Development and application of

biofilter systems

for intensive livestock operations to minimise odour emissions and nuisance potential

Evaluation of a pilot scale biofiltration system for odour reduction and recommendations for applying biofiltration to intensive animal housing in Korea

The report of international cooperative project carried out for the year 2005

Mark Dunlop, Neale Hudson, Jae Ho Sohn, & Yong Hee Yoo

NCEA

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Rural Development Administration

Queensland Government
Department of Primary Industries and Fisheries

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A cooperative research project between the University of Southern Queensland, operating through the NCEA, Australia and NLRI of the Rural Development Administration (RDA) of the Republic of Korea has been submitted.

Department of Primary Industries and Fisheries, Queensland, Australia (DPI&F) have worked collaboratively with the NCEA, Australia.

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December 2005

Project title

Development and application of biofilter systems for intensive livestock operations to minimise odour emissions and nuisance potential – Evaluation of a pilot scale biofilter system for odour reduction and recommendations for applying biofiltration to intensive livestock housing in Korea.

December 2005

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This milestone report forms part of a collaborative research project involving:
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Executive Summary

Objectives

A cooperative research project between the National Livestock Research Institute (NLRI) of the Rural Development Administration (RDA) of the Republic of Korea, Department of Primary Industries and Fisheries (DPI&F), Queensland, Australia, and the University of Southern Queensland, operating through the National Centre for Engineering in Agriculture (NCEA), Australia, has been completed.

The project had the following major objectives:

- Identification of technologies to reduce offensive odour emissions from intensive animal operations;
- Development of an efficient biofilter system to reduce odour emissions from animal housing and waste treatment facilities;
- Identifying best practice in terms of media selection and biofilter design; and
- Identifying how biofilters should be implemented at existing operations to achieve maximum air quality improvement with minimal expense and disruption.

The DPI&F undertook the following specific areas of research:

- Year 1 (2003): Researched the requirements of biofiltration systems and designed a pilot scale biofilter system.
- Year 2 (2004): Undertook long term field experimentation to reveal the efficiency of the developed pilot-scale biofilter system.
- Year 3 (2005): Continued field experimentation and identified strategies to implement biofilter technology at existing operations to achieve maximum odour reduction with minimum expense and disruption.

Summary for activities during 2005

The biofiltration system

A biofiltration system was used to treat odorous air derived from a small piggery building, located near Toowoomba, Queensland, Australia. This was a modular system comprising an inlet ducting system, humidifier and closed bed biofilter. It also included a monitoring and water application system. The inlet ducting system was installed beneath the slatted portion of the pig building floor and airflow was generated using an economical and efficient axial fan. Air was directed through a custom-built humidifier that added moisture to the airstream prior to it entering the biofilter. The closed bed biofilter was constructed from a 2700 litre polyethylene rain water tank and was partially filled with an organic medium of wood chips and pig manure screenings. Odorous air entered the biofilter at the top of the tank and was pushed downward through the filter medium where it was treated microbiologically.

The water content of this biofilter medium was strictly controlled using load cells to determine the total mass of the biofilter. Water was automatically applied to maintain the

moisture content of the medium within user defined limits. This was done gravimetrically by continually measuring the weight of the biofilter using load cells and a logger. This system provided very accurate and precise moisture control.

Performance evaluation

The biofilter system was evaluated using:

- dynamic olfactometry (to AS 4.323.3) to measure odour concentration;
- gas detection tubes to measure ammonia concentration;
- electronic nose (e-nose) system; and
- Gas chromatography – mass spectrometry (GC-MS) techniques to measure volatile organic compound (VOC) concentrations.

Olfactometric assessment indicated that the biofilter system was able to reduce odour concentration by about 42% to 43% provided the moisture content of the filter medium was maintained at 66%. If the moisture content of the filter bed declined, odour reduction also declined. Addition of the humidifier did not appear to have any long-term influence on the ability of the biofilter to reduce odour concentration. Unfortunately, olfactometry was unable to measure the hedonic tone or offensiveness of the odour at the inlet or outlet of the biofiltration system. The project team did however observe that the odour of the air exiting the biofilter was less offensive than the air entering the system. The air exiting the biofilter smelt like moist grass or earth, whereas the air entering the system had a distinctive piggery smell.

Gas detection tubes were used to measure the ammonia concentration at the inlet and outlet of the biofilter. The inlet concentration ranged from 5 ppm to 19.5 ppm. The outlet concentration was generally below the detection limit of the tubes (2 ppm). Ammonia removal efficiency ranged from 80% to 95% when the moisture content of the filter bed was maintained at 66%.

E-nose analysis indicated that the biofilter outlet air was different to the air at the inlet of the system and after the humidifier. In order for the e-nose to reliably predict the odour concentration, more odour samples would be required to improve the training of the odour - prediction algorithms.

The GC-MS techniques proved very useful in quantifying the performance of the biofiltration system. Measurement of specific odorants indicated that the removal efficiency of the biofilter system was approximately 84% for acetic acid, 64% for phenol and nearly 100% for butanoic acid, 3-methyl butanoic acid, pentanoic acid, 4-methyl phenol, indole, skatole, propanoic acid and hexanoic acid. Some of these compounds form the basis for the distinctive piggery smell evident at most piggeries. These results help to confirm the observations of the project team which indicated that the outlet air from the biofilter no longer smelt like piggery air.

Recommendations for designing biofilters for intensive livestock applications

The requirements for effective biofiltration, as well as the requirements for matching a biofiltration system to intensive livestock housing, have been summarised in this report. These recommendations address issues such as:

- choice of configuration (open or closed bed system);
- ensuring the chosen design will suit new or existing fan systems (flow rate and pressure drop);
- sizing (choice of dimensions, particularly bed area and depth);
- efficiently directing odorous air to the biofilter;
- selecting the flow rate to optimise odour reduction;
- using suitable materials (filter medium as well as structural materials); and
- providing the correct conditions for microbial activity.

A step-by-step procedure for sizing a biofilter for application to intensive animal housing has been provided, as well as a spreadsheet calculator to streamline the calculation process. The step-by-step procedure for sizing a biofilter has been applied to a range of specific piggery and manure storage scenarios including:

- manure storage tanks;
- aerated (or agitated) liquid fertiliser tanks;
- mechanically ventilated pig housing (especially farrowing and gestation buildings);
- naturally ventilated pig housing; and
- high-rise pig housing.

The results of these scenarios are displayed in the examples in Section 4.2.

Conclusion

This report concludes three years of research into biofilter systems for the purpose of reducing odours from intensive animal production. A pilot-scale biofilter was designed, constructed and evaluated to determine its performance. As a result of this research, a number of recommendations regarding the application of biofilter systems to intensive animal housing have been developed and are presented in this report.

Table of Contents

1 Introduction

This report summarises the progress that has been made in the development and assessment of a modular, pilot scale biofiltration system for odour control. This modular biofiltration system, comprising a closed bed woodchip/compost biofilter and a packed bed humidifier, has been constructed, installed into a piggery and evaluated for efficacy. Efficacy was determined primarily in terms of odour reduction, but also in terms of ammonia removal. The reduction of specific odorants has been assessed using a gas chromatograph-mass spectrometer (GC-MS). An electronic sensor-array (e-nose) was also used to assess biofilter performance by characterising differences between the biofilter's inlet and outlet airstreams.

The principles and processes used during the development and assessment of this pilot scale biofiltration system can be applied to the full-scale application of this technology. A number of potential applications for biofiltration have been identified, including:

- manure storage tanks;
- aerated (or agitated) liquid fertiliser tanks;
- mechanically ventilated pig housing (especially farrowing and gestation buildings);
- naturally ventilated pig housing; and
- high-rise pig housing.

Recommendations and guiding principles are provided in this report for designing and installing biofiltration systems for these situations.

2 Performance evaluation for pilot scale biofiltration system

2.1 Methods and materials

2.1.1 The biofiltration system

The biofilter system reported by Dunlop et al. (2004) was modified slightly for on-going performance evaluations in 2005. Apart from the modifications, all control systems and operation conditions remained the same.

The most significant modifications made to the previously reported system include:

- replacement of the centrifugal fan with an axial fan to reduce running costs;
- relocation of this fan to be prior to the humidifier (this was primarily due to convenience and availability of space); and
- relocation of the temperature and humidity sensors to the biofilter inlet and outlet (instead of the humidifier inlet and outlet).

These changes were made to the biofiltration system in December 2004. The current biofilter system is displayed in Figure 1.

