of the ponds covered completely, it was not possible to use this method. A cableway was created across each pond, from which the wind tunnel and accompanying air supply and sample lines were suspended (see Figure 7 and Figure 8). The wind tunnel could in theory be positioned anywhere along the cableway transect. Typically, samples were collected 12 m to 15 m from the pond margin. Once in position, the wind tunnel could be raised or lowered using remotely operated winch motors. This ensured that the wind tunnel achieved a good seal on the emitting surface without submerging the cover excessively. Absence of leakage at the interface between the wind tunnel and the emitting surface was assessed by measuring the air flow entering and exiting the wind tunnel. A difference in airflow at these points indicated a leak and the necessary adjustments were made.

Figure 7: Wind tunnel suspended from cableway above liquor, control pond, piggery C

Figure 8: Close-up of wind tunnel suspended from cableway above liquor, control pond, piggery C

All odour samples were collected using previously described materials and methods (Hudson et al., 2006; Hudson et al., 2007). Samples were stored in the shade until transported to the olfactometry laboratory for assessment. Samples were collected from all emitting surfaces on each sampling occasion in duplicate. All samples were analysed within six hours of collection.

3.6 Odour Sample Collection Points

To assess the efficacy of the pond covers, it was necessary to collect odour samples from the surface of the cover, as well as from the liquor beneath the cover. At each pond, a "window" was created in the surface of the polypropylene-shadecloth surface to allow access to the liquor. This window was usually covered by a flap of shadecloth. This flap could be peeled back to expose the liquor surface. The covered "window" and sampling off the exposed liquor is shown in Figure 9 and Figure 10.

Figure 9: Sampling from cover, adjacent to "window" cut into polypropylene cover

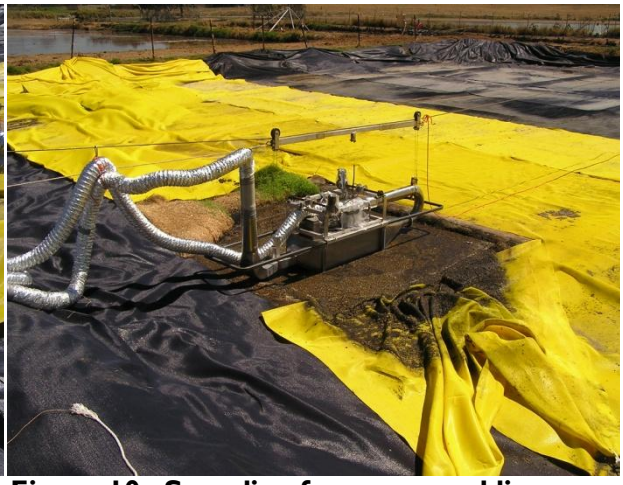


Figure 10: Sampling from exposed liquor, accessed by peeling back shadecloth cover

A number of sample points were defined for each pond:
At pond A, samples were collected from i) the surface of the combination polypropylene-shadecloth cover; ii) the surface of the shadecloth in contact with the liquor and iii) from the exposed liquor (total of three emitting surfaces).

At pond B, samples were collected from i) the surface of the combination polypropylene-shadecloth cover; ii) from the surface of the supported straw cover, and iii) from the exposed liquor (total of three emitting surfaces).

At pond C, samples were collected from i) the surface of the combination polypropylene-shadecloth cover; ii) the surface of the shadecloth in contact with the liquor; iii) from the exposed liquor of the covered pond, and iv) from the surface of the control pond (total of four emitting surfaces).

In all tables and charts, the data arising from each odour source is identified by the following abbreviations:

- PP refers to the polypropylene-shadecloth cover surface;
- S refers to the shadecloth-only cover surface;
- SW refers to the supported straw cover;
- L refers to the exposed liquor surface, and
- Lcon refers to the liquor surface for the control pond (pond C only).

3.7 Odour Sample Assessment

Odour concentrations were determined using an eight-panellist, triangular, forced-choice dynamic olfactometer constructed and operated in compliance with the requirements of the Australian/New Zealand Standard for Dynamic Olfactometry (Standards Australia and Standards New Zealand, 2001). This Standard was largely based on European Standard EN 13725 (CEN, 1999). Standard operating details were described previously (Hudson et al., 2006; Hudson et al., 2007). Odour concentrations were reported as odour units/m^3 (OU/m^3). Odour emission rates (OER or E) were calculated using Equation 1 and expressed in OU/m^2 s:

$$E = CV_t \frac{A_t}{A_s}$$

Equation 1

where C is the odour concentration in the sample bag (OU/m³), V_t is the wind speed inside the tunnel (m/s), A_t is the cross sectional area of the tunnel (m²), and A_s is the surface area covered by the tunnel (m²).

Equation 1 assumes that all background odour is removed from the air introduced into the wind tunnel by the carbon filter, and there is complete mixing between the emissions and the airflow in the tunnel (Smith and Kelly, 1996).

3.8 Measurement of Odour Emissions from Pasture Irrigated with Pond Liquor

Typical effluent irrigation application rates were calculated with consideration of the following variables: soil type and likely direct nutrient losses, infiltration rates, crop type, management practice and likely nutrient removal rates and typical liquor nutrient characteristics.

Values for critical variables used to calculate typical liquor application rates are summarised in Table 1:

Table 1: Values used to calculate typical liquor application rates

Variable	Value
Pasture dry matter yield	9 tonne/Ha/year
Nitrogen removal rate (@ 2% N)	180 kg N/Ha/year
Nitrogen losses:	
• during application	25%
• from soil	25%
Maximum N application rate	320 kg N/Ha/year
Typical liquor ammonia N concentration	537 mg/L

Application rates were calculated using Equation 2:

$$Liquor\ application\ rate = \frac{Maximum\ application\ rate\ (mass\ N/Ha/year)}{Average\ liquor\ N\ concentration\ (mass\ N/ML)} \qquad \textbf{Equation 2}$$

$$= \frac{320\ kg\ N/Ha/year}{537\ kg\ N/ML}$$

$$\approx 0.56\ ML/Ha/year$$

$$\approx 60\ mm/year$$

On each day, six applications equivalent to 10 mm precipitation depth were made to the pasture, which required an application of 10 L/m² on each pass. Each application of the total volume of liquor took place over a period of 20 to 30 minutes. This created an effective hydraulic application rate of 20 to 30 mm/hour.

An area of kikuyu lawn at the Tor Street campus of DPI&F was selected for the liquor application. Approximately 200 L of liquor was withdrawn from the covered and control ponds at piggery C and transported to Toowoomba in 200 L polyethylene drums. Liquor was applied to previously marked-out areas of turf using plastic watering cans equipped with fine rose spray nozzles.

Three areas were marked out for each application event. These areas were randomly allocated as:

- control area, where no liquor was applied,
- covered liquor application area, and
- control liquor application area.

The experimental procedures for liquor application and odour sampling are illustrated in Figure 11 and Figure 12.

Figure 11: Sampling from control area while covered liquor is applied to adjacent area

Figure 12: Sampling from area to which control pond liquor was applied

3.9 Measurement of Odour Emission Rates from Flume during Flushing

A simple flume was constructed to compare emission rates derived from liquor sourced from the covered and control pond at piggery C under turbulent flow conditions, analogous to conditions that occur in the flushing channel under slatted floor housing.

Liquor was pumped from either the covered or control pond using a centrifugal sump pump. The liquor was discharged into a simple enclosed flume set up adjacent to the ponds. The flume was set up on a sloping bed of crusher dust to create a fall of about 1°. The flume was continuously ventilated during the flushing operation with a small 240 VAC fan, creating emission conditions similar to those in a wind tunnel. The flume characteristics are summarised in Table 2:

Table 2: Characteristics of flume

Variable	Value
Flume length (m)	6.91
Flume width (m)	0.6
Flume height (m)	0.28
Flume floor area (m^2)	4.15
Flume cross-sectional area (m^2)	0.168
Ventilation rate within flume (m^3/s)	~ 0.042
Wind velocity within flume (m/s)	~0.25

The construction of the flume is shown in Figure 13 and Figure 14. The plastic lining was used to eliminate leakage from the flume. Creases in the lining also provided some irregularity to the surface of the flume, creating turbulence similar to that expected in a concrete channel, which would presumably increase odour emissions.

Figure 13: Partially constructed, unlined flume looking down-gradient

Figure 14: Partially constructed lined flume looking down-gradient

Figure 15 shows the numerous items of equipment required to operate the flume during odour sample collection (Figure 16). It was necessary to split the volume of flow delivered by the pump, which had a greater capacity than that required to generate a moderate flow through the flume.

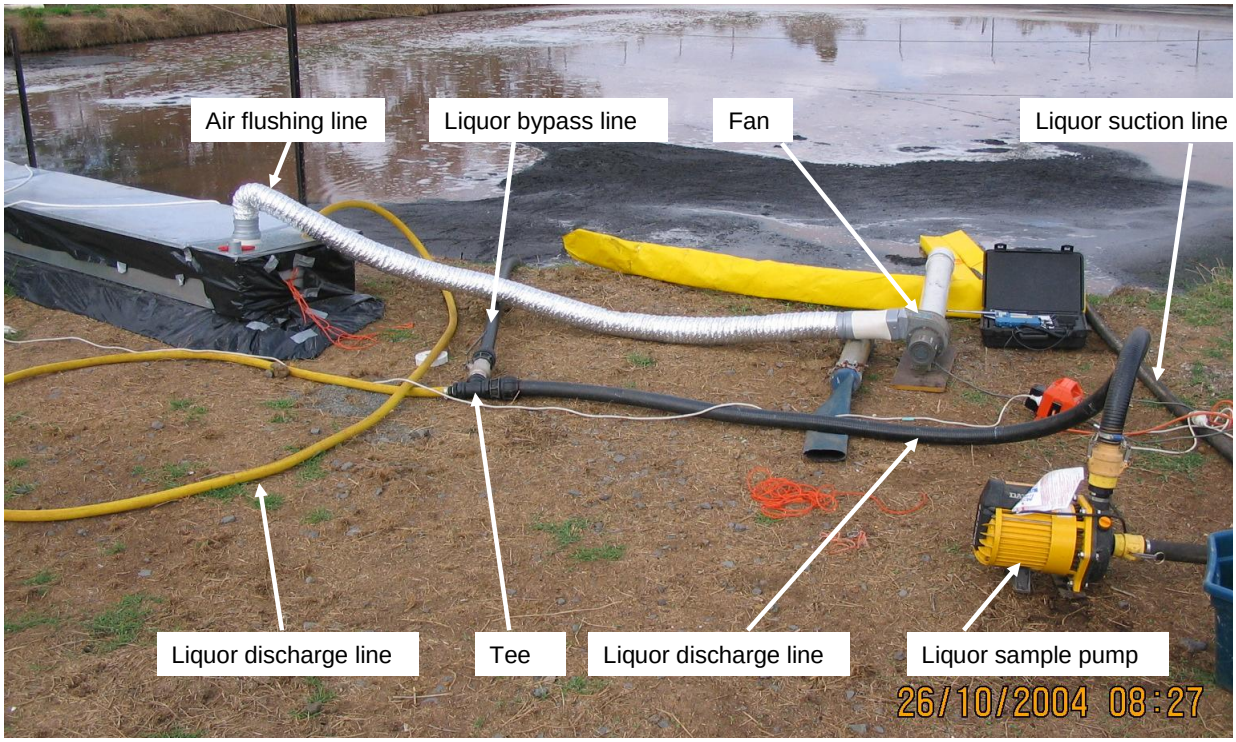


Figure 15: Ancillary equipment required during flume emission rate assessments

Figure 16: Odour sampling from flume during flushing

3.10 Measurement of Shed Odour Emission Rates Following Flushing

3.10.1 Ventilation Rate Estimation

It is difficult to accurately determine odour emission rates for naturally ventilated structures such as piggery buildings. The area of openings in the housing is often automatically controlled; the amount that shutters or curtains are opened is primarily controlled by ambient and shed temperatures. The effective air exchange rate is usually determined by the ambient wind speed. Ventilation may be improved using internally and externally mounted fans. Older style sheds may also have ridge vents to improve air flow. The combination of these physical characteristics makes it extremely difficult to estimate the shed ventilation rate. It is also difficult to identify a position where representative odour samples should be collected. As a consequence, estimates of odour emission rate made under these conditions may be quite inaccurate and difficult to replicate.

To overcome these issues, a small shed used to quarantine recently arrived weaners at piggery B was used to quantify shed odour emission rates. The shed was temporarily converted into a tunnel-ventilated structure, with well-defined air inlet and air exhaust points. Adequate air flow was achieved by making a leak-tight connection between a doorway and a large ventilation fan. The temperature control over the shutter openings was disabled while the shed was in tunnel ventilation mode. Under these conditions, ventilation was a function of:

- the fan capacity,
- any flow measuring section attached to the outlet of the fan, or
- any restriction to the air inlet to the shed.

The shed therefore became a large wind tunnel, subject to similar factors as the wind tunnel used for sampling from cover or liquor surfaces. This situation allowed ventilation rates to be set repeatedly and with the required accuracy.

The characteristics of the weaner shed are summarised in Table 3:

Table 3: Characteristics of the shed used to compare emissions resulting from use of covered and control liquor

Parameter	Value
Shed width (m)	5.5
Shed length (m)	19.5
Shed internal height at side walls (m)	2.61
Shed internal height at apex (m)	2.71
Shed cross-sectional area (m^2)	14.63
Flushing tank volume (L)	1,881
Number of flushing tanks	2

Table 4 summarises the performance data for the fan used to ventilate the shed, while

Table 5 summarises the actual shed ventilation conditions achieved with the experimental setup chosen.

Table 4: Characteristics of the fan used to ventilate shed to compare emissions resulting from use of covered and control liquor

Parameter	Value
Fan diameter (mm)	400
Typical air discharge velocity from fan (m/s)	25
Typical fan discharge rate (m^3/s)	3.1

Table 5: Shed ventilation characteristics during tunnel mode

Parameter	Value
Shed internal volume (m^3)	285.3
Ventilation rate (m^3/hour)	11,500
Exchange rate (/hour)	40
Exchange interval (minutes)	1.5
Wind velocity with shed (m/s)	~0.21

The weaner shed is shown in Figure 17 and Figure 18. The latter picture shows the side shutters raised by the automatic temperature control system, while in Figure 17 the shutters are lowered (tunnel ventilation mode).

Figure 19 shows odour sample collection in progress. The odour samples were collected from the discharge from the ventilation fan.

Figure 17: View of weaner shed from side where odour samples were collected

Figure 18: Making a leak-tight connection between shed doorway and fan

Figure 19: Odour sample collection

3.10.2 Flushing of Shed with Covered and Control Liquor

To assess the impact of the source of the liquor on the shed emission rate, it was necessary to flush the shed with liquor derived from both covered and uncovered ponds. Weaners from piggery C were grown out at piggery B – this made it possible to transport liquor from the control and covered ponds at piggery C to piggery B without raising biosecurity issues.

For this trial, liquor was withdrawn from the control pond and covered pond respectively into separate tankers by a commercial waste transport operator. This liquor was transported to the weaner shed at piggery B and discharged into the concrete flushing tanks at the end of the building. The road transport and one of the two tanks used to flush the shed are shown in Figure 20 and Figure 21 respectively. The air flow through the shed was derived from the doorway adjacent to the flushing tank shown in Figure 21.

Figure 20: Road tanker used to transport liquor from piggery C to piggery B

Figure 21: Concrete flushing tank on opposite end of shed to that used for odour sample collection

During the flushing/odour sampling process, the following routine was followed:

1. The shed was converted into tunnel ventilation mode and shed ventilation was stabilised.
2. The shed was flushed with liquor derived from the local pond.
3. Ventilation was allowed to proceed for about 30 minutes to allow odour emission to stabilise.
4. Odour samples were collected to determine the background shed odour.
5. The concrete flushing tanks were filled with liquor from the control pond of piggery C.
6. The shed was flushed with this liquor and the collection of the odour samples commenced immediately.
7. Ventilation was allowed to proceed for about 30 minutes to allow odour emission to stabilise once again.
8. The concrete flushing tanks were filled with liquor from the covered pond of piggery C.
9. The shed was flushed with this liquor and the collection of the odour samples commenced immediately.
10. The shed was converted back into natural ventilation mode.

Odour samples were collected after the initial flushing and stabilisation time (shed background odour), immediately after flushing with liquor from the control pond, and immediately following flushing with liquor sourced from the covered pond. At least 30 minutes was allowed between sample collection periods to allow thorough ventilation of the shed and dilution of residual odour.

3.10.3 Calculation of Shed Odour Emission Rate

Odour emission rates (OER) were calculated using Equation 3 and expressed in OU/m^2 s:

$$OER = \frac{Odour\ concentration \times shed\ air\ velocity \times shed\ \ face\ area}{shed\ \ floor\ area}$$ **Equation 3**

3.11 Calculation of Odour Reduction Efficiency of Various Cover Types

For pond A and pond B, the performance of the pond covers was calculated as a "relative" reduction in odour emission rate, using the odour emission rate measured from the various cover types and from the exposed liquor normally enclosed by the cover using Equation 4:

$$Percent\ reduction = 100 - \frac{\text{Pond cover OER}}{\text{Exposed liquor OER}} \times 100\%$$ **Equation 4**

For pond C, the performance of the pond covers was calculated as a "relative" reduction in odour emission rate as above using Equation 4 or as an "absolute" measure of odour reduction using Equation 5:

$$Percent\ reduction = 100 - \frac{\text{Pond cover OER}}{\text{Uncovered control pond liquor OER}} \times 100\%$$ **Equation 5**

3.12 Pond Liquor Sampling

A single grab sample of the pond liquor was collected on each sampling occasion. Samples were collected approximately 100 mm below the surface to prevent contamination by surface scum and debris. The samples were stored on ice in the field in 1 L opaque containers until they were delivered later on the day of collection to the laboratory. Typically, samples were analysed to determine the concentrations of total Kjeldahl nitrogen, ammonia-, nitrate-, and nitrite - nitrogen, total phosphorus, *ortho*-phosphate, chloride, sulphate, sulphide, total sulphur, sodium, magnesium, potassium, calcium, manganese, copper, iron, zinc, total solids, volatile solids and chemical oxygen demand in the pond liquor. Electrical conductivity and pH values were also measured for each sample. APHA methods (APHA, 1998) or methods derived from APHA methods were used for all analysis.

3.13 Investigation of Pond Water Quality Data Using PHREEQC

PHREEQC is a model based on the equilibrium chemistry of aqueous solutions interacting with minerals, gases, exchangers and sorption surfaces. The model incorporates an extensive chemical database. The model was used as-received, modified only to include a number of additional magnesium-, nitrogen- (as ammonium) and phosphorus-containing minerals and species identified from research into struvite recovery (Ali et al., 2003; Ali et al., 2005).

Results of analysis of pond liquor were input into the model for each pond. Saturation indices for various minerals predicted by the model were used to identify differences in pond chemistry for all ponds, particularly between the covered and control ponds at piggery C.

3.14 VOC Sample Collection

Two different but complementary techniques were used to assess the removal of specific odorants from the airstream as it passed through the biofilter system. These techniques included:

- Stirrer bar sorptive extraction (SBSE) sample collection (commercialised by Gerstel as Twister™); and
- Tenax™ sample collection.

3.14.1 SBSE Sample Collection

Stirrer bar sorptive extraction (SBSE) is a variant of the solid phase microextraction (SPME) technique originally developed by Chai and Pawliszyn (1995). SBSE also relies on partitioning of volatile materials between a polymer surface (polydimethylsiloxane, PDMS) and a fluid sample surrounding the polymer surface. In this situation, the fluid was air samples derived from the exhaust stack of the UNSW wind tunnel. A customised spiral stainless steel wire holder was used to position and hold the stirrer bar in the air stream during the sampling period. The sample was collected by exposing the SBSE device (see Figure 22) to the air stream for a fixed period of time. Sampling periods ranging from 20 to 120 minutes were assessed to determine optimal exposure periods. It was necessary to expose the SBSE device to the sample for at least 40 minutes to obtain detectable amounts of odorants.

The materials adsorbed on the stirrer bar were analysed without further treatment by placing the bar in a glass insert in the inlet port of the Gerstel® thermal desorption unit (TDU) attached to an Agilent 6890 gas chromatograph (GC). The volatile materials were recovered by rapidly heating the inlet port to 250 °C. These volatile substances were then trapped on a cooled inlet device (Gerstel® CIS), from which they were introduced onto the GC analytical column.

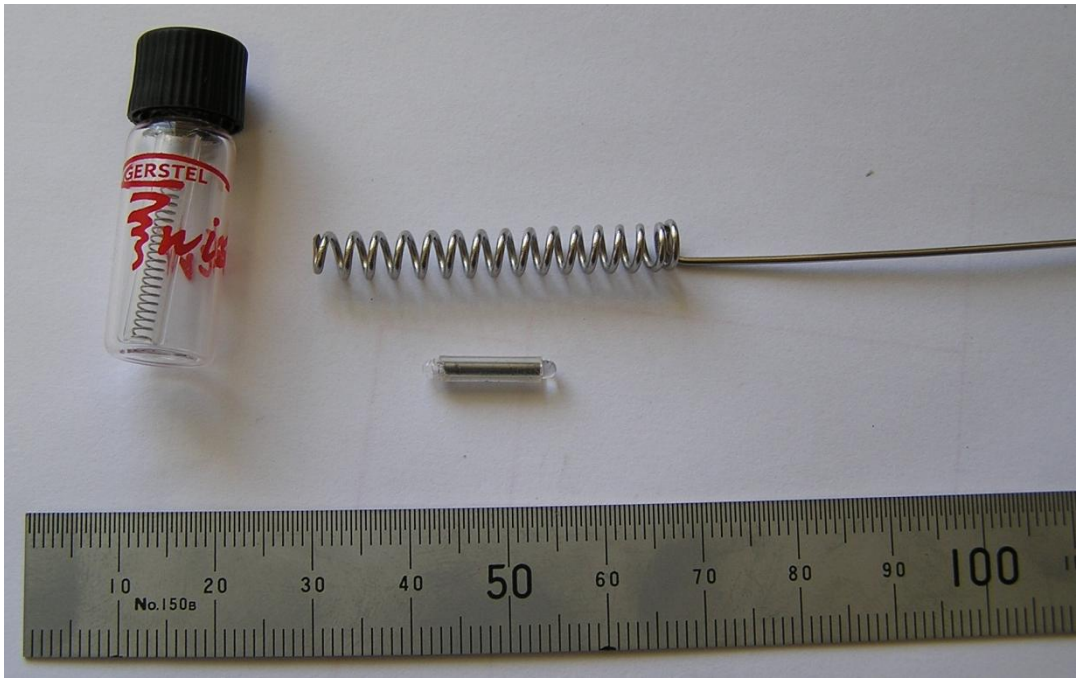


Figure 22: SBSE device (centre), storage bottle and customised spiral holder (mm scale)

3.14.2 Tenax Sample Collection

Two techniques were used to sample volatile materials from the air discharged from the wind tunnel using thermal desorption tubes packed with Tenax™. These techniques were determined by the equipment used to recover the volatile material and introduce it to the GC.

In the first technique, stainless steel tubes designed for a Perkin Elmer Turbomatrix TDU were used. Tube dimensions were ¼" od x 90 mm, with a bed length of about 55 mm. In the second method, samples were collected on tubes designed for the Gerstel® TDU system. The glass tubes were 6 mm od x 60 mm, with a bed length of 30 mm. For both types of tube, samples were collected using vacuum pumps (SKC® PCXR8 with low flow adaptor) operated at a measured flow rate, typically

100 mL/min. Sample collection periods were typically 30 to 60 minutes duration, giving effective sample volumes of 3 L to 6 L of air. Samples collected on the Perkin Elmer tubes were analysed by Queensland Health Scientific Services using a Perkin Elmer Turbomatrix TDU coupled to a Varian ITD GC-MS system. A standard "Air Toxics" analytical procedure was used for all samples.

Samples collected with the Gerstel® tubes were analysed by DPI&F, using the GC-MS system operated by Sustainable Intensive Systems (SIS), Toowoomba.

Details regarding collection of the sample from the wind tunnel are shown in Figure 23 to Figure 25:

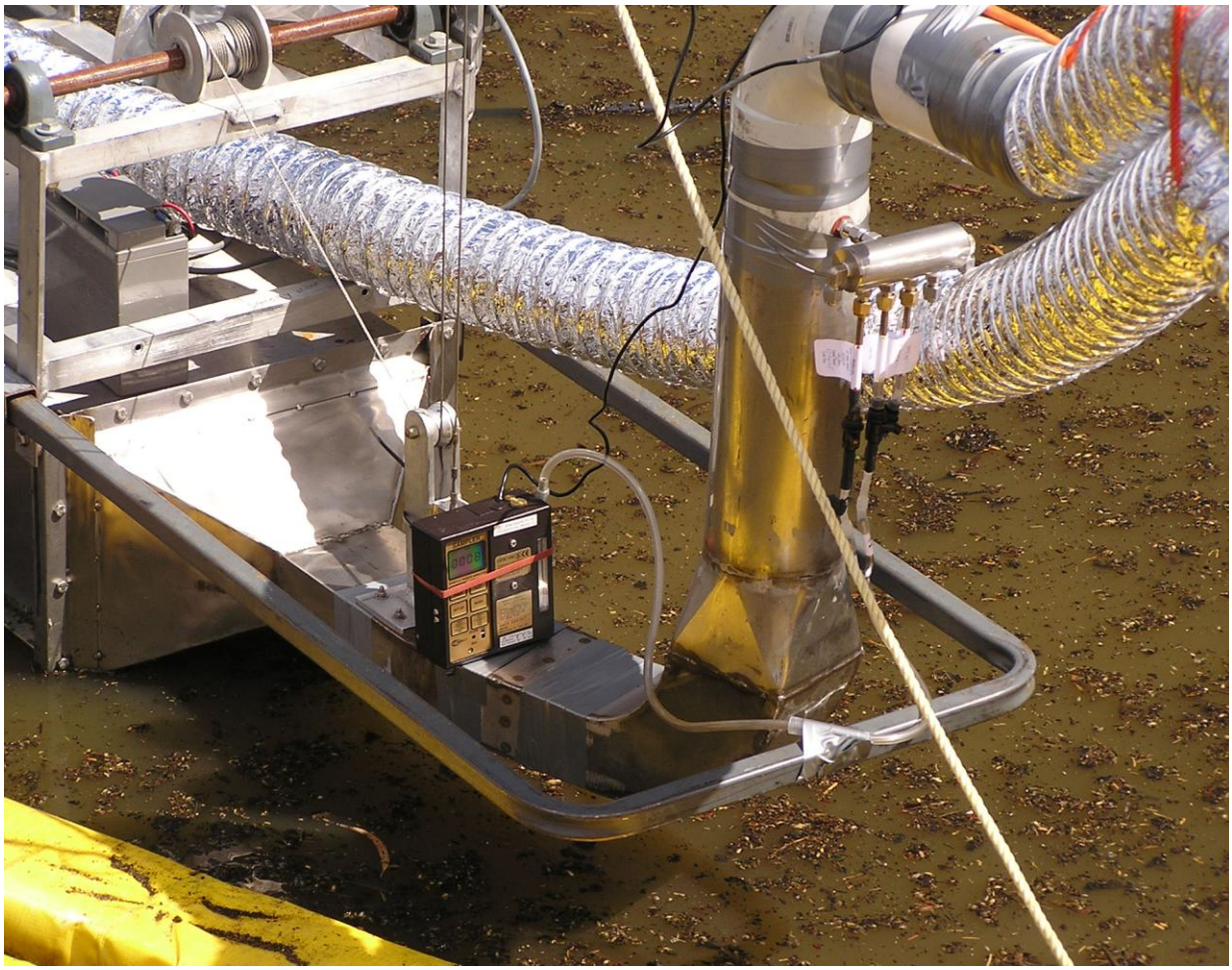


Figure 23: Wind tunnel with sample tube manifold and sampling pump

Figure 24: VOC sampling pump

Figure 25: Sample tubes attached to manifold

3.14.3 Gas Chromatography (SIS, Toowoomba)

The GC was operated using the following settings:

The initial TDU temperature of 15 °C was held for 1 minute. The TDU was then heated to a final temperature of 250 °C at 25 °C/minute, which was held for 3 minutes. The pneumatic system was set to solvent vent mode (analogous to splitless mode) for this operation.

On completion of the TDU heating and cooling cycle, the CIS was heated from 5 °C to 250 °C at 25 °C/minute, which was held for 1 minute. The pneumatic system was operated in splitless mode during the sample transfer period. Commencement of the CIS heating cycle also started the GC analytical system. The initial oven temperature of 35 °C was held for 2 minutes, followed by a multi-step heating program of 2 °C/min to 70 °C, 4 °C/min to 140 °C and 8 °C/min to a final temperature of 250 °C which was held for 5 minutes. The pneumatic system was operated in constant flow mode. Helium carrier gas flow through the 30 m x 250 µm x 0.25 µm film thickness HP-5MS capillary column was maintained at 1.2 mL/min, giving a nominal average velocity of 40 cm/s.

3.14.4 Mass Spectrometric Detection (SIS, Toowoomba)

Materials eluted from the GC column were detected using an Agilent 5973 mass-selective detector. It was operated in electron impact ionisation (EI) mode. Specific odorants were identified on the basis of retention times and their mass spectra. Quantification of specific odorants was made using chromatograms derived from the total ion chromatogram using the selected ion mode (SIM).

3.15 Measurement of Hydrogen Sulphide Emission Rates

In a previous investigation undertaken for APL, a wet chemical scrubber method was utilised to trap hydrogen sulphide (H_2S) in air samples derived from a UNSW-style wind tunnel (Hudson et al., 2004). It was concluded that concentrations of H_2S in samples derived from wind tunnels were too low to be detected unless unreasonably large volumes of air were collected. The technique was also quite irreproducible, providing very different results for samples collected consecutively from a treatment pond surface. As a consequence, use of this technique was discontinued.

For the current study, a TEI model M101E fluorescence H_2S analyser was utilised. Identical UNSW-style wind tunnels were deployed on the parallel treatment ponds at piggery C. Identical operating conditions were established in each wind tunnel. Sample air was collected continuously from each

wind tunnel exit stack at about 500 mL/min through ½" Teflon™ sample line. In addition, identical US EPA dynamic emission chambers were set up on the polypropylene and shadecloth cover and on the liquor of the control pond. These devices were operated in accordance with recommended conditions (Gholson et al., 1989). Air was sub-sampled from these devices using the SQUID, a sample multiplexer developed within SIS. The multiplexer allowed up to five different air samples to be directed to the analyser. The sample lines were automatically selected by a series of solenoid and rotary valves, the timing of which was controlled by a National Instruments Programmable Logic Controller (PLC). The H_2S analyser continuously analysed the air flowing through the reaction cell, reporting concentration data at 5 s intervals. These results were captured on a DT 500™ data logger. Data were retrieved from the data logger either by dial-up modem or manually during the frequent site visits. The H_2S analyser was calibrated manually using a standard gas mixture in nitrogen (BOC P/L).

It was necessary to deploy a mobile laboratory on site adjacent to the ponds at piggery C. The laboratory was constructed from a modified 20' insulated shipping container.

3.16 Measurement of Carbon Dioxide Emission Rates

Carbon dioxide (CO_2) concentrations in the air discharged from the same wind tunnel and flux chamber arrangement described in Section 3.15 were measured using a Vaisala model GMT 220 sensor and transmitter. In this study, the sensor was not calibrated because the focus was on comparing the concentrations derived from identical devices operated on different surfaces.
Air samples derived from the wind tunnel were directed to the CO_2 analyser using the SQUID multiplexer described previously. CO_2 concentrations were collected at 5 s intervals and captured on a DT 500™ data logger. The data were retrieved in the same way described previously.

3.17 Determination of Physical Strength Characteristics of Polypropylene Cover Fabric

Samples of the polypropylene cover fabric (3 m x 1 m) were physically cut out of the cover, washed thoroughly and submitted to a commercial laboratory. A range of tests were completed to describe the physical strength of the cover fabric. These included:

1. Determination of tensile properties – wide strip method (AS 3706.2) – ten replicates per direction;
2. Determination of trapezoidal tear strength (AS 37606.3) – five replicates per direction;
3. Determination of bursting strength – California Bearing Ratio (CBR) plunger method (AS 3706.4) – ten replicates per sample;
4. Determination of puncture resistance – Drop cone method (AS 3706.5) – ten replicates per sample;
5. Determination of maximum force and elongation using the strip method – narrow strip method (AS 2001.2.3.1 – 2001) – five replicates per direction.

3.18 Statistical and Graphical Analysis

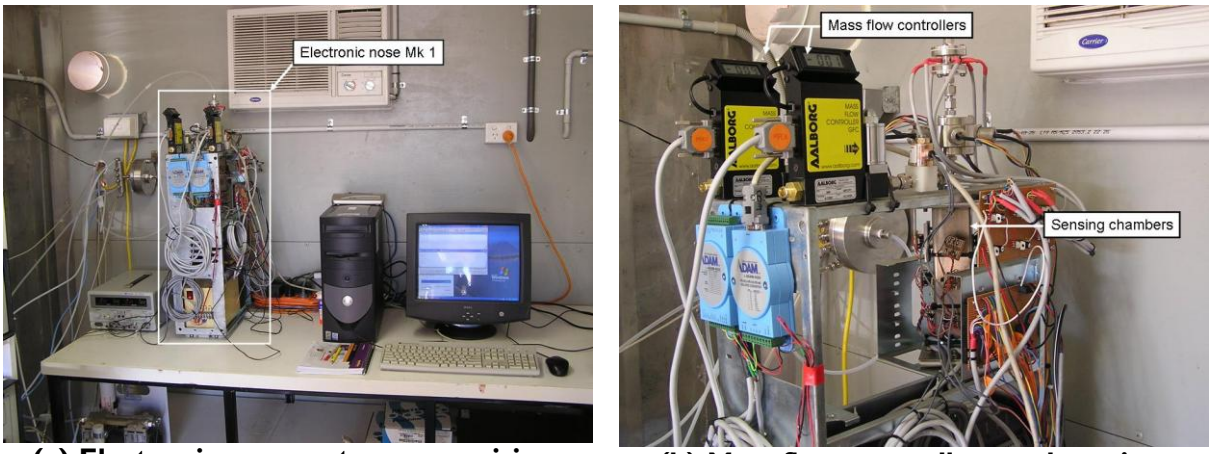
Standard procedures in the statistical software package Genstat (Lawes Agricultural Trust, 2005) were used to generate summary statistics and prepare line graphs and perform analysis of variance.
Genstat was used to prepare box-and-whisker plots according to the method of Tukey (1977). In these plots, the box spans the interquartile range of the values in the variate, with a line within the box indicating the median. Whiskers extend beyond the ends of the box as far as the minimum and maximum values. If several variates are input into the software, a box is drawn for each of them using the same scale. The plots allow for quick comparison of sets of data derived from different sources. In general, if the boxes overlap, formal significance testing confirms that the data sets are not significantly different.

Each odour sample was collected in duplicate. For the ANOVA analyses, each discrete odour emission rate value was used for the comparison. The individual results for each pair of samples for each emitting surface were randomly assigned to one of two groups. Each emitting surface was therefore represented by two sets of data. This allowed a comparison between the individual emitting surfaces as well as an assessment of the influence of the olfactometry on this comparison.

3.19 Electronic Nose Device

3.19.1 Electronic Nose Hardware

The electronic nose (EN) consisted of 12 different Metal Oxide Semiconductor (MOS) sensors. The sensors used for the EN are summarised in Table 6. The sensors were installed in a hexahedron-shaped stainless steel sensing chamber with an internal volume of 575 mL. Some of the components associated with the electronic nose are depicted in Figure 26.



(a) Electronic nose system comprising power supply and electronics, pneumatics control, sensor chamber and PC

(b) Mass flow controllers and sensing chamber

Figure 26: DPI&F MK I electronic nose system

Signals from all sensors were sampled at 60 Hz using a DT 800™ data logger. The outputs of temperature and relative humidity probes and sensor responses were acquired using a real-time data logging program developed in-house using Labview 7.1™. Odorous air samples were presented to the sensing chamber of the electronic nose at a flowrate of 500 mL/min. The sequence used for data acquisition is outlined in Table 7.

A temperature and relative humidity (RH) calibration model developed using chemometric approaches, was applied to the raw sensor responses of the EN (Sohn, 2007). The EN outputs were adjusted to provide results at 25°C and 25% RH, respectively.

Table 6: MOS sensors and operating conditions used for the DPI&F electronic nose

Logger channel	Sensor ID	Sensor type	Load resistor (R_L, Ω)	Signal voltage (V_C, V)	Heater voltage (V_H, V)
1	G	TGS 2620	120K	5.00	5.00
	A	TGS 832	27K	5.00	5.00
	L	TGS 2610	119K	5.00	5.00
2	H	TGS 2602	220K	5.00	5.00
	B	TGS 813	330K	5.00	5.00
	K	TGS 826	220K	5.00	5.00
3	J	TGS 2611	140K	5.00	5.00
	C	TGS 813A	330K	5.00	5.00
	F	TGS 880	330K	5.00	5.00
4	I	TGS 2600	180K	5.00	5.00
	E	TGS 821	56K	5.00	5.00
	D	TGS 822	27K	5.00	5.00
5	Temperature	Thermocouple K	n/a	5.00	n/a
	Relative humidity	Honeywell	n/a	5.00	n/a

Table 7: Data acquisition cycle used with electronic nose Data acquisition cycle used with the DPI&F electronic nose

Operating stage[1]	Time (seconds)
Stabilisation	30
Sample	600
Purge[2] & reference	600

[1] Repetition: 3 times/ sample

[2] Purging gas: instrument grade clean air from a cylinder

3.19.2 Analysis of Electronic Nose Output

3.19.2.1 Data Pre-Processing

Raw voltage responses from the electronic nose were converted to sensor resistances for further analysis. The data derived from the 12 sensors, plus temperature and relative humidity data, were stored in a personal computer (PC) in a binary format. Pre-processing algorithms were then applied to scale and normalise the input data prior to conducting principal component analysis (PCA). Seventy eight data files were available from the electronic nose trial. The pre-processing work and

data analysis was conducted using the SPSS™ statistical package and the Partial Least Squares (PLS) Toolbox 3.5 for Matlab™.

3.19.2.2 Outlier Handling

Prior to developing any model, it was necessary to identify and remove data which was classified as outliers. These were results significantly different from homologues belonging to the same population. Samples identified as outliers (greater than three standard deviations from the mean value, $p < 0.001$) were removed.

PCA was used to display data and detect outliers using the Q and T^2 diagnostic tests. Q is defined as the sum of the squares of residual matrix of each sample and indicates how each sample conforms to the PCA model. The T^2 test, known as Hotelling's T^2 statistic, is a measure of the variation in each sample within the PCA model.

3.19.2.3 Pattern Recognition Techniques for Qualitative Assessment

In the multidisciplinary field of sensor array analysis, the use of appropriate data analysis protocols is essential. Choosing appropriate pattern recognition algorithms for a given dataset is a critical component in the successful application of an electronic nose for odour assessment. In this project, Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLSDA) were used as classifiers to analyse outputs from the electronic nose. The Partial Least Squares (PLS) Toolbox 3.5™ for Matlab™ was used for the pattern recognition analysis.

3.19.2.4 Principal Component Analysis

PCA is an unsupervised data reduction method. The method allows the variation of a multivariate data set to be described in terms of a set of uncorrelated variables, each of which is a particular linear combination of the original variables. The original data matrix is projected from a high dimensional space into a lower dimensional space, preferably planar or three-dimensional. During the process the dimensionality of the original data set is reduced, i.e. is compressed, with as little loss of information as possible. This is achieved by filtering out the noise in the original data matrix, without removing essential information described in the variance of the data (Massart et al., 1988; Otto, 1999).

$$X = TP + E$$

Mathematically, the PCA process decomposes the original $i \times j$ data matrix X into its $i \times k$ score matrix T, its $k \times j$ loading matrix P and the residual matrix E according to:

$$X = TP + E \qquad \textbf{Equation 6}$$

Where, i is the number of samples, j is the number of variables and k is the number of principal components (PCs).

PCs are linear combinations of the original variables and can be calculated as follows:

$$t_{11} = x_{11} p_{11} + x_{12} p_{12} + \ldots + x_{1p} p_{p1} \qquad \textbf{Equation 7}$$

where, t_{11} is the first element of the first PC, x the original variables and p the loadings.

The PCs are determined on the basis of the maximum variance criterion. Each subsequent PC describes a maximum variance, which is not modelled by the previous one. According to this, the first PC contains most of the variance of the data (Otto, 1999; Everitt and Dunn, 2000). The relationship between samples can be visualised by plotting the scores against each other.

3.19.2.5 Partial Least Squares Discriminant Analysis

Partial Least Squares Discriminant Analysis PLSDA is often used to sharpen the separation between groups of observations by rotating PCA components such that a maximum separation among classes is obtained. PLSDA can also provide useful information about which variables carry the class separating information.

PLSDA is very similar to another common discrimination technique called Linear Discriminant Analysis (LDA). In fact, PLSDA is essentially the inverse-least-squares approach to LDA and produces essentially the same result but with noise reduction and variable selection advantages of the Partial Least Squares (PLS) modelling technique. In PLSDA, PLS is used to develop a model that predicts the class number for each sample.

3.19.2.6 Partial Least Squares Regression for Quantitative Assessment

When the variables are few in number, are not significantly redundant, and have a well-understood relationship to the responses, then Multiple Linear Regression (MLR) may be appropriate to turn data into information. However, the results from an electronic nose system may have many variables and non-obvious relationships, especially when the electronic nose is used to measure samples with complicated matrices. Odour is a very complex mixture of volatile substances. Therefore, a PLS regression was chosen as a more appropriate tool to construct an odour prediction model.