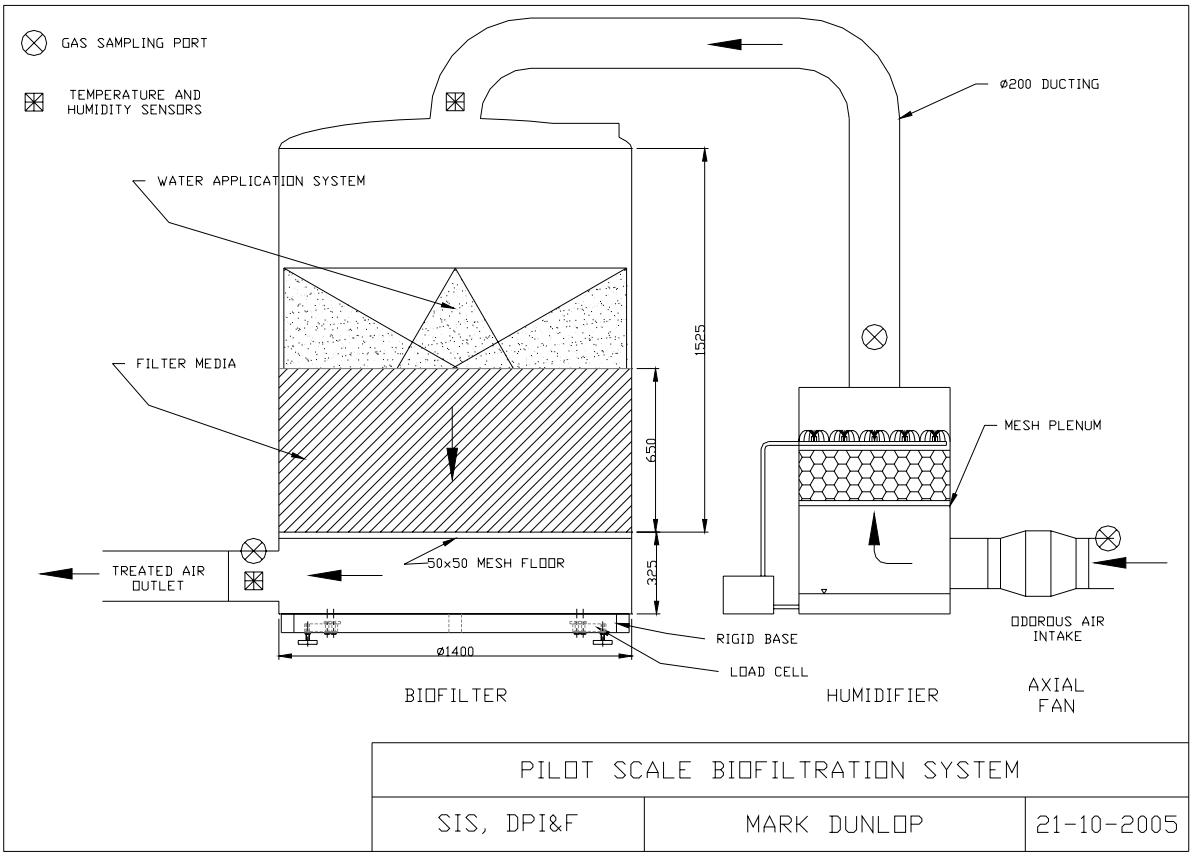

Figure 1. Current biofilter system displaying axial fan in new position and repositioned sensors

Fan replacement

The centrifugal fan used to provide airflow through the biofilter during 2004 (Dunlop et al. 2004) was replaced with a 200 mm mixed flow axial fan (Fantech Pty. Ltd., Victoria, Australia, model TD-800/200 “Mixvent” series). This fan was chosen because it could provide a comparable airflow for considerably lower running costs. The centrifugal fan was powered by a 4 kW, 415 V, three phase electric motor. This motor required 1500 W to power the fan at the chosen flow rate. In contrast, the axial fan required only 120 W to provide the same airflow. Apparently excessive power consumption by the centrifugal fan was primarily due to the oversized electric motor (which was available from previous research and was chosen to provide flexibility in terms of flow rates). An improved fan/motor combination would have almost certainly provided more economical performance.

Relocation of temperature and humidity sensor

The temperature and humidity sensors (AD590 and General Electric® HU10 relative humidity transmitter unit, respectively, as reported in Dunlop et al. (2004)) were relocated from the humidifier inlet and outlet to the biofilter inlet and outlet. The sensors were moved to assess the volume of water being evaporated from the biofilter during normal operation.

2.1.2 Research piggery for evaluation of biofiltration system

The biofilter was installed at a piggery close to Toowoomba, Queensland, approximately 100km west of Brisbane. The piggery was operated as a farrow-to-finish operation. The piggery buildings are an old design, being built in the 1970's and 1980's (see Figure 2).

Figure 2. Picture of the pig building where biofilter was installed

The biofilter was installed on a naturally ventilated, partly slatted grower building approximately 8 m wide, 19.5 m long and 2.4 m high (see Figure 2 and Figure 5). The building had twelve pens containing approximately 170 pigs ranging from 20 to 40 kg live weight (see Figure 3 and Figure 4).

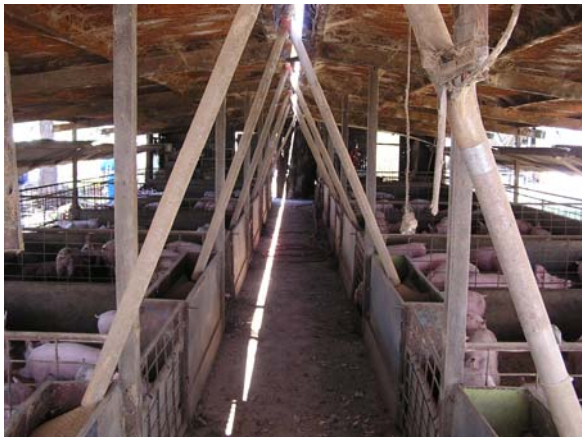

Figure 3. Photograph showing inside of pig building and pigs

Figure 4. Pig pen containing pigs and showing partially slatted floor.

The waste system in this building could best be described as a static pit system, with the waste being emptied twice weekly. The pits were re-filled with liquid from a secondary anaerobic pond. The static pits were approximately 1.4 metres wide, located directly beneath the slats and ran the entire length of the building. The pits were approximately 0.8 m deep at the deepest end (nearest the biofilter) where a depth of liquid 0.55-0.60 m was maintained. A head space of approximately 0.20-0.25 m was maintained between the slats and the pit liquid.

This building was selected because it allowed convenient access without disrupting farming operations or requiring major modifications to the building.

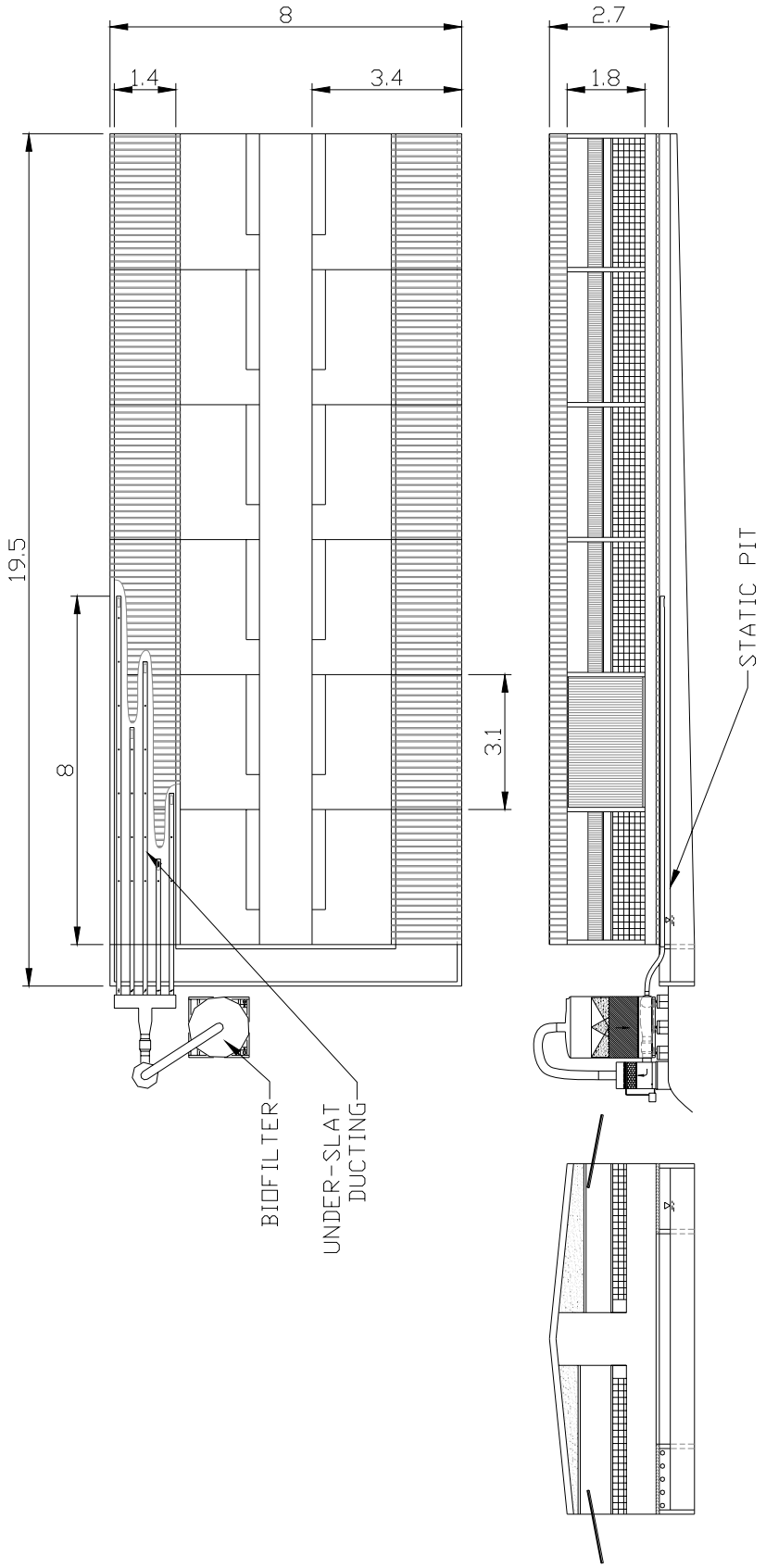

Figure 5. Illustration of pig housing showing location of biofilter and under slat ducting

Ventilation in the pig housing was controlled by shutters on each side of the building. These shutters were constructed from corrugated iron and were opened and closed manually by the piggery staff when required. The narrow end of the shed facing the biofilter had a curtain, which could be raised or lowered depending on the weather.

2.1.3 Biofilter ducting system

A ducting system comprising five, PVC stormwater pipes (each 100 mm diameter) was installed under the slats on one side of the piggery building (see Figure 6).

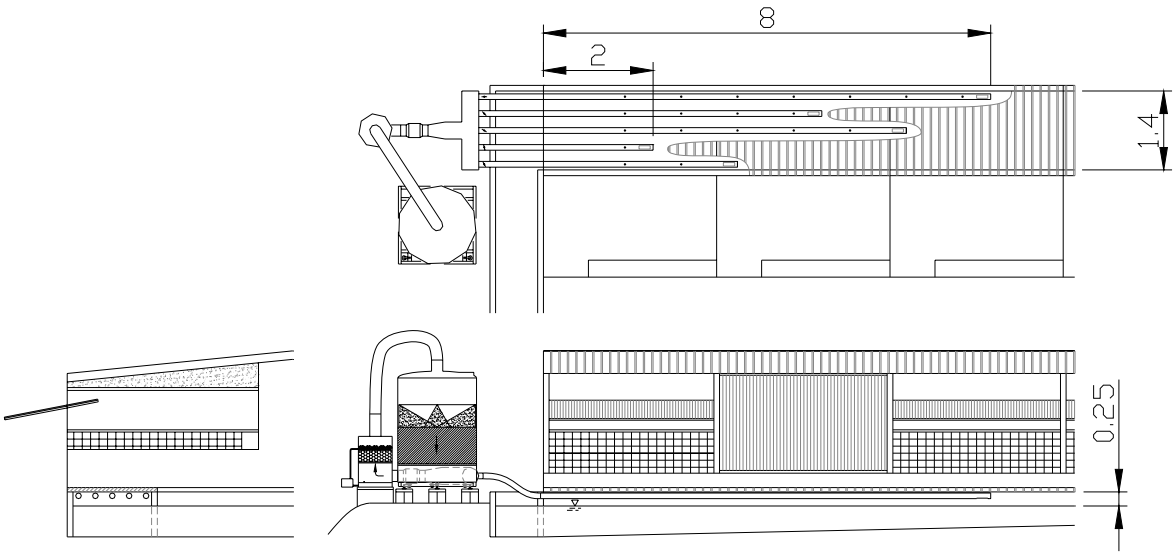

Figure 6. Installation of ducting system below piggery slats

The pipes were different lengths (maximum 8 m, minimum 2 m) to provide approximately even ventilation of the pit headspace. Each duct had 25mm holes drilled at 1 m intervals to enable the duct to drain (if accidentally flooded) and to draw some odorous air along the entire length of the duct. A larger hole (200 mm long and 60 mm wide) was cut into the end of each duct (see Figure 7). The end of each duct was then capped to prevent air being drawn directly into the end, effectively short-cutting the static pit headspace.

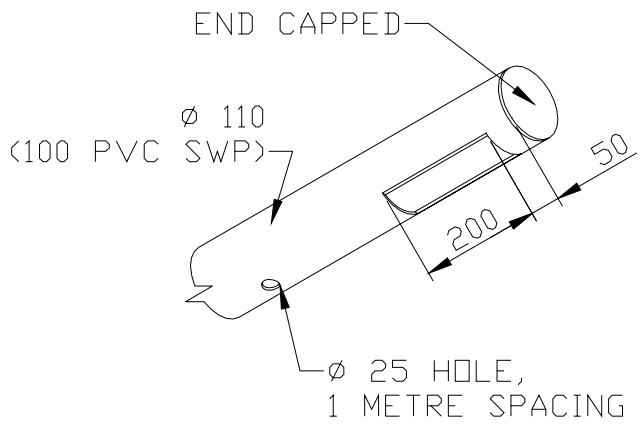

Figure 7. Diagram showing the end of each 100 mm PVC duct located under slatted floor

Figure 8. Manifold joining 5 individual ducts with vanes to equalise flows

A manifold was manufactured from 300 mm PVC stormwater pipe (see Figure 8). Fittings were plastic welded into this manifold to facilitate connection of the fan and the five ducts. An adjustable vane was installed into each of the five ducts to enable the flow to be equalised for each duct. A short length of flexible plastic tubing was utilised to connect the under-slat ducts to the manifold.

2.2 Performance evaluation

The performance of the biofilter system was evaluated in terms of odour, ammonia, and VOC reduction using four complementary techniques:

- reduction in odour concentration, measured by dynamic olfactometry;
- reduction in concentration of specific odorants determined using GC-MS;
- reduction in ammonia concentration using Drager® detection tubes; and
- qualitative comparison of samples collected from various locations on the biofilter system using a sensor array (e-nose).

2.2.1 Gas sample collection for odour and sensor array analysis

Samples of odorous air were collected from the inlet and outlet of the biofiltration system and, when applicable, from the duct connecting the humidifier to the biofilter (post humidifier). Odorous air was drawn into specially prepared 120 L Melinex® (polyethylene terephthalate) sample bags using negative pressure (lung method), which eliminates contamination by the sampling pump. All materials in the sampling train (other than the sample bag) were manufactured from stainless steel or polytetrafluoroethylene (PTFE, generic name for Teflon®).

2.2.2 Sampling program

The biofilter performance assessment program for 2005 continued from previous assessments during 2004 (Dunlop et al. 2004). During 2005, two different operating scenarios were evaluated.

For the first scenario, the biofilter bed moisture content was maintained at 66% (wet basis) and the humidifier was removed from the system. Flow rate through the system was approximately 380 m^3/hour allowing an empty bed contact time (EBCT) of approximately 7 s. The biofiltration system was operated under these conditions until 14 July 2005. During this period, odour was measured twice and ammonia was measured six times.

The second operating scenario was specifically aimed at measuring the influence of the packed bed humidifier on the complete biofiltration system. During this period, the humidifier was re-installed into the biofilter system and was activated. At the start of the trial, the water collection sump in the bottom of the humidifier was filled with fresh water, directly from the town water supply, and was not replaced for the duration of the trial. Fresh water was only added to the humidifier to replenish water lost through evaporation and water sample collection. A one litre sample of water was removed from the humidifier (five days a week) and analysed on site for pH and electrical conductivity (EC) levels. This sample was then analysed for ammonia nitrogen (NH_3-N), sulphide, total sulphur and total alkalinity (mg/L $CaCO_3$). During this trial, odour was measured on five occasions and airborne ammonia concentration was measured on six occasions. Removal of specific odorants was also assessed throughout this trial several times to correspond with odour sample collection.

2.2.3 Dynamic olfactometry

Samples were analysed for odour concentration using DPI&F's dynamic, triangular forced choice olfactometer, which involves of a panel of eight specially trained human air quality assessors. DPI&F's olfactometer was operated according to Australian Standards AS4323.3 (Standards Australia, 2001).

2.2.4 Gas chromatography – mass spectrometry (GC-MS)

Collection of samples for GC-MS analysis

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:

- SBSE sample collection; and
- Tenax™ sample collection.

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 (polydimethylsiloxane, PDMS) and a liquid sample surrounding the device. In this situation, the liquid samples were air samples derived from various points in the biofilter system. The sample was colleted by exposing the SBSE device (see Figure 9) to the air stream for a fixed period of time. Similar sampling periods (20 to 60 minutes) were used for all samples collected during a sampling event. 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 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.