PLS regression is a method for constructing predictive models when many factors exist and are significantly redundant. PLS regression has been used in disciplines such as chemistry, economics, medicine, psychology, and pharmaceutical science where predictive linear modelling, especially with a large number of predictors, is necessary. PLS regression has become a standard tool for modelling linear relations between multivariate measurements in chemometrics.

PLS regression is an extension of the MLR model (e.g., Multiple Regression or General Stepwise Regression). In its simplest form, a linear model specifies the (linear) relationship between a dependent (response) variable Y, and a set of predictor variables, the X's, so that

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_p X_p \qquad \textbf{Equation 8}$$

In this equation, b_o is the regression coefficient for the intercept and the b_x values are the regression coefficients (for variables $_1$ through $_p$) computed from the data.

3.19.2.7 Prediction Model Development Procedure

Figure 27 shows the multi-step process for transformation of the raw electronic nose responses to a database for PLS model development, as well as the odour prediction procedure, using the PLS model developed from the odour samples collected during the continuous odour monitoring trial. The following steps explain the procedure for the PLS odour prediction model development depicted in Figure 27:

1. The 68 odour samples were measured using the DPI&F electronic nose Mk 1.
2. The responses of the electronic nose sensor array were saved in ASCII format (.txt files in the figure) using the electronic nose Labview™ operating program.
3. The sensory data in the text files was converted into resistance values (Ω) and processed using pre-processing algorithms.
4. The processed electronic nose outputs were imported into Matlab™ to build data matrices.
5. From the matrices, the sensor responses corresponding to the equilibrium phase were extracted and used as the PLS factor dataset of the odour prediction model.
6. The 68 odour samples were also presented to the olfactometry panel to determine odour concentration (OU/m^3).
7. The odour concentrations were saved in text file format for establishing an odour concentration database.
8. Odour concentration database was imported into Matlab™.
9. The odour concentrations were saved as a PLS response dataset.
10. Removed outliers using PCA.
11. Developed an odour prediction model and check the root-mean-square error of cross-validation (RMSECV).
12. The database from continuous odour monitoring trials was used to develop a model for predicting odour concentration.

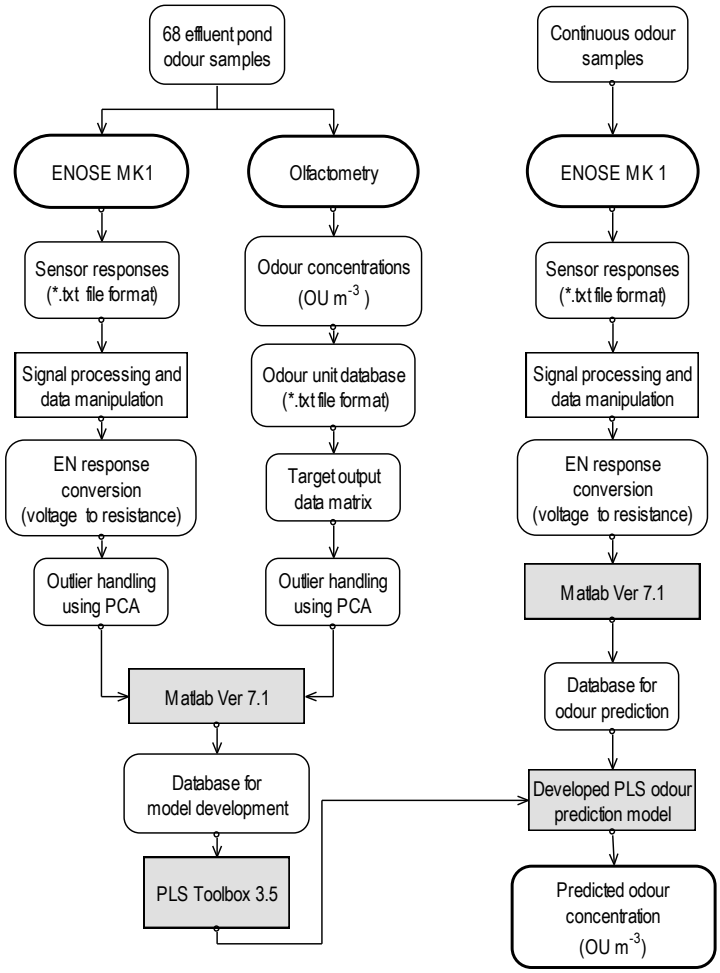


Figure 27: Process used to develop an odour prediction model using electronic nose responses and olfactometry results

4 Results and Discussion

4.1 Production of a Comprehensive "How to" Guide Regarding Manufacture and Use of Permeable Pond Covers

4.1.1 Selection of Cover Type, Materials and Manufacture

The selection of materials and manufacture of a permeable pond cover was covered briefly in Section 3.3. A comprehensive illustrated guide is included as Appendix 1. The Appendix identifies useful material from which a permeable cover may be constructed as well as some practical tips to simplify the manufacturing process. The document also summarises the experience that the research team has gained over the past six years regarding maintenance requirements for these covers.

It is not really appropriate to provide a prescriptive "recipe book" to guide potential users. Each application will create a specific set of obstacles which will have to be overcome by the team undertaking the deployment. The Appendix therefore identifies a set of basic principles to assist prospective users, rather than an exhaustive list of things that must be done. It is our belief that innovative producers will identify better ways of manufacturing and supporting these covers.

4.1.2 Methods of Maintenance and Maintenance Schedules

In similar vein, maintenance of permeable covers will also be strongly influenced by site-specific circumstances. While the Appendix provides adequate information regarding maintenance of permeable covers, it is worth emphasising some basic principles:

- While in general terms a polypropylene cover will probably require less maintenance than a supported straw cover, it is essential that the fabric be protected from UV damage. The consequences of failing to provide such protection are provided in Section 4.2.2.3.
- Permeable covers are not intended to support any additional weight. Ponds should therefore be adequately fenced to keep stock away. If it is desired to keep vegetation off the cover, good weed control should commence soon after cover deployment.
- Wind damage remains an ongoing threat to the shadecloth used to provide UV protection. The shadecloth must be anchored adequately around the entire margin of the pond. The joins between individual lengths of shadecloth should also be inspected periodically to identify requirements for repair.
- The straw layer of a supported straw cover will require "topping up" at least annually.
- The life expectancy of the straw layer appears dependent on the quality of straw used – it is recommended that good quality, well dried material be used wherever possible.

4.1.3 Diagnostic Factors Regarding Sustainable Pond Management

Section 4.3.1.3 discusses the impact permeable pond covers had on pond treatment processes. There is no evidence that placement of a permeable cover impairs waste stabilisation. It was not possible therefore to identify factors, actions or processes that may in general improve the sustainable management of a covered anaerobic treatment pond.

One area that should be considered is the requirement for removal of accumulated sludge from a covered pond. All types of cover are quite bulky and difficult to move once deployed on a pond. Complete removal of a cover is therefore impractical. Even partial removal is likely to be difficult and will carry the risk of damage to the cover.

Successful removal of accumulated sludge therefore depends on use of a technique which does not require removal of the cover. A contractor was able to remove most of the sludge from the covered pond at piggery C using a large PTO-driven agitator and a vacuum tanker. The following steps had to be performed during this activity:

1. Inflow of waste to the pond was diverted to the adjacent control pond.
2. The cover was detached from the pickets anchoring it around the margin on three sides.
3. The cover was pulled away from the edge toward the opposite bank of the pond, creating a strip of exposed liquor along one margin.
4. The cover was secured in this position with ropes to maintain the strip of clear liquor along the margin. Care was taken to ensure that the cover margin was maintained above the liquid surface to avoid accumulation of solids on the cover and submerging it further.
5. The contractor installed machinery to agitate the sludge layer, creating a viscous, homogenous liquid.
6. While agitation of the pond contents was maintained, sludge and liquor was withdrawn from the pond for land disposal.
7. As the pond liquid level was reduced, the cover subsided with the liquor, remaining afloat at all times.
8. On completion of sludge removal, waste was once more directed into the pond, allowing it to refill over a period of a few weeks.

9. Once the pond level was restored, the cover was moved back into place, and re-anchored around the pond margin.

4.2 Determine and Report Permeable Pond Cover Odour Reduction Performance, Life Expectancy and Costs

4.2.1 Efficacy of Reduction in Odour Emission Rate

Odour emission data derived from all ponds and surfaces at the three trial sites over the assessment period is summarised in Table 9 to Table 11. The data for each trial site are also summarised as a series of box and whisker plots in Figure 28 and as a series of time series plots in Figure 29. Statistics regarding odour concentrations and rates for all ponds and surfaces are summarised in Appendix 3.

The efficacy of the various cover types in reducing odour emission rate is summarised in

Table 8. Results for each pond are discussed separately in Sections 4.2.1.1 to 4.2.1.3.

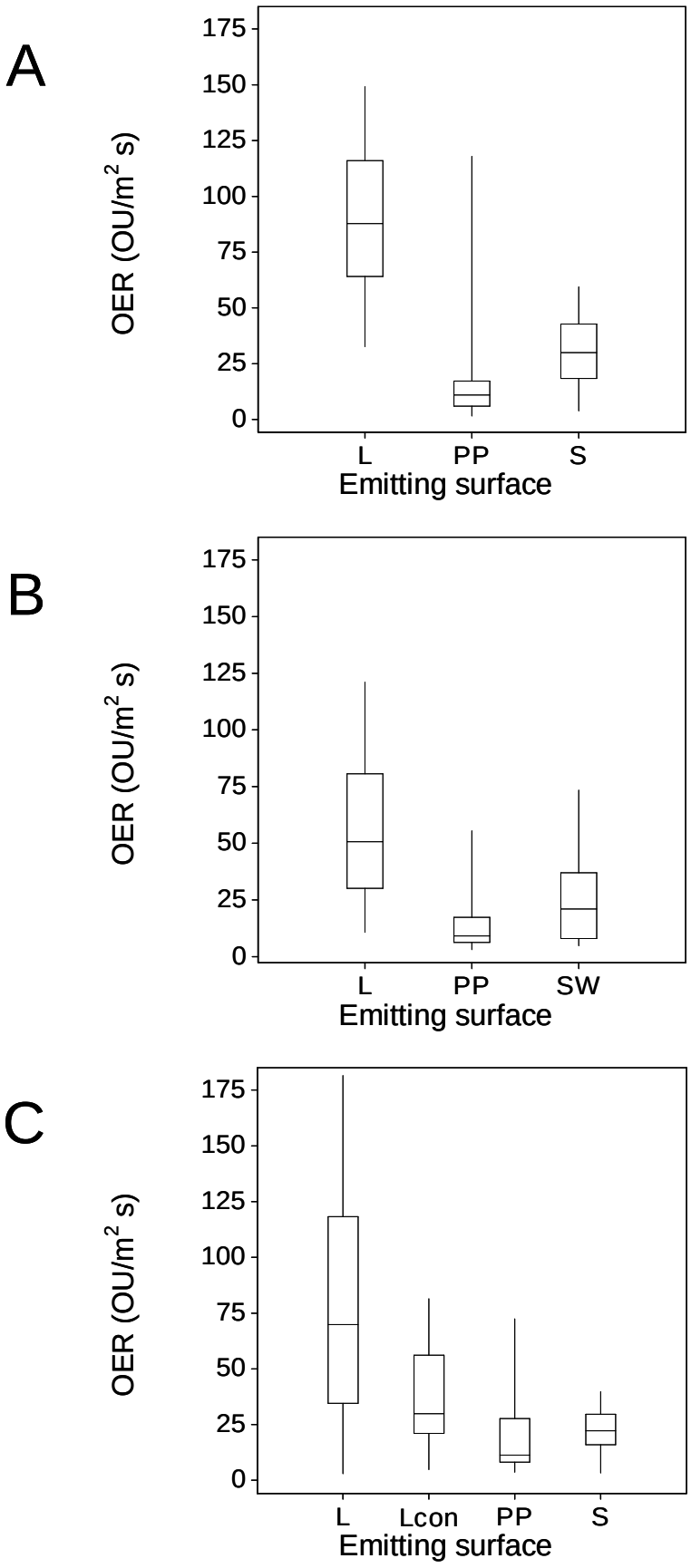


Figure 28: Comparison of odour emission rate by emitting surface, pond A, pond B and the ponds at piggery C

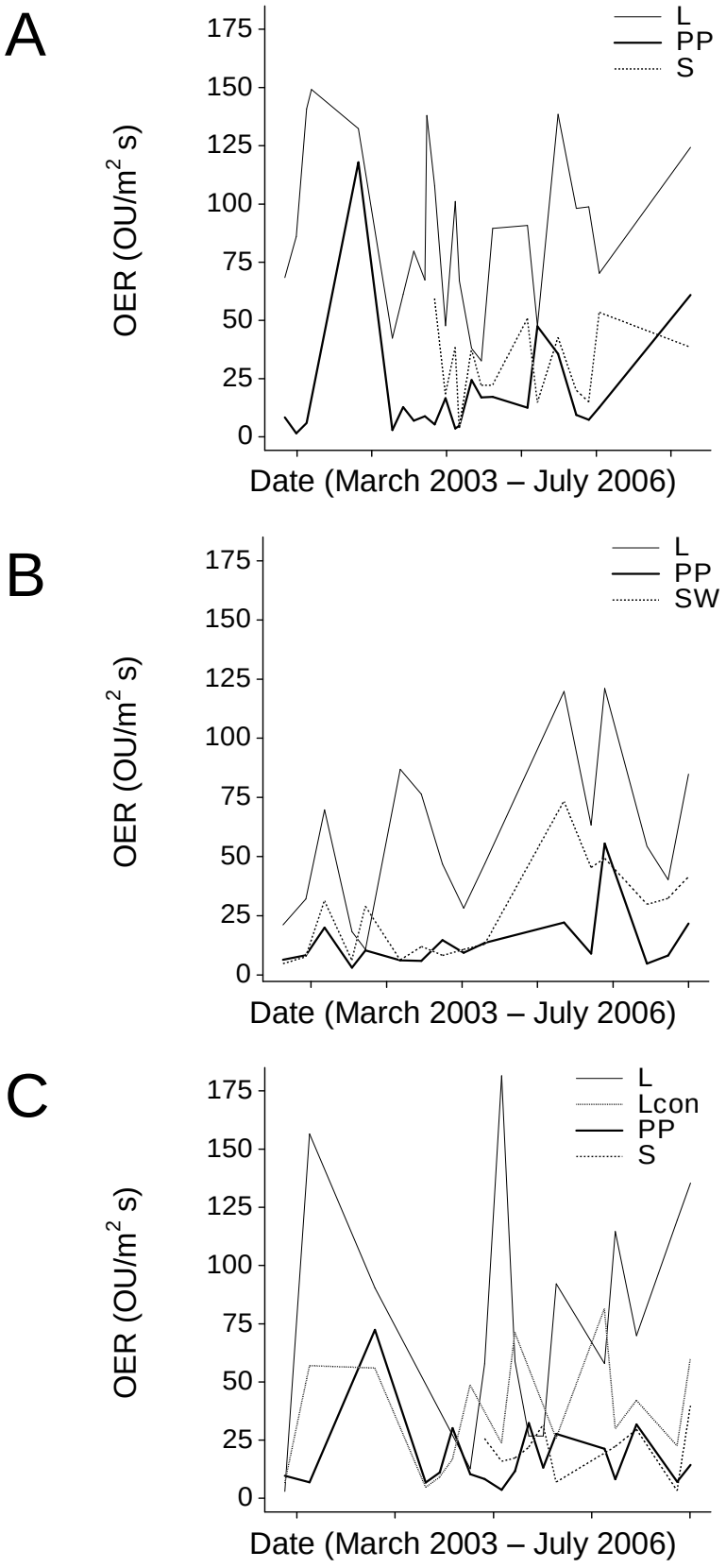


Figure 29: Comparison of odour emission rate over time by emitting surface, pond A, pond B and the ponds at piggery C

Table 8: Reduction in odour emission rate by pond cover type

Pond	Nature of comparison	Comparison surface	Reduction in odour emission rate by surface (%)			
			Exposed liquor	Polypropylene-shadecloth	Shadecloth	Straw
A	Internal	Exposed liquor	-	77	65	-
B	Internal	Exposed liquor	-	76	-	66
C	Internal	Exposed liquor	-	77	73	-
C	External	Control liquor	-121	50	41	-

4.2.1.1 Efficacy of Odour Reduction - Pond A

Emission rate characteristics for surfaces associated with pond A are summarised in Table 9.

Table 9: Emission rate characteristics of surfaces at pond A

Statistic (n = 50)	Odour emission rate (OU/m² s)		
	Liquor	Polypropylene geofabric & polyethylene shadecloth cover	Polyethylene shadecloth only
Average	88.2	20.0	31.3
Median	87.8	11.0	30.0
Minimum	32.7	1.6	3.9
Maximum	149.1	118.0	59.5
Standard deviation	35.4	26.5	16.8

For pond A, it was only possible to evaluate the odour reducing efficacy as an internal comparison, where the cover emission rates were compared with that of the exposed liquor surface of the same pond (see

Table 8). The average reduction in odour emission rate over the entire trial period was 77% for the polypropylene-shadecloth cover and 65% for the shadecloth-only cover. Reduction in median emission rates for these covers were 87% and 66% respectively.

Considerable variability in emission rate was observed from all surfaces over the trial period. There was however no trend indicating deterioration in cover performance over the trial – the OER of the polypropylene-shadecloth cover was consistently lower than that of the exposed liquor. ANOVA

testing (Table 10) indicated a significant difference between the odour emission rates of the exposed liquor and both the polypropylene-shadecloth cover and the shadecloth cover at the 5% level. There was no significant difference in OER between the two cover types at the 5% level.

Table 10: Results of ANOVA comparing emission rates of surfaces at pond A

Emitting surface[a]	Mean OER (OU/m² s)	Difference at 5% level[b]		
PP1	23.2	A		
PP2	28.2	A	B	
S2	38.1		B	
S1	38.2		B	
L1	88.4			C
L2	91.7			C

Least significant difference of means 12.4

[a] The numbers indicate results for paired duplicate odour samples, separated randomly into two groups

[b] Emission rates for surfaces with same letter not significantly different

4.2.1.2 Efficacy of Odour Reduction - Pond B

Emission rate characteristics for surfaces associated with pond B are summarised in Table 11.

Table 11: Emission rate characteristics of surfaces at pond B

Statistic (n=32)	Odour emission rate (OU/m² s)		
	Liquor	Polypropylene geofabric & polyethylene shadecloth cover	Supported straw cover
Average	57.6	13.7	25.1
Median	50.7	9.1	21.0
Minimum	10.7	3.1	4.8
Maximum	121.1	55.5	73.4
Standard deviation	33.8	12.6	20.0

The average relative odour reduction provided by the polypropylene-shadecloth cover at this pond was 76%, while the median value was 82%. These results were very similar to those observed using a similar cover at pond A. The supported straw cover also provided good odour reduction. Average and median odour reduction relative to the uncovered liquor was 66% and 59% respectively. These values were very similar to those measured for the shadecloth cover at pond A. During our previous investigations of supported straw covers we observed quite rapid deterioration and thinning of the straw layer from 100 mm to about 20 mm within a 12-month period (Hudson et al., 2006). Similar deterioration was observed for the larger straw cover used in this trial. Despite

the deterioration in cover thickness however, it continued to provide consistent reduction in odour emission rate.

ANOVA testing (Table 12) indicated a significant difference between the odour emission rates of the exposed liquor and both the polypropylene-shadecloth cover and the supported straw cover at the 5% level. There was however, no significant difference in OER between the two cover types at the 5% level.

Table 12: Results of ANOVA comparing emission rates of surfaces at pond B

Emitting surface	Mean OER (OU/m² s)	Difference at 5% level[a]	
PP2	10.3	A	
PP1	17.5	A	
SW2	23.3	A	
SW1	26.4	A	
L2	55.5		B
L1	59.6		B

Least significant difference of means 17.7

[a] Emission rates for surfaces with same letter not significantly different

The reduction in odour emission rate by the supported straw cover was not as good as that reported in our earlier study (Hudson et al., 2006). Previously, odour emission rates were reduced by between about 79 and 83% relative to the liquor. The apparently inferior performance of the supported straw cover in the current study could be explained in terms of the changes caused by complete coverage of the pond. Previously, average odour emission rates for the partially covered pond liquor were about 14 OU/m² s. In the current trial, however, this value increased four-fold to about 57 OU/m² s. The increased liquor odorant concentration obviously raised the potential for odour emission, which was observed as a reduction in cover performance.

Previously we reported difficulties in achieving a good seal between the uneven straw surface and the wind tunnel base (Hudson et al., 2006). We overcame the problem by employing a semi-detached polymer "skirt" and weighted frame. In the current study however, it was not feasible to utilise this system. A shorter, more rigid skirt constructed from a sheet of PVC was attached directly to the wind tunnel base. It provided a relatively flat, extended base to the wind tunnel, extending out from the perimeter by 400 mm. While it provided a greater area for contact between the wind tunnel and the straw, it was observed to bend and deform in response to the uneven straw surface. The seal was not as good as that obtained previously. To achieve a good seal, there was a tendency to lower the wind tunnel excessively on the straw surface, partially submerging it at times. Liquor could then permeate through the cover and increase the measured emission rate. The reported efficacy of the supported straw cover should therefore be regarded as conservative, worst-case performance.

4.2.1.3 Efficacy of Odour Reduction - Pond C

Emission rate characteristics for surfaces associated with pond C are summarised in Table 13.

Table 13: Emission rate characteristics of surfaces at pond C

Statistic (n = 36)	Odour emission rate (OU/m² s)			
	Liquor control pond	Liquor covered pond	Polypropylene geofabric & polyethylene shadecloth cover	Shadecloth only
Average	36.3	80.2	18.1	21.5
Median	29.8	69.8	11.3	22.2
Minimum	4.8	3.0	3.6	3.3
Maximum	81.4	181.5	72.3	39.7
Standard deviation	22.9	53.4	16.5	11.1

The paired measurements made on two ponds at this site allowed both within-pond (relative) assessment and between-pond (absolute) assessment. Both ponds experienced relatively light waste loading rates over the trial period. This was verified by the generally low odour emission rates measured from the control pond.

The within-pond assessment indicated that the polypropylene-shadecloth cover reduced average and median odour emissions relative to the exposed liquor by about 77% and 84% respectively. The shadecloth-only cover reduced mean and median odour emission rates by 73% and 68% respectively. These results were very similar to those observed for the other two trial sites. The time-series graph for the two ponds at piggery C in Figure 29 indicated that the performance of the covers was very consistent over the entire trial period, with no evidence of deterioration in cover performance. Comparison of odour emission rate results for the covered pond and the uncovered control pond indicated that a polypropylene-shadecloth cover reduced the average and median odour emission rate by 50% and 62% respectively. The shadecloth-only cover reduced average and median odour emission rates by 41% and 26% respectively over the same period. Emission rates measured off the exposed liquor confirmed that odorants accumulated in the liquor beneath the permeable cover. The average and median odour emission rates of the covered liquor were 121% and 134% greater than those of the uncovered control.

ANOVA testing (Table 14) indicated a significant difference between the odour emission rates of the control pond liquor and those of the temporarily exposed liquor of the covered pond, the polypropylene-shadecloth cover and the shadecloth cover at the 5% level. There was a significant difference in OER between the two cover types and the exposed liquor of the covered pond at the 5% level.

Table 14: Results of ANOVA comparing emission rates of surfaces at pond C

Emitting surface	Mean OER (OU/m² s)	Difference at 5% level[a]		
PP2	12.2	A		
S2	18.8	A	B	
S1	24.3	A	B	
PP1	26.6	A	B	
Lcon1	36.6		B	
Lcon2	36.6		B	
L1	71.5			C
L2	67.4			C

Least significant difference of means 22.6

[a] Emission rates for surfaces with same letter not significantly different

4.2.1.4 Performance of Polypropylene-Shadecloth Permeable Covers

The long-term average performance of these covers was about 76% (using internal comparison) and 50% based on comparison with an adjacent, uncovered pond (

Table 8). Although the efficacy of odour reduction based on relative performance was greater than about 75%, the performance was not as convincing when calculated relative to the emission rates of the uncovered control. When making this judgement, however, it is important to consider the nature of olfactometric assessment.

While olfactometry provides a quantitative estimate of odour concentration, it is based on a presence/absence test. During each round of assessment, panel members are expected to identify one of three samples presented as different. The nature of the odour is not considered during conventional odour assessment – it is the detection threshold that is determined. Samples derived from the permeable pond covers have a measurable odour concentration. Visual inspection of the cover helps explain why this should be. The covers are damp, have an abundant supply of nutrients, adequate oxygen supply and are exposed to full sunlight. Within days of deployment, the cover surface appears green, as a microbiological population colonises the surface. After rainfall, shallow pools of rainwater form on the cover surface and become bright green in response to rapid changes in biomass numbers and composition. Over time, generations of microfauna and flora grow and die, forming a black, sludge-like material on the cover surface. During field sampling, the sample team occasionally assessed the odour arising from this material by sniffing the odour just above the cover surface. The odour was not offensive. It persistently presented as a sea-weed like odour, or was reminiscent of algae-covered rocks. This background odour created by the biomass on the cover would obviously generate a response during the olfactometric process. During the odour sample collection, it was also possible for the sampling team to assess the air exhausted from the wind tunnel. While the air exhausted from the tunnel when in contact with either the covered or control liquor had a characteristic and highly offensive "piggery" odour, when in contact with the polypropylene-shadecloth cover, it was either difficult to detect an odour, or the odour was inoffensive.

Though the olfactometry process did indicate that permeable pond covers reduce odour emissions, anecdotal observations by the sampling team suggest that their performance was greater than those results indicate. Evidence of this was seen during deployment and partial removal of the covers. It was noted that odour emissions were greatly reduced following cover installation, whilst ambient odour concentrations increased immediately following partial cover removal as odorants in the liquor came into contact with the atmosphere.

Consideration of the growth of biomass on the pond cover and the nature of olfactometric assessment provides possible explanations for the apparent decline in performance observed by Bicudo et al. (2004). It was possible that the absence of biomass on the cover during the first year of assessment may have produced a surface with emission rate characteristics similar to those of a new cover, or a partial cover not subject to the full odour "load" generated by the pond. The latter circumstance would be similar to the situation described in our initial field-scale assessment (2006). One way to validate this hypothesis would be to measure the hedonic tone or offensiveness of the odour collected from the various surfaces. We propose that the odour emitted by the pond covers may be significant in terms of concentration, but will not be nearly as offensive as that emitted by the open liquor surface. The effective efficacy would be greater than the 50% reduction in odour concentration indicated by paired, between-pond comparison. Confirmation of this hypothesis would also support adoption of the technology by producers.

Analysis of water quality samples indicated that odorants (hydrogen sulphide in particular) appeared to accumulate in the covered liquor (see Section 4.3.2.7). This was confirmed anecdotally when assessing the influence of flushing liquor using the flume. Liquor derived from the covered pond at piggery C had a distinctive "rotten egg" smell, characteristic of elevated concentrations of hydrogen sulphide. Consideration of the factors that control emission processes identifies wind speed and the difference in concentration of odorants between the emitting liquid and air above the liquid as dominant driving forces. Sections 4.3.1.2 and 4.3.2.7 indicate that hydrogen sulphide concentrations increased five- to 10-fold once a cover totally covers the liquor surface. In the previous investigation, only a small fraction of the liquor surface was covered. This would not allow odorants to accumulate or the large concentration difference to develop. The long-term study therefore provides a more realistic assessment of the efficacy of a permeable cover.

4.2.1.5 Efficacy of Shadecloth-Only Covers

The performance of the shadecloth-only covers was unexpectedly good (

Table 8). Although the shadecloth was of the highest density available commercially, it has a relatively open weave. Considerable care was necessary when deploying the wind tunnel on the shadecloth surface to avoid submerging the cover below the liquor. In order to achieve an adequate seal between the wind tunnel base and the shadecloth surface, submergence of the cover around the edge of the wind tunnel was unavoidable. This caused some of the pond liquor to form a continuous pool above the surface of the cover around this margin. The liquor was obviously odorous and the presence of a limited amount of liquor above the surface of the cover would be expected to raise the odour emission rate. The shadecloth odour emission rates should therefore be regarded as worst-case results. Despite this situation, the shadecloth appeared able to reduce odour emission rates by more than 60% relative to the exposed liquor surface.

4.2.1.6 Efficacy of Supported Straw Covers

The performance of the supported straw cover used to partially cover the pond at piggery B was very similar to that of the shadecloth only surface (

Table 8). The cover provided about a two-third reduction in odour emission rate on the basis of an internal comparison. On the basis of odour reduction, it might be concluded that either a shadecloth or straw cover could be used to reduce odour emissions. It is therefore necessary to consider other factors when making a decision regarding selection of cover type. These are discussed fully in Section 4.2.2.6, where it becomes apparent that when factors such as construction cost, maintenance and practicality make a shadecloth cover more attractive.

While the performance of the straw cover was not as good as observed in the first investigation, factors similar to those noted in the discussion of the performance of polypropylene and shadecloth covers need to be considered. The measured increase in concentrations of odorants in the covered liquor is particularly relevant. This long-term study therefore provides a more realistic assessment of the efficacy of a supported straw cover for odour control.

4.2.2 Assessment of Cover Life Expectancy

A weakness in the results of the first investigation was that it was not possible to assess cover longevity under field conditions in a short term assessment. The initial study indicated that the biological material used to construct a supported cover would last approximately 12 months. No information was provided regarding the life expectancy that could be anticipated for a polypropylene-type cover.

4.2.2.1 Physical Strength Testing of Polypropylene Fabrics

Three samples of polypropylene fabric were submitted to a consulting laboratory to assess how the physical characteristics of the fabric had been influenced by this application under field conditions. Details of the deployment periods up to the date of sampling are summarised in Table 15:

Table 15: Details regarding polypropylene cover sunlight exposure prior to strength testing

Cover location	Period deployed prior to shadecloth installation (days)	Total deployment period prior to sampling for strength testing (days)
Piggery A	438	905
Piggery B	413	759
Piggery C	455	857

The results of mechanical strength tests are summarised in Table 16. The tabulated results are the average values derived from the number of replicates described in Section 3.17.

All cover fabric samples failed to comply with the specifications for new material. The magnitude of departure from the specification appeared to relate to the length of time the fabric had been exposed to sunlight, the total time the fabric had been deployed or a combination of these factors. Formal correlation analysis confirmed this initial interpretation and indicated a number of highly significant negative correlations [> ± 0.950, (probability)]:

- total deployment period and tensile strength (narrow strip) [-0.999 (0.1260];
- total deployment period and tensile strength (wide strip) [-0.991 (0.0428)];
- period of unshaded deployment and burst strength (CBR) [-0.999 (0.013)];
- period of unshaded deployment and trapezoidal tear [-1 (0.0078)], and

- period of unshaded deployment and tensile strength (wide strip) [-0.955 (0.0954)].

Additional sampling and analysis is scheduled to continue until 2010. The additional results should confirm these findings. They should also indicate whether chemical or microbiological processes occurring within the pond are contributing to ongoing deterioration of the cover fabric.

Table 16: Results of mechanical strength tests

Cover sample	Tensile strength – wide strip (kN/m)		Trapezoidal tear strength (N)		Bursting strength – CBR method (N)	Puncture resistance – drop cone method		Tensile strength – narrow strip	
	Machine direction	Cross direction	Machine direction	Cross direction		Puncture diameter d_{500} (mm)	Puncture resistance h_{50} (mm)	Machine direction	Cross direction
Pond A	21.3	33.6	602	820	4499	12	4130	1174	1080
Pond B	32.7	43.1	734	1088	6429	10	5120	1628	2280
Pond C	26.4	14.6	520	367	3371	17	2380	1307	779
Specification of new material	31.5		875		7455	-	-	1875	

4.2.2.2 Life Expectancy of Supported Straw Covers

The current study confirmed that the straw or hay used to manufacture a supported cover would probably have a life expectancy of 12 months or less. Being in direct contact with the liquor, it was inevitable that the straw layer would become damp, encouraging composting which would slowly erode the straw layer thickness. This appeared to take up to 12 months before the straw layer became too thin to provide an effective cover.

The series of photographs in Figure 30 illustrate the change in cover over a 14-month period during the current investigation. There is no clear explanation for the apparent difference in cover deterioration in different areas of the cover evident in iii) and iv). The cover area closest to the camera has clearly deteriorated more rapidly than the bulk of the cover further from the camera. One plausible explanation is that the material applied to the covers came from different bales of straw. Figure 7 and Figure 8 of Appendix 1 show the bales of straw arranged along the pond margin before application. It is likely that the area closest to the camera in Figure 30 iii) and iv) came mainly from one bale. The quality of straw may have been different to the other bales supplied. Another possibility is that the straw was applied less thickly than in other areas of the cover. The area of damage in the foreground of Figure 30 ii) arose from a wallaby venturing onto the cover, becoming trapped and then drowning.

i) November 2003 (during initial application)

ii) March 2004 (four months after deployment)

iii) August 2004 (nine months after deployment)

iv) February 2005 (14 months after deployment)

Figure 30: Gradual deterioration in supported straw cover observed over 14-month period

4.2.2.3 Life Expectancy of Polypropylene Covers

A polypropylene cover constructed from light-weight needle-punched, spun fibre fabric was trialled during the final four-month period of the initial investigation (March – June 2001). This cover remained viable until it was removed prior to the installation of the complete pond cover in 2003. There was no evidence of deterioration, fraying or UV damage to any part of the cover during this period.

July 2002 **March 2003**

Figure 31: Representative photographs of first polypropylene cover during its life (March 2001 – April 2003)

Similar results were observed for a larger composite trial cover (Figure 32). This cover was manufactured as a mosaic from both woven and non-woven polypropylene materials of various densities and thicknesses. This cover was deployed and assessed to identify any immediate issues relating to the selection of cover material, as well as to trial flotation devices. While the cover was in place less than one year, all cover materials appeared to perform acceptably for odour control and no obvious issues regarding durability were observed.

Immediately following deployment, June 2002 **Prior to decommissioning and removal, March 2003**

Figure 32: Representative photographs of trial composite polypropylene cover during its life (June 2002 – April 2003)

On the basis of these experiences, it was concluded that both woven and non-woven polypropylene fabrics provided similar odour reduction and exhibited similar physical strength characteristics and stability to UV radiation. In particular there was no evidence of fraying, weakening or disintegration that could be attributed to UV degradation. The project team had some concerns that the woven polypropylene fabric might provide quite limited permeability (restricted to the intersection of weft and warp elements). This might cause large volumes of biogas to be trapped under the cover, creating cover management issues. As a consequence, it was proposed that the non-woven, punched fibre polypropylene be used for future cover construction.

A series of photographs document the deterioration of the unprotected polypropylene cover at piggery A. Initially the deterioration was imperceptible. Once the cover had been weakened however, the damage occurred very rapidly. Figure 33 (iv) shows a small area of damage caused by physical strain (walking over the cover material). Within a two month period, further physical stress (foot traffic and ambient wind) had caused a very extensive area of damage [Figure 33 (v)]. It became necessary therefore to shield the cover from direct sunlight to prevent further damage. There was no sign of fabric deterioration on the cover itself.

Similar deterioration was observed at the other trial sites. Figure 34 illustrates the deterioration of the cover material around the pond margin at piggery C. Once again, there was no sign of fabric deterioration on the cover itself.

Deterioration was also observed on the cover at piggery B if adequate protection was not afforded (Figure 35). Owing to the size of the pond and the presence of floating pumps and discharge lines, some parts of the cover were not protected with shadecloth. On these areas, deterioration of the unprotected areas of polypropylene continued. It should be noted that such deterioration did not take place on the cover surface if it was in direct contact with the pond liquor or remained damp most of the time. This is clearly indicated in Figure 35 (iii), where the moist and dry areas of the unprotected cover are clearly shown. The damp cover surface is covered with a thick biofilm, the presence of which appears to afford in-situ protection to the polypropylene fabric against UV attack.

i) Cover following deployment, February 2003

ii) Cover after three months, May 2003

ii) Cover after nine months, December 2003

iv) Cover after 13 months (March 2004); Note minor damage (arrow)

v) Cover after 14 months (April 2004); Note extensive damage (arrow)

vi) Cover after 16 months (June 2004); shadecloth installed

Figure 33: Deterioration of polypropylene cover following deployment (piggery A)

i) Cover after three months, July 2003

iii) Cover after 11 months, March 2004

ii) Cover along pond margin after 11 months, March 2004

ii) Cover along pond margin after 11 months, March 2004

Figure 34: Deterioration of polypropylene cover following deployment (piggery C)

i) Polypropylene cover eight months after deployment (March 2004)

ii) Polypropylene cover eight months after deployment (March 2004)

iii) Polypropylene cover eight months after deployment (March 2004)

iv) Polypropylene cover 25 months after deployment - continued disintegration of cover not protected from sunlight (June 2005)

Figure 35: Deterioration of polypropylene cover following deployment (piggery B)

4.2.2.4 Improving the Life Expectancy of a Permeable Cover

The straw component of a supported straw cover clearly has an effective life expectancy less than about 12 months. The life of the straw layer may be extended by providing increased buoyancy to the cover. The costs of this would need to be balanced against the likely benefits. Being in contact with the liquor clearly hastens decay of the straw – it is not possible to avoid this using the technology trialled in this investigation.

The life expectancy of a spun-fibre polypropylene cover is strongly influenced by direct sunlight. Reducing sunlight exposure will significantly extend the life of the cover. This investigation demonstrated that a composite cover, comprising a lower layer of polypropylene and a protective layer of polyethylene shadecloth provides a reasonably practical method of extending the cover life. In this study it was necessary to deploy the covers in two separate operations. This increased the cost and difficulty of achieving the objective. During future cover deployments, the two cover materials should be deployed together. This will allow the two covers to be firmly attached to each

other, say by stitching the shadecloth to the polypropylene. This practice would minimise subsequent maintenance of the shadecloth cover.

We observed that the quality of polymeric cable ties varied quite significantly. Care was taken to only use UV resistant ties – despite this, a number failed within a two year period. These gaps allow strong winds to get under the shadecloth layer, lifting it and placing considerable strain on all other anchor and joining points. Direct attachment of the shadecloth to the polypropylene would greatly eliminate this possibility, or limit it to a small area of the cover only. While it is possible to repair minor tears or breakages by pulling a flat-bottomed boat onto the cover, this is a difficult and tedious operation best avoided by improving the quality of materials used and methods of construction.

The requirement for management of vegetation around the pond covers was not specifically investigated. It is probably good practice to mow around pond margins to reduce the potential for accidents, as well as the habitat for snakes. Mowing or spraying the grass that will naturally grow around the pond margin will delay the colonisation of the cover, but will probably not prevent it from happening. Wind-blown seeds, or seeds deposited by birds will eventually germinate on the cover. The straw cover will contain seeds that will be effectively "sown" during cover manufacture. On a large pond, the resulting plants could be almost 40 m from the margin, making removal difficult.

Figure 36: Failure of cable ties used to attach lengths of polyethylene shadecloth following deployment (piggery C)

In Appendix 1, attention was drawn to the possibility of a "self-maintaining" vegetative cover. One of the trial covers used in the original trial was incorporated into the straw cover at piggery B. This cover had supported a dense stand of Rhodes grass for over five years. Unfortunately the performance of the vegetation is not predictable. It is influenced by drought and the resulting increase in salinity of pond liquor, which may cause the vegetation to die completely. Should the cover manage to establish successfully, lush vegetation may encourage animals to stray onto it, with negative consequences for both the animal and the cover.

Left unchecked, grass can encroach on the cover rapidly. This is indicated in Figure 37. Growth of the biomass on the cover added a considerable mass to the cover. A significant root mass extended through the cover into the liquor, creating a dense mat on the underside of the cover (Figure 38). In addition to the extra mass, the extensive system of runners produced by the couch grass very effectively anchored the cover in place. The roots in turn firmly held the shadecloth in contact with the polypropylene layer, probably eliminating the prospect of wind damage. It is possible therefore to view extensive grass encroachment as being positive in terms of preventing wind damage, or a potential problem if the cover needs to be moved away from the bank to facilitate sludge removal.

i) Pond cover, May 2005 **ii) Pond cover, December 2006**

Figure 37: Encroachment of couch grass onto the pond cover (piggery C)

Figure 38: Extensive growth of roots of couch grass through the pond cover (piggery C)

4.2.2.5 Factors Most Influential on Cover Life Expectancy

The earlier discussion has demonstrated that different factors are likely to influence the anticipated life expectancies of polypropylene covers and straw-based covers.

4.2.2.5.1 Polypropylene Covers

Avoidance of UV damage from sunlight is a critical requirement to maximise the life expectancy of a polypropylene fabric cover. Unprotected, the cover fabric may weaken or completely disappear within 12 months of deployment. Where the cover is moist, the biomass that develops on the cover surface eliminates damage. Areas that remain dry do not receive this protection, and rapid failure may be expected around the pond margins or on the upper surface of areas kept dry by the flotation strips. Acceptable cover life expectancies could only be assured if a surface layer of polyethylene shadecloth were installed at the time of deployment.

While it is necessary to eliminate wind damage, this appears necessary for the shadecloth cover only. Direct attachment of the shadecloth to the polypropylene cover at suitable spacing is recommended. This is probably best done at the time of manufacture or deployment.

4.2.2.5.2 Straw Covers

Results from two trials have demonstrated that the straw in a supported straw cover has a life expectancy of up to 12 months. To ensure ongoing odour reduction and to eliminate UV damage to the supporting structure, it would be prudent to replenish the straw on an annual basis. Wind damage does not appear to be an issue for supported straw covers.

4.2.2.5.3 General Cover Management Issues

Adequate fencing would prevent stock or wild animals straying onto the covers. Deposition of material on the surface of the covers should be avoided – limited buoyancy is provided at the time of deployment and any additional weight may cause immersion of the cover. Even localised immersion should be minimised – it will trigger ongoing deposition of solids from the liquor onto the cover surface, with dire consequences for the cover and producer. Once deployed, all covers are quite

unwieldy – it is difficult and very messy to move a cover unit more than a few metres. Attempts to move the cover may exceed the capacity of fastenings and joiners, which in turn may require re-attaching cover units on the pond.

4.2.2.6 Costs Anticipated over a 10 Year Cover Life Expectancy

The costs associated with the initial purchase and installation of a typical cover as well as maintenance of the cover over a ten-year life expectancy are summarised in Appendix 2. The actual cost for purchase and installation of a commercially manufactured cover are about $ 12.00/m^2.

While this cost is greater than that proposed after the initial assessment, it is still considerably less than that of alternate odour control strategies. The cost of the material used in an impermeable pond cover is greater than about $ 20.00/m^2. Impermeable covers require reticulation and advanced treatment for the biogas that accumulates. Strategies must be developed and capital equipment must be installed to manage the rainwater that accumulates on the cover surface. In addition to the increased capital costs associated with a biofilter or gas incinerator, these devices will require active management by the producer. In contrast, permeable pond covers may be viewed as add-on technologies with low to no management requirements.

It must be stressed however that the low operating costs and estimated 10-year cover life will only be realised if:

- The cover is manufactured in a manner that reduces the risk of wind damage;
- The cover is manufactured using materials that will reduce the risk of UV damage to acceptable levels;
- The cover is managed to avoid deposition of material on the pond cover surface.

4.3 Impact of Pond Covers on Pond Characteristics and Performance

Anaerobic pond treatment is favoured for relatively high strength wastes such as those derived from piggeries for a number of reasons:

- Little or no energy inputs are required;
- Sludge volumes are lower than those produced by aerobic processes;
- They are able to tolerate wide ranges of waste loads, provided adequate buffering is available;
- The ratios of concentrations of nitrogen to phosphorus to sulphur generated by piggery wastes are favourable for methanogenic processes.

Care is required with anaerobic process during start-up (which may be protracted), or when the nature of the influent waste load varies widely. Of these two situations, it is probably issues associated with start-up of an anaerobic pond that are likely to create problems.

4.3.1 The Impact of Permeable Covers on Pond Physico-Chemical Status

The results of analysis of grab samples of pond liquor collected while odour sampling was in progress are summarised in Appendix 4 as a series of summary statistics. These data are also summarised in graphical form as a time-series and box and whisker plots in Appendix 5.

The data summarised in Appendix 4 and Appendix 5 reveals the following:

4.3.1.1 General Comparison of Water Quality Variables across All Sites

The water quality of pond B was quite different to that of the other three ponds, as illustrated by the very high electrical conductivity value.

Examination of the other variables indicates that the elevated electrical conductivity value is the result of elevated concentrations of chloride, potassium and sodium. Concentrations of ammonia-N and total Kjeldahl nitrogen are also considerably higher than in the other three ponds. These elevated concentrations increase the total solids concentrations in pond B relative to the other ponds.

Piggeries B and C draw water from a common source – the Wivenhoe dam. Piggery A draws water from the Cambooya Shire supply. In all cases water from these sources is treated to human drinking water standards.

The waste loading rate at piggery B is about 30 % greater than that of piggery C. It uses recycled liquor for flushing, whereas piggery C uses fresh water for this purpose. Piggery A has the highest waste loading rate and also uses recycled liquor for flushing. This water is drawn from a secondary pond.

Concentrations of volatile solids and COD were persistently higher at pond B than the other three ponds.

A previous investigation highlighted the impact of a prolonged drought on the quality of liquor in pond B (Hudson et al., 2004). Concentrations of salts increased over the three seasons studied. For example, sodium concentrations almost doubled from about 116 mg/L to about 220 mg/L, while concentrations of potassium increased from about 200 mg/L to about 600 mg/L. Over the period studied, concentrations of ammonia-N ranged from 400 to 500 mg/L, while those of total Nitrogen were between 450 and 700 mg/L. Concentrations of all variables increased from summer 2000/2001 to summer 2001/2002. Concentrations of a number of water quality variables therefore appear to be generally higher in pond B than the other ponds.

4.3.1.2 Trends in Concentrations of Water Quality Variables over Time

Examination of the time series plots for all ponds in Appendix 5 does not indicate an obvious trend in concentrations of any variables at any site. The elevated concentrations of a number of variables observed in pond B are therefore not related to the deployment of the pond cover – they reflect conditions that existed in the ponds before the covers were installed. These results corroborate those observed in the laboratory-scale trials (Hudson et al., 2001). Previously, concentrations of selected variables (notably ammonium-N and hydrogen sulphide) appeared to increase rapidly once a permeable cover was installed on the liquor. Once the concentration had achieved what was described as a new equilibrium value, there was no indication of an on-going trend. The concentration of the variable appeared to stabilise at some new, elevated value. Examination of the results for the covered and control ponds at piggery C (Figure 39) indicates that this happened within weeks of the installation of the pond cover. Figure 40 shows that liquor pH values were also relatively stable, with no sign of decrease over the period of the study.

Figure 41 confirms that the installation of a pond cover increases hydrogen sulphide concentrations in the liquor under the cover. While average hydrogen sulphide concentrations appear five to ten times higher in the liquor of the covered ponds than in the control pond at piggery C, there is no evidence of increasing hydrogen sulphide concentration in the liquor of any of the ponds over the assessment period.

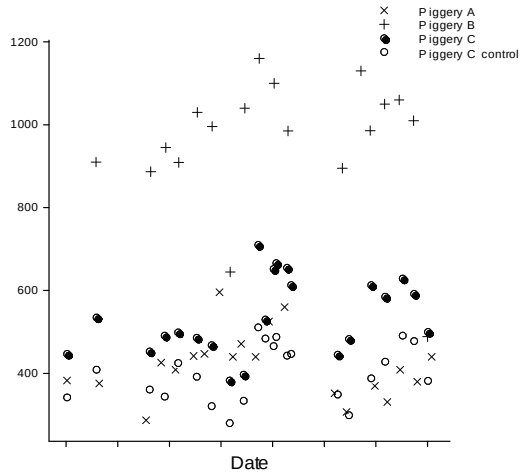


Figure 39: Trends in concentration of ammonia-N

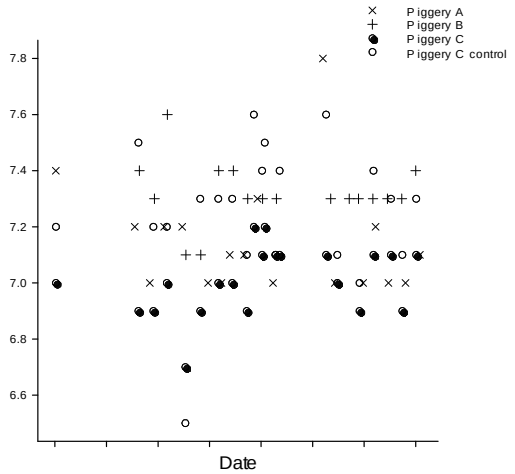


Figure 40: Trends in value of liquor pH

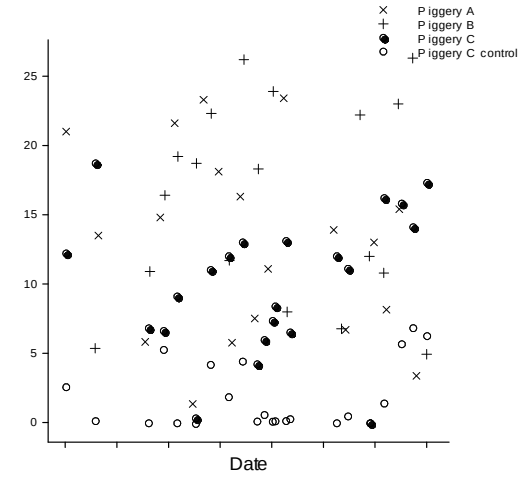


Figure 41: Trends in concentration of hydrogen sulphide

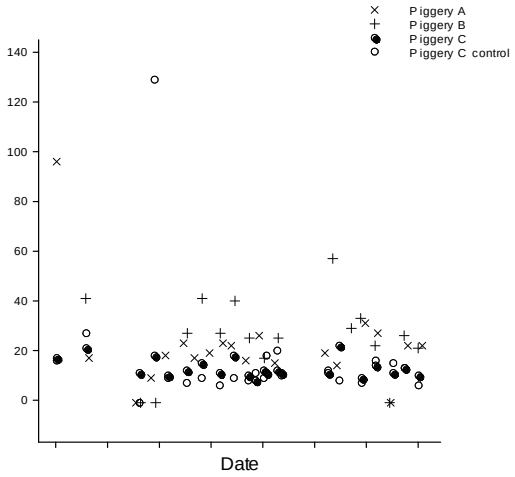


Figure 42: Trends in concentration of total sulphur

There was some indication of seasonal variation in concentrations of some variables. This possibility was investigated graphically using box and whisker plots. Results for selected variables are summarised in Appendix 6.

Concentrations of conservative variables (ionic species that tend to remain in solution and not precipitate out) appeared to be elevated in spring (September – December) and have lowest concentration in summer/autumn (e.g. chloride, potassium and electrical conductivity values).
Concentrations of nitrogen species appeared to be at their greatest in spring and summer and at a minimum in autumn (e.g. ammonia-N and TKN).

4.3.1.3 Impact of Permeable Covers on Pond Performance

The following discussion of pond performance relates to waste stabilisation, addressing the underlying question "Is waste treatment impaired by covering a pond with a permeable pond cover?" Pond treatment is usually regarded as an anaerobic process [e.g. (Casey and McGahan, 2000)]. In wastewater treatment terms, an anaerobic process is regarded as a biological treatment that occurs in the absence of oxygen (Tchobanoglous et al., 2003). The large surface area of anaerobic ponds typically used for the treatment of piggery wastes ensures that there is opportunity for significant inputs of oxygen from the atmosphere. The large oxygen demand created by the waste load rapidly

utilizes this oxygen. As a consequence, measurable concentration of dissolved oxygen are only observed in the surface layer of pond liquor. Deployment of a permeable pond cover may be anticipated to reduce the input of oxygen to the pond quite significantly. The permeable cover may therefore be anticipated to increase the anaerobic nature of the pond, while effectively eliminating any facultative characteristics.

For this discussion, impairment of waste treatment is considered from the perspective of accumulation of un-reacted organic matter in the pond liquor. If this were taking place, increases in concentrations of volatile solids and chemical oxygen demand in the pond liquor would be anticipated. Data presented in Figure 43 to Figure 45 provides no indication of increases in concentrations of total or volatile solids or chemical oxygen demand in pond liquor over the life of the project.

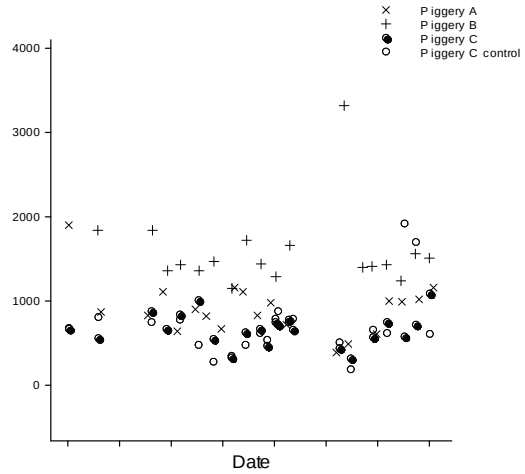


Figure 43: Volatile solids concentration trends

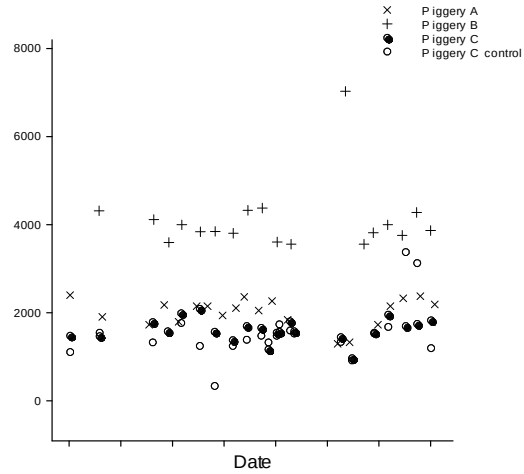


Figure 44: Total solids concentration trends

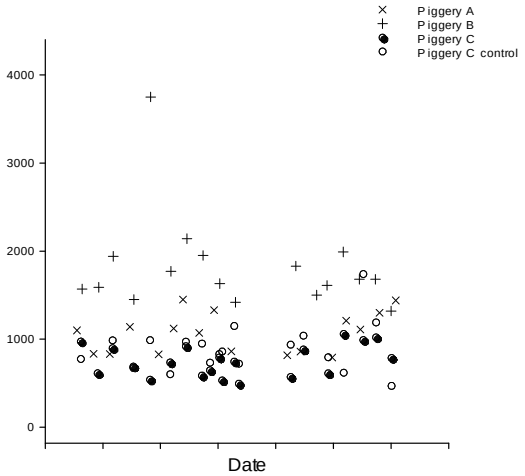


Figure 45: Chemical oxygen demand concentration trends

Average results for the four ponds used during this study were compared with those derived from two earlier pond surveys conducted by DPI&F (Casey, 2001). These results are summarised in

Table 17. With the exception of total Kjeldahl nitrogen for pond B, average results for all other variables were lower than those previously measured in typical anaerobic treatment ponds in Queensland.

Table 17: Comparison of average concentrations of selected water quality variables

Water quality variable	Average concentration (mg/L)					
	Previous results		This research			
	1994	1999	Pond A	Pond B	Pond C	Pond C control
Total Kjeldahl nitrogen	998	871	540	1097	609	483
Total solids	8618	8700	2015	4097	1618	2620
Volatile solids	4411	2500	910	1579	866	1472
Chemical oxygen demand	*N/D	*N/D	1064	1813	754	1527

*N/D = not determined

Considering the results for the current study specifically, average concentrations of volatile solids and chemical oxygen demand in the three covered ponds appeared lower than those of the uncovered pond at piggery C. There was no indication of significant accumulation of material in the pond liquor. Consideration of the visual appearance of the liquor in the control and covered pond at piggery C provides some indication regarding the relative magnitude of organic material in the liquor of these two ponds.

It is recognised that elevated concentrations of ammonia-N and hydrogen sulphide may impair anaerobic treatment processes (Tchobanoglous et al., 2003). Sulphate-reducing bacteria compete with methanogenic bacteria for available chemical oxygen demand and may thereby reduce the amount of methane produced. Concentrations of hydrogen sulphide above about 20 mg/L increasingly inhibit methanogenic activity. The toxicity is exacerbated by decreases in pH, which shifts the equilibrium concentrations toward unionised H_2S, which is more toxic than the ionised sulphide (S^{2-}) or hydrogen sulphide (HS^-) species. While concentrations of total sulphide were larger in the liquor of the covered ponds, they were all lower than 20 mg/L, above which inhibition of methanogenesis may occur.

Free ammonia (ammonia-N) may also inhibit methanogenic organisms. While toxicity has been reported at free ammonia-N concentrations above about 100 mg/L or at ammonium-N concentrations above about 1500 mg/L at pH greater than 7.4, acclimation also appears possible. As a consequence, ammonia-N toxicity was not observed with liquor ammonium-N concentrations in a range of 5000 to 8000 mg/L following long-term acclimation (Tchobanoglous et al., 2003).

The pH of pond liquor can provide insights regarding the likely failure of an anaerobic digestion process. Anaerobic treatment of wastes with high concentrations of sugars and soluble starch may increase concentrations of volatile fatty acids and hydrogen in the liquor, which in turn depress pH. In severe cases, almost complete failure of the waste treatment process may then follow. There is no indication of deterioration in anaerobic treatment performance in the data summarised in Figure

46. An absolute difference in pH values of about one pH unit was observed over all the ponds over the entire period of the investigation.

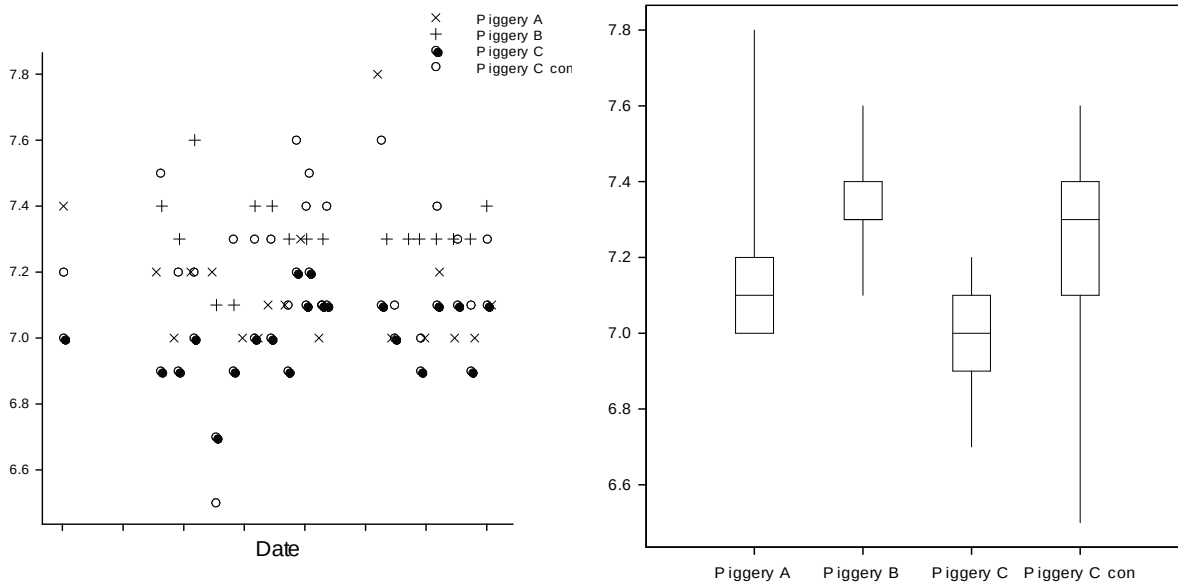


Figure 46: Comparison of liquor pH values

Finally, it is interesting to note that the appearance of the liquor from the two ponds at piggery C is distinctly different. Figure 47 and Figure 48 show the liquor discharging from the flume. The liquor from the control pond has a characteristic reddish colour and is quite turbid. This is probably due to the presence of photosynthetic bacteria ("blue-green algae") that form a significant population in the pond liquor. Liquor from the covered pond had a green colour and was quite clear, without much turbidity. This comparison is further highlighted in Figure 49. An explanation is hypothesized for these observations in Section 4.3.1.4.

Figure 47: Flushing flume with liquor from control pond (turbid, with brown colouration)

Figure 48: Flushing flume with liquor from covered pond (clear, with green colouration)

Figure 49: Comparison of liquor from covered pond (clear, with dark green colouration, LEFT), with that from control pond (turbid, RIGHT)

4.3.1.4 Impact of Permeable Covers on Pond Microflora

A limited number of samples were collected to assess the impact that pond placement might have on the microfloral population of anaerobic treatment ponds. Analysis of these samples was undertaken by an external service provider working under the auspices of Queensland Health. After a few samples had been analysed, the terms governing external consulting work altered and this laboratory was no longer able to provide the service. An alternate service provider could not be identified. Available results are summarised in Table 18.

The limited data indicated that the cover placement dramatically altered the pond microfloral composition in terms of both population composition and species numbers. The number of photosynthetic bacteria declined sharply. This appeared to allow green algae to more successfully colonise the pond liquor. Total numbers of green algae rose, while as a percentage of population they became the dominant organism.

These results partially corroborate the explanation offered regarding the visual appearance of the pond liquor in the previous section, illustrated in Figure 47 to Figure 49. The reduced light levels beneath the cover possibly provides a competitive advantage to larger, more intensely pigmented algal species. It is postulated that the higher chlorophyll concentration allows these organisms to survive despite the very low incident light intensity. The implications of this situation on pond function cannot be explained on the basis of available information. It is unlikely, however that this will alter pond treatment processes. Establishment of a suitable microfloral population is important for facultative and tertiary treatment systems, where they are associated with uptake of nutrients. Results in Appendices 4 and 5 indicate that phosphorus concentrations do not appear to be significantly influenced by deployment of a permeable pond – the availability of phosphorus in the pond liquor does not appear to be influenced appreciably.

Table 18: Comparison of average organism count of pond microflora

Organism	Average organism count (cells/mL)			
	Pond A	Pond B	Pond C	Pond C control
Diatoms (Bacillariophytes)	*N/C	12.5	3,000	N/C
Green algae (Chlorophytes)	*N/C	81,800	50,200	6,880
Blue-green algae (Cyanophytes)	*N/C	3,035	14,000	7,540,000
Total cells/mL	*N/C	84,200	84,700	7,920,000

*N/C = not counted owing to excessive detritus

4.3.2 Impact of Permeable Covers on Gaseous Emissions from Ponds

4.3.2.1 Evolution of Odour in Piggery Waste Treatment Systems

During extended periods of storage and treatment that occur in anaerobic ponds, complex wastes are transformed through chemical and microbiological processes to simpler molecules. Three basic steps are involved with the anaerobic digestion of waste materials:

1. Hydrolysis
2. Fermentation (or acidogenesis) and
3. Methanogenesis.

Hydrolysis is the conversion of complex or particulate materials to soluble compounds which can then be further degraded to simple monomeric substances suitable as substrates by bacteria. This process would be particularly relevant to undigested feed materials. Extra-cellular enzymes are primarily responsible for this process (Hill and Cobb, 1993).

Fermentation involves degradation of sugars, amino acids and fatty acids to produce acetate, propionate, butyrate and hydrogen and carbon dioxide. Butyrate and propionate are generally fermented further to hydrogen, carbon dioxide and acetate.

During methanogenesis, the products of fermentation (principally acetate, carbon dioxide and hydrogen) are utilised to produce methane.

The relationships between the various stages of anaerobic waste treatment are shown in Figure 50:
A range of non-methanogenic organisms (acidogens) are responsible for hydrolysis and fermentation. These include *Clostrium spp*, *Bifidobacterium spp*, *Staphylococcus* and *E. coli*. Many other groups are also involved in the process through production of various enzymes.

The micro-organisms responsible for the production of methane (methanogens) are strict obligate anaerobes, many of which are similar to organisms isolated from the stomachs of ruminants or from sediments in lakes and rivers (Tchobanoglous et al., 2003). A limited number of these organisms utilise acetate to produce methane directly, while the majority oxidise hydrogen with carbon dioxide to produce methane.

The methanogens and acidogens form a mutually beneficial (syntrophic) relationship in which the methanogens convert fermentation end products to methane and CO_2. The ability of the

methanogens to utilise the hydrogen formed during fermentation is critical – if the hydrogen produced is not utilised sufficiently quickly, propionate and butyrate fermentation slows and these volatile fatty acids (and other intermediate metabolic products) accumulate, reducing pH, which further slows the fermentation process. In addition to compromising waste treatment, accumulation of butyrate and propionate results in increased odour emissions. In extreme circumstances, anaerobic treatment fails.

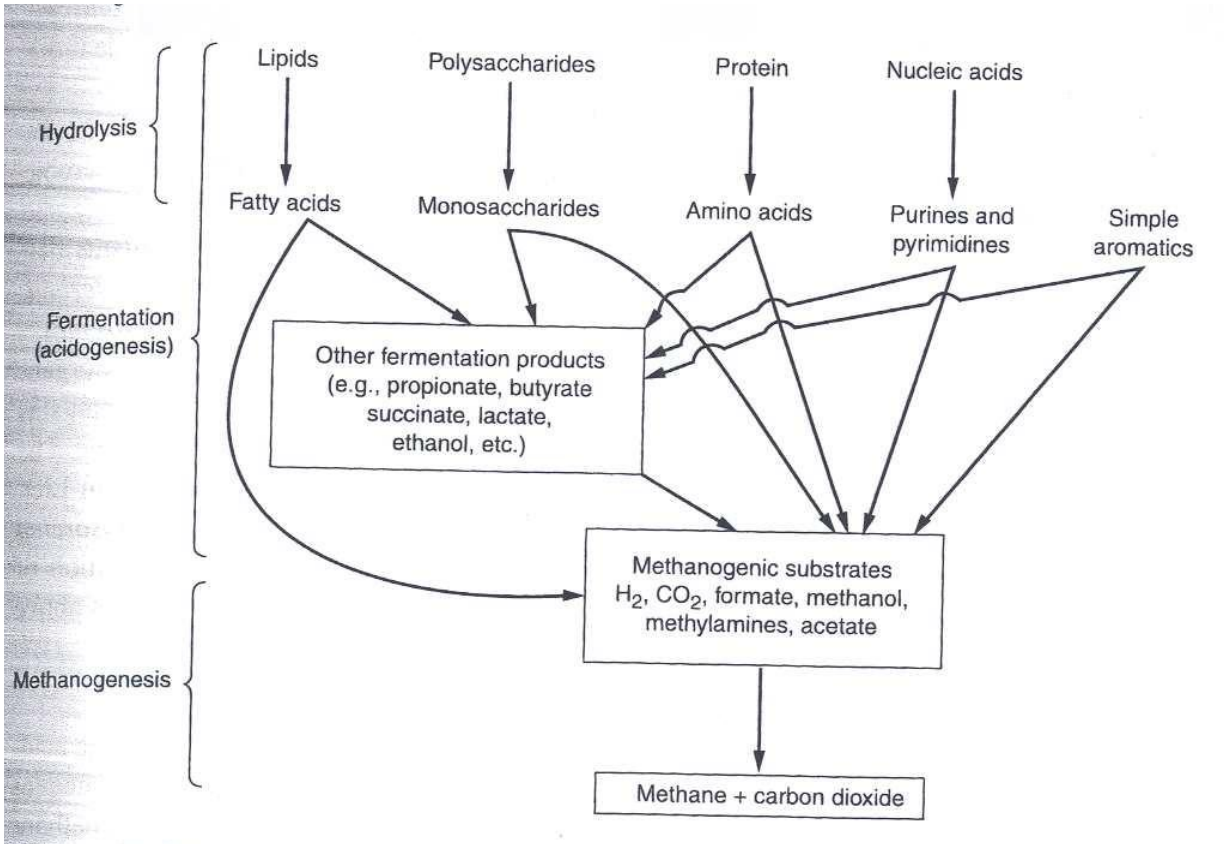


Figure 50: Anaerobic process schematic showing hydrolysis, fermentation and methanogenesis (Tchobanoglous et al., 2003)

The microbial biochemical basis for odorant production has been comprehensively reviewed by Hobbs et al. (2004), Mackie et al. (1998) and Spoelstra (1980). These reviews indicate:

- A close association between undigested protein and low molecular weight, branched volatile fatty acids, some reduced sulphides and indoles and phenols. Specific amino acids have been identified as precursors of key odorants (Mackie et al., 1998; Hobbs et al., 2004);
- Complex carbohydrates in particular have been associated with volatile fatty acids (mainly C_2 to C_4, with smaller amounts of C_5 to C_7 acids) (Zhu et al., 1999);
- Deamination of organic N-containing materials present in large amounts in excreta to form ammonia and volatile fatty acids (Mackie et al., 1998);
- Other relationships that have been identified clearly link specific compounds with odorants, including tyrosine (phenol, 4-ethyl phenol), tryptophan (indole and skatole) and phenylalanine (phenyl acetate, phenyl propionate and benzoic acid) (Mackie et al., 1998);
- Assimilatory microbial processes result in formation of cysteine and methionine, breakdown of which releases hydrogen sulphide and mercaptans;
- For dissimilatory processes, sulphate is used as a terminal electron acceptor and reduced to hydrogen sulphide directly (Mackie et al., 1998);

- A range of microbes were identified which were able to produce a series of volatile amines (Spoelstra, 1980).

4.3.2.2 Identification of Key Odorous Chemicals

As a consequence of the large number of microbiological species, environmental conditions and large volumes of waste, many odorous chemicals have been identified in piggery wastes. For example, Schiffman et al. (2001) identified 203 odorous chemicals in air samples adsorbed on Tenax® and 112 in air samples adsorbed on cotton fabric, while a further 167 were identified in pond liquor samples. A number of researchers draw attention to the fact that not all odorants have equal odour nuisance potential (Zahn et al., 2001; Keener et al., 2002; Wright et al., 2005). As a result, a smaller number of chemicals have been identified as key odour-causing compounds. Hobbs et al. (1997) suggested that chemicals from four distinct chemical classes (sulphides, volatile fatty acids, phenols and indoles), were responsible for the distinctive odour of animal wastes. Zahn et al. (2001) developed a "synthetic swine odour" based on a suite of 19 volatile organic compounds previously correlated with odour arising from piggeries (Zahn et al., 2001). Keener et al. (2004) selected 19 similar odorants to create an odour suite.

In their investigations of emissions of odorants from 29 piggeries, Zahn et al. (2001) drew attention to the metabolic processes involved in the formation of volatile sulphur-containing compounds. The formation of complex sulphur-containing odorants (e.g. thiols and mercaptans) requires energy expenditure, whereas sulphate reduction to hydrogen sulphide yields energy, making it energetically more favourable. Assimilatory processes are also more sensitive to environmental factors, including piggery and waste management systems. It should therefore be anticipated that emissions of volatile sulphur would be dominated by hydrogen sulphide, with other compounds present in lower concentrations.

Two independent investigations have confirmed that only a small fraction of the total number of volatile and odorous compounds emitted from manure storages have ever been detected and quantified downwind of the source:

- Zahn et al. (2001) highlighted the fact that downwind concentrations of hydrogen sulphide were much lower than the detection threshold. This finding in part explains the previously observed lack of correlation observed between hydrogen sulphide concentrations and odour concentrations (Hobbs et al., 1998; Hobbs et al., 1999);
- Wright et al. (2005) did not detect hydrogen sulphide, dimethyl disulphide or methyl mercaptan in samples collected downwind of a major piggery. They identified 4-methylphenol, 2'-aminoacetophenone, isovaleric acid and 4-ethylphenol as the most significant odorants.

It is important to consider the nature of piggery waste investigated in many of the studies in the literature. In many cases, the piggery waste is described as "slurry". Total solids content of these slurries indicate a much greater concentration than observed in this study, which ranged from 1.6 to 4.1 g/L. Results reported by Zahn et al. (1997) were derived from a storage vessel with a total solids concentrations of about 22 g/L. Slurries used by Hobbs et al. (1998) had solids concentrations that ranged from 4 to 8.4 g/L. In the case of Zahn et al. (1997), wastes were derived from a dry-scrape removal system utilising minimal flushing water. Hobbs et al. (1998) recovered the slurry directly from beneath the slats after about six weeks storage. In both cases, the manure would have been much "fresher" than for wastes in a pond. In addition, the waste would not have been subject to sunlight, natural inputs of oxygen from surface aeration or the influence of algae. Hobbs et al. (1998) also refer to the impact of wind mixing and odour stripping (owing to the higher methane

production rate likely under lower waste strength pond conditions) on resulting odour emission rates and odour composition.

4.3.2.3 Measurement of Odorous Chemicals in Air Samples from Piggeries

Most researchers draw attention to the low concentrations of odorous chemicals present at intensive livestock production facilities and the analytical challenges caused by these low concentrations. Pre-concentration using solid phase sorbents or cryotrapping is essential for most volatile compounds. Schiffman et al. (2001) utilised Tenax® (2,6-diphenyl-*p*-phenylene oxide polymer) and specially prepared cotton fabric swatches to collect odorants from air samples. Air samples of about 320 L volume were collected from the exhaust fans of piggery sheds for analysis by GC-MS following thermal desorption (TD). Zahn et al. (1997) used two techniques utilising Tenax® sorbent tubes to identify and quantify odorants at piggeries. For one technique, they sampled 35 to 70 L of air at a flow rate of 700 mL/min, while about 126 L of air was passed through the tube at the same flow rate in the other technique. Analytes were recovered from the Tenax® using a supercritical fluid extraction technique prior to analysis by GC-MS.

Wright et al. (2005) utilised SPME to analyse odorants at piggeries and feedlots. This technique is inherently sensitive, but is difficult to utilise for quantitative measurements. All results provided were on the basis of relative differences between locations and as such are qualitative.

Sunesson et al. (2001) collected between 14 and 17 L of air from ambient air in and near milking sheds to assess VOCs on Swedish dairy farms. Tenax® was used as the sorbent. Rabaud et al. (2002) used Tenax® and Carboxen tubes for sampling odorants from ambient air at dairy farms. Sample volumes of one to 33 L were collected at flow rates from 20 to 65 mL/min (30 to 420 minute sampling periods).

The low concentrations of odorants in air necessitate the sampling of large volumes of air. For "conventional" air quality studies, the manufacturers of the various sorbent materials generally recommend sampling rates of about 100 mL/min and sample volumes of about 5 L (~ 50 min sampling period).

DiSpirito et al. (1998) developed a chamber to facilitate collection of odorants from air in contact with liquid waste during storage. The device was a essentially a closed chamber with low flushing rates, where concentrations presumably would be quite high. This would make detection and analysis relatively simple. Filipy et al. (2006) used a closed 20 L glass jar to simulate a waste pond holding dairy wastes. Air samples were collected from the unflushed headspace above the liquor using a cryogenic trap. The authors rationalised the use of a headspace approach to sampling because "measurement of emissions from lagoon 2 was unsuccessful due to extreme atmospheric dilution of the compounds".

The difficulties associated with deployment of bulky wind tunnels on liquid surfaces and low odorant concentrations appear to have discouraged measurement of rates of emission of specific odorants. Few studies have been published which involved the collection of air samples from chambers or wind tunnels placed on liquid surfaces. Lim et al. used a Buoyant Convective Flux Chamber (actually a wind tunnel) (Heber et al., 2002; Lim et al., 2003) to collect odour samples for olfactometry and for analysis of odorants. Air was sub-sampled from these bags onto Tenax® tubes at about 7 L/min; up to about 25 L of air was drawn through each tube. No other studies involving use of wind tunnels to measure emission rates of odorants were identified in a review of the literature.

4.3.2.4 Measurement of Odorous Chemicals in Samples Collected from Covered and Uncovered Piggery Ponds

Five different strategies were explored to analyse odorants in air samples derived from piggery treatment ponds. Changes were necessitated owing to the availability of equipment and ongoing technical problems.

1. In the initial proposal, it was anticipated that the air samples would be analysed using a Perkin Elmer GC-MS with thermal desorption capability. A series of technical issues led to the abandonment of this option after about 12 months of investigation. Limited money had been allocated to this aspect of the project because undertaking these analyses had been associated with a post-graduate research project. Lack of financial resources therefore eliminated undertaking large numbers of these analyses by commercial laboratories at full cost.
2. Use of a GC-MS operated by the Centre for Food Technology (DPI&F, Hamilton, Brisbane) was investigated. While the instrument was in perfect working order and provided excellent results, it did not have a thermal desorption inlet system, essential for investigations of this nature. Attempts were made to convert a Purge & Trap device (used for collecting volatile materials from liquid samples), but this was unsuccessful. The use of SPME sampling of odorants from odour sample bags was also explored, with limited success.
3. Use of an older model GC-MS with a thermal desorption unit (Animal Research Institute, DPI&F, Yeerongpilly, Brisbane) was also explored, with partial success. The instrument did not appear to have the sensitivity necessary for the task.
4. An arrangement was made to analyse samples using a suitable instrument operated by the Investigative Chemistry section of Queensland Health Scientific Services. The instrument comprised a Varian GC coupled to a Varian Ion-trap Detector (similar to a mass spectrometer). The unit had a Perkin Elmer Turbomatrix Thermal Desorption unit (TDU) as sample inlet system; use of this system ceased as the next system became available and owing to the relatively high costs of the analyses.
5. Finally, a GC-MS system with TDU was acquired by Sustainable Intensive Systems, DPI&F.

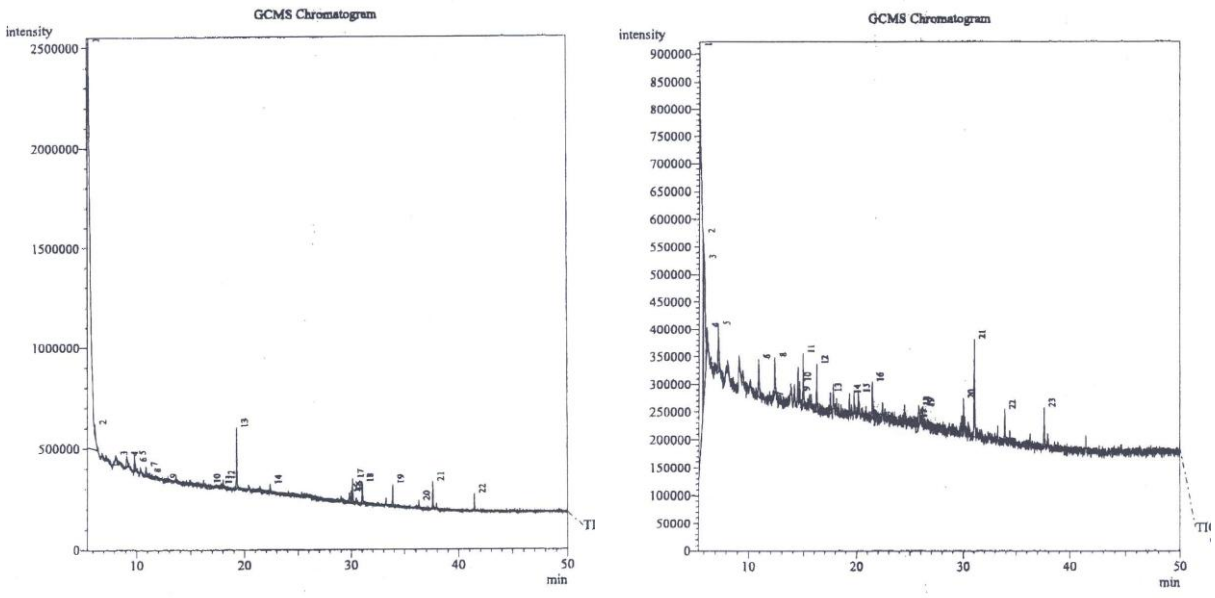
4.3.2.4.1 Analysis of Odorous Chemicals Using Purge and Trap Sampling

A series of samples were collected from the pond cover surface and from the exposed liquor surfaces at pond A. The samples were collected using a dynamic emission chamber or flux chamber (Balfour et al., 1987). This sampling device was selected because it creates more concentrated samples than the UNSW wind tunnel (Nicholas et al., 2004). Results of the analyses are summarised in Table 19. Typical chromatograms are presented in Figure 51. All of the compounds identified were present in relatively low concentrations. The exposed liquor surface samples contained a large number of volatile compounds, mainly short chain hydrocarbons. Some of these were present in the cover samples as well. The cover samples contained essential oils, presumably derived from the eucalypt leaves that collected on the cover. The only true odorant identified was dimethyl sulphide. The much less odorous carbon disulphide was also present.

The complete absence of more typical odorants identified in Sections 4.3.2.1 and 4.3.2.2 indicated that this technique was not suitable for this project, and this method of isolation and analysis of pond odorants was not pursued.

Table 19: Volatile chemicals identified in samples derived from liquor and cover flux chamber samples

Name	Area count	
	Liquor surface	Cover surface
pentane	2362	
dimethyl sulphide	4497	2946
carbon disulphide	783	3550
2-butanone	2834	
hexane	630	1492
3-penten-2-one	685	
methylcyclopentane	2210	
benzene	561	
2,4,4-trimethylhexane	712	
2,4-dimethylheptane	696	
4,4-dimethyl 2-pentene	1113	
toluene	873	
1,2-dimethylbenzene	882	
alpha-thujene		1902
3,4-dimethylheptane	1164	
1-chlorooctane	2978	
2,3,7-trimethyloctane	604	
limonene		2210



i) Exposed liquor surface **ii) Polypropylene and shadecloth surface**

Figure 51: Representative chromatograms showing results of GC-MS analysis of samples derived from odour sample bags (note differences in scale)

4.3.2.4.2 Analysis of Odorous Chemicals Using Sorbent Traps – QHSS Analyses

In-field trapping of odorants proved to be a more successful strategy for their isolation and analysis. Odorants could be trapped on Tenax® sorbent materials and stored in this form for a period of time without significant loss of material. It continued to be difficult to trap sufficient material on the traps to enable detection and quantification. Collection of samples ranging in volume from 10 to 40 L were investigated. At least 20 L volume appeared necessary; typically 25 L samples were collected at flow rates of 150 to 300 mL/min. Standard sample collection periods were 100 minutes duration.

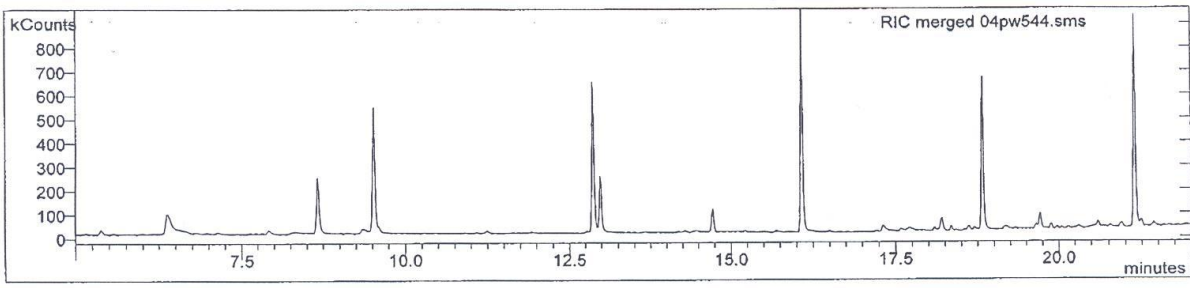
Typical chromatograms for samples derived from wind tunnels are shown in Figure 52. Most of the peaks in the chromatogram are internal standards (used for quality control purposes) or contaminants arising from the sorbent material or the chromatographic column. It is necessary to use a technique known as Selected Ion Monitoring (SIM), wherein abundances of specific mass fragments are measured. In Figure 52, the ions for the respective odorants are listed in the table beneath each chromatogram. For example, ion mass 107 was used for the quantification of *meta*- and *para*-cresol (3- or 4-methylphenol).