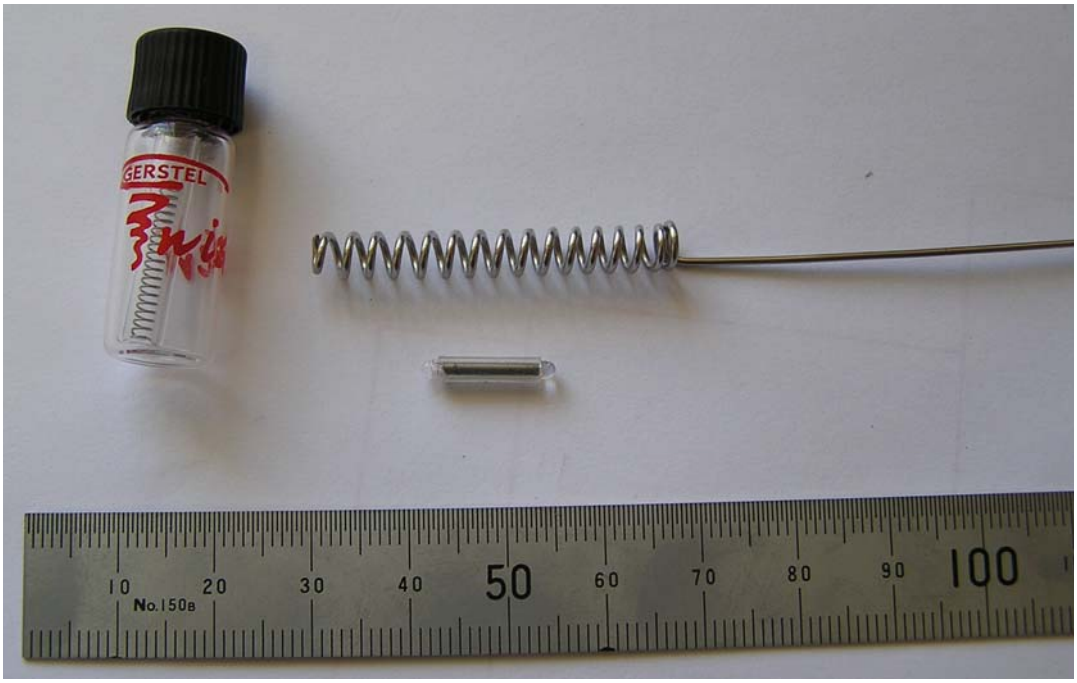

Figure 9. SBSE device (centre), storage bottle and customised holder (mm scale)

Tenax sample collection

Two techniques were used to sample volatile materials 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. These were ¼"od x 90 mm tubes 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. Flow rates were typically 100 mL/min. Sample periods were typically 30 to 60 minutes duration, giving effective sample volumes of 3 L to 6 L. 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 Department of Primary Industries and Fisheries (DPI&F), using the GC-MS system operated by Sustainable Intensive Systems (SIS), Toowoomba.

Gas chromatography analysis (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 split-less 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 split-less 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.

Materials eluted from the GC column were detected using an Agilent 5973 mass-selective detector. It was operated in electron 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).

Calculation of removal efficiencies

All quantification was relative. This was done by comparing the peak areas for the various contaminants on the basis of sample source. Removal efficiencies were calculated for each compound using Equation 1:

$$removal\ efficiency\ (\%) = \frac{Area_{inlet} - Area_{outlet}}{Area_{inlet}} x100 \qquad \textbf{Equation 1}$$

It was possible to calculate removal efficiencies for the humidifier only, biofilter bed only or biofilter system as a whole.

2.2.5 Electronic sensor array

Samples were analysed using the AromaScan® A32S, a commercial electronic nose comprising 32 conducting polymer sensors. The polymers are based on heterocyclic compounds such as aniline and pyrole. Sensitivity to volatile organic chemical compounds makes polymer sensors suitable for odour detection. Figure 10 shows the AromaScan® A32S electronic nose system.

Raw sensor responses were calibrated for temperature and humidity, then pre-processed using principal component analysis (PCA) to extract features from the raw sensor data. The extracted features were used to develop an artificial neural network model to predict odour concentration.

Figure 10. AromaScan A32S electronic nose system

2.2.6 Ammonia measurement

Two different methods were used to measure ammonia concentration. The first method was used until 27 January 2005. This was a wet chemistry method previously described by Dunlop et al. (2004). After this date, airborne ammonia concentration was measured using Drager® gas detection tubes (see Figure 11). These tubes provide reasonable accuracy (10-15%) and are readily available. The tubes change colour by reacting with the target gas. The amount of colour change is proportional to the concentration of the selected chemical (in this case ammonia gas). Tubes of two different detection ranges were used, namely, 2 ppm to 30 ppm (Ammonia 2/a) and 0.25 ppm to 3 ppm (Ammonia 0.25/a). The tubes were used in conjunction with a Drager® bellows pump (see Figure 12).

Figure 11. Drager® tubes illustrating colour change during measurement (22/2/05)

Figure 12. Measuring ammonia concentration at the humidifier outlet

Ammonia concentration was measured directly from the biofiltration system at the same sampling points where odour samples were collected. Using these sampling points, ammonia concentration was measured at the biofiltration system inlet, after the humidifier, and at the biofilter outlet. Tubes were connected to the sampling points using stainless steel Swagelok® fittings and Tygon® tubing.

On one occasion, ammonia measurements were taken within the piggery building, and on the downwind side of the building. These were collected using Drager® tubes with a detection range of 0.25 ppm to 3 ppm. Ammonia was measured at approximately 700mm above the floor (or ground).

Results of all ammonia measurements are given in section 3.3.

3 Results and discussion

3.1 Odour measurement

Odour concentration was measured on seven occasions during 2005. Figure 13 displays the results of these measurements. The first two pairs of odour measurement shown in Figure 13 were undertaken to assess the ongoing performance of the biofilter. The following five sets of data were specifically collected to assess the influence of the humidifier on the biofiltration system. During this humidifier assessment period, fresh water was used to fill the humidifier sump on the first day (29/8/05). For the remainder of the period, fresh water was only added to replenish water lost through evaporation. The humidifier sump was not emptied, rinsed or refreshed with clean water for the remainder of this period.

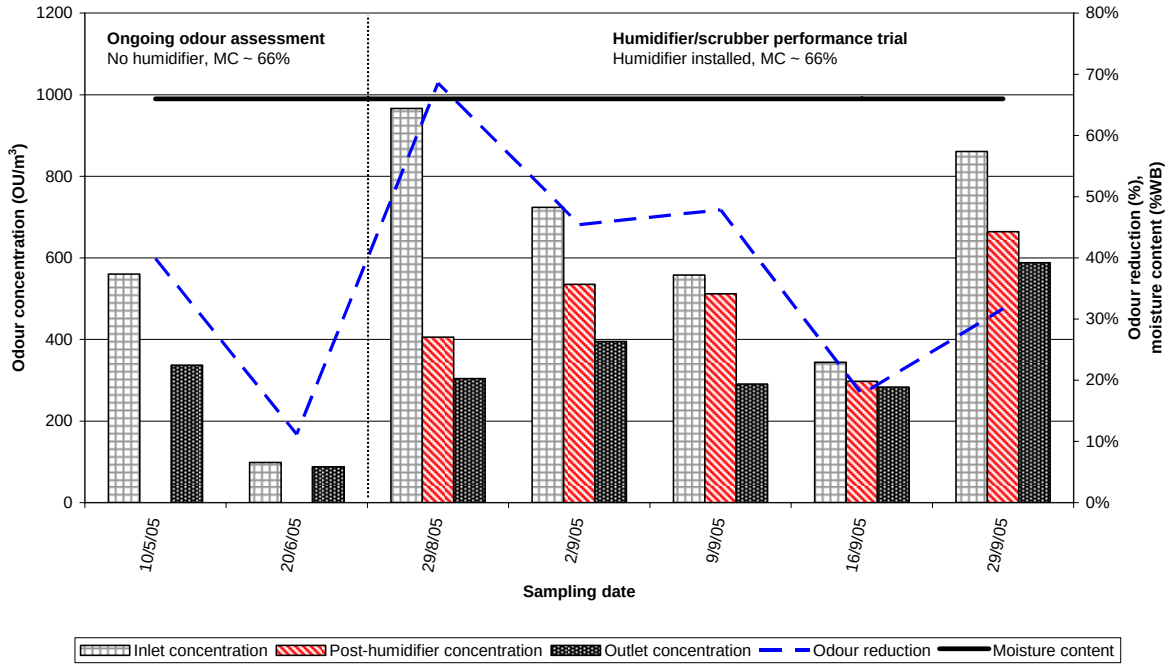

Figure 13. Odour concentration and odour removal efficiency (2005)

The data shown in Figure 13 indicates that without the humidifier installed in the system, odour removal efficiency ranged from 10-40%. On the occasion when the odour removal efficiency fell to 10%, odour concentration at the inlet to the biofilter system was only 98.5 OU. Given that the biofilter produces its own background odour, it was not surprising that odour removal was small on this occasion.

When the humidifier was initially reintroduced to the biofilter system with fresh, uncontaminated water, odour removal efficiency of the whole system increased to 69%. It is clear that with fresh water in the humidifier, odorants were removed from the airstream. As time passed, and contaminants in the humidifier water accumulated, its ability to remove

odorants diminished. Contaminant accumulation in the humidifier is further explained in section 3.5.