It is not feasible for a consulting laboratory to identify and quantify each peak in every chromatogram. For the samples analysed by QHSS, the focus was restricted to a selection of volatile fatty acids and substituted phenols. It was felt that these would adequately represent the odorants produced by anaerobic piggery ponds. A limited amount of exploratory work indicated that this focus was justified. The results of 58 discrete analyses, derived from 14 batches of samples collected from the three piggeries are summarised in Appendix 8. A limitation of the data set is the large number of results where quantities of the specific odorous chemicals were below the limit of detection of the analytical method. These results do not mean that the odorants were absent – it was just not possible to collect enough material to reliably confirm their presence or how much was present.

Print Date: 07 Jun 2005 10:57:11 Sample Report for 04pw544.sms

VOC analysis of ATD tubes for Air Quality Services

Sample ID:	04pw544	Operator:	
Last Calibration:	31/05/2005 12:46 PM	Acquisition Date:	14/04/2005 12:34 PM
Data File:	d:\... \04pw544.sms	Calculation Date:	7/06/2005 10:56 AM
Method:	D:\Airdata\2005\053105_wacol\Fatty acids, m-cresol 2.mth		



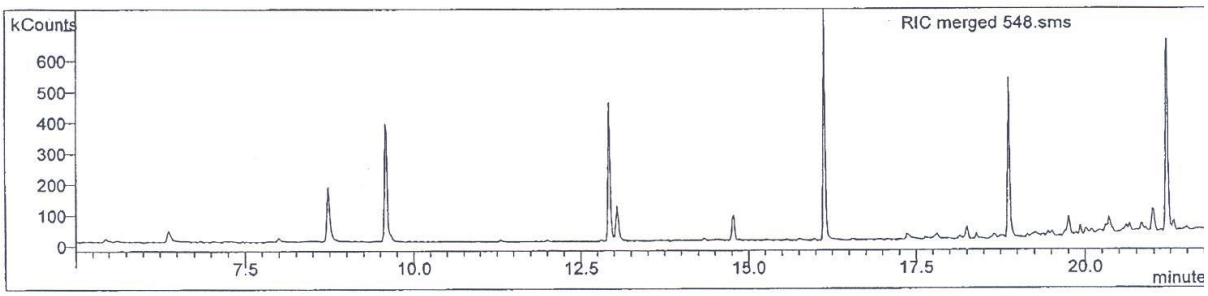
Target Compounds

#	RT	Compound Name	Res Type	Quan Ions	Area	Amount
1	10.807	Propionic Acid	Miss.	73	0	0.0
2	12.975	Isobutyric Acid	Miss.	73	0	0.0
3	13.801	Butyric Acid	Miss.	60	0	0.0
4	15.653	Valeric Acid	Miss.	60	0	0.0
5	17.554	Caproic Acid	Miss.	60	0	0.0
6	19.490	m-Cresol	Miss.	107	0	0.0

Print Date: 07 Jun 2005 10:51:06 Sample Report for 548.sm

VOC analysis of ATD tubes for Air Quality Services

Sample ID:	548	Operator:	
Last Calibration:	31/05/2005 12:46 PM	Acquisition Date:	31/05/2005 8:12 PM
Data File:	d:\... \548.sms	Calculation Date:	7/06/2005 10:49 AM
Method:	D:\Airdata\2005\053105_wacol\Fatty acids, m-cresol 2.mth		



Target Compounds

#	RT	Compound Name	Res Type	Quan Ions	Area	Amount
1	11.272	Propionic Acid	Miss.	73	0	0.0
2	12.848	Isobutyric Acid	Miss.	73	0	0.0
3	13.750	Butyric Acid	Miss.	60	0	0.0
4	15.677	Valeric Acid	Miss.	60	0	0.0
5	17.730	Caproic Acid	Miss.	60	0	0.0
6	19.280	m-Cresol	Fail	107	7527	3.3

Figure 52: Representative chromatograms showing results of GC-MS analysis of samples derived from wind tunnels, pond A (upper chromatogram pond cover surface, lower chromatogram exposed liquor surface)

4.3.2.4.3 Analysis of Odorous Chemicals Using Sorbent traps – SIS Analyses

Acquisition of a GC-MS system by SIS in July 2005 allowed additional measurements of VOC emission rates. Alternate methods of sample collection were also explored. Volatile chemicals were sampled from odour sample bags and the wind tunnel exhaust with either Tenax sorbent tubes

or SBSE (PDMS). Some representative results of the GC-MS analyses of these samples are shown in Figure 53 to Figure 58. These Figures illustrate:

Very complex chromatograms, with more than 50 poorly resolved peaks in each sample (Figure 53, Figure 56 and Figure 58). The mass spectral capability helps identify many of the chemicals present in these samples – most of them were likely to have low odour thresholds or be odourless. Highly odorous chemicals were present in most samples, often in low concentrations and usually as peaks that were not perfectly resolved from other compounds. This created difficulties when quantifying the material present in the peak with other compounds.

The capability of Selected Ion Monitoring (SIM) is highlighted in Figure 55 and Figure 57, where the presence of two key odorants is clearly revealed in SIM chromatograms as well-resolved peaks with good peak shape, essential criteria for identification and quantification.

Figure 58 also provides very useful insight into the composition of the air samples presented to an olfactory panel as "odour". Of particular interest is chromatogram C, derived from a sample collected from the permeable cover surface. It obviously is the most complex of all the samples (having the greatest number of peaks). In Section 4.2.1.4 the apparently lower than anticipated performance of permeable pond covers was discussed in terms of the biomass that developed on the cover surface. It was proposed that this biomass (microphytes, bacteria, mould and fungi) would produce a range of chemicals, some of which would be volatile. The series of chromatograms in Figure 58 appears to support this hypothesis.

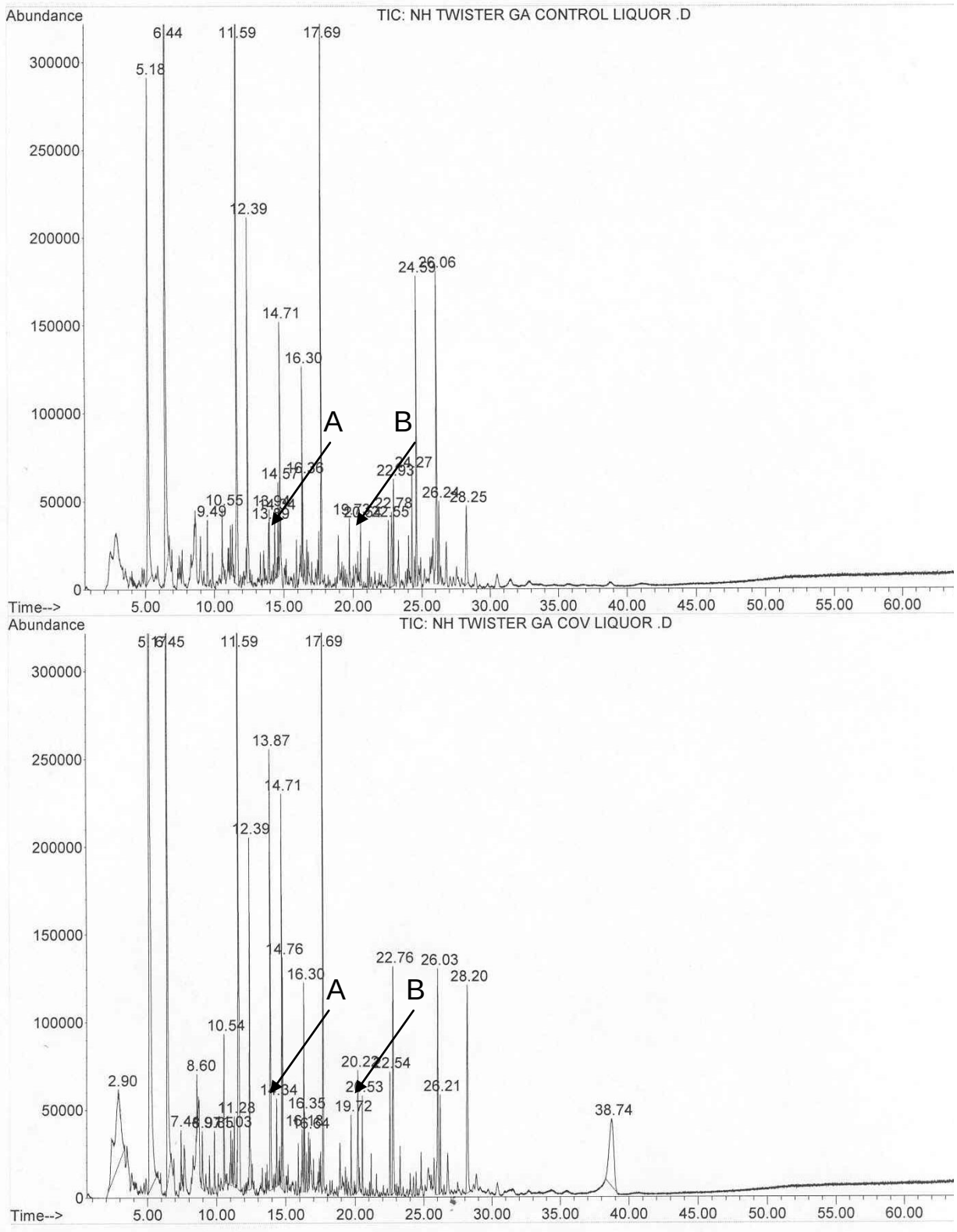


Figure 53: Representative Total Ion Count chromatograms showing results of GC-MS analysis of SBSE headspace samples of pond liquor: Control pond at piggery C (upper chromatogram), Covered pond at piggery C (lower chromatogram). Arrows indicate peaks for *p*-cresol (A) and indole (B) respectively.

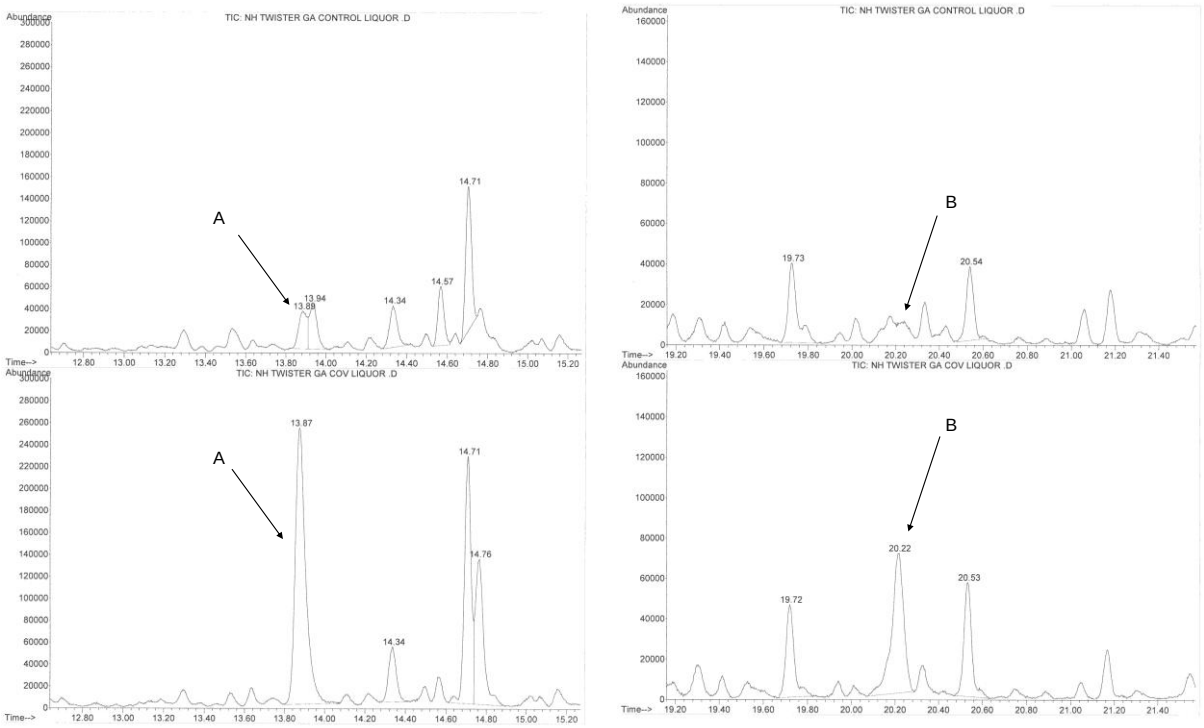


Figure 54: Enlargement of selected region of Total Ion Count chromatograms in Figure 53 showing peaks for *p*-cresol (A) and indole (B): Piggery C control pond liquor (upper chromatogram), Piggery C covered pond liquor (lower chromatogram).

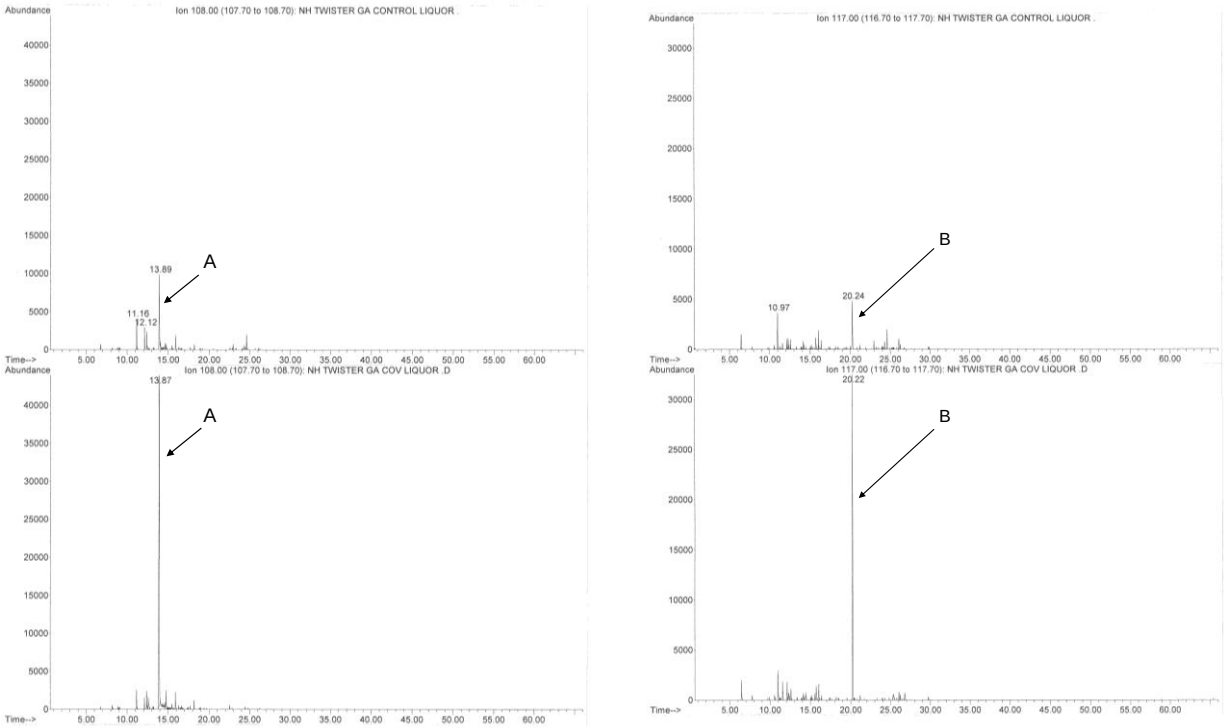


Figure 55: Enlargement of selected region of Total Ion Count chromatograms in Figure 53 showing peaks for *p*-cresol (A) and indole (B): Piggery C control pond liquor (upper chromatogram), Piggery C covered pond liquor (lower chromatogram).

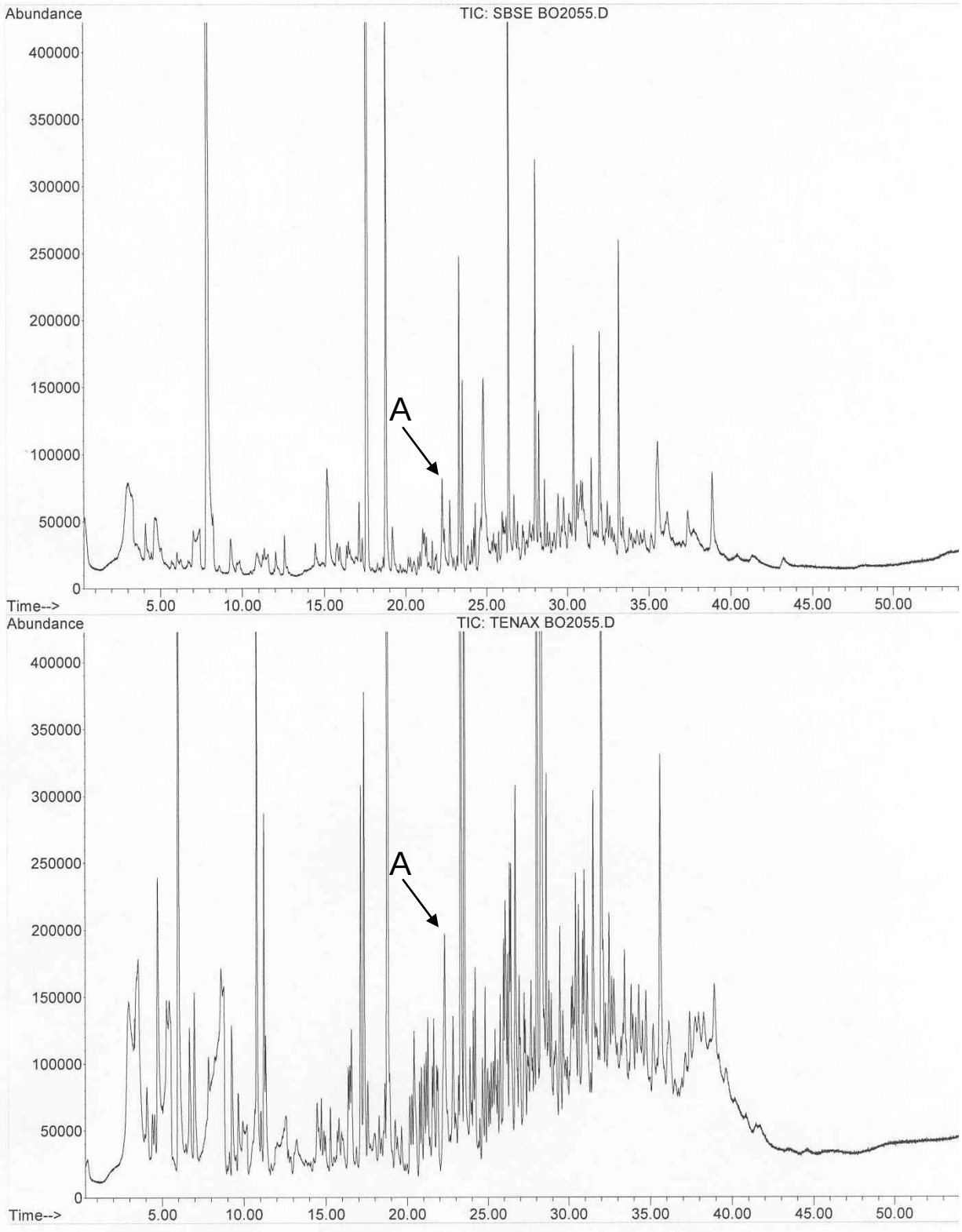


Figure 56: Representative Total Ion Count chromatograms comparing results using two different techniques for sampling from single odour bag sample: Chromatogram obtained using SBSE technique (upper chromatogram), Chromatogram obtained using Tenax® sorbent tube (lower chromatogram). Arrows indicate peaks for *p*-cresol.

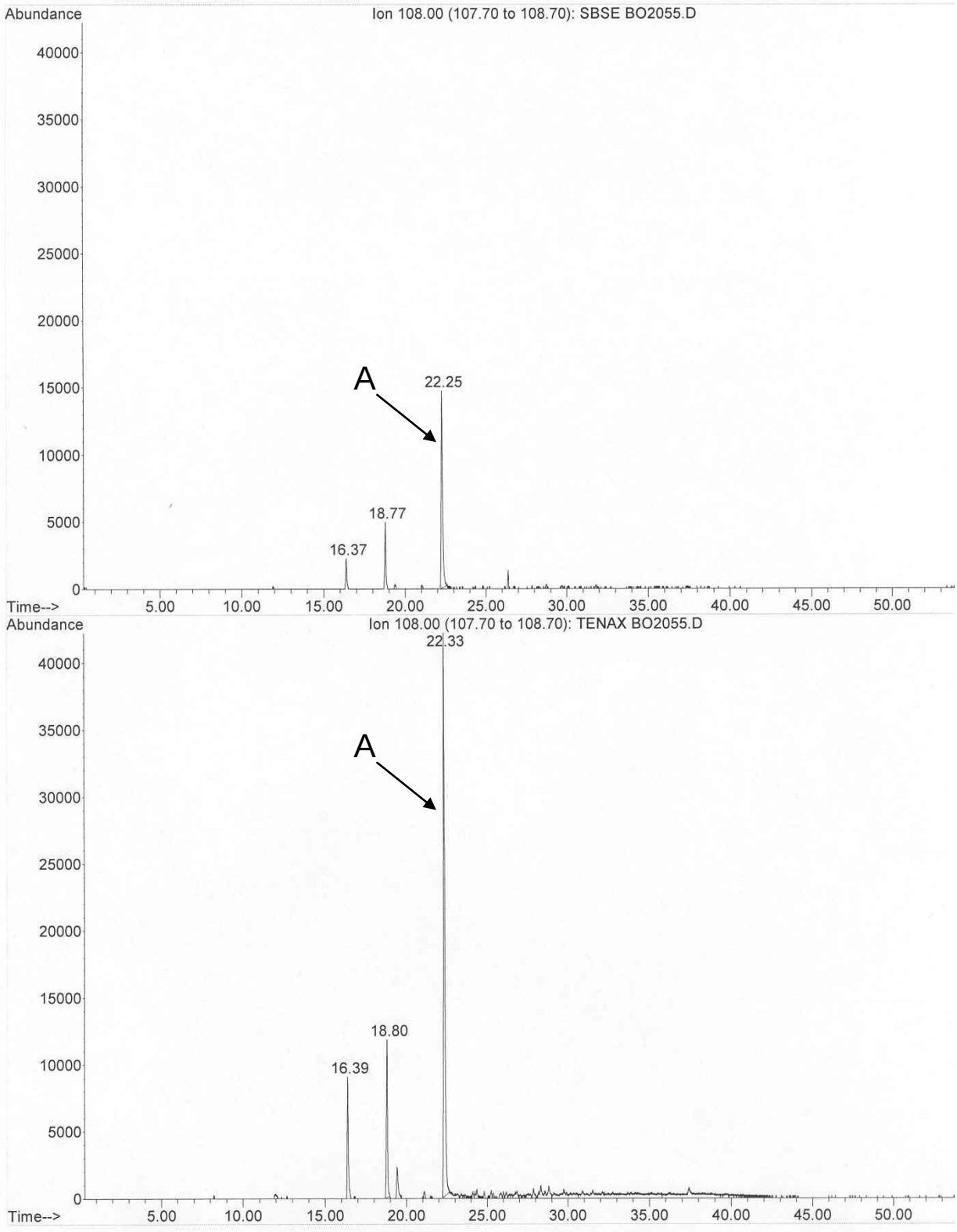


Figure 57: Representative Selected Ion Count chromatograms comparing results obtained using two different techniques for sampling from single odour bag sample: Chromatogram obtained using SBSE technique (upper chromatogram), Chromatogram obtained using Tenax® sorbent tube (lower chromatogram). Arrows indicate peaks for *p*-cresol.

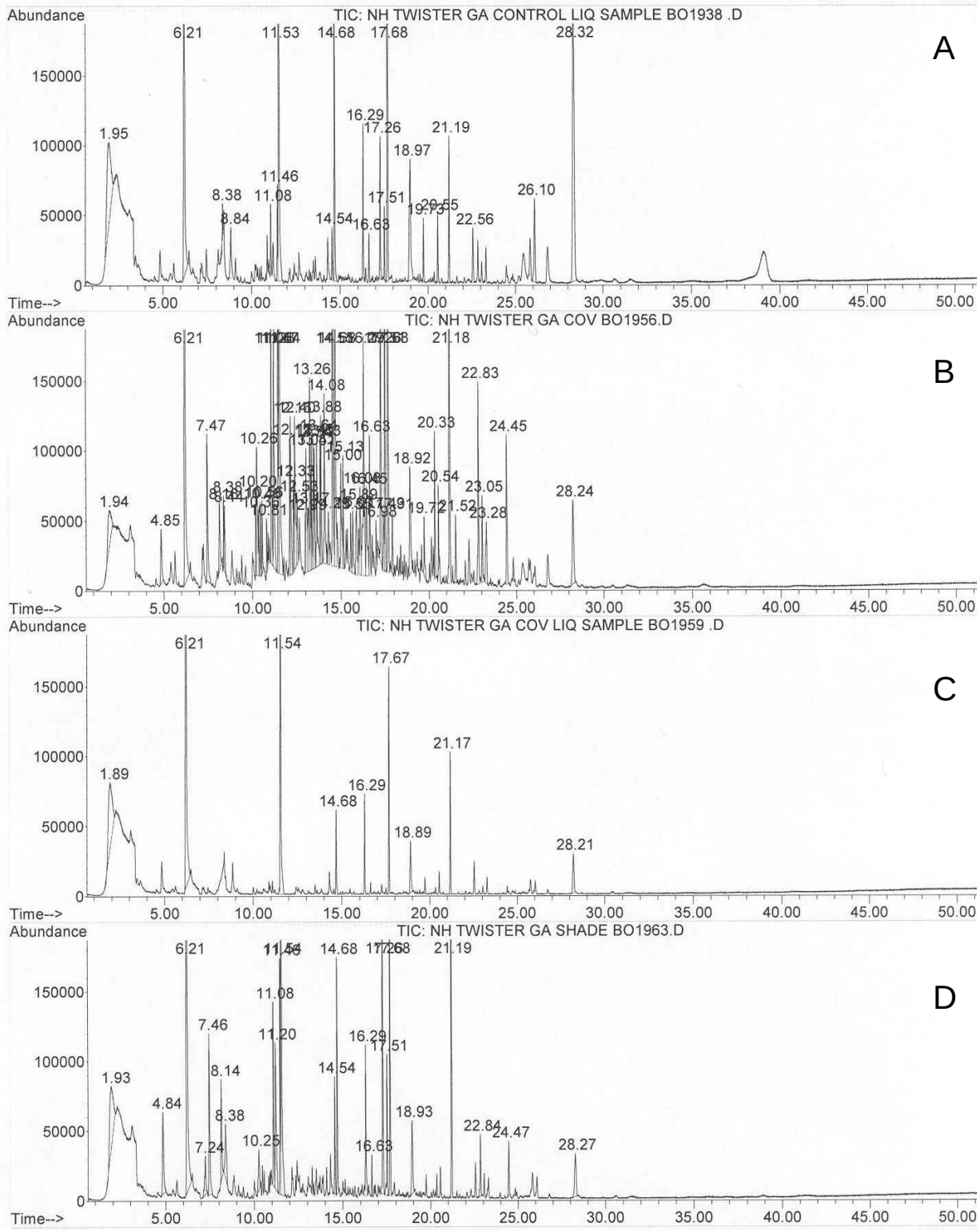


Figure 58: Representative Total Ion Count chromatograms showing composition of volatile materials in bag odour samples derived from sources at piggery C using a wind tunnel for sample collection and SBSE for extraction:
A - chromatogram obtained from control pond liquor,
B - chromatogram obtained from surface of polypropylene and shadecloth cover,
C - chromatogram obtained from covered liquor,
D - chromatogram obtained from shadecloth only cover.

4.3.2.5 Impact of Permeable Covers on Emissions of VOCs

An assessment was made of the efficacy of the covers in reducing rates of emission of odorants analogous to that used for odour emission rates in Section 4.2.1,

Table 8. Reductions of odorant emission rates by emitting surface as indicated by the samples analysed by QHSS are summarised in Table 20, while results from the samples analysed by SIS are summarised in Table 21.

Results in Table 20 represent the reduction in emission rate of the cover surface relative to the exposed liquor:

Table 20: Reduction in odorant emission rate by pond cover (QHSS analyses)

Date	Piggery	Reduction in odorant emission rate (%)					
		Propanoic acid	iso-Butyric acid	Butyric acid	Valeric acid	Caproic acid	*m*- & *p*-Cresol
1/04/2005	A	0	0	0	0	0	100
26/05/2005	A	0	0	-50.2	-164.9	-145	98.7
21/06/2005	A		0	38.1	-81.6		95.2
16/08/2005	A	0	0		0	0	
13/09/2005	A	0		0	0	0	100
29/04/2005	B	0	-1004.7		-949.1	-140.9	-184.9
17/05/2005	B	0	0	-22.5	-169.2	-271.9	
14/06/2005	B	0	0	0	0	-305.8	88.4
12/07/2005	B	100	0	99.9	0	-82.4	-375
9/08/2005	B	0	0	0	0	0	0
5/09/2005	B	0	0	0	0	0	0
19/05/2005	C	0	0	-111.1	-148.3	-109.8	96.6
10/08/2005	C	0	0	0	0	0	
6/09/2005	C	0	0	0	0	0	0

With respect to results presented in Table 20, it was necessary to ignore certain apparent increases or decreases in emission rate. In some cases emission rates were increased or decreased by factors of 60 000% or more. These results are not meaningful and reflect the very low concentrations measured and uncertainties associated with the amounts of VOCs present in the samples. The results that were removed are indicated by shading in Table 20. The values used to calculate these results are retained in Appendix 8 for reference.

According to the results summarised in Table 20:

- Plausible reduction rates were obtained for nine of 14 sets of data;
- For volatile fatty acids, pond covers appeared to reduce emission rates for only three of 18 results;
- Emission rates for substituted phenols were reduced by pond covers for six of eight values.

The results in Table 21 present results from the SIS instrument comparing rates of emission of VOCs for cover surfaces relative to the exposed liquor. Values reported for the control pond surface at piggery C indicate that emission rates from the control pond surface are about half those of the exposed liquor of the covered pond. These results are consistent with those provided by the olfactometry.

Table 21: Reduction in odorant emission rate by pond cover (SIS analyses)

Piggery	Data	Reduction in odorant emission rate by surface (%)		
		Control	Cover	Shade
A	phenol	-	5.2	
	4-methylphenol	-	84.9	
	indole	-	75.7	
	skatole	-	99.4	
B	phenol	-	-11.7	
	4-methylphenol	-		
	indole	-	90	
	skatole	-	80.2	
C	phenol	50	-1	-28.2
	4-methylphenol	50	-85.8	
	indole	50	48.4	
	skatole	50	84.4	

In the only other studies where VOC emission rates were measured for pond covers, Bicudo et al. (2004) and Zahn et al. [results tabulated by Bicudo et al. (2004)], reported an increase in VOC emissions from pond covers relative to uncovered control pond surfaces. VOC emission rates from covered ponds increased by about 50% and 14% in the years 2000 and 2001 respectively. The increase in VOC emission rate includes methane and other non-odorous or slightly odorous compounds.

The logistical and technical issues presented by the VOC measurements severely reduced the number of samples collected and analysed. About 400 odour samples were collected and analysed over the life of the project to demonstrate the efficacy of the various covers. In contrast, 124 samples were submitted to the four laboratories for VOC analysis over the life of the project. Approximately 30 additional samples were used for developing sampling and analytical methods. As a result of the relatively large number of discrete sample sources (three piggeries, four pond systems, nine emitting surfaces, three sample types and three sampling/concentration options), relatively few results were generated for each option. The results are generally quite consistent with the results of conventional olfactometry, and assist with the interpretation of the olfactometry results. A number of general conclusions can be drawn from this work which should guide future investigations:

- Volatile fatty acids do not appear to be significant odorants for pond treatment systems in Australia. All laboratories had problems isolating and quantifying VFAs in air samples derived from wind tunnels. Initially this was attributed to low concentrations and inadequate sample volumes collected. Supplementary analysis of samples collected from US EPA-style dynamic emission chambers ("flux hoods"), and the headspace of pond liquor also failed to reveal these odorants. Both of these sample sources provided highly concentrated samples.
- It appears that the lower loading rates and higher temperatures to which Australian pond treatment systems are subject, relative to North American and European treatment systems, make the formation and/or accumulation of VFAs less favourable.
- Of the non-sulphur containing classes of odorants, phenols and indoles appear to be significant contributors.

- The efficacy of removal of the indoles and phenols by permeable pond covers appear similar to that observed for a biofilter treating odorous air from a piggery (Dunlop et al., 2004). Odorant removal rates for the biofilter for phenol, 4-methylphenol, indole and skatole were 64.2, 99.5, 98.7 and 100 % respectively. Phenol removal efficiencies were quite variable. These results were similar to those observed for permeable pond covers (this study).

Future investigations of this nature should have regard for the cautionary comment of Zahn et al. (2001): "Commercially available analytical systems for VOC concentration and for water-carbon dioxide management were found to be well-suited for the analysis of non-water soluble analytes with low boiling points and relatively high Henry's law constants (i.e. halogen hydrocarbons, alkanes, alkenes and aromatic solvents), but did not provide quantitative results for analysis of the 19 VOCs associated with swine odour".

4.3.2.6 Impact of Permeable Covers on Greenhouse Gas Emissions

In the original research undertaken on permeable pond covers, greenhouse gas emission rates were investigated under laboratory conditions. It was observed that the presence of a cover had no impact on methane emission rates, but did appear to influence rates of carbon dioxide emission. Carbon dioxide emission rates also appeared sensitive to the type of cover material.

Since that research was undertaken, very few results from other trials have been published. Jungbluth et al. (2001) reported that covering manure storages with straw increased nitrous oxide and methane emissions. Sommer et al. (2000) measured emissions of nitrous oxide and methane from covered and uncovered storages over significant periods of time under field conditions. They noted that nitrous oxide emissions only occurred from covered slurry storages under drying conditions. They concluded that nitrous oxide formation occurred in the interface between the slurry and the cover. Emission rates were highly variable. Methane emission rates were 38 % lower from covered slurry storages than uncovered ones, with lowest emission rates observed for straw-covered storages. They attributed this to additional oxidation of methane during transfer across the surface layer. In sharp contrast, Cicek et al. (2004) reported a very significant increase in methane emission rates (241%) and a slight increase in nitrous oxide emission rates from straw covered storages.

In this investigation, emphasis was given to the impact of permeable polypropylene and shadecloth covers on carbon dioxide emission rates. This was determined in part by the results of the first study, where methane emission rates were shown to be independent of the presence and type of cover. It was demonstrated that nitrous oxide concentrations could not be measured with the instrumentation available (packed and capillary column gas chromatographs with flame-ionisation and thermal conductivity detectors).

Carbon dioxide concentrations were measured at 5 Hz frequency on samples derived from a UNSW-style wind tunnel deployed on each pond, as well as a US EPA dynamic emission chamber deployed on each pond. These data were then summarised as 5 min, 12 min or 60 min average data. Considerable redundancy was evident in the high frequency data and 60 min average data were quite adequate for the assessment of differences between the cover types. Results for the wind tunnel devices are shown in Figure 59 to Figure 61. Figure 60 and Figure 61 show concentrations for weeks two and five of the measurement period. Both Figures indicate a distinct diurnal pattern in measured carbon dioxide concentrations. This is displayed in box and whisker format in Figure 62.
Formal statistical testing indicated that there was no significant difference in carbon dioxide concentrations derived from the two wind tunnels at the 95% confidence level (p = 0.125). Figure

59 shows a near perfect correlation between carbon dioxide concentrations derived from wind tunnel samples from the two surfaces. These results do not agree with those observed in the laboratory-scale trials. An explanation is provided when the conditions created within the two sampling devices are considered. Carbon-filtered air was used to flush both wind tunnels. Ambient air contains about 330 ppmV carbon dioxide, which will provide a constant background concentration for each sample. Air was passed through each wind tunnel at about 0.3 m/s, creating an effective flushing rate of about 1,800 L/min. Under these circumstances, the large volume of flushing air would make it difficult to detect increases in carbon dioxide concentration unless very high emission rates existed. The sampling and analytical methodology did not allow us to measure small changes in relatively large numbers with sufficient accuracy or repeatability to detect differences in emission rate.