Figure 14 and Table 1 display all odour concentration data collected from the biofilter for the period 16 June 2004 to 29 September 2005. Over this period of time, a number of configurations (varying bed moisture content and presence of humidifier) have been tested. An initial comparison of bed moisture content and odour removal efficiency indicates that the reduction in bed moisture content correlated with a decline in odour removal efficiency.

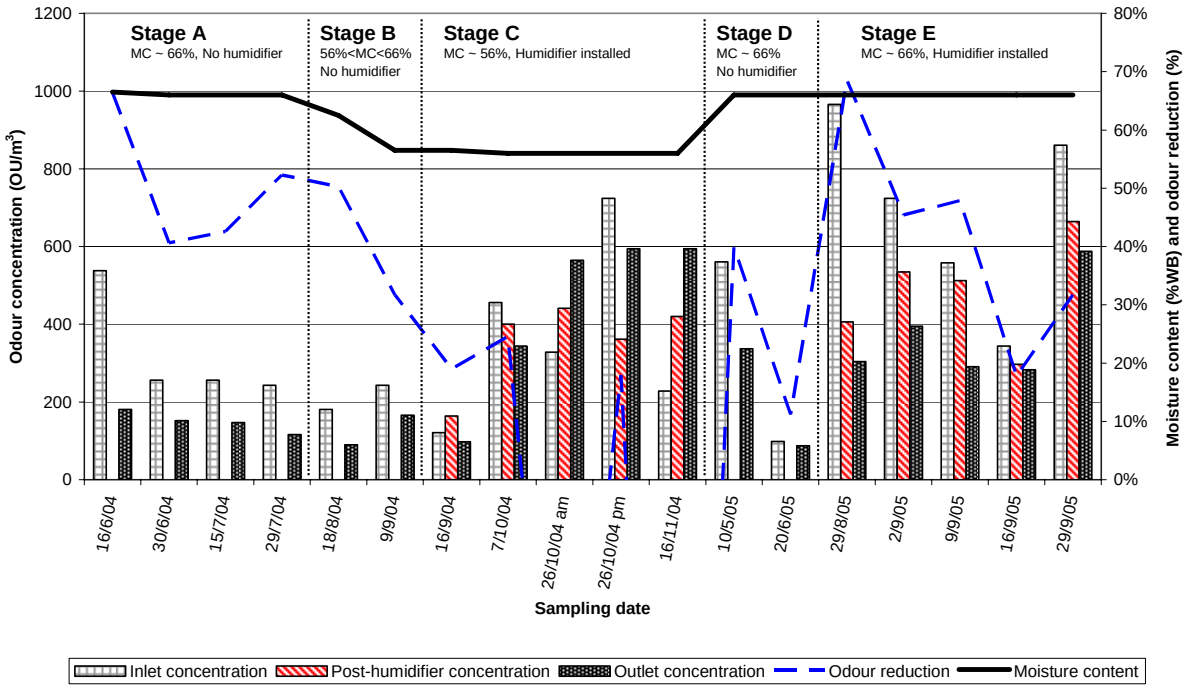

Figure 14. Odour concentration and odour removal efficiency (all data)

Table 1. Odour concentration results and odour removal efficiency for biofilter system

Date	Flow Rate (m^3/h)	Moisture Content (%)	Inlet Odour (OU)	Post-Humidifier Odour (OU)	Outlet Odour (OU)	Humidifier removal efficiency (%)	Biofilter only removal efficiency (%)	Total removal efficiency (%)
16/06/04	345	67	538		181		66	66
30/06/04	339	66	256		152		41	41
15/07/04	339	66	256		147		43	43
29/07/04	339	66	243		116		52	52
18/08/04	339	63	181		90		50	50
9/09/04	377	57	243		166		32	32
16/09/04	418	57	121	164	98	-36	40	19
7/10/04	407	56	456	400	344	12	14	25
26/10/04	400	56	328	441	565	-35	-28	-72
26/10/04	412	56	724	362	594	50	-64	18
16/11/04	409	56	228	420	594	-84	-41	-161
10/05/05	407	66	560.5		337		40	40
20/06/05	385	66	98.5		87.5		11	11
29/08/05	379	66	966	406	304	58	25	69
2/09/05	390	66	724	535	395	26	26	45
9/09/05	377	66	558	512	291	8	43	48
16/09/05	372	66	344	297	283	14	5	18
29/09/05	396	66	861	664	588	23	11	32
Average reduction (%) at 66% MC						26	34	43

Analysis of variance tests (VSN International Ltd, 2005) were applied to the odour concentration data to identify significant differences at a 95% confidence level. These tests indicated:

- The inlet odour concentration did not alter significantly throughout the sampling period (including times when biofilter bed moisture content was varied or when the humidifier was added/removed from the system). This finding justifies comparison of the performance of the biofilter system under different operating configurations because the inlet odour concentration was comparable between tests.
- When the humidifier was installed, the odour concentration in the duct following the humidifier was not significantly different to the inlet odour concentration. This showed that the humidifier did not significantly reduce odours. The result of this statistical test also justifies comparison of the biofilter outlet concentration to the inlet, regardless of whether the humidifier was installed.
- When the moisture content of the biofilter bed was 66%, the outlet odour concentration *was* significantly different to the inlet odour concentration.

- When the moisture content of the biofilter bed was reduced to 56%, the outlet odour concentration *was not* significantly different to the inlet odour concentration.
- This indicates that it is pointless to calculate removal efficiencies of the biofilter system when the moisture content was reduced because the outlet and inlet odour concentrations were similar.

Figure 15 is a box plot of the odour concentration data. It can be seen that the inlet, post humidifier and outlet (56% MC) odour concentrations are similar to each other. Only the outlet odour concentration (66% MC) is noticeably lower.

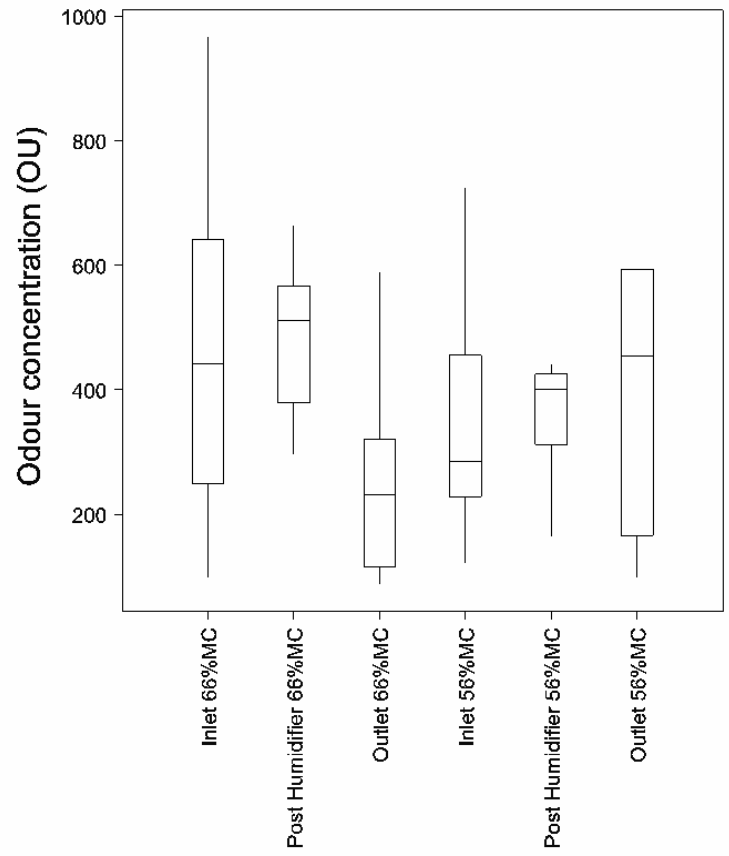

Figure 15. Summary of odour concentration data

A comparison of the odour reducing performance of the biofilter system with and without the humidifier (only for the times when the moisture content of the filter bed was 66%) indicates that the humidifier did not influence the ability of the biofiltration system to reduce odour. Average odour removal from the system without the humidifier was 43%, and with the humidifier was 42%.

The odour concentration data indicates that:

- the humidifier did not assist in reducing odour concentration; and
- maintaining suitable filter bed moisture content (66%) was critical for effective odour removal.

Odour assessment is more complicated than simply measurement of odour concentration. Odours are composed of a range of specific odorants. Different combinations of odorants produce odours of different character and offensiveness. It is important to address the issue of odour character when describing overall biofilter performance.

3.2 Odour character observations

Section 3.1 indicated that the average overall odour removal efficiency of the biofiltration system was approximately 42% (based on measurement of odour concentration). While this figure is low, it is important to comment that measurement of odour concentration by olfactometry is based solely on a presence/absence test. The odour sample is initially diluted below the detection threshold of the panel. It is then serially increased in concentration and presented to the panel until at least half the panel is able to detect presence of an odour correctly and with certainty. There is no requirement to identify what the odour is, where it has come from or to describe whether it has an offensive, pleasant or neutral character.

The biofilter bed was formed by mixing cypress pine wood chips with screenings recovered from the waste flushed from the pig housing. Both cypress pine and the screenings had quite strong and distinctive odours, which rapidly altered once the system was operational. It is likely that the biofilter bed was rapidly colonised by a range of aerobic or facultative bacteria, along with moulds and fungi. It is well known that these materials are able to produce odours. The odour exiting the biofilter had a noticeably different character to the odour entering the system. The smell emitted from the biofilter smelt like moist compost whereas the odour entering the biofilter system had a distinctive piggery/anaerobic pond odour. On-site observations by the research team indicated that the air emitted from the biofilter was much less offensive compared to the inlet air being sourced from the static pit.

Qualitative assessment of odour offensiveness using an olfactometer and assessors is possible. The German Institute of Engineers (VDI) has developed an analytical procedure to determine hedonic tone of odour samples (Verein Deutscher Ingenieure, 1994). Samples are presented to a panel at supra-threshold concentrations (i.e. recognition is possible). The panel then scores the sample in terms of offensiveness on a scale from -4 (highly offensive) through 0 (neutral odour) to +4 (very pleasant). It is also possible to describe the odour using a set of standard terms. The DPI&F olfactometer was not able to perform the VDI or a cheaper in-house hedonic tone test at the time of this trial, therefore this information cannot be included in these discussions.

Complementary results from GC-MS and sensor array assessments do however confirm the anecdotal observations made by staff during field inspections and sampling. Results from these techniques are described in section 3.4 and section 3.6 respectively.

3.3 Ammonia measurement

Reduction of ammonia in the biofilter system

Ammonia concentration results are shown in Figure 16 and Table 2 (all data from 19 November 2004 to 29 September 2005). Ammonia concentrations were measured at the inlet to the biofilter system (biofiltration system inlet), after the humidifier (post humidifier) which is also the inlet to the biofilter, and at the biofilter outlet (biofiltration system outlet). Figure 16 also displays the ammonia removal efficiency (of the whole biofilter system) and the biofilter bed moisture content. The Drager® tubes used to measure ammonia concentration from 22 February 2005 till 29 September 2005 had a minimum detection limit of 2 ppm. For most of the measurements at the biofilter outlet, the packing within the tube either didn't change colour, or only very slightly changed colour. This indicated that the ammonia concentration was very low, most probably ranging from 0 to 0.5 ppm. However, since these values are less than the minimum detection limit (2 ppm), the actual concentrations are unknown and have been reported in Figure 16 as 1 ppm.

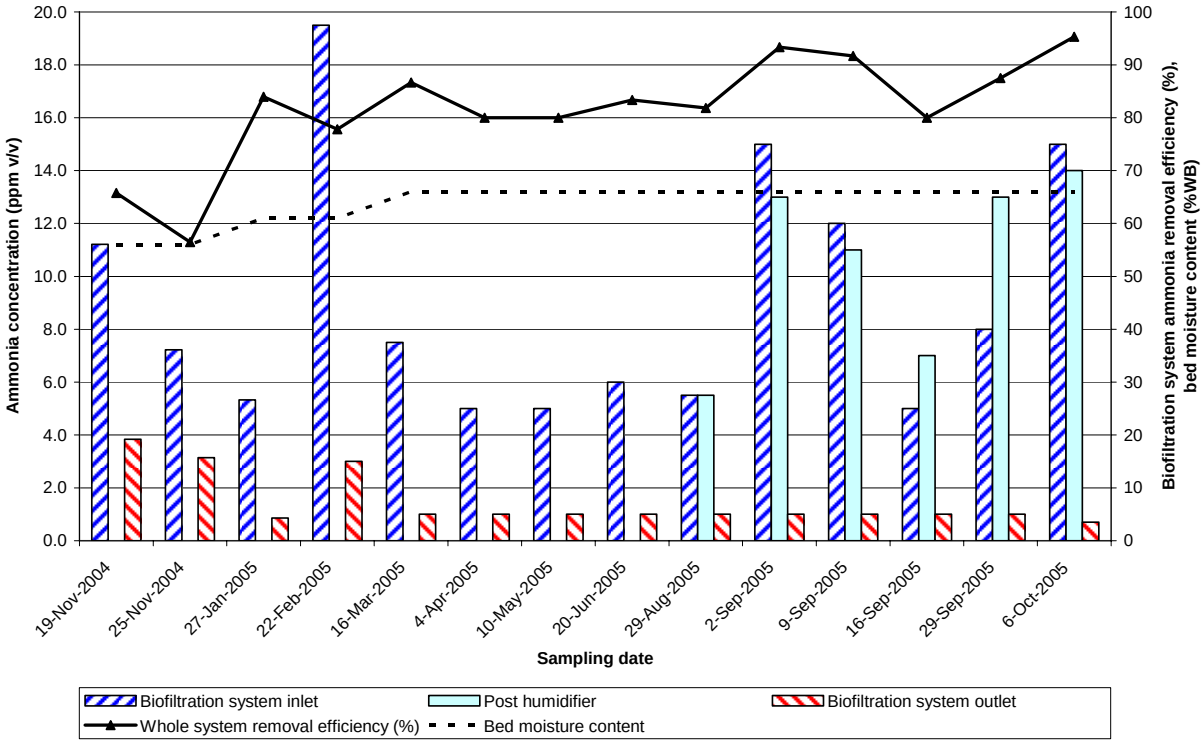

Figure 16. Chart of ammonia concentration results for biofiltration system

Table 2. Ammonia concentration data from biofilter system

Date	Moisture Content	Flow Rate (m^3/h)	Inlet (ppm)	Post Humidifier (ppm)	Biofilter Outlet (ppm)	Humidifier removal efficiency (%)	Biofilter removal efficiency (%)	Total removal efficiency (%)
19/11/04	56	409	11.2		3.8		66	66
25/11/04	56	389#	7.2		3.1		56	56
27/01/05	61	389#	5.3		0.9		84	84
22/02/05	61	389#	19.5		3.0		78	78
16/03/05	66	389#	7.5		1.0*		87	87
4/04/05	66	389#	5.0		1.0*		80	80
10/05/05	66	407	5.0		1.0*		80	80
20/06/05	66	385	6.0		1.0*		83	83
29/08/05	66	379	5.5	5.5	1.0*	0	82	82
2/09/05	66	390	15.0	13.0	1.0*	13	92	93
9/09/05	66	377	12.0	11.0	1.0*	8	91	92
16/09/05	66	372	5.0	7.0	1.0*	-40	86	80
29/09/05	66	396	8.0	13.0	1.0*	-63	92	88
6/10/05	66	389#	15.0	14.0	0.7	7	95	95
Average		389#	9.1	10.6	1.5	-12.4	82.3	81.7

*If Concentration = 1, recording was below detection limit of tube (detection limit = 2)
#Flow rate was estimated from average flow rate (= 389)

Ammonia removal efficiency of the entire biofilter system is displayed in Figure 16 (absence of ammonia concentration results for the post humidifier sampling location indicates that the humidifier was not installed at that time). When the moisture content of the filter bed ranged from 56% to 61%, the removal efficiency ranged from 56% to 84% (biofilter only, humidifier was not installed). When the moisture content was increased to 66%, removal efficiency of the biofilter ranged from 80% to 95%. Removal efficiency of the humidifier alone was poor, ranging from -62% (actually released ammonia) to 13%. Removal efficiency of the whole biofiltration system ranged from 80% to 95%.

Analysis of variance (VSN International Ltd, 2005) was undertaken to test whether the post humidifier and biofilter outlet samples were significantly different to the inlet ammonia concentrations (at 95% confidence level). Figure 17 presents the ammonia concentration results from all sources. It is clearly shown (and proven statistically) that regardless of biofilter bed moisture content, the outlet ammonia concentrations are significantly lower than the post humidifier and inlet concentrations.

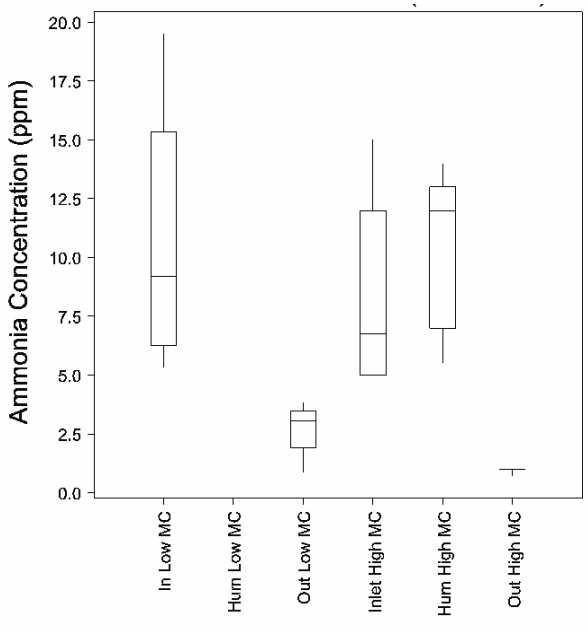

Figure 17. Box plot of ammonia concentrations for each source

Figure 16 and Figure 17 illustrate that the humidifier had limited ability to remove ammonia from the airstream. This was confirmed using analysis of variance, which determined that the post humidifier concentrations were not significantly different to the inlet ammonia concentration. Inability to remove ammonia from the airstream was most likely due to the way the humidifier was operated. Specifically, the chemical composition and properties (such as dissolved nitrogen content and pH) of the humidifier liquid were not controlled. To target ammonia removal in the humidifier, pH and chemical composition in the humidifier liquid would need to be monitored and controlled.