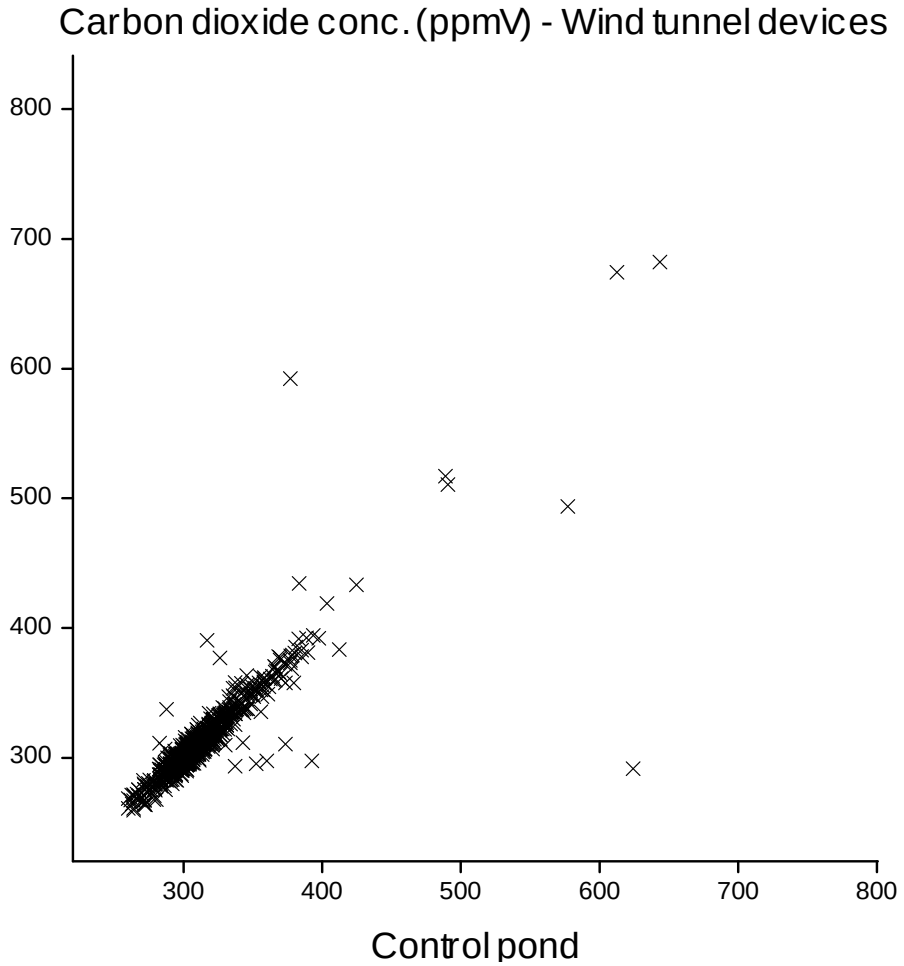


Figure 59: Comparison of carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using a wind tunnel

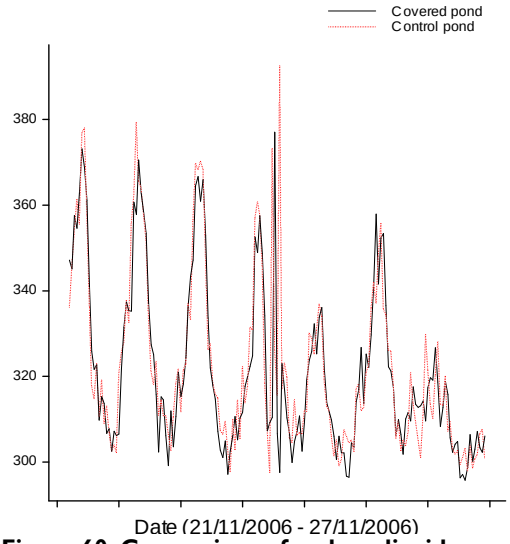


Figure 60: Comparison of carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using a wind tunnel – week 2

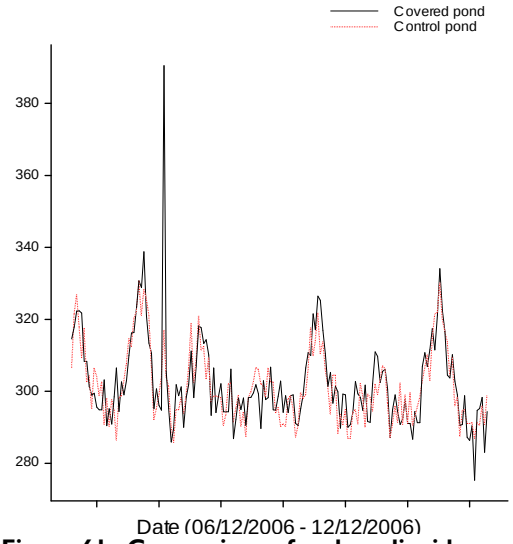


Figure 61: Comparison of carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using a wind tunnel – week 5

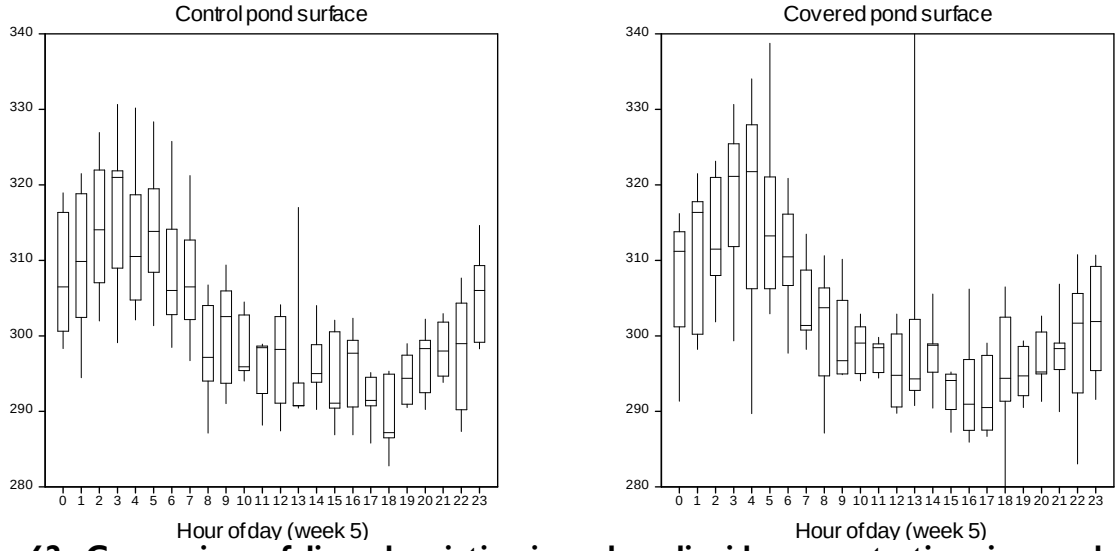


Figure 62: Comparison of diurnal variation in carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using a wind tunnel – week 5

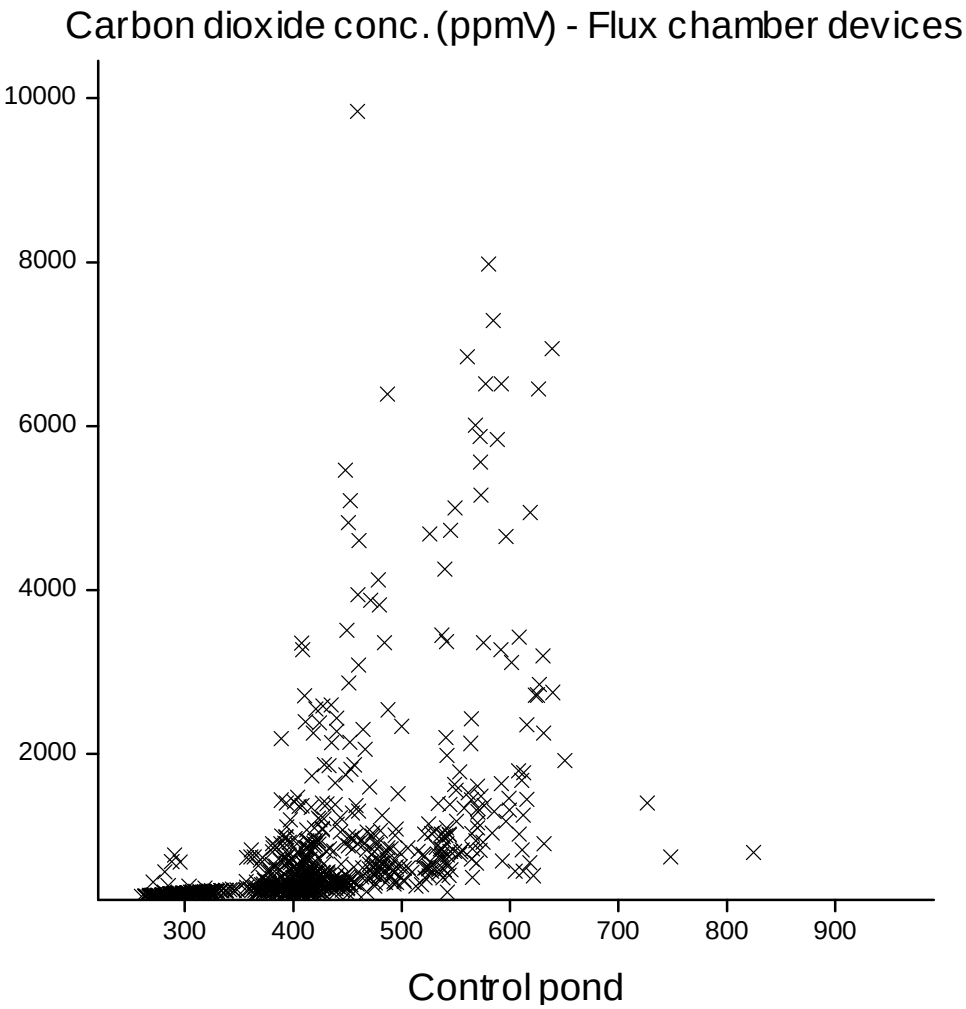


Figure 63: Comparison of carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using US EPA dynamic emission chambers

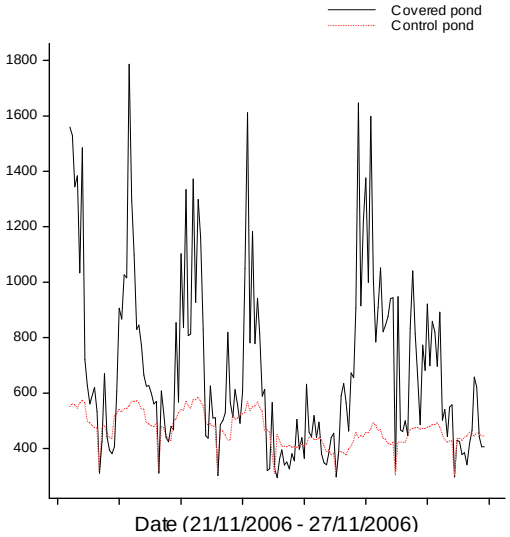


Figure 64: Comparison of carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using US EPA dynamic emission chambers – week 2

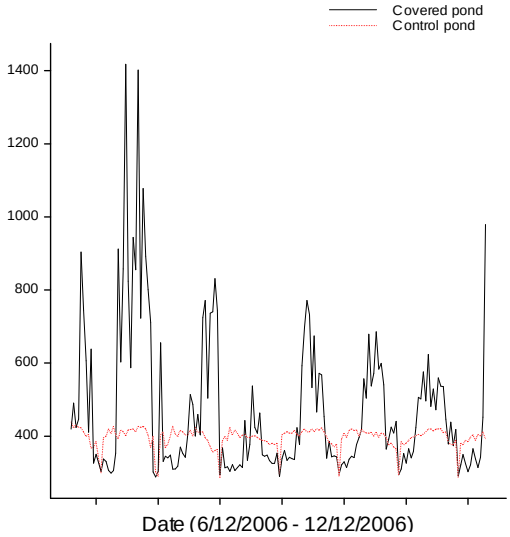


Figure 65: Comparison of carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using US EPA dynamic emission chambers – week 5

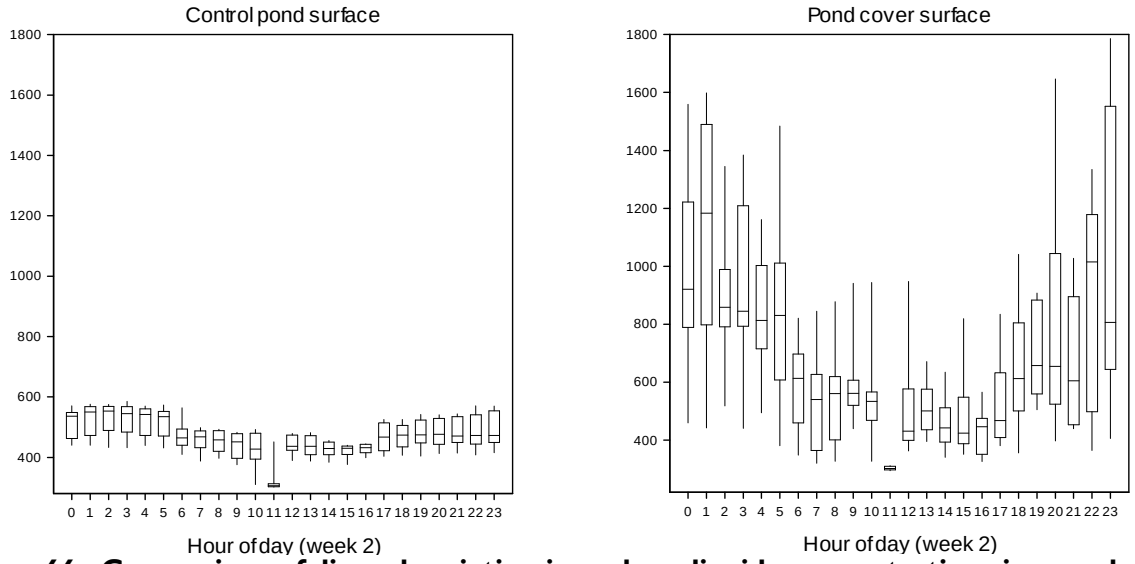


Figure 66: Comparison of diurnal variation in carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using dynamic emission chambers – week 2

Figure 63 to Figure 65 show that carbon dioxide concentrations measured above the pond cover surface were generally higher than those measured above the control pond when a dynamic emission chamber is used to collect the sample. The diurnal pattern of variation in CO_2 concentrations shown in Figure 66 and Figure 67 was consistent with that obtained from wind tunnel sampling devices – the concentration values were however quite different.

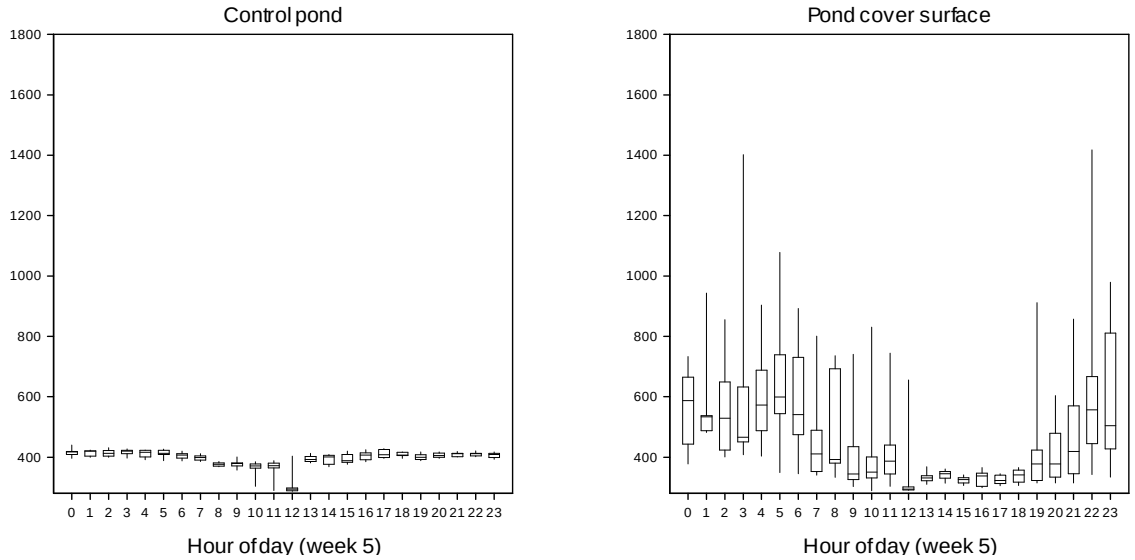


Figure 67: Comparison of diurnal variation in carbon dioxide concentrations in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using dynamic emission chambers – week 5

The selection of a device to determine rates of emission of volatile materials falls outside of the scope of this project. It was demonstrated that wind tunnels and flux chamber devices provide quite different odour emission rate estimates (Nicholas et al., 2004). The theoretical basis for the differences in measured emission rate is currently under investigation (Hudson and Ayoko, Submitted for publication; Hudson and Ayoko, Submitted for publication). While the reasons for the

differences observed may not be critical for this report, the reader must be aware that the value quoted for an emission rate may be influenced significantly by the technique used to collect the sample. For this research project it is proposed that the flux chamber values will provide a reasonable estimate of the relative difference in CO_2 emission rates. The absolute value may however be quite different to values provided by other measurement techniques.

Median and average carbon dioxide emission rates by hour of day were calculated for the entire six-week investigation period. These data are summarised in Figure 68. A number of features are revealed in this Figure:

- The strong diurnal variation in measured carbon dioxide concentrations was reinforced for the covered pond;
- There was a marked difference in the magnitude of median and average carbon dioxide emission rates for the covered pond – this indicated that the data sets were highly skewed, with a number of extremely large concentration values influencing the average concentration values. These values were presumably associated with ebullition;
- Median and average CO_2 concentrations and emission rates for the control pond were quite similar, indicating less dominance by extreme values;
- It is likely that the pond cover is creating the differences in concentrations, possibly as:
    - a physical barrier,
    - as a support on which significant biological activity occurs, leading to much higher respiration.

Further research will be required to identify the role of these and other factors in determining carbon dioxide emission rates.

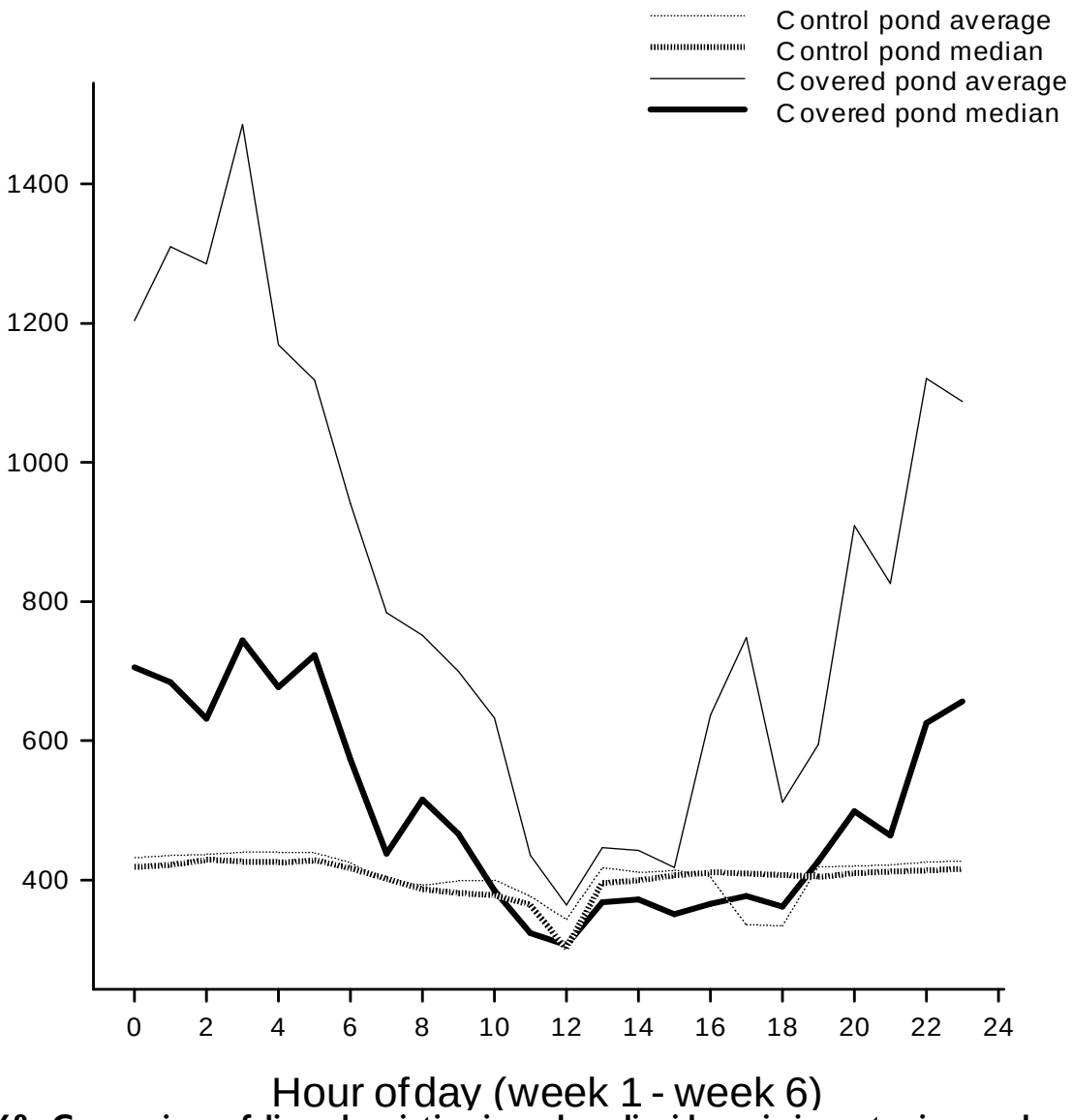


Figure 68: Comparison of diurnal variation in carbon dioxide emission rates in samples derived from the pond cover surface and liquor surface of treatment ponds at piggery C using dynamic emission chambers

Median carbon dioxide concentration and emission rate data for the pond cover and control pond liquor surfaces are summarised in Table 22. The difference in median carbon dioxide emission rate is also shown in Figure 69. The data in this Table and Figure were calculated from the data describing the entire six-week monitoring period. This Figure clearly shows a diurnal pattern in differences in carbon dioxide emission rate between the two surfaces. Figure 68 and Table 22 shows that there is relatively little difference in the concentration and emission rate of carbon dioxide emissions from the control pond surface over a 24-hour period. In contrast, the carbon dioxide concentrations and emission rates were highly variable over a 24 hour cycle for the covered pond. Highest carbon dioxide emission rates and concentrations were observed from the cover surface during periods of low sunlight. It is proposed that increased respiration in the cover layer may contribute to the excess carbon dioxide emitted during low light level periods.

Further research will be required to fully explain these observations. It is clear, however, that recognition of diurnal variations in emission rates must be made in order to accurately quantify

emissions from waste treatment systems. Emission rate estimates based on periods of extremely high or low emission may provide spurious emission factors.

Table 22: Comparison of carbon dioxide concentrations and emission rates by emitting surface and sampling device, piggery C

Hour of day	Median carbon dioxide concentration (mg/m³)		Median carbon dioxide emission rate (mg/m²/h)		Difference in emission rate (%)
	Cover surface	Control pond surface	Cover surface	Control pond surface	
0	1268	753	2880	1710	68
1	1229	758	2793.6	1720.8	62
2	1135	772	2577.6	1753.2	47
3	1336	765	3038.4	1738.8	75
4	1216	764	2764.8	1735.2	59
5	1298	770	2952	1749.6	69
6	1030	748	2340	1699.2	38
7	786	721	1785.6	1638	9
8	926	695	2106	1580.4	33
9	838	685	1904.4	1555.2	22
10	692	678	1573.2	1540.8	2
11	581	654	1321.2	1486.8	-11
12	551	543	1252.8	1234.8	1
13	661	712	1501.2	1616.4	-7
14	668	719	1519.2	1634.4	-7
15	630	731	1432.8	1663.2	-14
16	657	739	1494	1677.6	-11
17	677	733	1537.2	1666.8	-8
18	650	731	1476	1659.6	-11
19	767	726	1742.4	1652.4	5
20	896	737	2037.6	1674	22
21	833	741	1893.6	1684.8	12
22	1124	744	2552.4	1692	51
23	1179	748	2678.4	1699.2	58

The carbon dioxide emission rates observed were quite similar to those reported by Jungbluth et al. (2001). The data in Table 22 shows median emission rates of 1899 and 1670 mg/m²/h for the cover and control pond surfaces respectively. Jungbluth et al. reported values of 1830, 2711 and 2368 mg/m²/h for covered pig and cattle manure, whereas uncovered manures had emission rate values of 1376 and 1499 mg/m²/h. No indication was given by Jungbluth et al. of diurnal variations in emission rate from manure storage systems. They did however provide data which demonstrated a strong seasonal influence on carbon dioxide emission rates. Winter emission rates were much lower generally (1376 vs 766 mg/m²/h for uncovered manure in summer and winter respectively). There was however a reversal in the difference in carbon dioxide emissions between covered and uncovered surfaces. Covered storages had a 33% higher carbon dioxide emission rate than uncovered storages in summer, while in winter, covered storages had a 53% lower emission rate. No explanation was provided for these observations.

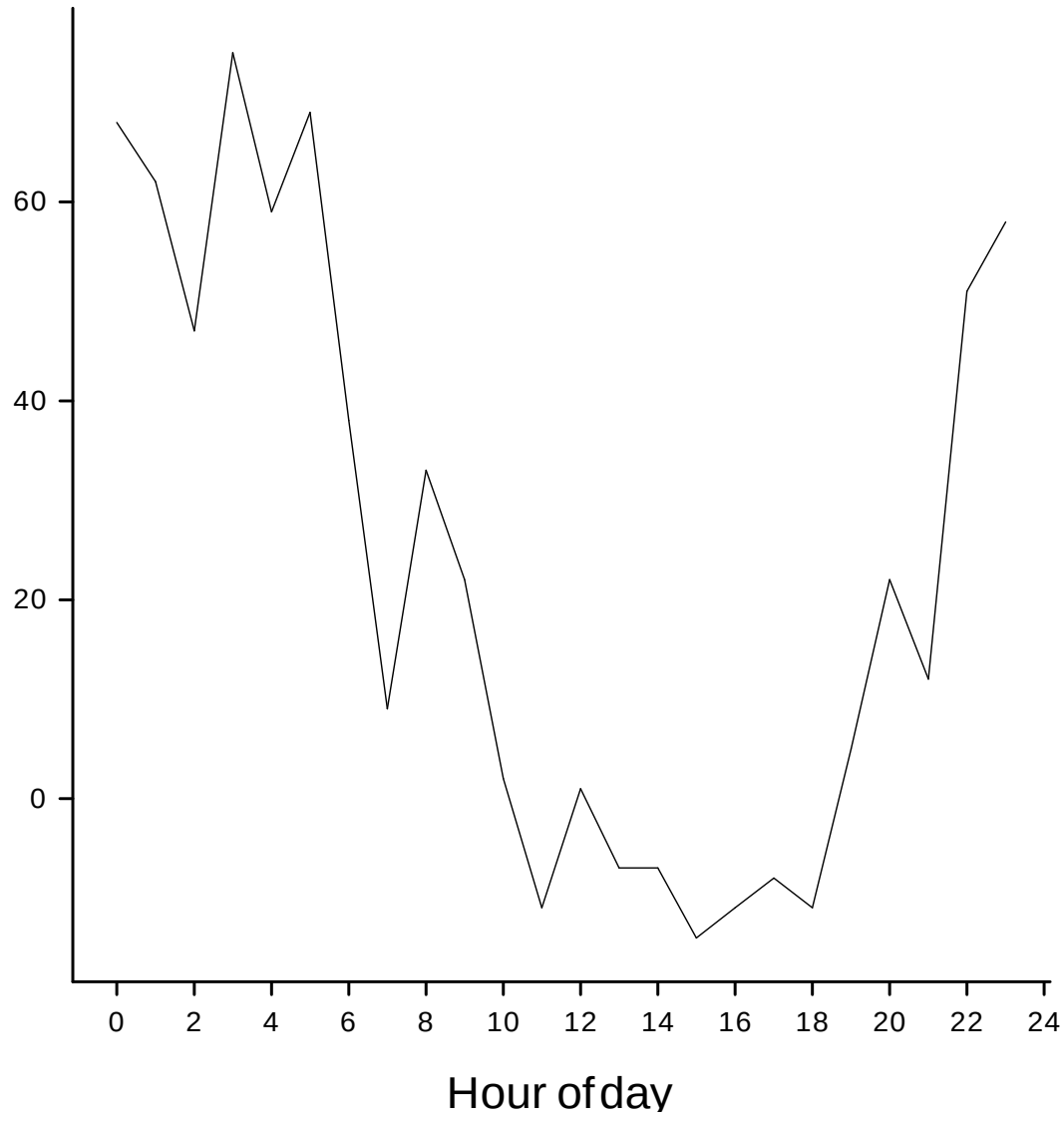


Figure 69: Difference in median carbon dioxide emission rate by hour of day between the pond cover surface and control pond liquor surface at piggery C measured using dynamic emission chambers

4.3.2.7 Impact of Permeable Covers on Hydrogen Sulphide Emissions

4.3.2.7.1 Some Aquatic Chemistry Principles and Implications for Hydrogen Sulphide Emissions

The water quality data summarised in Appendix 4 and Appendix 5 indicates that hydrogen sulphide concentrations were greater in the liquor of all covered ponds than in the control pond liquor. The laboratory-scale trial had previously indicated that hydrogen sulphide accumulated in the liquor once a pond cover was installed.

Hydrogen sulphide exists in aqueous solution as undissociated hydrogen sulphide gas (H_2S), or in two ionic forms – HS^- or S^{2-} (hydrogen sulphide ion or sulphide ion). In the context of emission rates, only the amount of undissociated H_2S is of concern – the ionic species are not volatile. The relative amounts of each form are determined by the pH of the solution according to the following equilibrium reactions:

$$H_2S \leftrightarrow HS^- + H^+$$ **Equation 9**

$$HS^- \leftrightarrow S^{2-} + H^+$$ **Equation 10**

Two dissociation constants apply to these equilibria:

$$\frac{[HS^-][H^+]}{[H_2S]} = K_{a1} \qquad K_{a1} = 1 \times 10^{-7} \text{ mol/L at 25 °C}$$ **Equation 11**

$$\frac{[S^{2-}][H^+]}{[HS^-]} = K_{a2} \qquad K_{a2} = 1 \times 10^{-19} \text{ mol/L at 25 °C}$$ **Equation 12**

The proportion of H_2S in solution can be determined as a function of pH using the relationship in Equation 13, which is presented graphically in Figure 70:

$$H_2S\ (\%) = \frac{[H_2S] \times 100}{[H_2S] + [HS^-]} = \frac{100}{1 + [HS^-]/[H_2S]} = \frac{100}{1 + K_{a1}/[H^+]}$$ **Equation 13**

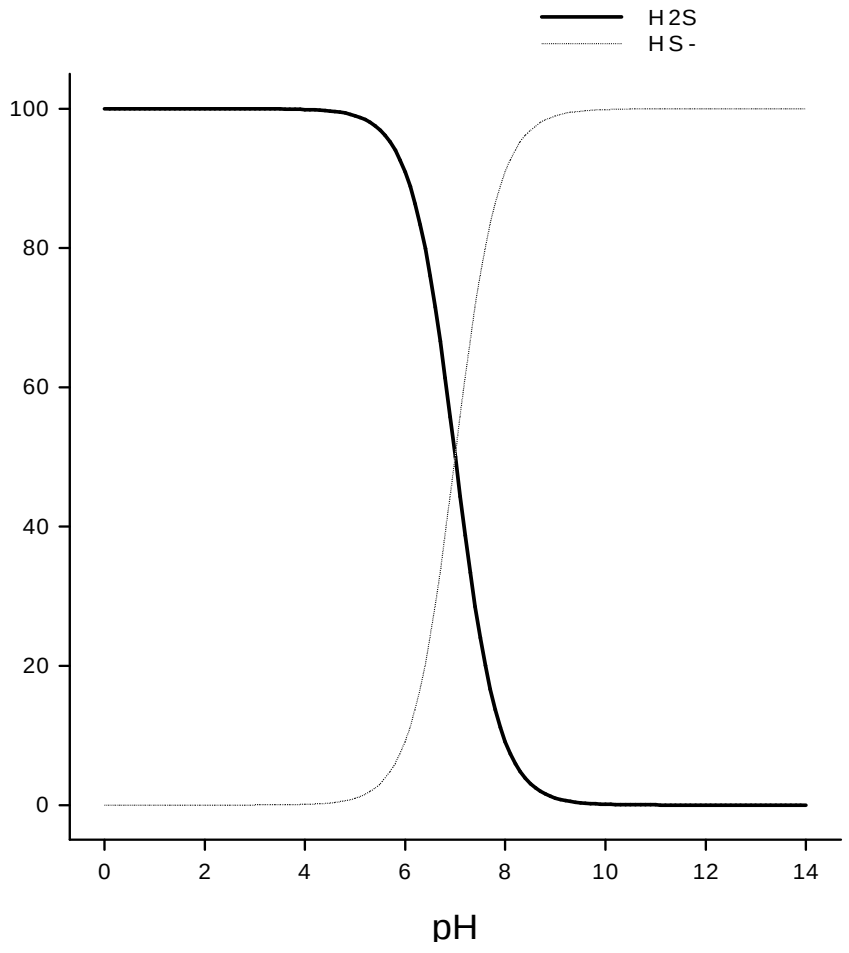


Figure 70: Relationship between H_2S and HS^- as a function of solution pH

Pond liquor pH values ranged between 6.5 and 7.8 (Appendix 5). According to the pH – H_2S relationship curve (Figure 70), approximately 60% or less of the total sulphide present in the pond

liquor would be in the volatile H_2S form. If the liquor pH increased, the equilibrium in Equation 9 would shift to the left, favouring the formation of non-volatile HS^-. This would favour accumulation of sulphur, increasing total sulphide concentrations. This was not observed, indicating that sulphide accumulation was probably favoured by the physical presence of the permeable cover, rather than a dramatic change in pond chemistry.

4.3.2.7.2 Hydrogen Sulphide Emission Measurements

The equipment used to collect air samples for the determination of carbon dioxide emission rates was also used to measure hydrogen sulphide emission rates.

Hydrogen sulphide concentration data collected over the six week monitoring period is presented in Figure 71. These graphs compare concentration data measured from the surface of each pond on the basis of the sampling device used. As was observed for carbon dioxide measurements, hydrogen sulphide concentrations were much greater in samples collected with US EPA dynamic emission chambers than those collected from a wind tunnel. Once again, the higher flushing rate in the wind tunnel was responsible for the lower concentrations. Results derived from flux chamber samples indicate that this device was probably unsuitable for the covered pond surface. Many of the results exceeded 20000 ppbV, the upper concentration limit of the analyser. These values indicate that the concentrations of hydrogen sulphide in the emission chamber rose very significantly above ambient air concentrations. One of the criticisms levelled against the flux chamber is that the low flushing rates allow the concentrations of volatile substances to increase in the chamber headspace. This increase in headspace concentration reduces the concentration difference between the surface-liquid interface and the bulk air, thereby depressing the major force driving emission. Concentrations measured under these circumstances are unlikely to provide accurate emission rate estimates.

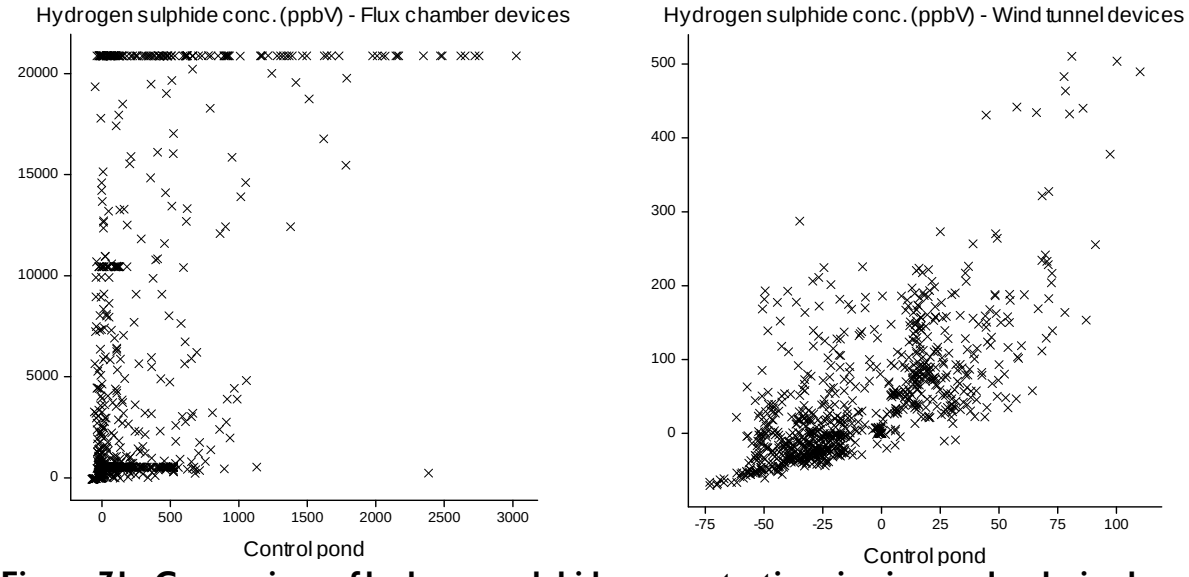


Figure 71: Comparison of hydrogen sulphide concentrations in air samples derived from covered and control pond surfaces, measured using different sampling devices - US EPA dynamic emission chamber (left) and UNSW-style wind tunnel (right)

Figure 71 also reveals a problem with the wind tunnel samples. Many of the concentrations recorded for the control pond surface have negative values. This is the result of the hydrogen sulphide analyser settings. The 12-minute sampling schedule was inadequate to allow the response of the analyser to stabilise. As a consequence of these two issues, the results obtained are probably

not sufficiently accurate to describe absolute emission rates. The large number of sample results allows relative differences in emission rate to be described for the pond cover surfaces.

Figure 72 presents concentration data derived from the two sampling devices for the two emitting surfaces for a one week period. Both emitting surfaces and both sampling devices indicate a diurnal pattern. The absolute range in concentrations derived from samples from the two devices is quite different. During this seven day period, concentrations measured using the flux chamber-covered pond surface combination varied by 20000 ppbV. During this period values measured for the wind tunnel-covered pond surface varied over a range smaller than 300 ppbV. The timing of the maxima do not coincide either. While no explanation can be offered for these results at present, it is likely that some highly localised phenomena caused these very different results. The fact that these extremely elevated concentrations were only observed in the pond cover samples indicates that the cover is responsible in some way. One possible reason could be the formation of bubbles of gas under the cover surface. These bubbles are sometimes visible in the cover over a period of days. It is possible that elevated concentrations of hydrogen sulphide occur in these bubbles. These bubbles then become very localised, relatively high emission sources. Gas with elevated hydrogen sulphide concentrations could therefore diffuse into the flux chamber headspace over a prolonged period.

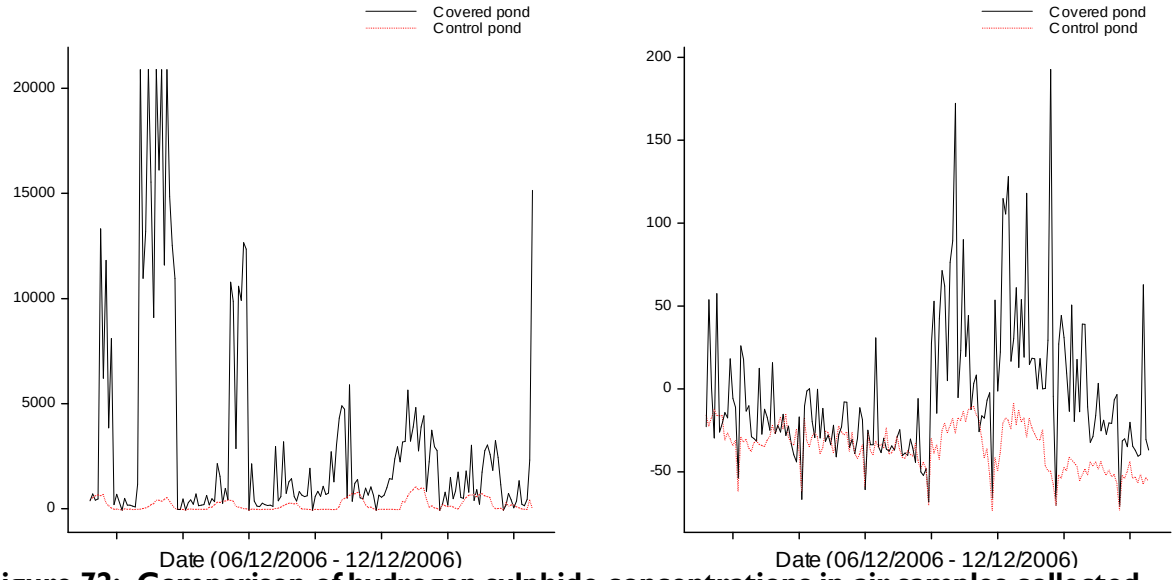


Figure 72: Comparison of hydrogen sulphide concentrations in air samples collected from surface of covered pond and control pond using two different devices - – US EPA dynamic emission chamber (left) and UNSW-style wind tunnel (right)

Hydrogen sulphide concentration and emission rate characteristics are summarised by sampling device and emitting surface in Table 23 and Table 24 respectively. The diurnal variation in hydrogen sulphide emission rate is also summarised graphically in Figure 73 on the basis of emission device.

These data indicated:

- hydrogen sulphide emission rates were higher for the covered pond than for the control pond;
- emission rate estimates based on dynamic emission chambers were about an order of magnitude greater than those provided by wind tunnels;
- the diurnal variation in emission rate was not as obvious as observed previously for carbon dioxide, and additional research will be required to demonstrate the existence of such variation.

Table 23: Comparison of hydrogen sulphide concentrations by emitting surface and sampling device, piggery C

Hour of day	Hydrogen sulphide concentrations (µg/m^3)							
	Flux chamber samples				Wind tunnel samples			
	Cover surface		Control surface		Cover surface		Control surface	
	Average	Median	Average	Median	Average	Median	Average	Median
0	11161.7	4306.2	664.9	700.3	73	34.8	-7.1	-22.9
1	11196.4	1630.6	751.7	724.5	67.9	37.8	-3	-18.2
2	10902.2	2298.1	824.5	724.5	61.3	27.3	-1.7	-8
3	10957.7	1038	892.9	724.8	58	22	2.6	-6.4
4	10560.8	2203.8	888.2	724.8	54.7	46.7	5.4	-2.7
5	12199.8	7013.7	880.9	725	57.8	17.8	5.6	-1.9
6	10494.2	5176.3	747.4	621.2	48	32.9	5.2	-4.3
7	7600.7	1737.5	407.6	161.7	51.2	42.8	-3.2	-8
8	8731.8	2819.9	237.9	105.1	38	17.8	-12	-25.7
9	8276.6	856.2	149.5	93.4	41.2	28.9	-18	-36
10	6106.1	1186.5	106.7	61.9	57.2	19.7	-20.8	-35.8
11	5186	724.4	37.2	-0.3	4.7	4	-31.7	-41.9
12	122.1	-72.2	-21.4	-71.2	-12.7	-68.8	-47.2	-69.6
13	3139.1	724.4	97.8	47.6	72.5	51.2	-16.4	-24.3
14	4608.7	724.4	122.3	46.9	78.4	44.9	-25.7	-40.5
15	3558.2	724.4	233.3	36.1	94.8	43	-19.6	-42
16	5989.6	724.4	189.8	49.5	108.8	53.2	-17.2	-35.8
17	5462.2	724.4	224.8	69.1	64.8	47.7	-12.7	-24.6
18	6430.9	881.2	256.7	59.8	111.8	71.3	-12.7	-26.1
19	7452.2	775.8	274.8	90.9	57	15.1	-16.3	-31.4
20	9446.4	821.6	347.4	140	86.4	41.6	-14.2	-30.4
21	8912.2	724.4	377.9	179.4	86.1	65.7	-12.2	-24.5
22	10399.8	3454.1	501	307.8	88	39.4	-10.3	-19.4
23	10198.6	1379.4	562.9	436.7	66.1	44.6	-9.3	-24.2

Zahn et al. (2001) measured hydrogen sulphide emission rates for four broad classes of piggery waste treatment systems that ranged from 2.4 to 11.0 µg/m^2 s. The group they identified as Type 4, characterised by the presence of anoxic photosynthetic bacteria, were probably most similar to the ponds at piggery C. This system had the lowest hydrogen sulphide emission rate, about 2.4 µg/m^{2}s. Bicudo et al. (2004) measured hydrogen sulphide emission rates from covered and uncovered ponds treating piggery wastes. These ponds were more heavily loaded than the ponds used in this study, with much higher liquor volatile solids, chemical oxygen demand and total Kjeldahl nitrogen concentrations. Total sulphide concentrations were about five times greater than were observed in this study, and the liquor pH also tended to be about 0.5 pH units larger. The latter characteristic predicts that hydrogen sulphide emission rates would be lower than observed in this study. Using a UNSW-type wind tunnel, they reported hydrogen sulphide emission rates of 6.4 and 1.81 µg/m^2 s for control and covered pond surfaces respectively. These were average values obtained over a two-year measurement period.