Overall, ammonia reduction through the biofilter system is very encouraging. Assuming that the moisture content of the biofilter bed can be maintained at approximately 65%, ammonia removal rates of 80% (or higher, remembering that the outlet concentrations were assumed to be 1 ppm but were probably lower) are achievable.

Measurement of ammonia in the pig house

On 6 October 2005, ammonia concentration was measured in and immediately downwind of the pig house using Drager® ammonia detection tubes (0.25 ppm to 3.0 ppm detection range). Ammonia concentration was measured at three locations within the shed at one location on the downwind side as shown in Figure 18 (indicated by black dots). At each of these locations, measurements were undertaken approximately 700 mm to 800 mm above the ground or shed floor. At the time when ammonia was measured, wind speed through the shed was measured using an anemometer. Wind direction was in the direction shown in Figure 18. Ammonia and wind speed results are provided in Table 3.

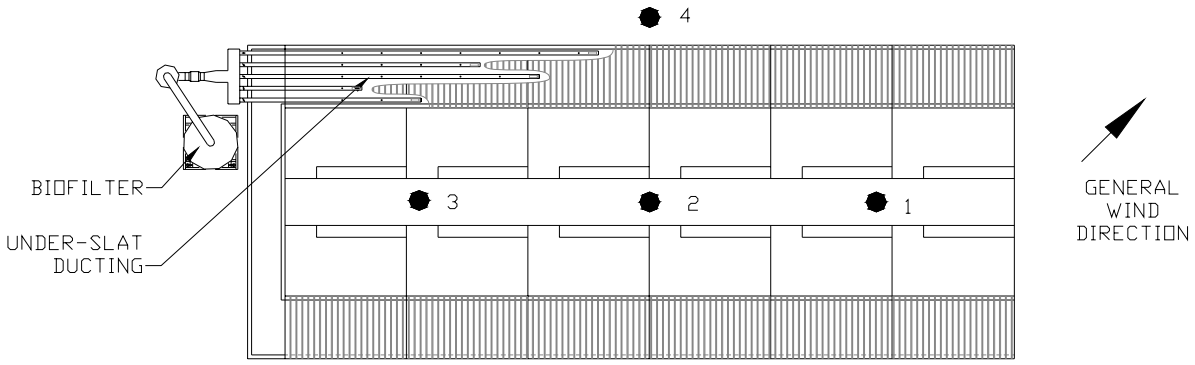

Figure 18. Location of ammonia sampling points within piggery building

Table 3. Ammonia concentrations measured in pig building

Sampling point	Ammonia concentration (ppm)	Wind velocity (m/s)
1	0.6	1.4
2	0.9	1.58
3	0.6	0.58
4	0.8 to 0.9	0.71
Biofilter inlet duct	15	n/a

From the results reported in Table 3, it can be seen that ammonia concentration ranged from 0.6 ppm to 0.9 ppm within the pig house and on the downwind side. While the measurements were made, wind velocity through the building ranged from 0.6 m/s to 1.6 m/s. It can also be seen that the ammonia concentration below the slatted floor (as measured in the inlet duct to the biofiltration system) was considerably higher at 15 ppm.

3.4 GC-MS analysis of specific odorants

More than 300 specific odorants have been identified in air and liquor samples derived from piggery wastes (Schiffman et al. 2001). Zahn et al. (2001) were able to demonstrate that nine specific chemicals present in piggery waste could be used to create an artificial odour mixture that was perceived by panellists as piggery odour. This artificial odour included five volatile fatty acids, three phenol derivatives and 3-methyl indole (skatole). In the assessment of biofilter performance, we propose that these chemicals could serve as surrogates for "whole odour", allowing application of instrumental methods of analysis such as gas chromatography to assess "odour" removal efficiency.

Some common odorants found in agricultural odours are listed in Table 4. This list is provided for clarity when referring to odorants throughout this report.

Table 4. List of common odorants

Odorant name	Chemical formula	Synonyms
ethanoic acid	$C_2H_4O_2$	acetic acid
propanoic acid	$C_3H_6O_2$	propionic acid
butanoic acid	$C_4H_8O_2$	butyric acid
3-methyl butanoic acid	$C_5H_{10}O_2$	*iso*-valeric acid
pentanoic acid	$C_5H_{10}O_2$	valeric acid
4-methyl pentanoic acid	$C_6H_{12}O_2$	iso-caproic acid
hexanoic acid	$C_6H_{14}O_2$	caproic acid
phenol	C_6H_6O	
4-methyl phenol	C_7H_8O	*para*-cresol
indole	C_8H_7N	
3-methyl indole	C_9H_9N	skatole

The chromatograms for three typical sets of results for the biofilter system are shown in Figure 19. The peaks in the chromatograms represent all materials eluted from the analytical column present in concentrations above the detection threshold of the mass spectrometer. While a number of the peaks are present in all the chromatograms, some are present in one or two chromatograms only. The concentrations in the three samples are quite different as well, as indicated by the differences in peak heights and/or areas.

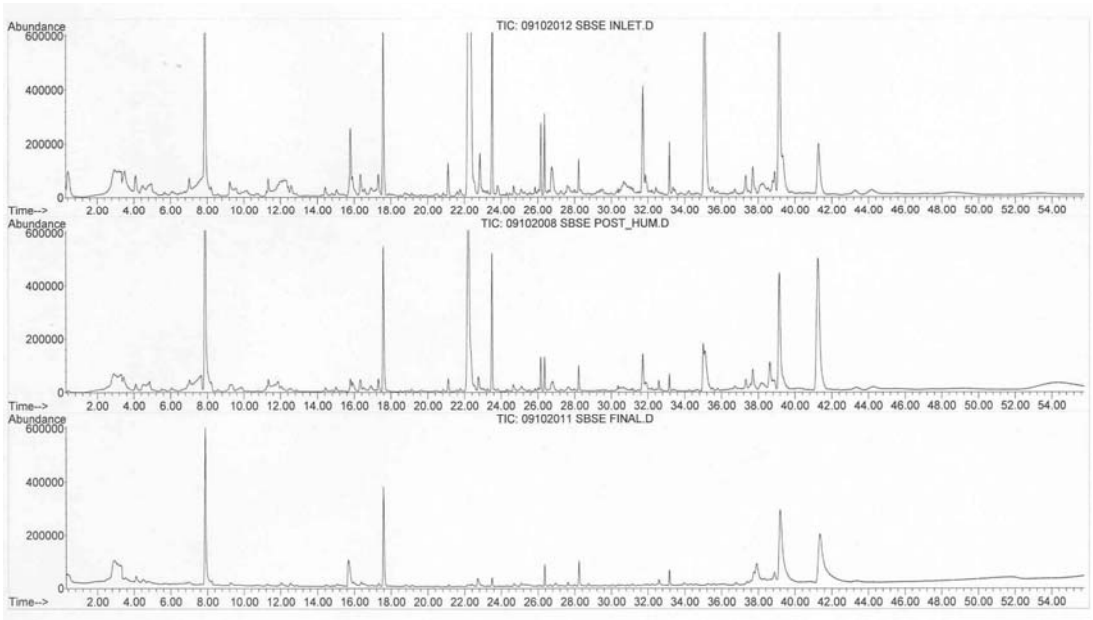

Figure 19. Total ion chromatograms for samples from biofilter system – inlet to system (top), post-humidifier sample (middle) and discharge from biofilter system (bottom)

Using the technique of selected ion monitoring (SIM), it is possible to extract information about specific compounds from the chromatogram. This is particularly useful for complex chromatograms (with many peaks) or where the concentration of the compound of interest is very low relative to other compounds present in the sample. The SIM chromatograms for selected odorants derived from the chromatograms shown in Figure 19 are shown in Figure 20 to Figure 22. In each series of chromatograms the removal of odorants by the two active components of the biofilter system (humidifier and biofilter bed) is clearly evident.