Table 24: Comparison of hydrogen sulphide emission rates by emitting surface and sampling device, piggery C

Hour of day	Hydrogen sulphide emission rate (µg/m²/s)							
	Flux chamber samples				Wind tunnel samples			
	Cover surface		Control surface		Cover surface		Control surface	
	Average	Median	Average	Median	Average	Median	Average	Median
0	7.05	2.72	0.42	0.44	0.68	0.33	-0.07	-0.21
1	7.07	1.03	0.47	0.46	0.64	0.35	-0.03	-0.17
2	6.88	1.45	0.52	0.46	0.57	0.26	-0.02	-0.07
3	6.92	0.66	0.56	0.46	0.54	0.21	0.02	-0.06
4	6.67	1.39	0.56	0.46	0.51	0.44	0.05	-0.03
5	7.7	4.43	0.56	0.46	0.54	0.17	0.05	-0.02
6	6.63	3.27	0.47	0.39	0.45	0.31	0.05	-0.04
7	4.8	1.1	0.26	0.1	0.48	0.4	-0.03	-0.08
8	5.51	1.78	0.15	0.07	0.36	0.17	-0.11	-0.24
9	5.23	0.54	0.09	0.06	0.39	0.27	-0.17	-0.34
10	3.85	0.75	0.07	0.04	0.54	0.18	-0.19	-0.34
11	3.27	0.46	0.02	0	0.04	0.04	-0.3	-0.39
12	0.08	-0.05	-0.01	-0.04	-0.12	-0.64	-0.44	-0.65
13	1.98	0.46	0.06	0.03	0.68	0.48	-0.15	-0.23
14	2.91	0.46	0.08	0.03	0.73	0.42	-0.24	-0.38
15	2.25	0.46	0.15	0.02	0.89	0.4	-0.18	-0.39
16	3.78	0.46	0.12	0.03	1.02	0.5	-0.16	-0.34
17	3.45	0.46	0.14	0.04	0.61	0.45	-0.12	-0.23
18	4.06	0.56	0.16	0.04	1.05	0.67	-0.12	-0.24
19	4.7	0.49	0.17	0.06	0.53	0.14	-0.15	-0.29
20	5.96	0.52	0.22	0.09	0.81	0.39	-0.13	-0.29
21	5.63	0.46	0.24	0.11	0.81	0.62	-0.11	-0.23
22	6.57	2.18	0.32	0.19	0.82	0.37	-0.1	-0.18
23	6.44	0.87	0.36	0.28	0.62	0.42	-0.09	-0.23

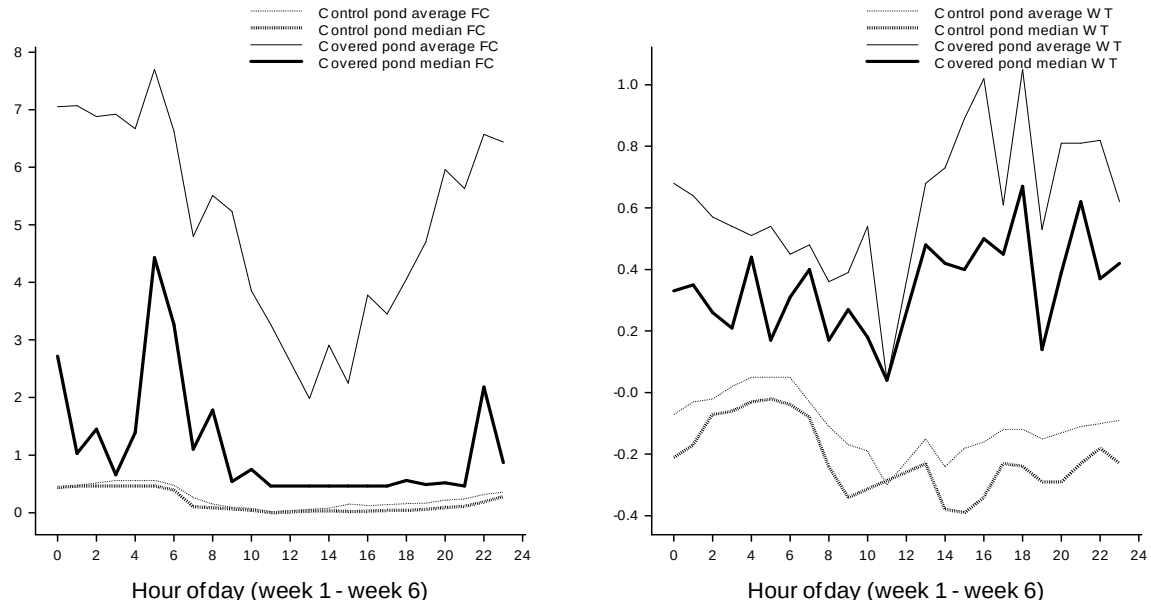


Figure 73: Comparison of hydrogen sulphide emission rates for covered and control pond surfaces derived from different sampling devices – US EPA dynamic emission chamber (left) and UNSW-style wind tunnel (right) equipment.

While the instrument problems experienced in this study do not allow us to compare absolute emission rate values, it is interesting that the work of Bicudo et al. (2004) indicated that permeable pond covers reduced hydrogen sulphide emission rates. Picot et al. (2001) assessed the impact a floating peat cover had on hydrogen sulphide emission rate for ponds treating municipal wastewater. They showed that the peat covers reduced hydrogen sulphide emission rates by about 95%; they also identified that the sulphur that was not being emitted was retained in the peat cover material as elemental and organic sulphur.

In this study, hydrogen sulphide emission rates were higher for the pond cover surface than for the control liquor. Further measurements should be made to confirm these observations. It would also be useful to examine the sulphur concentrations and species present in the cover layer and associated biomass to identify whether sulphur was accumulating.

4.3.3 Typical Ranges for Pond Liquor Chemical and Physical Variables Following Cover Deployment

The results of analysis of grab samples of pond liquor collected while odour sampling was in progress are summarised in Appendix 4 as a series of summary statistics. These data are also summarised in graphical form as a time-series and box and whisker plots in Appendix 5.

Seasonal variation in concentrations or ranges of values of physical variables are included as Appendix 6.

4.3.4 Identifiers of Pond Performance or Failure

No evidence was obtained during the period of this investigation which suggested that pond failure was occurring. Management of a pond enclosed with any sort of cover would need to focus on measurement of a few key water quality variables:

- Decreasing pH values would indicate that methanogenesis was probably being impaired by increasing concentrations of volatile fatty acids and hydrogen;
- Decreasing pH would also make the available total sulphide increasingly toxic;
- Increasing concentrations of both ammonia and hydrogen sulphide might also provide warning of decreasing anaerobic treatment efficiency.

4.3.5 Assessment of Liquor Chemistry Using PHREEQC

PHREEQC is a model based on the equilibrium chemistry of aqueous solutions interacting with minerals, gases, ion exchangers and sorption surfaces. The model incorporates an extensive chemical data base. The model was used as-received, modified only to include a number of additional magnesium-, nitrogen- (as ammonium) and phosphorus-containing minerals and species identified from research into struvite recovery (Ali et al., 2003; Ali et al., 2005).

Results of analysis of pond liquor were input into the model for each pond. The model utilises the concentrations of various elements, liquor pH values and gas concentrations in the atmosphere above the liquor to calculate solubility constants for a large number of minerals. The calculation of a solubility constant (K_{SO}) for a solid phase containing metal Me and a ligand L is shown below:

$$Me_a L_b \leftrightarrow aMe^{b+} + bL^{a-}$$

$$K_{SO} = \{Me^{b+}\}^{a} \{L^{a-}\}^{b} \qquad \textbf{Equation 14}$$

The product $\{Me^{b+}\}^{a}\{L^{a-}\}^{b}$ in a solution is known as the ion activity product (IAP), which is useful in determining whether a solution is supersaturated with respect to a particular solid phase. The computer model PHREEQ calculates a saturation index using the following expression:

$$saturation\ \ index = \log\left(\frac{IAP}{K_{SO}}\right) \qquad \textbf{Equation 15}$$

If the saturation index is positive, the solution is supersaturated (which makes formation of a solid phase likely), while a negative value indicates undersaturation.

Saturation indices (SI) were calculated using the results of analysis of all solutions on each sample collected from each pond. Average saturation indices were then calculated. These average values are tabulated in Appendix 10. There are a number of subtle differences in SI values across the four pond systems for various minerals and chemical species. SI values indicating differences between ponds have been highlighted in Appendix 10. These results have been extracted and are summarised in Table 25:

Table 25: Comparison of saturation index values for selected species by pond

Phase	Formula	Saturation index - average for all samples			
		Pond A covered	Pond B covered	Pond C covered	Pond C control
Anhydrite	$CaSO_4$	-0.57	-1.04	-1.24	-1.18
Cuprite	Cu_2O	0.6	2.48	1.01	0.5
$Fe(OH)_3(a)$	$Fe(OH)_3$	1.09	1	0.6	3.01
$Fe_3(OH)_8$	$Fe_3(OH)_8$	40.06	39.65	38.71	45.7
Ferrihydrate	$Fe(OH)_3$	10.87	10.79	10.39	12.79
FeS(ppt)	FeS	1.84	1.83	1.54	2.28
Goethite	FeOOH	6.49	6.41	6.01	8.41
$H_2S(g)$	H_2S	-1.89	-1.82	-1.94	-3.39
Hematite	Fe_2O_3	7.98	7.84	7.01	11.81
Jarosite-K	$KFe_3(SO_4)_2(OH)_6$	-1.37	-2.36	-3.52	2.97
Lepidocrocite	FeOOH	7.36	7.29	6.88	9.28
Mackinawite	FeS	2.58	2.56	2.27	3.02
Maghemite	Fe_2O_3	18.37	18.23	17.41	22.21
Magnesium potassium phosphate	$MgKPO_4{:}6H_2O$	-0.37	0.34	-0.46	-0.38
Mg-Ferrite	$MgFe_2O_4$	41	41.09	39.78	44.95
Sulfur	S	14.5	14.9	14.25	13.22
Tenorite	CuO	17.1	18.21	17.21	17.17
Vivianite	$Fe_3(PO_4)_2{:}8H_2O$	0.63	-0.38	0.29	5.94

Some of the differences observed probably indicate a difference based on the source of water used in the piggery and differences caused by feed inputs. Examples include:

- andydrite for pond A;
- cuprite, tenorite and magnesium potassium phosphate for pond B;
- the SI value for struvite at pond B is also the largest – this piggery has had an history of struvite precipitation within the recycle and flushing system.

The remaining differences are all associated with the control pond at piggery C. This indicates that the presence of a cover on the other ponds induces differences in the chemical speciation. Most of the differences observed relate to iron-containing minerals. Liquor in the control pond at piggery C

is most saturated with regard to iron-containing minerals, i.e. has the greatest tendency for iron-containing minerals to precipitate out of solution. Stated differently, iron-containing minerals are more likely to dissolve in the liquor of the covered ponds.

This tendency is reversed for sulphur and hydrogen sulphide. The uncovered control liquor is least saturated with respect to sulphur and hydrogen sulphide (i.e. sulphur will tend to dissolve, relative to liquor in the covered ponds). In the case of hydrogen sulphide, liquor in the uncovered pond is under-saturated, i.e. it has capacity to retain H_2S.

For both metals and sulphur-containing species, the SI value indicates a tendency toward dissolution or precipitation of various species. It does not indicate that large amounts of any given species is definitely dissolving or precipitating. These results are entirely consistent with the presence of a physical device at the surface of three of the ponds which limits or restricts the amount of oxygen entering the pond liquor. Elevated concentrations of metals (specifically iron and manganese) in the deepest waters of lakes and dams are a well-known problem in the water treatment industry. Water with elevated metal concentrations also often have elevated hydrogen sulphide concentrations.
These results do not indicate any significant water quality or waste treatment issue as a consequence of deployment of a permeable cover. The outputs of the speciation modelling confirm the emission behaviour identified earlier for hydrogen sulphide. The modelling indicates that some minerals will be more soluble in the liquor of a covered pond. This may in turn may elevate the concentration of phosphorus in covered liquor. The water quality data in Appendices 4 and 5 indicate that this may be true. The absolute increase in concentration does not, however, appear to be very significant.

4.4 Basic Processes whereby Permeable Covers Reduce Odour Emissions

Bicudo et al. (2004) suggested that biofiltration within the permeable cover was the dominant odour removal process. They linked apparent deterioration in cover performance with clogging of the geotextile and leakage of the odorous biogas from under the cover. This hypothesis was not really consistent with their method for sampling the odour however; the wind tunnel used was placed above the cover surface, not the edge of the cover where more odorous biogas could leak into the wind tunnel. They did not report large bubbles of gas forming under the cover either, which would be evidence that the cover permeability was decreasing.

We previously proposed that permeable covers reduced odour emissions through two mechanisms (Hudson et al., 2006):

1. As a physical barrier, obscuring the free liquor surface and hindering the exchange of volatile chemicals from the underlying liquor to the atmosphere, and
2. As a biofilter, where the microbiological population that colonised the cover surface utilised the volatile chemicals (including odorants) as an energy source, converting this material into biomass, carbon dioxide and water.

Our observations caused us to initially favour the first mechanism as the dominant one. Following this long-term assessment, the physical barrier mechanism appeared consistent with and explains the immediate odour reduction that occurred when a cover was installed. However, the biofiltration mechanism remains plausible. Over this longer assessment period, the field sampling team often observed quite significant ballooning of the cover surface following substantial gas ebullition. These large bubbles of biogas were particularly noticeable in the early morning, but had usually disappeared by mid-morning. The presumably odorous gas trapped in these bubbles diffused slowly through the cover surface into the atmosphere above the cover. Despite the relatively thin layer in which

biofiltration could potentially occur, the slow gas flux would enable relatively long residence times of odorous substances in the cover layer. This situation would favour odorant removal through biofiltration.

It is suggested therefore, that permeable pond covers be regarded as both physical barriers that minimise inter-phase transfer, and as biofilters with very shallow but large surface area beds.

4.5 Investigate the Relationship between Odorant Concentrations and Olfactometry

4.5.1 Quantification of Relationship between Air Concentrations of Odorants and Odour Concentration

Owing to the technical difficulties associated with collection and measurement of odorants in samples derived from wind tunnel samples, it was not possible to satisfy this objective. Very few samples were analysed to assess both odour concentration and the concentrations of individual odorants.

Prior to this research, very limited work had been done in Australia to identify odorous chemicals in air samples associated with intensive livestock facilities [e.g. (Jiang and Sands, 2000)]. Most of the work undertaken was of a qualitative nature, with no quantification of individual chemicals identified. No attempt was made to identify relationships between odour and odorants.

Previous research undertaken in both the USA and the UK had also failed to identify convincing relationships between olfactometry results and instrumental methods of analysis including GC-MS. For example, Lim et al. (2003) measured odour and odorant emission rates using a wind tunnel device. No relationship between the concentrations of discrete odorants and odour concentrations was observed. Similar results were obtained by Hobbs et al. (1995), who concluded "The synergy of odours and the changing chemical and atmospheric conditions combine to make odour measurement difficult and leave the instrumental measurement of odours a challenging field of study".

The extreme complexity of odour composition, the instability of odour samples following collection and the difficulties associated with collecting a sample for instrumental analysis that adequately represent the original odour sample have caused researchers to focus on artificial odorants.

Zahn et al. (2001) were able to develop a model based on human panel responses to a suite of 19 odorous chemicals. It is important to recognise that 328 air samples collected from 29 swine production facilities were analysed to identify these odorous chemicals. A standard "cocktail" of these chemicals was prepared, which was diluted with distilled water to provide samples of varying odour potential. A customised emission device was prepared whereby emissions from various dilutions of these odorants could be presented to a panel of assessors. It was possible to demonstrate a relationship between solution odorant concentration and odour intensity. Antagonistic/synergistic interactions were investigated for nine key odorants. While three of the nine key chemicals had a particularly strong influence on a model developed for swine odour intensity, it was shown that simpler models were not sufficiently accurate.

An important contribution by Zahn et al. (2001) was the identification of a process for future investigations of machine-based odour intensity studies. A successful protocol would include:

1. Collection of ambient air samples from the production facility or odour source;
2. Determining the concentration of specific odorants using gas chromatography, and
3. Processing the concentration data using an olfactory model to estimate perceived intensity.

4.5.2 Comparison of Concentrations of Odorants in Pond Liquor with those in Air Samples

A sub-theme associated with the development of a model based on measurements of odour was a comparison between concentrations of odorants in liquor with those in air. The relationship between concentrations of volatile chemicals dissolved in water and the air concentration in equilibrium with that solution is determined by Henry's law:

$$H_i = \frac{p_i}{c_{i\,water}}$$ **Equation 16**

Where H_i is the Henry law coefficient (typical units mol/m³ Pa), p_i is the partial pressure (Pa) and $c_{i\,water}$ is the concentration of the chemical of interest in water. Henrys law may also be expressed in a non-dimensional form, H':

$$H' = \frac{c_{air}}{c_{water}}$$ **Equation 17**

Where c_{air} and c_{water} represent the air and water concentrations of the compound of interest (units mass/volume).

Under environmental conditions, however, equilibrium conditions are not likely to be achieved. Diffusion will create resistance to the movement of molecules in both the liquid and air phases, while turbulence in both phases will also influence transfer rates. It has been demonstrated that atmospheric turbulence is likely to have a significant impact on mass transfer rates for odorous chemicals (Chiou et al., 1980; Chiou et al., 1983; Lee et al., 2004). The implications of the value of the Henry law constant on odorant emission rates and selection of sampling devices has recently been reviewed (Hudson and Ayoko, Submitted for publication).

These theoretical considerations indicate that:

- Air-phase concentrations of odorous chemicals will be influenced by wind speed (turbulence), either caused by natural wind speed or wind speeds within the device selected to collect the sample,
- Developing a relationship between liquor odorant concentrations and atmospheric odorant contributions must take into account wind speed effects, and
- In view of the chemical nature of key odorants (polar organic compounds such as volatile fatty acids, substituted phenols), they are likely to be sensitive to the effects of pH, analogous to hydrogen sulphide emission rate; this will have to be incorporated in the model development process.

Limited work undertaken by the DPI&F (Hudson, Duperouzel, D, and Dunlop, M, 2003) has confirmed that sample odour concentrations and emission rates are dependent on wind tunnel air velocities. Development of a robust relationship between the liquor odorant concentrations and ambient air concentrations of odorants will therefore require analysis of an adequate number of samples, collected under a range of temperature and wind speed conditions.

The process will also need to recognise that techniques used for sampling and concentration of odorants from liquid and air samples is likely to cause significant discrimination between classes of odorant or specific odorants with a class. The difficulties in obtaining representative samples of

odorants were previously described and discussed [e.g. (Zahn et al., 2001; Zahn et al., 2001; Wright et al., 2005)].

Once a model has been developed for a particular odour source or category of source, it must also be demonstrated that it will predict odorant and odour concentrations derived from another source accurately.

4.5.3 Future Research Opportunities

Despite the practical difficulties associated with identifying and describing relationships between odorants in liquor and air samples and odour concentration, many research opportunities have been identified. This research has also identified some of the practical issues that must be recognised and addressed if such modelling is to be concluded successfully.

Specific areas include:

4.5.3.1 Sampling Considerations

- Application of optimised techniques to the collection of odorants from environmental sources, including:
  - Use of polymeric sorbents such as Tenax®, with recognition of likely discrimination effects;
  - Collection of adequate sample volumes, with recognition of the potential for problems caused by excess water;
  - Selection of suitable gas chromatography columns (wax-type columns might be necessary to detect and quantify volatile fatty acids).
- Investigation of newer techniques for sample collection based on equilibrium processes, such as SPME and SBSE, with recognition of the difficulties of quantification.
- Greater recognition of the influence that turbulence has on the composition and concentration of odour and odorants, and the possibility that turbulence effects introduced by sampling devices may alter the sample composition.

4.5.3.2 Analytical Considerations

Gas chromatography is the method of choice should it be necessary to identify and quantify specific odorants. Correct selection sampling devices, detectors and analytical columns is critical for analysis of some of the more reactive odorants.

- Sample inlet systems should include thermal desorption and solid phase sorbent techniques such as SPME and SBSE.
- Sample inlet systems should be thoroughly deactivated to minimise loss of labile compounds.
- The analytical columns available for separation of odorants should include non-polar, moderate polarity and wax phase columns, allowing maximum flexibility in analysis.
- A sulphur-specific detector may offer benefits in terms of detection limits and elimination of interference with closely eluting peaks.
- Mass-selective detectors have become increasingly sensitive, particularly with the Selected Ion Monitoring capability. They also offer the benefit of spectral analysis, useful for confirming the identity of peaks.

4.5.3.3 Emerging Technologies

Recent developments in instrumental methods of analysis hold great promise for real-time analysis of odorants at ambient concentrations. For example, proton-transfer reaction mass spectrometry (PTRMS) enabled quantification of volatile chemicals produced by temperate and tropical forests in

real-time (Hansel et al., 1995; Lindinger et al., 1998). Analyses were performed using a mobile instrument flying at altitudes up to 12 km above forest canopies. It was possible to quantify volatile chemicals at concentrations above the detection limit - between 1 to 300 pmol/mol (ppt v/v) in scan mode, and 1 to 100 pmol/mol in high frequency mode. The precision of quantification was better than ±30% for molecules with low mixing ratios.

The instrument is conceptually very simple – a capillary tube is used to deliver ambient air continually to a cell where the sample is conditioned and reaction occurs, after which mass spectral analysis takes place. There is no requirement for separation of the components of the sample using chromatographic columns. Theoretically all volatile compounds may be detected and quantified simultaneously in real time at very high sampling rates.

Should a relationship between odorant concentrations and odour concentration be established, it may be possible to use a PTRMS device to measure ambient air odour concentrations in real time. Under these circumstances, emission rate estimates that do not require sampling devices (such as micrometeorology) may become feasible. Emission rates obtained in this fashion may not be subject to sampling device errors, providing "true" emission rate estimates.

This instrument also offers the potential to quantify odorants at concentrations similar to those experienced by receptors under ambient conditions. This may be a very useful tool when investigating odour complaints.

While the cost of the most sensitive instruments is very high, lower cost portable versions have been released commercially. It will be some time however before this instrumentation will be a routine analytical tool at many research or regulatory agencies.

Sensor array based instruments have shown great potential for air quality and odour measurement. They are relatively simple devices, comprising an array of sensors (with varying selectivity and sensitivity to different broad classes of volatile material), temperature and humidity sensors and a sampling pump. The changes in electrical resistance of the sensors are recorded continuously at high frequency. These data are post-processed using advanced statistical techniques to provide qualitative and quantitative air quality information. Following compensation for temperature and humidity effects and suitable calibration of the response, it is possible to produce models that allow prediction of odour concentration. Sohn et al. (2003) demonstrated good correlation between odour concentrations measured using dynamic olfactometry and those predicted with an electronic nose. More recently, Sohn et al. (2006) demonstrated that an electronic nose device was able to quantify poultry shed odours continuously and provide an estimate of odour concentrations that was within about 80% of the values measured using dynamic olfactometry.

As statistical techniques, data logging facilities and the range of sensors are expanded, it is likely that sensor-based olfaction will become an increasingly used tool for air quality assessment. While measurement of odour concentrations downwind of a source at the concentrations experienced by receptors has not been demonstrated to date, active development of these devices indicates that real-time odour measurement under field-conditions may be possible in the near future.

A demonstration of the capability of sensor-array technology in the field of air quality and odour assessment is provided in Section 4.8.

4.6 Investigation of Impact of Pond Covers on Housing Emissions and Effluent Irrigation Areas

In the report for the original research it was noted that the decrease in total odour emitted from an effluent pond may be accompanied by an increase in the concentrations of odorants in the supernatant. The possibility therefore exists that these odorants might be released from the supernatant in larger than normal amounts when recycled liquor is used for flushing animal housing. If this were to occur, the total emission from an intensive livestock facility may not decrease as anticipated. The odorants might also be released as a "pulse" during or following shed flushing. Significant off-farm odour impact might still arise under these circumstances.

4.6.1 Comparison of Rates of Emission from Housing Following Flushing with Liquor Derived from Covered and Uncovered Ponds

In Section 3.10 the difficulties associated with measuring emission rates from naturally ventilated structures were discussed briefly. To overcome these practical difficulties, two strategies were investigated to enable adequate measurement of odour emissions from housing during flushing and immediately after flushing.

4.6.1.1 Comparison of Rates of Odour Emission from a Housing Model Following Flushing with Liquor Derived from Covered and Uncovered Ponds

The details of a flume used to compare likely rates of odour emission from a model housing were summarised in Section 3.9. Results of separate measurements of odour emission rate are summarised graphically in Figure 74.

Formal testing indicated that rates of odour emission obtained following use of liquor derived from these two sources were significantly different at the 95% level (p = 0.049). Observations by the field team during the flushing and odour sampling operation indicated that the odour from the covered pond had a distinct "rotten-egg" character. This was probably due to the elevated concentrations of hydrogen sulphide that developed in the pond following deployment of the cover. These results indicated that a potential existed to generate more odour from housing while the flushing was in progress should liquor from a covered pond be used.

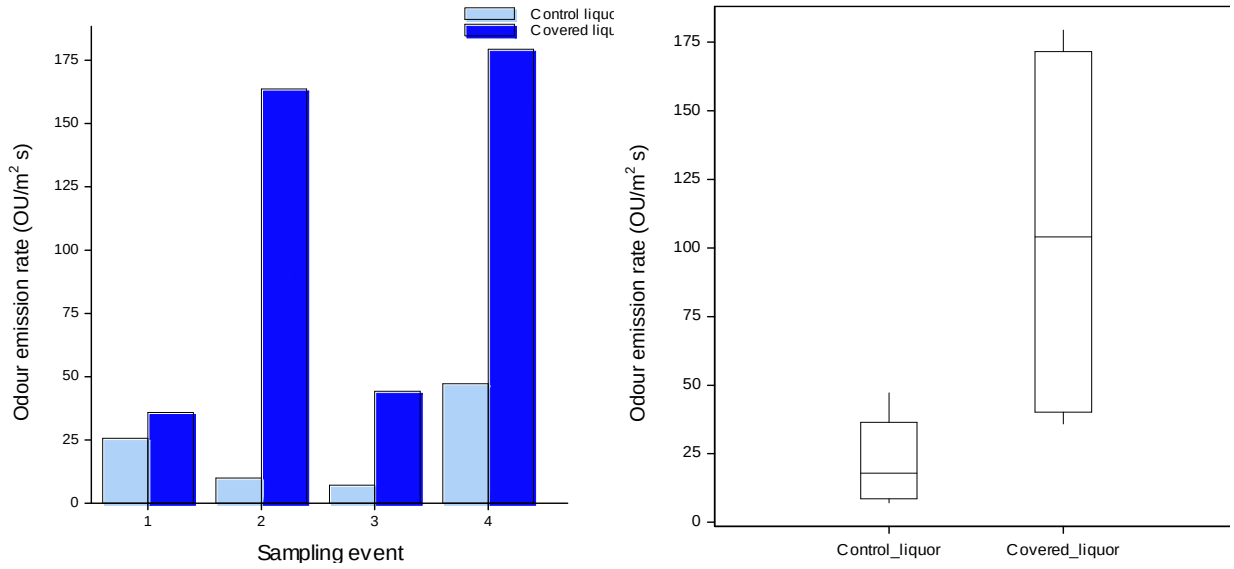


Figure 74: Comparison of odour emission rate produced in a flume during flushing with liquor from covered pond with that from control pond

4.6.1.2 Comparison of Rates of Emission from a Housing Structure Following Flushing with Liquor Derived from Covered and Uncovered Ponds

Three discrete sets of data were collected for the housing emission work:

- odour samples were collected from the shed after flushing with liquor from the local covered pond (pond B) and following a period of ventilation,
- during and immediately after flushing with liquor from the control pond at piggery C, and
- during and immediately after flushing with liquor from the covered pond at piggery C.

The emission rate results are summarised in Figure 75. It was not possible to show a significant difference in emission rate on the basis of the source of the flushing liquor.

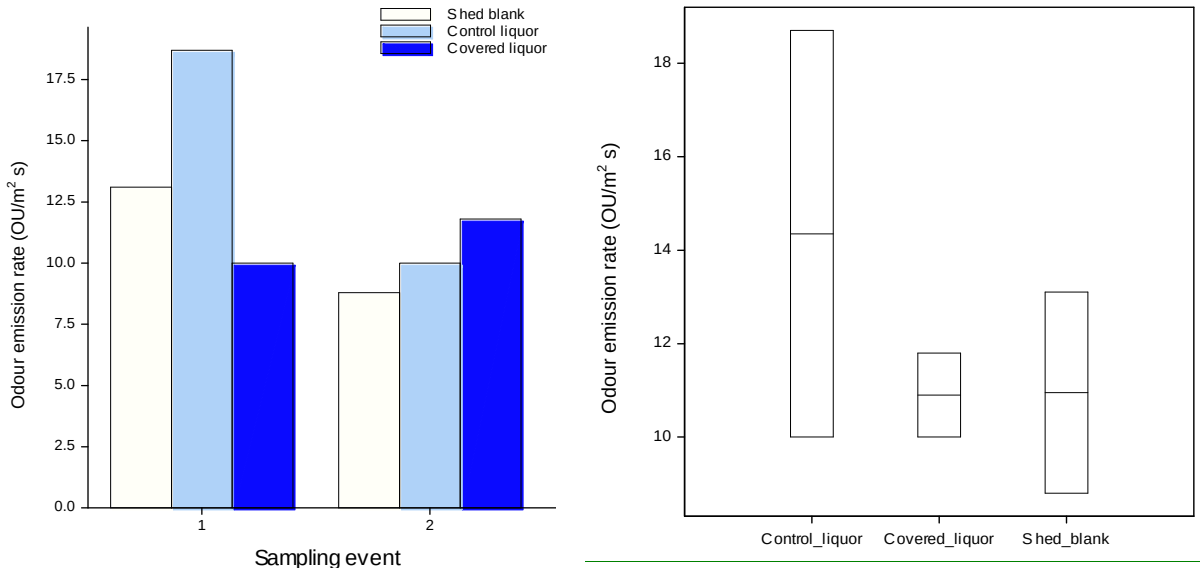


Figure 75: Comparison of shed odour emission rate during flushing with liquor from covered pond with that from control pond

These results were quite different from those previously observed using the flume as a housing model. A number of factors could be considered to explain the difference between the two series of measurements:

1. During the flume trials, odour was emitted continuously into a relatively small volume of flushing air. High odour concentrations would be anticipated under these circumstances. In the shed, however, the odour derived from a relatively small volume of liquor (about 4,000 L) was emitted into a much larger volume of flushing air, reducing odour concentrations.
2. Within the flume, the air stream was in active contact with the odorous liquor flowing in turbulent fashion through the flume. These conditions were highly conducive to inter-phase mass transfer, where high odour emission rates would be expected (Schwarzenbach et al., 2003; Hudson and Ayoko, Submitted for publication).
3. Significant residual or background odour appeared to exist in the shed (as evidenced by the shed blank emission results). Presumably this odour arose from the slatted floor, animal bodies, walls and other surfaces. During the actual flushing event, a relatively small increase in odour emission was possibly obscured by the high residual odour that persisted in the shed.
4. During flushing, the liquor and odour generated from the flushing channels is partially separated from the bulk air in the shed by the slatted floor. While this barrier is highly porous, odour would only move from beneath the slats into the bulk shed air if a driving force existed. This would require some kind of positive air flow from the air space below

the slats to the air space in the shed above the slats. In the absence of such a driving force, the odorous air would be transported by relatively passive processes, such as diffusion. Under these circumstances, a large spike of odour release from the shed would be unlikely.

As a consequence of these and other factors, while the potential for increased odour emissions might exist should liquor derived from a cover pond be used, the impact on shed emissions may not be as significant as initially thought.

4.6.2 Comparison of Rates of Emission from Areas Irrigated with Liquor Derived from Covered and Uncovered Ponds

The experimental details followed to allow an assessment of odour emissions from covered and uncovered liquor were described in Section 3.8. The emission rate results are summarised graphically in Figure 76.

There was no statistically significant difference in odour emission rate measured from any of the sources. This should probably not be an unexpected result. During irrigation of pond liquor, odour emission will probably take place only during three phases:

1. During the spraying process, in the relatively short period of time between ejection from a spray nozzle and contact with the soil or vegetation (duration seconds), and
2. During the period between alighting on the soil or vegetation surface and infiltration into the soil (duration seconds to minutes), or
3. In the longer period while the odorant is in the soil surface layers, from which it may be re-emitted (duration minutes to hours).

Owing to the chemical and physical properties of most odorants, rates of emission will be strongly dependent on turbulent processes, in particular wind speed (Roberts and Dandliker, 1983; Schwarzenbach et al., 2003). Highest emission rates may therefore be expected during periods 1) and 2) above, when turbulent atmospheric processes may have the most impact. Once the liquor has infiltrated the soil, emission will be governed by the slower process of molecular diffusion.

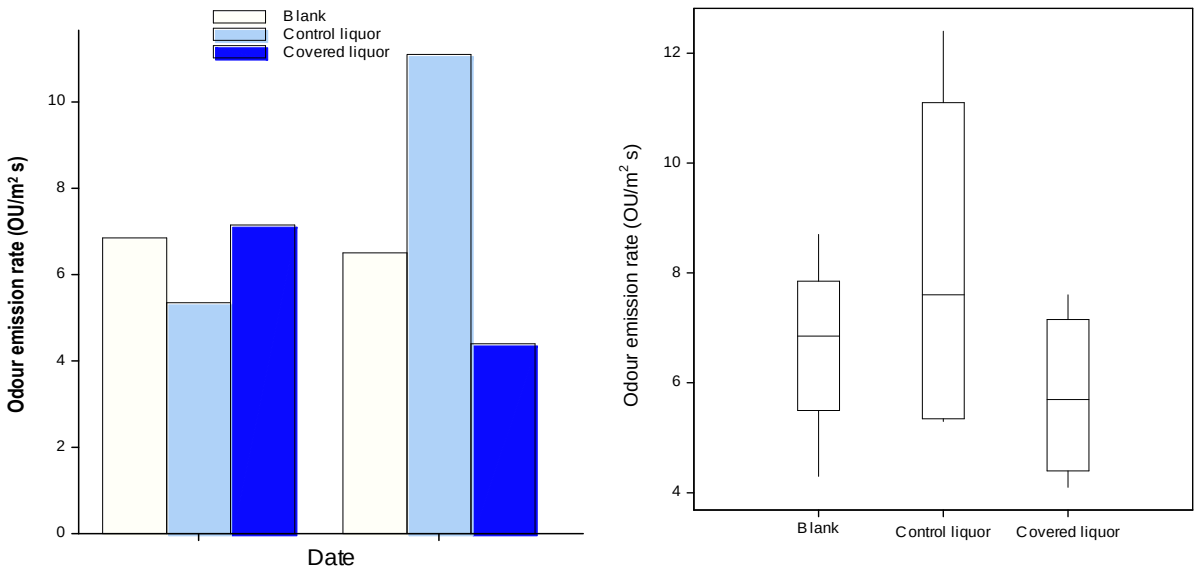


Figure 76: Comparison of rates of odour emission from pasture following irrigation with liquor from either a covered pond or control pond

Odour emission rates reported for covered and control liquor sources in Table 13 indicate that odour emission rate may increase by a factor of two to three following deployment of a permeable pond cover.

During land application of pond liquor, a fraction of the total odorant concentration will be released to create an odour potential. Use of more odorous covered pond liquor will increase the odour risk, but not by a prohibitive amount. As with many other activities, application of liquor to land should be undertaken when conditions minimise the odour potential. The marginal increase in odour potential during infrequent, short-duration activities such as irrigation of liquor should not therefore create a barrier to implementation of permeable pond covers as a generally effective odour management tool.

4.7 Assessment of Impact of Permeable Covers on Odour Intensity and Offensiveness

Odour intensity was assessed using an in-house method derived from VDI method 3882. The modified method was discussed and trialled by other practitioners and appeared to provide credible results (Galvin and Schulz, 2005).

The modified method involved presentation of odour samples at supra-threshold concentrations following completion of the standard odour concentration assessment process. Samples were presented in ascending concentration steps and panellists registered their responses via keypad. Once a panellist registered a response indicating a "strong" perception, they were excluded from further presentations by the software. This exclusion was implemented to minimise the potential for sensory overload and instrument contamination. It is important to realise that the technique is essentially an extension of the normal olfactometry assessment process. One of the prerequisites for the intensity assessment is training of the assessment panel regarding the concept of "distinct" odour. This is not a qualitative rating of the presented odour (i.e. pleasant or unpleasant); rather it is a quantitative measure, implying a dilution step (i.e. concentration) at which the odour may be recognised or identified. A more intense odour would provide a response rated "distinct" at a lower concentration than one which was less intense. A response rated distinct is rated as 3 on the five-step intensity scale. The concept of distinct odour and a method for communicating this to the olfactory panel has been discussed fully by Jiang et al. (2006).

All odour samples in the project were collected in replicate. For samples identified for intensity assessment, one of the pair of samples was randomly assigned for intensity assessment as well as concentration assessment. During the olfactometry process, panel responses during intensity assessment were automatically captured. The results were then reviewed and processed post-analysis.

Results were separated according to the nature of the source – control pond (i.e. uncovered surface), polypropylene and shadecloth cover, shadecloth only surface, straw cover and exposed liquor (i.e. liquor normally beneath cover).

During interpretation of the intensity data, the following assumption was made:

- Because all samples were collected using the same equipment, operated under similar conditions; it was appropriate to compare the odour concentrations of samples collected from these sources.
- Typically, emission rate results are compared because they are normalised by the wind tunnel.

The odour concentration, emission rate and intensity data have been summarised as a series of tables. Table 26 summarises the intensity results and the odour concentration values for the associated samples.

Table 26: Mean odour concentration values and corresponding mean odour concentration values eliciting a response rated "distinct" (intensity score 3)

Odour source	No. results	Mean odour concentration (OU/m³)	Mean odour concentration eliciting intensity score 3 (OU/m³)
Straw cover	6	88.7	5
Polypropylene and shadecloth cover	22	92.6	7.4
Shadecloth-only surface	9	214.8	5.1
Exposed liquor	23	331.2	5.3
Control liquor (piggery C only)	3	468.3	5.8
Housing emissions, flushed with control liquor	5	2406	2.3
Housing emissions, flushed with covered liquor	5	9953.8	2.8

Referring to Table 26:

- There appears to be a weak inverse relationship between odour concentration and odour concentration at intensity score 3 for samples derived from these sources.
- The concentration values for intensity score 3 provide an indication of the concentration required for a receptor to identify, distinguish or recognise the odour;
    - From these data, it could be concluded that it would be possible for a receptor to recognise an odour derived from a highly odorous sample at a lower concentration than one derived from a less odorous source.
    - For these samples, the highly odorous samples coincide with those that might be regarded as more offensive (pond liquor samples), while the less odorous samples are derived from less offensive sources (permeable covers),
    - These conclusions coincide with and are supported by anecdotal observations by field staff.

The intensity data was disaggregated on the basis of the different emitting surfaces that existed and were sorted:

- according to mean odour concentration (Table 27), and
- odour concentration rated distinct (Table 28).

Table 27: Selected concentration and intensity data ranked according to mean odour concentration for entire data set (highlighted)

Surface	Piggery code	Values for entire data set			Values for intensity results only		
		No. results	OER (OU/m^2 s)	Odour conc. (OU/m^3)	No. results	Odour conc. (OU/m^3)	Odour conc. eliciting "distinct" response (OU/m^3)
Polypropylene & shadecloth cover	C	35	17.5	**100.1**	9	108.1	9.1
Polypropylene & shadecloth cover	A	40	16.7	**101.9**	8	88.5	6.1
Straw	B	22	18.5	**102.8**	5	71.2	6.3
Shadecloth	C	14	20.3	**119**	4	175.3	5.8
Polypropylene & shadecloth cover	B	22	10.8	**129.5**	5	71.2	6.3
Shadecloth	A	18	29.8	**172.3**	6	234.5	4.7
Control liquor	C	32	32	**183.7**	3	468.3	5.8
Exposed liquor	B	23	48.5	**347**	11	224.5	7.2
Exposed liquor	C	26	73.7	**452**	5	465.2	3.2
Exposed liquor	A	56	79.7	**869.5**	7	403.3	3.7
Flush samples, control liquor	C	5	-	**2406**	5	2406	2.3
Flush samples, covered liquor	C	5	-	**9953.8**	5	9953.8	2.8

The ranking of odour sources indicated by Table 27 and Table 28 was reasonably consistent and probably what may be intuitively expected. In both cases, the samples derived from the exposed liquor appear to be quite intense – a relatively low concentration would probably elicit response of "distinct". In contrast, samples derived from the various covers appear to provide less intense samples.

One exception is revealed in Table 28. Samples derived from the exposed liquor at piggery B rank second in the table, implying that the odour derived from this source is not very intense, requiring a receptor to be exposed to a concentration of about 7.2 OU/m^3 to elicit a "distinct" response.

This result does not appear to correlate with either the odour concentration data, or the emission rate data. This apparent anomaly cannot be explained with the information currently available. Absence of qualitative information regarding the character of the order also limits interpretation of these results. Anecdotal observation by the field team indicated that odour samples derived from the control pond has a characteristic "piggery pond" odour. Odour samples derived from the various covers had different odours, but were always regarded as less offensive than samples derived from liquor surfaces.

It was anticipated that the DPI&F olfactometer would be modified to allow hedonic tone assessment of odour samples to be undertaken as an additional routine test. Implementation of this test required a major reworking of the software used to operate the olfactometer. The software upgrade was undertaken at the same time as an upgrade of the panellist keyboards. As a consequence, the upgrade was only undertaken at the end of the fieldwork component of this project. Insufficient data regarding hedonic tone exist to allow the usefulness of this analysis tool to be evaluated at present.

Table 28: Selected concentration and intensity data ranked according to odour concentration eliciting "distinct" response (intensity rating 3, highlighted)

Surface	Piggery code	Values for entire data set			Values for intensity results only		
		No. results	OER (OU/m^2 s)	Odour conc. (OU/m^3)	No. results	Odour conc. (OU/m^3)	Odour conc. eliciting "distinct" response (OU/m^3)
Polypropylene & shadecloth cover	C	35	17.5	100.1	9	108.1	**9.1**
Exposed liquor	B	23	48.5	347	11	224.5	**7.2**
Polypropylene & shadecloth cover	B	22	10.8	129.5	5	71.2	**6.3**
Polypropylene & shadecloth cover	A	40	16.7	101.9	8	88.5	**6.1**
Control liquor	C	32	32	183.7	3	468.3	**5.8**
Shadecloth	C	14	20.3	119	3	175.3	**5.8**
Straw	B	22	18.5	102.8	6	88.7	**5**
Shadecloth	A	18	29.8	172.3	6	234.5	**4.7**
Exposed liquor	A	56	79.7	869.5	7	403.3	**3.7**
Exposed liquor	C	26	73.7	452	5	465.2	**3.2**
Flush samples, covered liquor	C	5	-	9953.8	5	9953.8	**2.8**
Flush samples, control liquor	C	5	-	2406	5	2406	**2.3**

At present it is not clear how these results could be used either as an odour management tool at the producer level, or in a regulatory framework. Additional investigation will be required to demonstrate the value of intensity measurement. It would be prudent to undertake hedonic tone assessment concurrently with intensity measurements to include information regarding the offensiveness of an odour. It is likely that the three tests may prove synergistic, with each test providing subtle information to assist in the odour assessment or management process.

4.8 Application of Electronic Nose Technology to Odour Assessment

DPI&F (through Sustainable Intensive Systems) has invested significant research in the development and application of sensor array technology to odour assessment. Use of this technology for air quality measurement involves a number of inter-related processes, from which qualitative and quantitative information may be generated.

4.8.1 Qualitative Results

The origin of samples collected from the various piggery ponds and emitting surfaces formed the basis for classification of the odour samples. A total of 10 sample sources were identified in addition to the clean air (instrument grade air) used as a reference gas to assess drift of sensors or contamination of the sensor array. The ten odour sources are listed in Table 29.

Table 29: Ten odour emitting surfaces identified at the three trial sites

Piggery	Odour source – emitting surface
Piggery A – covered pond	Exposed liquor surface
	Shade cloth cover
	Polypropylene and shadecloth cover
Piggery B – covered pond	Exposed liquor surface
	Straw cover
	Polypropylene and shadecloth cover
Piggery C – covered pond	Exposed liquor surface
	Straw cover
	Polypropylene and shadecloth cover
Piggery C – control pond	Liquor surface

The data used to characterise the emissions from the ten sources is listed in Appendix 9. Analysis of the data involves the creation of a 14-dimensional array. Processing of the data creates a two dimensional array, which may be displayed as a PCA plot. This is shown in Figure 77.

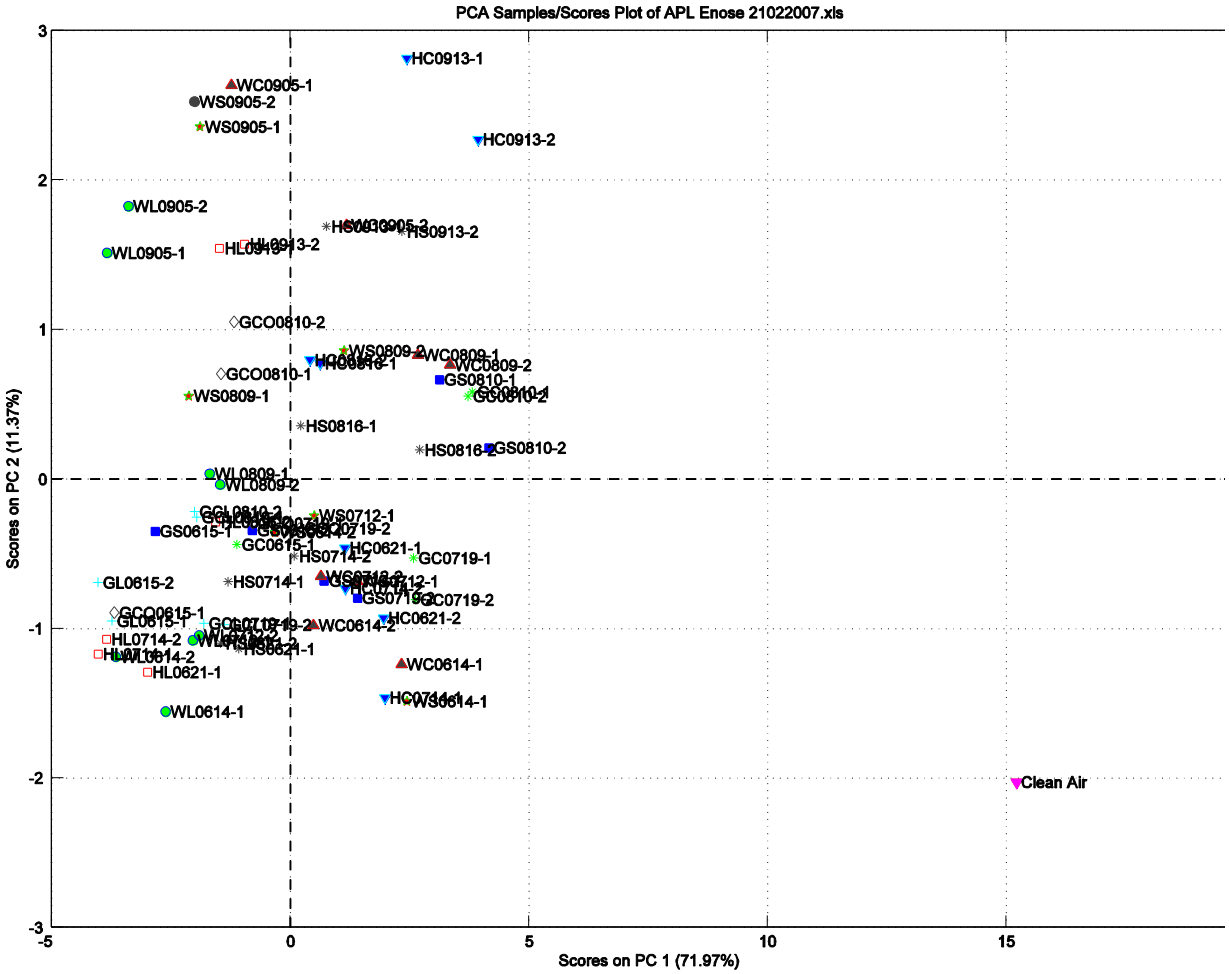


Figure 77: PCA plot of e-nose results following analysis of odour samples from all sources; Samples labelled H are from pond A, W from pond B and G from piggery C

This Figure is based on entirely un-trained, raw data. It reveals the following information:

- Results for the various samples are clearly distinct from the results for the clean air;
- There is considerable overlap of samples derived from the ten sources previously identified;
- While there is considerable overlap, there is also evidence of broad categorisation (i.e. data from various sources tending to group together).

Categorisation of the data was further explored by determining the Euclidean distance between the centroid representing each category of odour source and the clean air cluster in this two-dimensional array. These results are presented in Table 30:

Table 30: Euclidean distance between each centroid and the clean air cluster

Piggery	Emitting surface	Euclidean distance
-	Clean air	0
C	polypropylene and shadecloth cover	13.050
A	polypropylene and shadecloth cover	13.819
B	polypropylene and shadecloth cover	14.103
C	shadecloth	14.391
A	shadecloth	15.126
B	straw	15.801
C	control liquor	16.744
C	exposed liquor	17.758
A	exposed liquor	17.848
B	exposed liquor	17.923

The results in Table 30 indicate the "likeness" of the samples derived from each odour source and the clean air reference gas. Near proximity to the reference gas indicates a less odorous sample (i.e. more like instrument grade air) than one that plots a greater distance (likely to be more odorous). It is of interest to note that the sequence in which the various covers, shadecloth surfaces and liquor surfaces appear in Table 30 are identical.

Principal component analysis is not particularly powerful tool for discrimination analysis. A partial least squares (PLS) analysis of the full data set was undertaken with the objective of demonstrating discrimination between samples derived from the ten sources identified. These results are presented as a series of plots in Appendix 9. It must be noted that discrimination is demonstrated only by absence of overlap along the Y-axis. These plots demonstrate that the ten odour sources may be at least partially distinguished from one another. Sources that may be considered similar (e.g. liquor surface samples from the different ponds) tend to be poorly resolved. However, they tend to be reasonably well differentiated from samples from other surfaces (e.g. cover samples versus liquor or shadecloth surfaces). This demonstrates that e-nose technology is able to discriminate between closely related samples.

The discrimination ability may be improved if the PLS technique is applied to a smaller set of samples. The four surfaces associated with the two pond system at piggery C were selected for this purpose. Results for these surfaces are shown in Figure 78 to Figure 81 (results for the other surfaces are included in Appendix 9). The horizontal stippled line at Y value of about 0.4 is a detection threshold determined by the model based on the number of data and the power of the discrimination test. The cover samples, shadecloth samples and covered liquor samples can be clearly discriminated from the other three sample types. The model cannot clearly distinguish samples from the control pond liquor from the covered liquor – overlap occurs for one sample from

each group. This is not surprising – the only difference between samples derived from these two sources is the presence of a cover on one of the liquor surfaces.

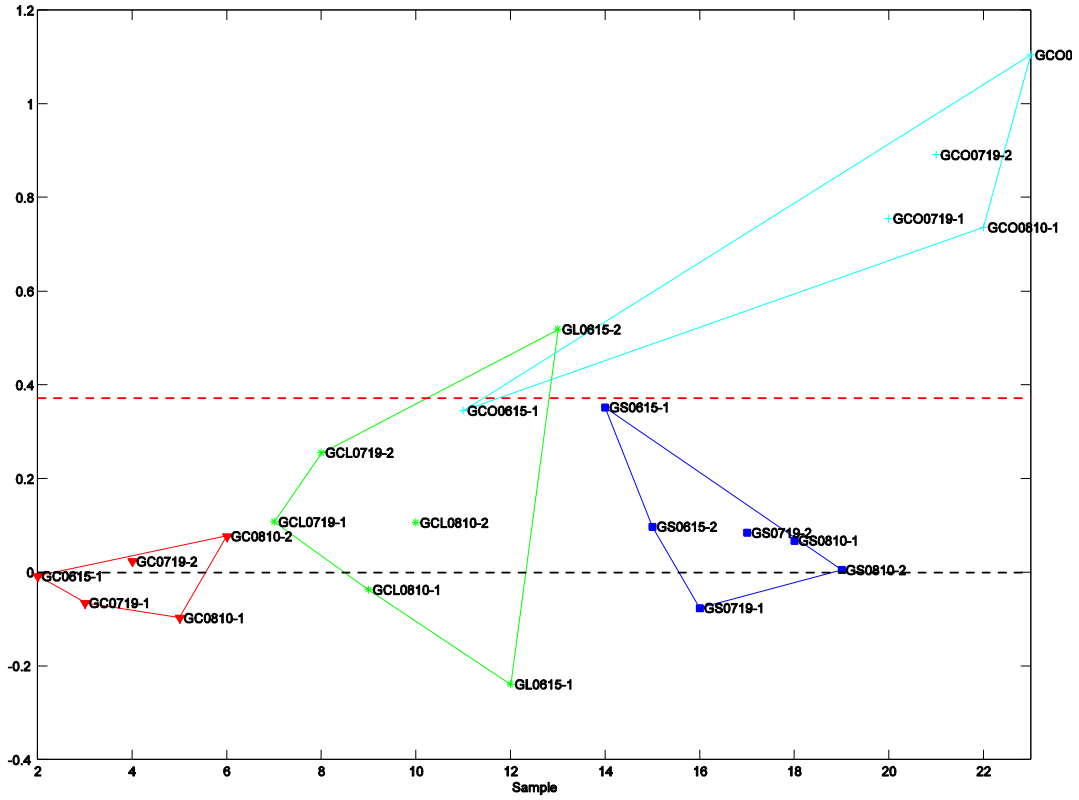


Figure 78: PLSDA plot of e-nose results following analysis of odour samples from all sources at piggery C; model optimised to discriminate odour sampled from the surface of the control pond

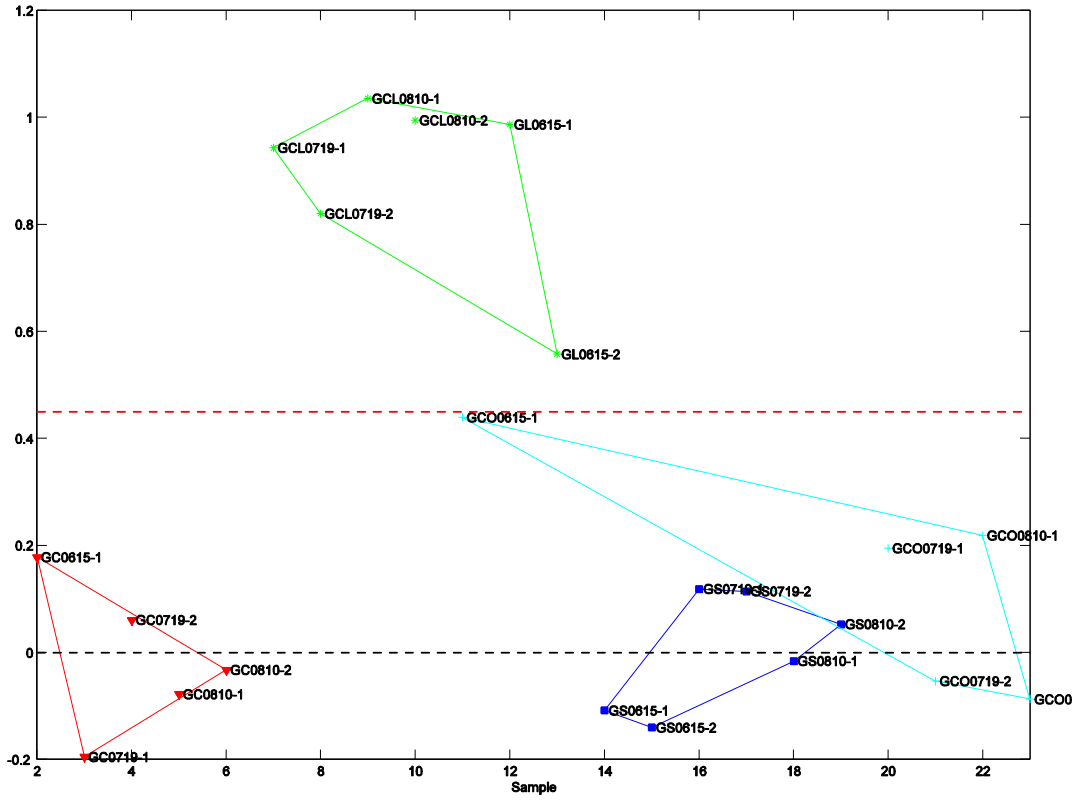


Figure 79: PLSDA plot of e-nose results following analysis of odour samples from all sources at piggery C; model optimised to discriminate odour sampled from the exposed liquor of the covered pond

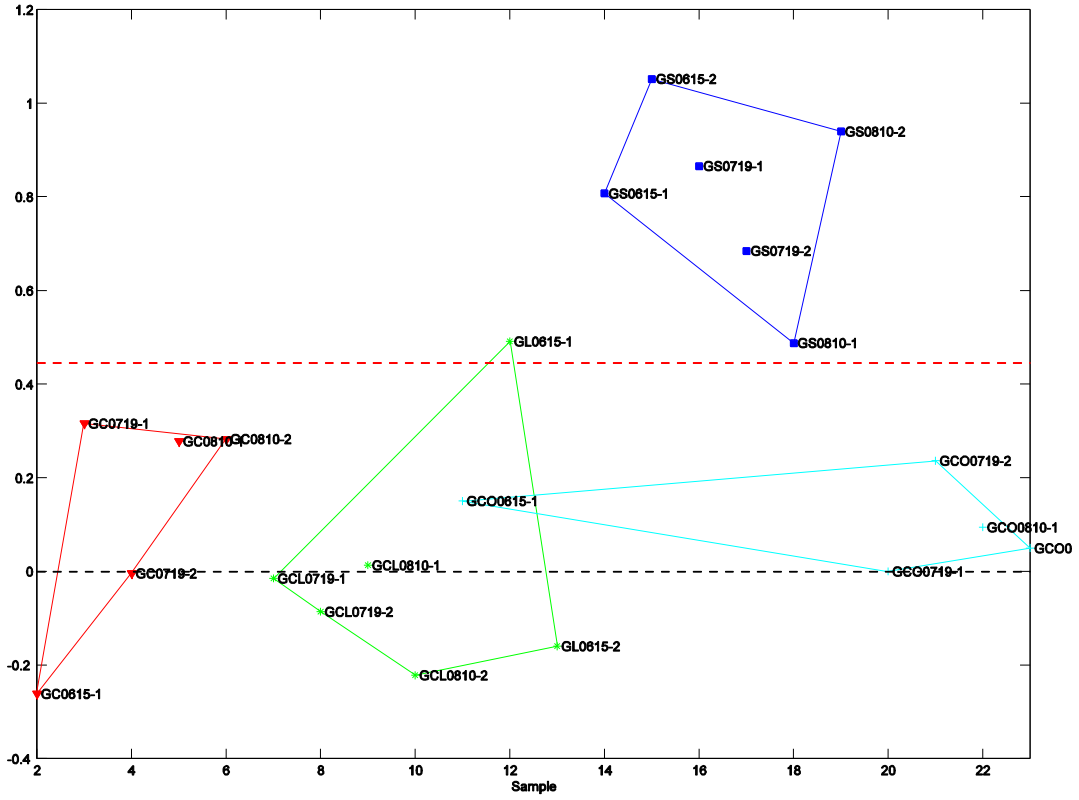


Figure 80: PLSDA plot of e-nose results following analysis of odour samples from all sources at piggery C; model optimised to discriminate odour sampled from the shadecloth surface on the covered pond

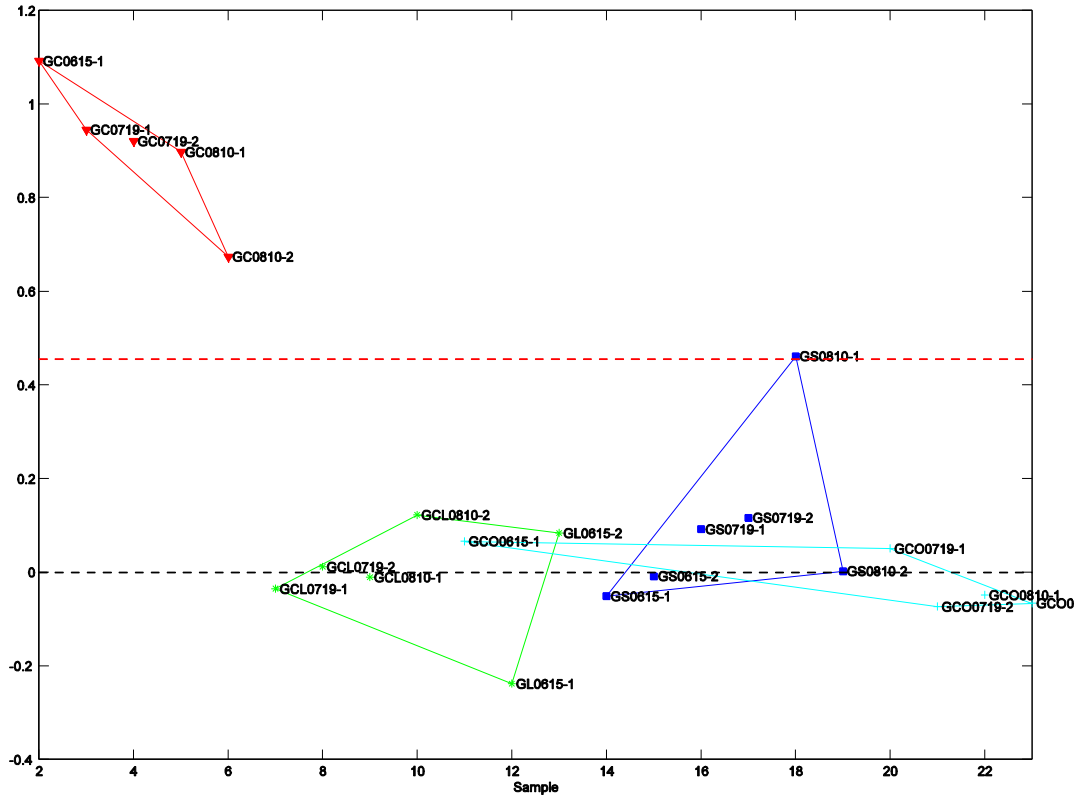


Figure 81: PLSDA plot of e-nose results following analysis of odour samples from all sources at piggery C; model optimised to discriminate odour sampled from the polypropylene and shadecloth surface on the covered pond

Results following assessment of odour samples derived from all sources at the other piggeries were quite consistent with those observed for the ponds at piggery C.

It is proposed that these results support both the anecdotal observations made by the field sampling teams regarding the nature of the odour derived from each surface, as well as the results of the GC-MS analyses of air samples. In Section 4.3.2.4.3 it was demonstrated that key odorants were eliminated from the air samples collected above the covers relative to those collected from the liquor. Figure 56 also demonstrated a clear difference in the complexity of composition of samples collected from a pond cover surface. The complexity of these samples was attributed to the production of volatile chemicals by the biomass on the permeable cover surface. The results of the PLS assessment appear consistent with these other, independent assessment techniques.

4.8.2 Quantitative Results

Combining the outputs of 12 of the sensors with the odour concentration value derived from dynamic olfactometry using a chemometric approach allowed an odour prediction model to be created. In the development of this model, all olfactometry results from all surfaces were used. The results of the model development is shown in Figure 82. The model was able to account for 94% of the variability in the sensor array data and 78% of the variability in the olfactometry data.

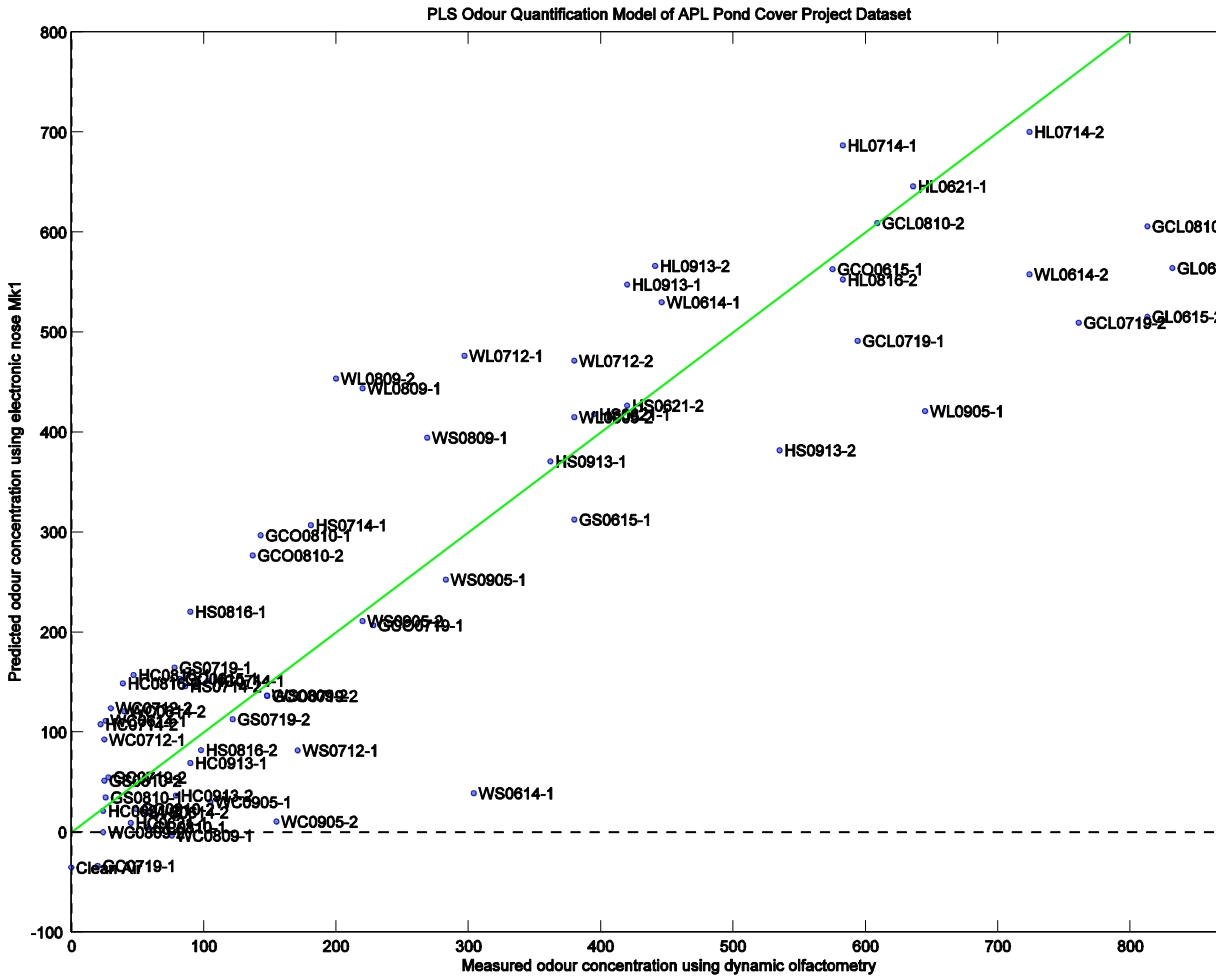


Figure 82: Comparison of odour concentration predicted using the E-nose and PLS model and actual odour concentrations measured using dynamic olfactometry

This Figure reveals the following information:

- Examination of model parameters (specifically RMSEC and RMSECV) indicates that the model accuracy is ± 133 OU. Without removal of possible outlier results, most of the data falls within these limits.
- While the results tend to be scattered reasonably evenly about the 1:1 line at low concentration values, this relationship appears less favourable at higher concentrations.
- Examination of the source of the samples at the low and high concentration end of the relationship indicates:
  - Low concentration results tend to be from the pond cover surfaces, whereas
  - High concentrations results tend to be from exposed liquor surfaces.

The previous Section demonstrated that there were qualitative differences between samples derived from the different sources – these differences may in part account for the poor model fit for high concentration results.

4.8.3 The Role of E-Nose Devices in Odour Assessment

The SIS group of DPI&F has been actively investigating e-nose technology over the preceding three year period. During this time, advances have been made in the selection of sensors and the sensor housing. Very significant advances have been made with the identification and application of

statistical procedures and data mining techniques. The development of temperature and humidity compensation models has also taken place over this period, addressing one of the major criticisms levelled against early sensor array investigations.

As a consequence of these developments, the SIS group has been able to develop models allowing continuous measurement of odour concentrations in poultry housing. The assessment of odour samples from pond covers has demonstrated considerable potential for both qualitative and quantitative assessment of air samples from odour sources of an entirely different nature.

One of the constraints that has been identified is the requirement to determine the odour concentration of air samples using conventional dynamic olfactometry. All commercially available olfactometers increase the strength of odour presented to the panellists in a step-wise fashion, creating a logarithmic increase in odour concentration. This effectively limits the resolution and thereby the precision and accuracy of the results derived from an olfactometer. In contrast, the sensor array has extremely high resolution capability, effectively limited only by the digital-to-analogue converter. As a consequence, the accuracy of an odour quantification model developed from olfactometry for an electronic nose device will be limited by the quality of the dynamic olfactometry, not the sensor array.

It could be argued that a model able to predict odour to within 130 OU of that measured by an olfactometer may be adequate for some air quality applications. This would probably be true for reasonably concentrated odour samples collected at the emitting surface.

To achieve increased accuracy and to enable assessment of odour present at ambient concentrations (i.e. at concentrations to which neighbours of odour sources are exposed), improvements will be necessary for the sensor array, but more importantly, dynamic olfactometers. Lower detection thresholds and smaller dilution steps will be required to improve the accuracy of the olfactometry.
Improved calibration of an e-nose device may be achieved in a completely different manner – utilising the information derived from adequately trained field assessment panels. Calibration of an e-nose by a field assessment team would be a particularly useful technique – it would make deployment of an e-nose to continually assess odour concentrations under field conditions a practical reality. This would be particularly useful for regulatory purposes and for resolution of odour complaints.

5 Conclusions

5.1 Selection of Cover Material

The odour reducing efficacy of straw and polypropylene and shadecloth composite covers are quite similar.

It is recommended that polypropylene and shadecloth covers be used in preference to supported straw covers on the basis of cost and reduced maintenance over the life of the cover.

Maintenance of polypropylene and shadecloth covers appears to be largely driven by site-specific factors, provided the polypropylene is protected from UV damage.

5.2 Performance, Life Expectancy and Costs of Permeable Pond Covers

5.2.1 Efficacy of Reduction of Odour Emission Rates

When compared with the emission rate of the uncovered liquor of each pond, polypropylene and shadecloth cover reduced odour emission rate by about 74%, shadecloth alone reduced odour emission rate by about 70% while a supported straw reduced odour emission rate by about 66%.
When compared with the emission rate of an uncovered pond, a polypropylene and shadecloth cover reduced odour emission rate by 50%, while a shadecloth only cover reduced odour emission rate by 41%.

The true efficacy of these covers is probably a lot higher – the nature of the odour released from the various cover surfaces is much less offensive than that emitted from the liquor. The apparently poor performance of the permeable covers is a reflection of the process of dynamic olfactometry - a presence/absence test, rather than a test of odour character or offensiveness.

5.2.2 Cover Life Expectancy

The straw component of a supported straw cover is about 12 months. Cover efficacy can be maintained by an annual application of good quality straw.

Polypropylene covers require careful protection to ensure an acceptable life expectancy. Direct sunlight causes severe deterioration of the non-woven cover material within a 12-month period.
Manufacture and deployment of a composite cover comprising a non-woven geofabric, shadecloth and flotation devices is likely to provide a cost-effective odour management device with an effective life of at least ten years.

5.2.3 Cover Costs

A cover of this nature is likely to cost about A$ 12.00/m^2 for the initial construction and deployment. Taking into account the costs of managing the cover over an effective life of 10 years, the total costs over this period are likely to be about A$ 35,000.00 (about A$ 3,500.00 per annum).
Ongoing management is probably limited to infrequent inspection of the cover and periodic management of vegetation around the pond margin. The presence of a cover will not unnecessarily complicate sludge removal provided a suitable method is used and some simple precautions are taken.

5.3 Impact of Permeable Pond Covers on Pond Characteristics and Performance

5.3.1 Impact on Pond Performance

No evidence of impairment of anaerobic waste treatment was observed. There was no sign of decrease in pond liquor pH at any of the ponds. Liquor from the covered pond at piggery C had lower volatile solids, chemical oxygen demand and total solids concentrations than the uncovered control pond. Values of these variables at all covered ponds were within the ranges previously observed across a number of ponds surveyed in southeast Queensland.

5.3.2 Impact on Pond Physico-Chemical Characteristics

Concentrations of volatile compounds appeared to increase in covered pond liquor. The average concentration of sulphide in the liquor of covered ponds was up to five times higher than in the uncovered control pond at piggery C. The lowest ammonia-N liquor concentrations occurred in the uncovered control pond; average ammonia-N concentrations were 20 to 550 mg/L higher in the liquor of the covered ponds.

There was considerable variability in the concentrations of a number of water quality determinants prior to the installation of the pond covers. These differences arose from factors such as historical pond management and sources of fresh water inputs to the ponds. Not all of the variation can be attributed to the presence of the pond covers. Overall, there is no evidence that installing a pond cover causes changes in pond chemistry likely to compromise treatment processes or increase pond management requirements.

5.3.3 Impact on Pond Microbiological Characteristics

Limited data makes it difficult to draw strong conclusions. The presence of a pond cover appears to alter the microfloral population in terms of algal species and numbers quite substantially. The major change appears to be the reduction in numbers of blue-green algae. The total number of algae also appears to reduce very significantly. Effective removal of light explains these observations.

5.3.4 Impact on Gaseous Emissions

On-going difficulties associated with equipment made quantification of VOCs difficult. It was soon apparent that collection of measurable amounts of odorants was an onerous task, quite different to the analysis of the standard "Air-toxics" suite (as identified by US EPA methodology). While the UNSW provides emission rate estimates that are more credible than those of other sampling devices, the operating conditions within the wind tunnel effectively dilute the odorants. Collection of volatile chemicals from large volumes of air onto Tenax® sorbent tubes appears essential. This makes access to a modern, sensitive GC-MS system mandatory. The sample inlet system should be reasonably flexible, allowing recovery of trapped odorants from sorbent tubes using thermal desorption and other equilibrium-based sampling techniques such as SPME and SBSE.

Odour emissions from Australian piggery pond treatment systems appear to be dominated by phenols and nitrogen heterocycles such as indole and skatole. Volatile fatty acids appear to be present at lower concentrations than those measured in Europe and North America. Phenol emission rates were not reduced significantly by permeable pond covers, whereas rates of emission of 4-methylphenol, indole and skatole appeared to be reduced quite markedly.

Measurement of carbon dioxide emission rates using a UNSW-style wind tunnel was also difficult. The large flushing rates and relatively high background concentrations of carbon dioxide in the flushing air made measurement of the incremental change caused by the permeable cover difficult. Not statistically significant difference in rates of emission were observed between covered and uncovered ponds using wind tunnel sampling systems.

Using a US EPA dynamic emission chamber, net median and average carbon dioxide emissions were 17% and 24% higher from covered pond surfaces than from an uncovered control pond. These values were reasonably similar to those reported in the literature (increases in the range 33 to 38%, with one report of a 97% increase from a straw covered pond).

A distinct diurnal pattern in carbon dioxide emissions was observed – it is likely that biological activity in the surface of the cover may be responsible for the emission rate characteristics from the covered pond.

Despite the difficulties experienced with measurement equipment, both wind tunnel and flux chamber sampling devices indicated hydrogen sulphide concentrations were greater from the surface of the permeable cover than the liquor of the control pond. These results were consistent with the

pond chemistry results, which indicated that median total sulphide concentrations were more than about 30 times greater in the covered pond liquor than the uncovered control.

5.3.5 Impact on Pond Liquor Chemistry

Between-pond differences appeared more significant to pond liquor quality than differences in pond chemistry brought about by deployment of a permeable pond cover. Liquor concentrations of hydrogen sulphide and ammonia appeared to increase following cover deployment. No significant differences in concentrations of variables that might indicate pond treatment failure were observed. Liquor pH values and volatile solids concentrations and chemical oxygen demand concentrations showed no signs of increasing or decreasing trend. The discharge from a covered pond did not appear to contain increased concentrations of under-treated waste material which could increase the loading rate on a secondary or facultative pond.

5.4 Mechanisms whereby Permeable Covers Reduce Pond Emissions

The reduction in odour emission rates observed over the period of this research indicate that both physical barrier and biofilter mechanisms are likely to contribute to the efficacy of the covers.

5.5 Relationship between Odorant Concentrations and Olfactometry

It was not possible to develop a model relating odorant concentrations to the odour concentrations determined by dynamic olfactometry. The volume of data available describing the odorant signature of the odour samples was inadequate for the task.

It was possible however to demonstrate that a sensor-array was able to provide quantitative and qualitative information which was entirely consistent with the information derived from olfactometry. In view of the simplicity, lower capital and operating costs of sensor-based technology and demonstrated capability, this emerging technology is considered worthy of future investigation as an odour investigation tool.

5.6 Impact of Pond Covers on Emissions from Housing or Effluent Irrigation Areas

Use of a housing model indicated that odour emissions from housing flushed with covered pond liquor was likely to be about five times greater than that from liquor derived from an uncovered pond.

Actual measurements from housing showed that the differences in emission rate from a shed flushed with liquor derived from covered and uncovered ponds were unlikely to have an impact on downwind receptors. The exchange of odorants from the air space below the slats with the bulk air above the slats was probably less efficient than the exchange process that took place within the housing model, where a dynamic and turbulent interface was created between the air and liquid phases.

No statistically significant difference in emission rate was detected between grass covered surfaces irrigated with liquor derived from covered or uncovered ponds. The presence of an additional odorant load in liquor derived from a covered pond is likely to pose an odour risk only during the actual application period. This is an inherently odorous activity – the odour potential is best managed by timing the application appropriately, rather than desisting from effluent irrigation completely.

5.7 Assessment of the Impact of Permeable Covers on Odour Intensity and Offensiveness

Using an in-house method based on a published procedure, it was demonstrated that an inverse relationship existed between odour concentration and odour intensity score three ("distinct"). This trend coincided roughly with the different emitting surfaces. Highly concentrated (and generally more offensive odour samples) were classified as "distinct" at lower concentrations than samples derived from surfaces such as the pond covers. Practical application of these results is not obvious at present however – additional information, such as a rating of offensiveness, may be required before this technique may be used in an improved regulatory framework.

5.8 Alternate Odour Assessment Tools

While GC-MS is a well-established and sensitive investigation tool, it does appear to have specific limitations in the context of odour assessment. Odorants elicit a response in receptors at very low concentrations. These may be near the limits of detection for the GC-MS technique. At these concentrations, it is very difficult to quantify these odorants. Many of the sampling and pre-concentration techniques necessary for odorant detection introduce bias into the process – they may "select" or concentrate certain chemicals from the suite of odorants, and "ignore" or eliminate others. Typically this happens if the concentration technique does not adsorb an odorant, or if it is irreversibly adsorbed. Odour investigation using GC-MS techniques must therefore have regard for a number of factors, including:

- Adequate sensitivity of the analytical detector (the mass spectrometer or mass-selective detector);
- Sufficient inertness of all components of the instrument that make contact with the sample inside the instrument gas flow path;
- Access to a suitable pre-concentration technique, such as tubes containing a sorbent matrix of the correct selectivity.

It must also be recognised that such analysis is unlikely to include all odorous chemicals – an effort must be made to ensure that as many significant odorants as possible are included in the analysis.

5.8.1 Gas Chromatography – Mass Spectrometry - Olfactometry

Techniques such as GC-MS-Olfactometry (GC-MS-O), where the flow from the analytical column is split between a conventional detector (such as a mass-selective detector) and a human assessor may prove particularly useful in identifying the presence of unknown odorants.

The sample is derived from a portion of the flow from the analytical GC column, where compounds are separated primarily on the basis of boiling point. These separated materials are presented continuously through a nose cone to a trained assessor who sniffs the discharge from the column, recording their response on a keypad to indicate intensity, while their perception of the odour character is recorded in speech. An "aromagram" can be prepared at the end of the analysis, which may be overlaid with the chromatogram to confirm the identity of odorous chemicals, or indicate the presence of ones not detected by the instrument. Examples of use of this technique for investigation of odour arising from intensive livestock operations include Wright et al. (2005), Cai et al. (2006) and Rabaud et al. (2002).

This technique has particular application in resolving odour issues associated with a treatment process. For example, an apparently healthy biofilter may not be achieving an anticipated odour reduction target. GC-MS-O may identify a specific odorant which not be removed from the air stream without additional treatment, such as pH control or nutrient addition. In more general

applications, the technique is able to provide qualitative information to an essentially instrumental method of analysis.

5.8.2 Proton-Transfer Reaction – Mass Spectrometry

The capability of this technique was discussed briefly in Section 4.5.3.3, where the sensitivity of the technique was highlighted. The high sensitivity allows real-time analysis of air samples. This may effectively eliminate the requirement for odour sampling and concentration steps. It is known that these processes introduce bias into the assessment process because of sample discrimination – PTRMS allows analysis of the "whole" air sample, avoiding loss of potentially important odorants from the sample. For this to take place however, the instrument will need to be operated on site. The combination of high capital cost of the equipment and high operating costs probably means that it will be some time before this technique will be seen in routine use.

5.8.3 Sensor-Array Devices – "Electronic Noses"

Sensor array devices have been investigated as electronic noses and used in the assessment of livestock odours for more than a decade (Hobbs et al., 1995; Stuetz et al., 1999; Di Francesco et al., 2001; Qu et al., 2001; Gralapp et al., 2001). Many of these applications used the electronic nose as a qualitative tool, discriminating between air samples derived from different sources. Recent work undertaken in association with DPI&F demonstrated that it was possible to develop statistical models to quantify odour samples derived from anaerobic treatment ponds (Sohn et al., 2003). More recently, the discrimination and quantification capabilities of sensor array-based devices were demonstrated, including in assessment of the performance of a biofilter (Dunlop et al., 2004) and continuous measurement of odour concentration in a poultry shed (Sohn et al., 2006). This research demonstrated the ability of sensor array based instruments to discriminate between samples derived from closely related sources. This work also demonstrated that temperature and humidity compensation models are robust, providing repeatable results. Advanced statistical and chemometric processes have also provided models allowing accurate odour quantification.

An opportunity for future research includes investigation of electronic nose devices for assessment of ambient air quality, including odour. Demonstration of this capability will require overcoming a major hurdle – achieving adequate sensitivity with odorants present in air at ambient concentrations. All previous work was undertaken with samples derived from the odour source – the inlet and outlet from a biofilter, the surface of anaerobic ponds or the interior of a poultry shed.

The performance of the E-nose developed at DPI&F provides compelling evidence that sensor-array technology has a promising future in air quality and odour research. These results should encourage all industries and regulatory agencies concerned with odour impacts to invest in future development and refinement of this technology.

6 Implications and Recommendations

This research has demonstrated that supported straw and permeable polypropylene-based cover were able to reduce odour emissions over a three-year period. There is no reason to believe that the reduction in odour emission rates should not continue over the life of the cover.

Cover life expectancy has not been quantified fully. Evidence to date indicates that the straw component of a supported straw cover has a life expectancy of about 12 months duration. Annual straw application is required to maintain efficacy. Failure to replenish the straw will lead to gradual increases in odour emission as the cover area decreases.

Covers based on spun-fibre polypropylene must be protected from UV damage to achieve useful life expectancies. It is anticipated that a composite shadecloth – polypropylene cover will achieve a life expectancy of at least ten years.

Maintenance requirements do not appear onerous – weed control is recommended. Good fencing is recommended to prevent stock wandering on to the cover and causing physical damage. Solids must not be allowed to accumulate on the cover surface. Consolidation of loose soil around the pond margins and provision of adequate buoyancy around the pond margin will ensure that the likelihood of submersion of the cover is minimised.

Over a ten-year life, the cost of a permeable cover (including on-going maintenance and one sludge removal exercise) will be about A$ 3,500 per 1000 m^2 area of cover per year.

No evidence of impairment of pond waste treatment processes was observed over the three year period following deployment of the cover.

No evidence of significant alteration of the pond liquor chemistry was observed over the three year period following deployment of the cover. Concentrations of ammonium-N and total sulphide increased, but not to values that indicated future impairment of normal anaerobic processes was likely.

Increases in odorant concentrations in the covered liquor did not appear to raise odour emissions associated with flushing of housing or irrigation of liquor to land. Odour problems associate with the latter activity should continue to be managed on a site specific basis.

Carbon dioxide emissions from permeable covers appeared to be about 25% greater than those from an uncovered control pond. It is likely that this increase in emission rate is associated with respiration occurring within the pond cover itself. It is possible that this could indicate reduced emissions of methane.

Assessment of cover performance was principally assessed using dynamic olfactometry. GC-MS techniques demonstrated removal of specific odorants that supported the results of olfactometry. It was not possible to develop a relationship between the results of dynamic olfactometry and instrumental methods of analysis based on GC-MS. It was however possible to develop a model based on sensor array technology. Electronic nose assessment was able to quantify odour concentrations, as well as discriminate between odour samples derived from different sources. It is anticipated that the "data mining" processes that made development of these relationships possible could be applied to the results of other instrumental methods of analysis, including GC-MS.

Assessment of gas emissions from ponds confirmed that two sampling devices in common use in Australia provide non-equivalent estimates of emission rate. The same order of difference has been demonstrated for odour emission rate estimates from a range of sources. It is clear that the selection of a method for odour sample collection has the potential to influence the result. There is a requirement that this issue be resolved to ensure consistent emission rate estimates are used nationally.

6.1 Recommendations

1. Permeable pond covers have been demonstrated to be a cost-effective method for reducing odour emissions from anaerobic treatment ponds. There does not appear to be any impediment to recommending their adoption by the industry as an odour management tool.
2. The suite of gases emitted from anaerobic ponds should be investigated in more detail to determine whether the increase in carbon dioxide emissions may in fact be a consequence of reduction in methane emissions.
3. Further investigation of instrumental methods for odour assessment should continue. Use of GC-MS should have regard for the practical difficulties identified in this research.
4. The very promising capability of sensor-based technology should be further explored as a matter of urgency. This research has demonstrated that electronic nose devices are able to differentiate between odours from different sources and quantify odour concentrations. The modest construction and operating costs of sensor-array technology, coupled with a capability for unattended field assessment, make this a particularly promising technology.
5. The pig industry, other intensive livestock industries, dispersion modelling consultants and regulatory agencies need to have regard for recent research regarding odour emission processes. They should also jointly commission some focused research to resolve issues associated with odour sampling, dispersion modelling and odour impact criteria.

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Appendix 1 - Guide to the Manufacture and Use of Permeable Pond Covers

Table of Contents

Executive Summary

When is a Permeable Pond Cover Potentially of Use?

It has been demonstrated over a period of more than five years that permeable pond covers are able to consistently reduce odour emissions from anaerobic ponds by up to 90%.

If an anaerobic treatment pond is causing odour complaints, installing a permeable pond cover may be an appropriate management strategy.

What is a Permeable Pond Cover?

It is a permeable barrier or layer that floats on the surface of the liquor of a waste treatment pond. It can be manufactured from a number of materials including supported straw or polypropylene geofabric. The permeable nature of the cover allows gases to diffuse through the cover and rainwater to percolate into the pond. The microbial population that colonises the cover appears to utilise the odorous chemicals in the emitted gas as a food source.

How is a Permeable Cover Manufactured and Deployed?

Supported Straw Cover

A supported straw cover comprises an open-weave support and an upper layer of biological material. The support has been successfully manufactured form polyethylene hail or bird netting (support matrix) and polyethylene backer rod (buoyancy). Polyethylene cable ties, light rope or stainless steel twist ties have been used to attach the buoyant material to the support matrix. The upper layer of straw can be applied manually from the bank of the pond as the cover support is gradually moved onto the pond, or can be spray-applied using customised equipment once the support material has been deployed. Maintenance application of straw can also be conveniently performed using spray equipment.

Polypropylene Cover

Polypropylene covers have been manufactured using both spun fibre non-woven fabric and woven material. While measured odour reduction was similar for both materials, non-woven product has been used most extensively because of the reduced likelihood of sealing of the cover surface. Reduction of cover permeability has not been actually measured to date, and may not be an issue at all.

Polypropylene covers have been manufactured in individual units about 400 m^2 in size; units of this size can be moved conveniently by a team of about five individuals. The cover is manufactured by stitching lengths of fabric together using industrial sewing machines and monofilament nylon thread. Pockets are sewn onto one face of the cover, into which flotation material is inserted. Closed-cell polystyrene wrapped in waterproof Canvacon® has performed well as flotation material in field trials.

Individual cover units are dragged onto the pond using ropes. Individual cover units are then stitched together using suitable polyethylene rope. The joined cover units are then moved forward incrementally and additional units are attached until the entire pond surface is covered.

Polyethylene shade cloth cover

Non-woven polypropylene fabric has not withstood UV damage by sunlight very well. Significant deterioration has been observed within 12 months of deployment. This damage can be prevented by covering the polypropylene fabric cover with a polyethylene shade cloth. The shade cloth cover

is installed in the same manner as the straw support of polypropylene cover – as a series of individual units joined together on site as the cover is deployed. There is no requirement to attach flotation devices to the shade cloth cover, which is entirely supported by the polypropylene cover.
The supported straw and polypropylene covers are quite heavy once in position, making wind damage unlikely. The covers are conveniently anchored to star pickets driven in around the pond margin. The shade cloth cover is susceptible to wind damage, because it has a relatively low density and is not in direct contact with the pond liquor. It is necessary to anchor this cover very securely around the pond margin. The stitching used to join the lengths of shade cloth should also be quite dense to minimise wind disturbance.

Cover Maintenance
Cover maintenance is not an onerous task and can be reduced by careful selection of materials, and attention to detail during manufacture and deployment.
Stock should be excluded from the cover by fencing to reduce the risk of them straying onto the cover surface.

Deposition of soil and detritus on the cover should be avoided by ensuring that the banks are adequately stabilised and that the discharge of waste to the pond cannot occur onto the surface of the cover. Overgrowth of the cover and/or banks by grasses may be an issue, but is easily controlled through regular but infrequent mowing or herbicide application.

UV damage to non-woven polypropylene fabric has been discussed – it is best avoided by including a protective surface layer of shade cloth.

Rainwater is not an issue for permeable ponds – ponded rainwater percolates through the cover, which is subject to continuous upward displacement as a consequence of gas evolution. In the same manner, gas evolved under the cover is trapped in transient bubbles under the cover, from which it gradually diffuses to the atmosphere above.

The straw used on supported straw covers is subject to natural degradation. A life expectancy of about 12 months could be expected from a barley straw cover. The life expectancy does appear to depend on the quality of the straw originally applied, as well as the amount of rainfall received.

Cover Manufacture and Maintenance Costs
It is difficult to estimate these accurately. Costs are determined by the cost of raw materials, delivery charges and the use of contractors to undertake specific activities. While economies of scale may apply, the added difficulties of associated with covering a large pond may necessitate using contractors to manufacture and install the entire cover. A do-it-yourself cover may appear less expensive, but may present hidden costs in terms of the time and labour commitment
.
Supply and spray application of straw by a contractor was about $ 3.00 /m^2. Manufacture of the grass support was about $ 5.00/m^2, indicating that a cover could be deployed for about $ 10.00/m^2. Annual straw application will be required, presenting an ongoing cost.

The materials for non-woven polypropylene covers cost about $ 4.00/m^2; manufacturing costs are highly dependent on contractor rates. A manufactured and deployed cover will cost about $12.00 - $17.00/$m^2$, with lower maintenance costs over the cover life.

Areas of Current and Future Research

Odorants appear to accumulate in the liquor under permeable pond covers. This does not appear to increase housing odour emissions except during and immediately the flushing activity (if recycled liquor is used for flushing).

While long-term odour reduction provided by permeable pond covers is unlikely to deteriorate, this can only be confirmed through physical measurement of odour emission rate. This will continue over the life of the project until September 2010.

The long-term assessment of cover performance will include mechanical strength testing, providing a clear indication of likely cover material life expectancy.

1 Background

Permeable pond covers were relatively recently developed to minimise odour emissions from anaerobic treatment ponds. Research funded by APL and undertaken by DPI&F Queensland has shown that a wide range of materials is able to reduce odour emissions from anaerobic treatment ponds. While the range of materials that could potentially be used to reduce odour emissions is large, practical issues and costs constrain this selection significantly.

Emissions from anaerobic pond occur in a number of ways.

13. Relatively infrequent, short duration localised upwellings emit significant volumes of gas from the sludge layer within the pond. While most of this gas is methane and carbon dioxide, odorants are also transported out of the liquor into the air above the pond, where they have the potential to create an odour nuisance.
14. Observation of a pond surface indicates that gas (once again mainly carbon dioxide and methane) is continuously emitted as small bubbles across the entire surface of the pond. This process effectively strips odorants dissolved in the anaerobic liquor, creating an odour nuisance potential.
15. The third (and probably most important emission process) does not rely on physical movement of the liquor by bubbles, temperature gradients or density. Random molecular processes such as diffusion drive odour emission. Odorous chemicals in the liquor move to the liquor surface, from which they are emitted. External processes, particularly wind speed, then plays a significant role in determining the amount of odour emitted.

Reduction of the odour emission using permeable pond covers is achieved through two complementary processes:

1. Permeable pond covers do not attempt to completely contain the gases emitted from the liquor. They limit the contact between the liquor and the air above the liquor. This physical separation limits exchange of odorous material between the liquor and the air above it, effectively reducing dispersion of odour.
2. Gases emitted from the liquor are required to travel through the permeable barrier to the air above the cover. This is a relatively slow diffusion process. During transport of the odorous gas through the cover membrane, opportunity exists for the bacteria, fungi and moulds that colonise the cover material to utilise these odorants to meet metabolic requirements. This effectively converts the odorants into odourless carbon dioxide, water and cell biomass. This process is analogous to that of the biofilter, which has been well established as an odour management tool.

Reducing odour emission from pond surfaces using permeable membranes has surprisingly few requirements:

- The liquor surface must be completely covered;
- The cover must not sink;
- The cover must not blow away;
- The materials used for cover construction must be durable to ensure adequate cover life;
- The cover must be affordable;
- It should be possible for a small team to cover the pond within a reasonable timeframe with reasonable effort.

Three basic materials have been used to construct successful permeable pond covers – straw (or other biomaterial), polypropylene geofabric and polyethylene shade cloth. The discussion that follows refers to the construction and deployment of covers manufactured from these materials.

2 Cover Design & Manufacture Considerations

Successful covers can effectively be divided into roughly five constituent parts, each of which is discussed in detail:

- buoyant support and open weave support matrix (straw covers only);
- straw;
- geofabric;
- UV protection (geofabric only);
- stitching, joining and anchoring materials.

2.1 Buoyant Support

The buoyant support ensures that the permeable cover remains above the liquid surface at all times. The intention is to satisfy the flotation requirements of the cover only, and not to provide additional buoyancy to meet any other load. As such, the cover will not support deposition of appreciable amounts of soil, or the weight of stray animals or humans.

2.1.1 Supported Straw Covers

Supported straw covers require support at close spacing to provide almost continuous buoyancy across the cover surface. An extruded, closed-cell polyethylene product manufactured for the construction industry and sold as backer rod has performed well in this application. It is available in 130 m rolls in diameters up to 30 mm. 40 mm diameter material is available in 2 m lengths.

The straw cover requires a matrix to support the straw. Polyethylene hail or bird netting was identified as a cost effective, durable material. It is available as a knitted product, with hole sizes up to about 10 mm. This netting provided a substrate onto which the buoyant material could be conveniently attached. Adequate buoyancy was provided by attaching the rod as a regular rectangular matrix at about 400 mm centres (shown in Figure 83), or as a series of parallel lines at about 400 mm centres.

Figure 83: Straw support materials – hail netting and backer rod.

The backer rod can be conveniently attached to the hail net using polyethylene cable ties or grade 316 stainless steel. Negligible mechanical strength is required, so attachment at 1 m spacing proved adequate.

2.1.2 Polypropylene Geofabric Cover

This cover material has a specific gravity just less than one, which means that it is basically self-supporting. Limited buoyancy was deemed appropriate so that the risk of the cover sinking was

minimised. Closed-cell polystyrene block was selected as a buoyancy aid – it is available commercially in 150 mm x 100 mm x 1800 mm blocks. The polystyrene was wrapped in Canvacon®, a reinforced vinyl fabric, which was heat-sealed to provide a waterproof protective layer around the polystyrene block. The wrapped polystyrene block was not attached to the geofabric – it was inserted into sleeves sewn into the geofabric cover itself (see Figure 84). This eliminated tying bulky buoyant blocks to the cumbersome cover material.

Figure 84: Inserting Canvacon® covered polystyrene rods into pockets in the polypropylene cover.

2.2 Cover Materials

2.2.1 Biological Cover Material

A range of biological materials were trialled as potential covers, including:

- Barley straw;
- Wheat straw;
- Sorghum straw;
- Lucerne straw;
- Flax straw,
- Sugarcane trash and
- Rhodes grass hay.

All reduce odour emissions equally. The flax straw and sugarcane trash appeared to degrade more quickly than the other cover materials. The selection of material for cover manufacture was thereafter made on the basis of cost and availability. Under full cover conditions, barley straw offered an effective life of at least 12 months.

2.2.2 Geofabric Cover Material

Preliminary trials by DPI&F (Hudson *et al*. 2001) had shown that a very light polypropylene geofabric (about 100 g/m^2) reduced odour emissions as much as a supported straw cover. This fabric was produced as a weed suppressant in nursery situations. The very light nature of the fabric meant that the cover was not sufficiently strong to cover an entire pond. A heavier fabric manufactured from polypropylene was selected for complete pond coverage.

Two grades of product are available commercially:

- Woven geofabric
- And non-woven or spun fibre material.

The woven product is produced by weaving strips of polypropylene (about 3 mm wide) in the same manner that fabric is woven. It produces a tough thin layer with predictable physical properties (GSE Lining Technology Pty. Ltd., ; Geosynthetic Consultants Australia, ; Permathene Pty. Ltd., ; Geotextile Supplies and Engineering Pty. Ltd.,)(see Appendix 1). A composite cover comprising various grades of woven and non-woven geofabric was manufactured and trialled in terms of reducing odour emission and physical performance under field conditions. All fabric types performed as well as the earlier supported straw and light polypropylene fabric cover.

While the woven product reduced odour as well as the non-woven product, it appeared to trap and retain gases released from the pond more that the non-woven product. This was regarded as a less desirable characteristic because it increased the prospect for wind damage. As a consequence, the non-woven product was selected for the full-size cover.

Geofabric 1601 (density about 450-500 g/m^2) was selected for the full-scale cover. It offered significant physical strength, which would enable the cover to be moved and positioned on land. The relatively thick fabric (~4 mm) would also provided a good contact time between the gas and the fabric and associated micro-organisms as it diffused through the permeable surface, which would assist with odour elimination.

The fabric was commercially available in 60 m long rolls in up to 4 m roll widths. Individual fabric widths could be joined using a commercial bag-stitching machine to provide much larger cover units. The pockets used to contain the buoyancy devices were also stitched to the cover during the manufacturing process to become an integral component of the cover. A single filament nylon yarn was used for the stitching – it has excellent UV and scuff resistance qualities, ensuring that the individual fabric pieces will not separate under field conditions.

The performance of all fabrics used in the trial covers appeared similar in terms of physical strength and resistance to UV damage. The covers actually manufactured for the full pond cover however were different to those manufactured for the earlier trials. The fabric in contact with the liquor surface was always damp and appeared to support the growth of algae and other micro-organisms. This biomass created a protective layer that practically eliminated sunlight from the cover surface. In contrast, the buoyant strips raised the fabric immediately around them above the liquor so that this material was permanently dry and in full sunlight. Consequently, the geofabric above the buoyant strips or on the banks of the pond experienced significant UV damage.

The UV degradation of the cover material compromised the integrity and therefore the odour control performance of the full cover. A decision was then made to apply a protective layer of polyethylene shade cloth above the polypropylene cover (discussed below).

The woven polypropylene material deserves consideration as a cover material, if only from the perspective of resistance to UV damage. Anticipated life expectancy under full sunlight conditions is at least five years, obviating the use of protective material such as shade cloth. An issue that does need to be explored is potential clogging of the pore spaces in this material by biomass. This may over time reduce permeability to gas, causing ballooning of the cover and increasing the potential for

wind damage. This problem may not be insurmountable – for example, reinforced breather holes may be installed across the surface of the cover to allow excess gas to escape.

The potential benefits make further investigation of this cover material attractive.

2.2.3 Polyethylene Shade Cloth

Polyethylene shade cloth has been used for many years as an external cover material. Our uses of this material to date have been to protect the polypropylene fabric from UV damage. We are however collecting some data regarding performance for odour control, which will be made available later.

Two basic grades are available:

- products intended for the "domestic" market, with life expectancies of at least five years, and
- agricultural/industrial grade product, with a guaranteed life expectancy of 10 years.

The shade cloth can be purchased from a number of suppliers in rolls up to 6 m in width, and up to 50 m long. Most shade cloths have good physical characteristics both along and across the roll. The woven monofilament construction makes it difficult to tear, while the reinforced strips along the length ensure that the cover material can be towed along the ground without causing physical damage.

The shade cloths used to date have had a "95 % +" specification, indicating exclusion of 95 % of sunlight.

2.3 Stitching, Joining and Anchoring Materials

The supporting base of the straw cover was conveniently joined together using polyethylene cable ties or stainless steel wire ties. Individual six-metre widths of the straw covers could be joined with these materials or light polyethylene rope (4-6 mm diameter).

Monofilament nylon yarn was selected to sew individual 4 or 6 metre widths of polypropylene geofabric together. The pockets used to contain the buoyant rods were sewn onto the cover using this yarn as well.

The edge of the polypropylene cover was stitched double thick to strengthen the edge and minimise physical damage. Metal eyelets were also inserted in this thickened hem to facilitate tying the cover to anchor points or to join individual cover units.

Good quality six- and eight mm polyethylene rope was extensively used to join individual cover units together, anchor the covers into position and to tow the covers out on the pond during deployment. Eight- 10 mm rope is necessary to tow the larger and heavier covers into position.

Anchoring the straw and polypropylene covers in position is achieved by attaching adequately sized ropes to 1200 mm long star pickets driven in around the pond margin at three to four metre spacing. At this spacing the mechanical stresses exerted on individual pickets or tie points on the cover are reduced, minimising the potential for tearing of the cover or the pickets being pulled out of the bank. Wind shear does not appear to be an issue because the surface tension of the liquor and the increased mass of the wet cover effectively eliminates the possibility of strong winds lifting the cover once in position.

Attachment of the polyethylene shade cloth is more demanding. The shade cloth is laid on the surface of the cover, which means that it is usually dry. Wind lift is a definite possibility, particularly while the cover is being installed. Once in position the shade cloth must be attached at numerous points around the margin. Complete anchoring by burying the edge of the material in a shallow trench dug around the pond margin should be considered when securing products of this nature.

2.4 Designing a Pond Cover

2.4.1 Background

The method of manufacture must be considered carefully. Will the producer be manufacturing the cover on-site using their own resources, or will the cover be purchased ready-made from commercial suppliers? Either method of construction will require careful design.

It is important to accurately measure the pond dimensions so that the practicalities of manufacture and deployment of the cover can be assessed. Estimates of cost and resource requirements will also be more accurate. Ponds are often designed as part of a piggery licence application. While the design dimensions of the pond might be used for manufacture of the cover, it would prudent to verify the actual as-built dimensions. Use of a Global Positioning System (GPS) to measure the overall pond size offers a number of advantages:

- it enables accurate measurement of the overall dimensions of the pond;
- allows the actual irregular shape of the pond to be captured, while
- the location of fence lines, posts, trees and other obstacles can also be captured.

This information is very useful in planning and undertaking the actual deployment of the cover following construction.

Pond size will dictate the number of individual cover units required to completely cover the liquor surface. The cover materials are generally not very dense, but once a number of individual units are joined together the material can become bulky and cumbersome. Access to lifting equipment and tractors or four-wheel towing vehicles will greatly assist with the cover installation. It will also minimise damage to the cover materials.

Use of lifting and towing equipment will also be determined by the site conditions. The presence of steep banks because of local topography or turkey-nest type pond construction will limit use of vehicles due to health and safety considerations. If such equipment cannot be used, the ability of available labour to move the bulky cover materials will dictate the size of individual units actually constructed. Our experience has shown that polypropylene covers larger than about 400 m^2 are too large and bulky to be moved manually by a team of five reasonable fit males unless the site is reasonably flat and obstacle-free.

Factors to consider during the design process:

- Size of the pond to be covered;
- Site topography, numbers of and location of obstacles;
- Suitability of site for use of equipment for lifting and towing;
- Availability of labour.

2.4.2 Do-it-yourself or a Ready Built Product?

The actual cover is relatively simple technology. A range of commercial products is assembled into a series of manageable units that are deployed on-site and joined together to form a single cover. The final cover could be produced in a number of ways:

- A contractor could source all materials and assemble them into a series of individual units which are delivered to the site for deployment;
- Deployment could be performed by a contractor or undertaken by the producer;
- The producer could procure the constituent materials and assemble them into the individual units on site, followed by deployment, either by a contractor or by the producer using local resources.

Handling large rolls of bulky material requires access to lifting equipment and labour. Large areas of uncluttered space are required to unroll material and join them together. Specialist stitching equipment is required to join geofabric – this may have to be purchased or hired in. Time will be required to learn how to handle the materials and work with it. Labour will have to be hired in or taken from other activities on the farm.

While the costs for materials may be estimated quite easily, the labour requirements may prove more difficult to determine. A turnkey solution is appealing because the costs are identified up-front and resource requirements can be readily identified. The do-it-yourself approach does however favour customisation of the cover, allowing incorporation of specific features or requirements.

Supported straw covers are possibly more suited to do-it-yourself manufacture than polypropylene covers. The materials are lighter to handle and the method of manufacture is labour intensive but requires little skill.

The decision to select either turnkey, do-it-yourself or a mix of these options will be determined by the size of the pond, access to resources, costs of service and materials and probably most important, the desire of the producer to become involved with an activity not core to operating a profitable piggery.

Factors to consider when choosing between do-it-yourself or turnkey solution:

- Commitment to success;
- Availability of resources – time, labour, equipment and facilities;
- Physical considerations – the size of the pond, local topography, ease of access;
- Cost of turnkey solution.

2.5 Selection of Materials

Currently full-scale covers have been produced using supported straw and non-woven polypropylene geofabrics only. Odour reduction performance data are available for covers manufactured from these materials as well. In the absence of observations for woven polypropylene as a full pond cover material, it is difficult to recommend it as a pond cover material at present. Future investigation may well indicate suitability as a cover material.

The choice between supported straw and non-woven polypropylene geofabric will be determined largely by the costs involved. The supported straw cover is potentially cheaper to purchase, construct and install, but will require maintenance to achieve consistent odour control. In contrast, the polypropylene cover will be more expensive initially, but will incur lower maintenance costs over the cover life.

Specifications for geofabrics are well documented in terms of requirements for civil engineering applications, so consistent product performance may be reasonably expected. Specific attention should be paid to specifications regarding physical strength to ensure that the limits of the materials

are not exceeded during manufacture. UV stability must also be considered – materials should be as UV resistant as possible and should not be exposed unnecessarily to sunlight.

Tight performance specifications are also available for products such as hail netting or bird netting. While UV stability is not an issue for these products, exposure of the polyethylene backer rod to sunlight should be minimised to reduce adverse effects.

Ropes should be at least 6 mm in diameter. This will provide good mechanical strength and will reduce the likely adverse effects of sunlight. Monofilament polyethylene rope has performed adequately in field trials to date.

Factors to consider when choosing cover materials:

- Choice between do-it-yourself and turnkey solution;
- Local availability of cheap biological cover material (straw etc);
- Commitment to maintaining the cover periodically to ensure a full cover is maintained, as well as availability of resources to maintain a straw cover – time, labour, straw and spray equipment;
- Physical considerations – the size of the pond, local topography, ease of access;
- Cost of turnkey solution.

2.6 Suppliers of Materials

Polypropylene geomembranes and fabrics are available from a number of engineering suppliers. While many of the products are manufactured locally, imported products are also available.

Supplier	Product/ Service	Contact name	Contact phone number	Comments
Geotextile Supplies & Engineering Pty. Ltd.	Non-woven geofabric Woven geofabric Canvacon® covered polystyrene flotation rods Cover manufacture	Traico Vo	02-9601 8077	Company will supply materials only, or will custom make covers according to client specifications
Landplan Engineering Supplies	Non-woven geofabric Woven geofabric	Grant Sigston	07-3366 6101	Company will supply materials only
Geofabrics Australasia Pty. Ltd.	Woven geofabric Non-woven geofabric	Greg Farrel	07-3279 1588	Company will supply materials only, or will custom make covers according to client specifications
Ten Cate Nicolon Australia Pty. Ltd	Woven geofabric Non-woven geofabric	Lance St. Hill	07-3890 3188	Company will supply materials only, or will custom make covers according to client specifications; Company has access to significant overseas research experience
Netpro Pty. Ltd.	Polyethylene shadecloth		07-4681 6666	Manufacturers of a range of other polyethylene products
Gale-Pacific Ltd.	Polyethylene shadecloth		03-9518 3333	Manufacturers of a range of polyethylene shade cloth products
Visy Plastics, trading as Absolute Trade Supplies	Polyethylene shadecloth		1300-138 304	Manufacturers of a range of polyethylene shade cloth products
Thermotec Australia Pty. Ltd.	Polyethylene backer rod	Peter Robson	02-9771 6400	Supply a range of extruded, closed cell polyethylene products
Netpro	Polyethylene bird and hail netting		07-4681 6666	Manufacturers of a range of polyethylene products
Evergreen Power Seeding Pty Ltd.	Straw application		07-3245 1655	Straw applied on a supply and application or application only basis
Various	Straw and other cover materials	Materials and suppliers should be selected on basis of local supply, costs and ease of availability		

Please note that listing of suppliers and products does not imply endorsement of these products or suppliers – prospective customers are urged to verify all details personally prior to purchase.

3 Methods of Construction and Deployment

3.1 Supported Straw Covers

As noted previously, a supported straw cover is relatively simple, comprising only a buoyant support structure and biological cover material. The manufacturing and deployment process is illustrated in the series of photographs that follow (Figure 85 to Figure 99):

Figure 85: Trial supported straw cover, manual application of straw on pond margin 1

The cover support was prepared off-site and transported to the pond.
Barley straw was applied manually to the support surface.

Figure 86: Trial supported straw cover, manual application of straw on pond margin 2

Manual application of straw to cover support – cover being progressivley moved out onto pond as straw is applied.

Figure 87: Trial supported straw cover, manual application of straw 3

As the barley straw was applied to the surface, the cover and straw was dragged out on the pond surface. This limited the weight of the cover, reducing friction between the cover and the bank surface and reduced the risk of physical damage to the cover.

Figure 88: Trial supported straw cover in position

The trial cover in position on the pond surface.
Once the cover was afloat, it was very easy to manoeuvre and position.

Figure 89: Full-size supported straw cover, manual application of straw 1

Straw being manually applied to a full-scale pond cover.
The support was prepared off-site and transported to the pond.
A single strip of the support material was spread along the pond margin prior to straw application.
Straw was delivered in large round bales which were moved adjacent to the pond margin as required.
A team of five staff manually applied the straw to the cover using pitchforks and rakes.

Figure 90: Full-size supported straw cover, manual application of straw 2

The first cover strip moved out onto the pond surface as the straw application continues.
Once the first cover strip was covered, a second strip was arranged along the pond margin. It was joined to the first strip using polyethylene cable ties.
Straw was then applied to the second cover strip.

Figure 91: Full-size supported straw cover, manual application of straw 3

Straw application to the second cover strip nearing completion.
Note how the joined covers have been progressively moved out onto the pond surface.

Figure 92: Full-size supported straw cover, manual application of straw 4

Application of straw to final strip nearing completion.

Figure 93: Full-size supported straw cover, manual application of straw 5

View of completed pond cover (background strip).
The supported straw cover covered approximately 1/3 of the surface area of the pond at Piggery B.
Supported straw cover dimensions were approximately 40 m x 30 m (about 1,200 m^2)

Figure 94: Degradation of straw 15 months after manual application of straw

Supported straw cover 15 months after initial straw application.
Note severe degradation of straw in foreground. This appeared to be as a result of the quality of the straw applied – the remainder of the straw cover was still in fairly good condition, as can be seen in the top left.

Figure 95: Mechanical application of straw to supported cover 1

Equipment used to spray-apply straw to the original cover 15 months after initial application.
The equipment comprised a customised shredder/fan unit, which chopped the straw and blew it out the nozzle.
The straw bales were all stockpiled on the truck, which was used to move the shredder/fan unit into position.
Note that this technique is equally applicable to maintenance or initial application of cover material.

Figure 96: Mechanical application of straw to supported cover 2

Chopped straw being blown onto the pond cover.
The distance the straw can be blown depends on the direction and strength of the prevailing wind. Straw can be blown for distances up to about 80 m with the equipment as used, if the prevailing wind is favourable.

Figure 97: Mechanical application of straw to supported cover 3

Chopped straw being blown onto the pond cover.

Figure 98: Mechanical application of straw to supported cover 4

Application of tackifier to the upper surface of the applied straw is the final task in the operation.
The tackifier is an aqueous solution of guar gum plus a blue dye. It prevents the wind from blowing the applied straw out of position. The blue dye assists with application by making the surfaces to which the gum has been applied visible.

Figure 99: Refurbished supported straw cover

Cover appearance following re-application of straw and tackifier. The entire operation lasted about four hours and required a labour commitment of three individuals. Much of the time taken involved waiting for the wind to blow from a favourable direction.

3.2 Polypropylene and Polyethylene Shade Cloth Covers

The series of photographs that follow are based on the scenario that when a large polypropylene geofabric cover is being constructed, a series of discrete cover units are manufactured commercially and delivered to the piggery. The piggery operator then deploys the cover unit on the pond using local labour and equipment (Figure 100 and Figure 101).

For the polyethylene shade cloth cover, rolls of product are delivered to the site. The producer then uses local labour to join lengths of material together to create a complete pond cover. This cover is intended to provide protection from UV damage to an existing polypropylene cover. As such, manufacture does not include buoyancy. Installation of a cover at Piggery C is illustrated in the sequence Figure 102 through Figure 106.

Figure 100: Deployment of polypropylene cover 1

Permeable pond cover unit positioned along pond margin.
Buoyant material inserted into pockets along cover margin and across cover surface according to ~3 m x 4 m grid array.
Rope attached to cover edge to facilitate dragging cover onto pond from opposite bank.

Figure 101: Deployment of polypropylene cover 2

Permeable polypropylene cover unit dragged across pond surface.
Note grid formed by buoyancy material along cover margin and across cover surface.
Ropes attached to star pickets to anchor cover in position.

The basic steps required are similar for both polypropylene geofabric or polyethylene shade cloth, as seen in Figure 102 through Figure 106:

Figure 102: Creating a shade cloth cover 1

Lengths of polyethylene shade cloth laid out on flat surface to facilitate joining individual units.

Detail of join between individual lengths of shade cloth using cable ties at approximately 1 m spacing.

Figure 103: Creating a shade cloth cover 2

Joined units of polyethylene shade cloth deployed over existing permeable pond cover. Note that shade cloth edge is retained on pond bank to facilitate attachment of next shade cloth unit.

Figure 104: Creating a shade cloth cover 3.

Deployment of individual shade cloth units completed, creating a single cover.

Figure 105: Creating a shade cloth cover 4.

Pickets driven around pond margin to anchor polyethylene cover.

Figure 106: Creating a shade cloth cover 5.

4 Maintenance of Permeable Pond Covers after Installation

4.1 Risk Minimisation

Maintenance of supported straw and polymer-based permeable pond covers is greatly reduced if adequate care is taken during the design, construction and deployment phases. Much of this attention to detail is risk minimisation. Use of good quality materials will ensure that breakage and physical damage is minimised. Ropes should be sufficiently thick to handle the load applied. Pickets need to be driven to an adequate depth to prevent them from working lose.

Wind damage deserves specific mention. The forces brought to bear on large areas of materials during strong wind events should not be underestimated. This is particularly relevant to polyethylene shade cloth when used as a UV protectant. The material is not in contact with the liquor, allowing the wind to lift it. The consequences of this are illustrated in Figure 107.

Figure 107: Wind damage to a polyethylene shade cloth cover.

During a storm, the wind lifted a shade cloth cover (covering approximately 1800 m^2), moved the entire cover laterally about 20 m, as well as draping the material over an overhead cable. Significant effort was required to return the cover to the correct position – this reinforces the point that the cover should be adequately tethered to avoid difficult repair work.

Another issue that must be recognised is the danger stock and wild animals such as wallabies pose to supported covers. In one application, grazing goats disturbed the soil on steep banks surrounding the pond margin. Heavy rainfall then transported the soil onto the surface of the cover, causing it to gradually sink. The before and after scene is shown in Figure 108 and Figure 109:

Figure 108: Permeable pond cover immediately after installation – note steep, unstable bank and absence of buoyant material along cover margin

Figure 109: Permeable pond cover some time after installation – note submersion of cover along margin following erosion of bank material.

In another instance, a wallaby ventured onto a supported straw cover. Unfortunately, one of its claws became entangled in the hail net and the animal drowned about 10 from the bank. Although the straw was disturbed, no permanent damage was caused to the cover.

While domestic stock is unlikely to try to walk across a cover, the grass, which grows around the pond and onto the cover, may attract them to the edge of the pond. Normal fencing should keep unwanted stock away from the pond and cover and prevent damage.

4.2 Weed Control

Encroachment of vegetation (particularly Kikuyu and couch grass) onto the surface of a pond can be a problem on uncovered ponds. The same is true of covered ponds.

The impact of vegetation encroachment onto permeable pond covers is currently not clear. In the initial trial of these covers, Rhodes grass became established on two of the supported straw covers. This grass in effect became a self-replenishing straw cover – the grass grew well in spring and

summer, dying back in the winter. It was not necessary to replace the straw on this cover once it had become established for nearly five years, as shown in Figure 110 through Figure 114. It appears that the grass cover died off during the summer of 2004/2005 – reasons for this are unclear. The low rainfall and increasing salinity of the pond liquor are probably responsible.

Figure 110: Trial supported straw covers soon after deployment (July 2000)

Figure 111: Trial supported straw covers 24 months after deployment (July 2002) – note well established grass cover on left hand cover unit.

Figure 112: Relocated trial supported straw cover 45 months after deployment (April 2004) – note persistent grass cover

Figure 113: Relocated trial supported straw cover 45 months after deployment (April 2004) – note persistent grass cover

Figure 114: Relocated trial supported straw cover 57 months after deployment (April 2005) – grass cover under stress

Encroachment of grass onto the pond margin should be avoided for health and safety reasons. Dense growth makes it difficult to identify the edge of ponds or steep banks, making it possible for humans or stock to fall onto the cover or down banks. Dense grass growth also hides the location of cover anchors and ropes – if mowing is attempted without identifying the location of these obstacles, damage to the cover and/or plant and equipment is likely.

Figure 115: Encroachment of couch grass onto pond prior to deployment of polypropylene cover

Figure 116: Encroachment of couch grass onto cover 12 months after deployment

The adage "a little often" applies to vegetation and weed control around pond margins. Consideration should be given to chemical or mechanical control around anchors, rope lines and access points. Reducing vegetation will improve access to the pond and cover, reduce the risks from snakebite and encourage maintenance of the cover when required.

4.3 Rain Events

Rainfall is a significant management issue for impermeable pond covers. As their name implies, incident precipitation will collect on the cover and remain in place. Pumps, pipe work and sumps need to be installed into the cover surface to remove this water and prevent damage. The consequences of water collecting on the pond surface are shown in Figure 117 and Figure 118.

Figure 117: Water ponded on surface of impermeable cover

Figure 118: Water ponded on surface of impermeable cover

Rainfall is not an issue for permeable pond covers. As the name implies, the cover is permeable, allowing gases and liquids to cross the barrier. In the same way that gas may accumulate temporarily underneath the cover before gradually diffusing through it, water will pond on the surface of a cover to create a series of pools defined by the buoyant supports. The upward pressure exerted by the buoyancy will ensure that the cover will eventually rise to the surface of the liquid, requiring that the rainfall slowly percolate through the cover into the liquor beneath the cover. This process takes place over a period of days to weeks.

The most noticeable effect on the cover is the proliferation of green algae on the cover within a few days of the rainfall. This is illustrated in Figure 120. This material dries up as the ponded liquid disappears from the cover surface, eventually becoming a dark sludge, or drying further to become a friable, coarse cake (see Figure 123 and Figure 124).

The temporary ponding of rainwater, growth of algae and transient development of bubbles under the covers does not appear to adversely affect odour management or cover longevity. No additional maintenance requirements are imposed by these events either.

Figure 119: Water ponded on surface of permeable cover 1

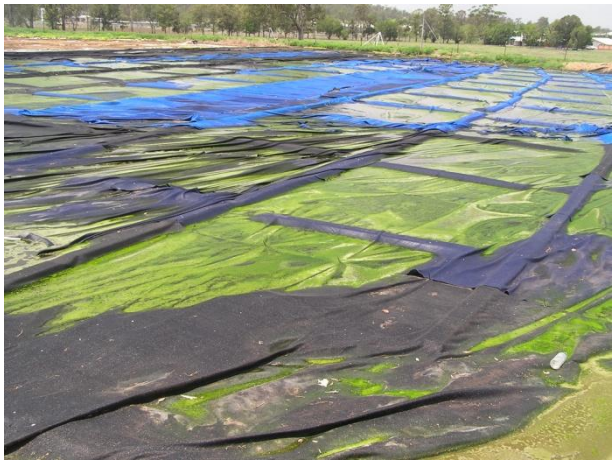

Figure 120: Water ponded on surface of permeable cover 2

Figure 121: Water ponded on surface of permeable cover 3

Figure 122: Water ponded on surface of permeable cover 4

Figure 123: Biomass drying on cover surface to form sludge

Figure 124: Biomass drying on cover surface to form dried cake

5 General

Research undertaken by DPI&F, Queensland on behalf of Australian Pork Limited, has shown that permeable pond cover provide a very effective odour control strategy. The only other effective odour control technique that has been identified to date is enclosure of a treatment pond using an impermeable pond cover.

While impermeable pond covers offer a zero odour emission potential, this can only be achieved through the inclusion of additional plant. This is necessary in order to manage the gas continually derived from anaerobic metabolic processes. Managing emission of this odorous gas requires equipment such as biofilters, gas scrubbers and incinerators. All of this equipment presents additional costs to the producers, and impose additional management requirements.

Use of permeable pond covers can therefore be viewed as a relatively simple method for managing odorous emissions from anaerobic treatment ponds. They can be included in the design of new production facilities, or retrofitted to existing treatment ponds with minimal redundancy of existing facilities.

On-going research funded by APL will identify additional maintenance requirements, improve estimates of costs and confirm odour reduction performance characteristics.

6 Reference List

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GSE Lining Technology Pty. Ltd. Woven Geotextiles. Anonymous Moorebank, NSW.

Hudson, N., Casey, K., Melvin, S. and Gies, A. (2001). Efficacy of supported straw covers for odour reduction in piggery effluent ponds. Final report for Australian Pork Limited, Project DAQ 1473. Queensland Department of Primary Industries & Fisheries: Toowoomba, Queensland.

Permathene Pty. Ltd. Woven Geotextiles. Anonymous Sunshine, Victoria.

Appendix 1 - Geotextiles Technical Specifications
(Geotextile Supplies and Engineering Pty Ltd)

"GEOTEX" Geotextiles											
Test Method	Test Reference	Non Woven, Needle-Punched, polypropylene, Staple Fibre and Geotextiles									
		311	401	451	501	601	701	801	861	1001	1601
Wide Trip (kN/m)	AS3706-2	7	9	10.5	12.5	15	16	17.5	19	21	31
Trapezoidal Tear (N)	AS3706-3	175	240	265	330	350	400	445	500	575	870
CBR Burst (kN)	AS3706.4	1555	1845	2110	2445	2670	3445	3780	4005	4450	7340
G Rating	QMRD	> 1000	> 1400	> 1550	N/A	> 2200	> 2800	> 3000	> 3600	> 4200	> 7400
Grab Tensile (N)	AS2001.2.3	420	555	620	755	775	1000	1090	1290	1445	1825
Pore Size Microns	ASTM D4751	150	150	150	150	150	150	150	150	106	106
Flow Rate ($l/m^2/s$)	AS3706.9	380	350	290	N/A	260	220	220	220	160	100
Permeability Coefficient	10^{-4}m/s @2kPa	27	29	26	N/A	27	38	45	45	45	43
Specification sheet of typical mechanical and indicative hydraulic values. GEOTEX geotextiles are manufactured by Synthetic Industries in one of the largest non-woven manufacturing plants in the world. They are under a quality system conforming to ISO9002. Product specifications are subject to change without notice as part of ongoing development. 02/09/1999											

Woven Geotextiles					
Test Method	Test Reference	Woven PP			
		GSE W1000	GSE W2000	GSE W4000	GSE W5000
Wide Trip (kN/m)	AS3706-2	32	54/42 md/cmd	N/A	N/A
Trapezoidal Tear (N)	AS3706-3	440	650/520 md/cmd	N/A	N/A
CBR Burst (kN)	AS3706.4	3.9	7.6	N/A	N/A
G Rating	QMRD	3800	8000	N/A	N/A
Grab Tensile (N)	AS2001.2.3	1100	2300/2000 md/cmd	N/A	N/A
Specification sheet of typical mechanical and indicative hydraulic values. Product specifications are subject to change without notice as part of ongoing development. 2nd September, 1999					