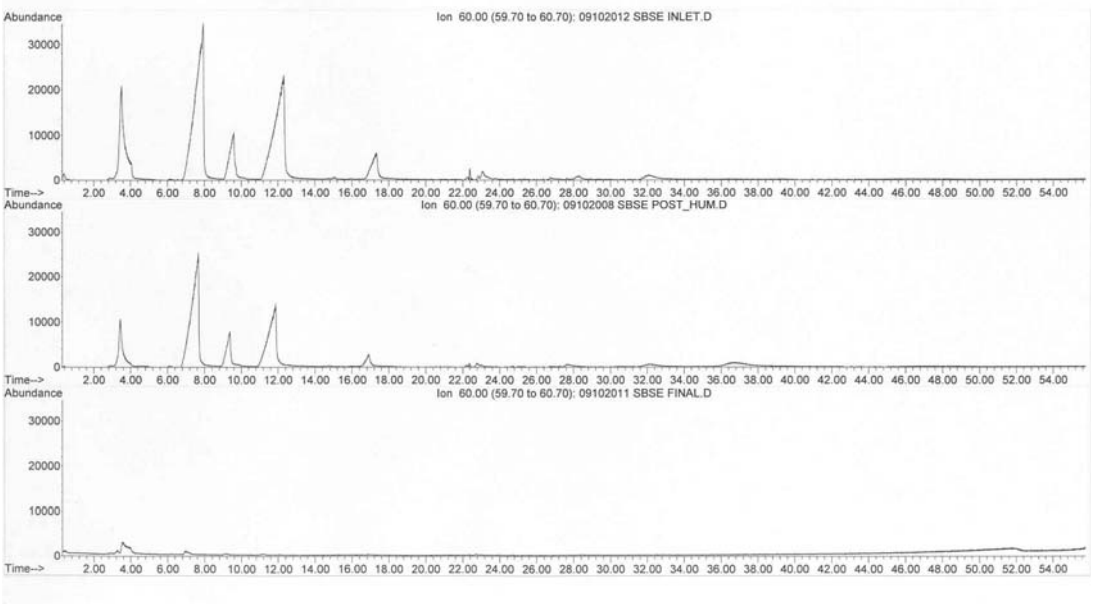

Figure 20. SIM chromatograms for samples from biofilter system showing relative concentrations of volatile fatty acids – inlet to system (top), post-humidifier sample (middle) and discharge from biofilter system (bottom)

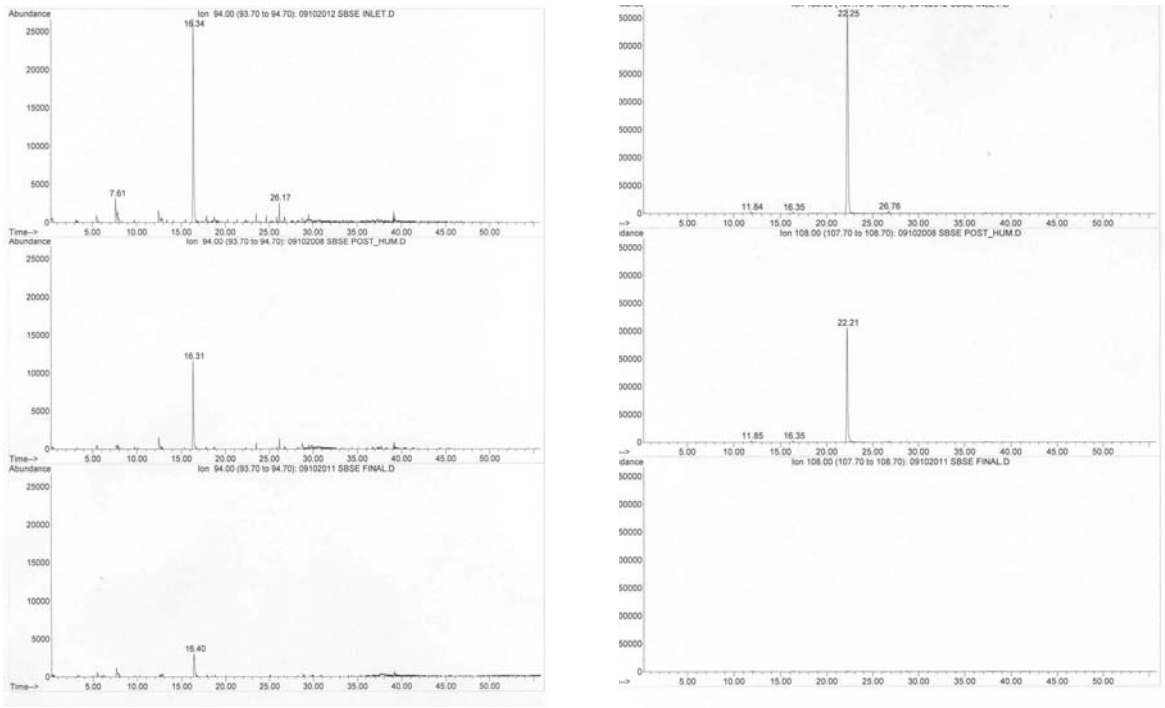

Figure 21. SIM chromatograms for samples from biofilter system showing relative concentrations of phenol (left) and 4-methyl phenol (right) – inlet to system (top), post-humidifier sample (middle) and discharge from biofilter system (bottom)

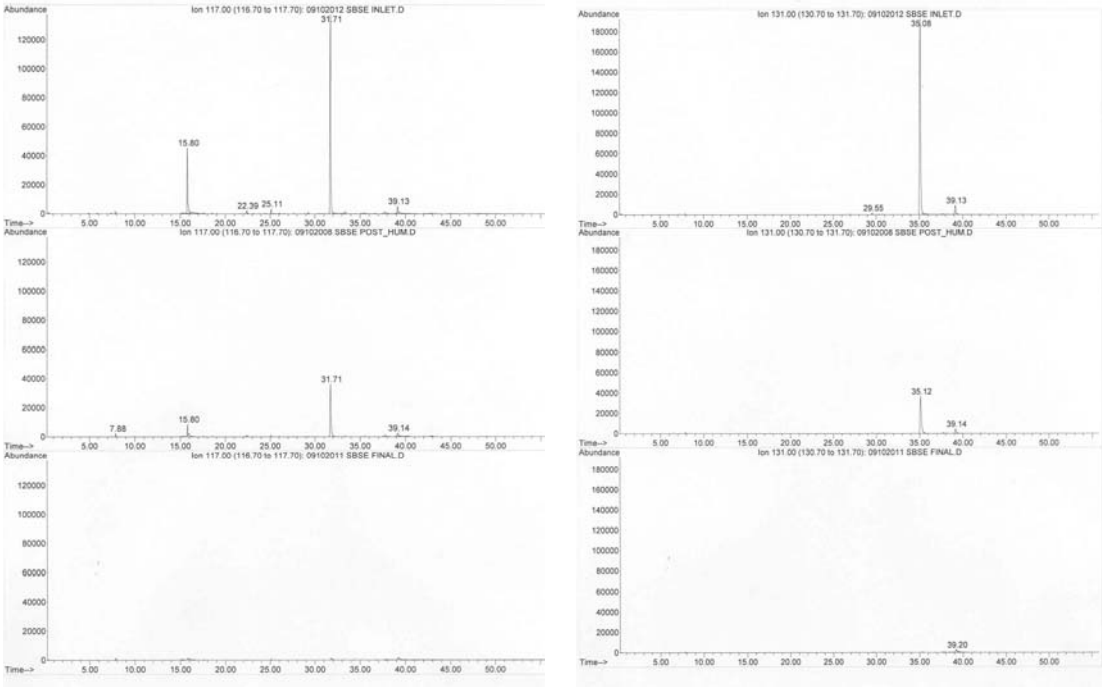

Figure 22. SIM chromatograms for samples from biofilter system showing relative concentrations of indole (left) and 3-methyl indole (right) – inlet to system (top), post-humidifier sample (middle) and discharge from biofilter system (bottom)

The relative concentrations of selected odorants are compared on the basis of sample source in Figure 23 to Figure 28:

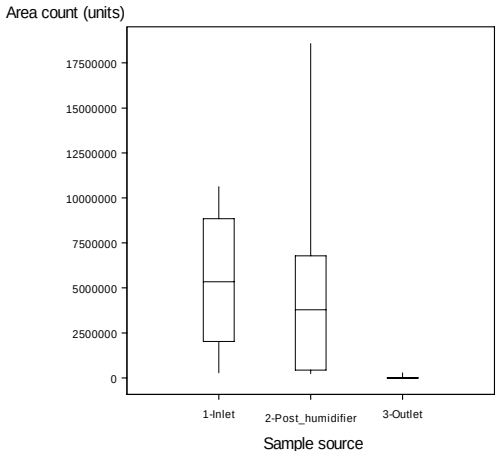

Figure 23. Comparison of relative concentrations of butanoic acid by sample source

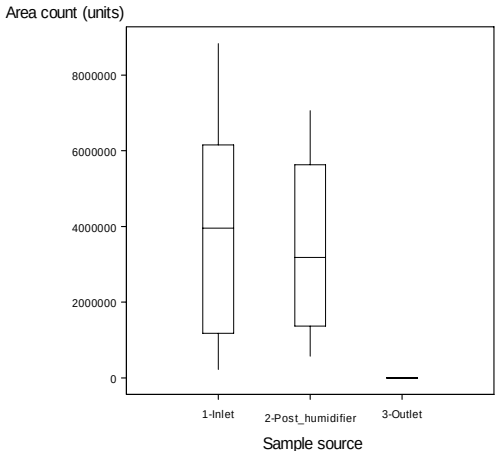

Figure 24. Comparison of relative concentrations of hexanoic acid by sample source

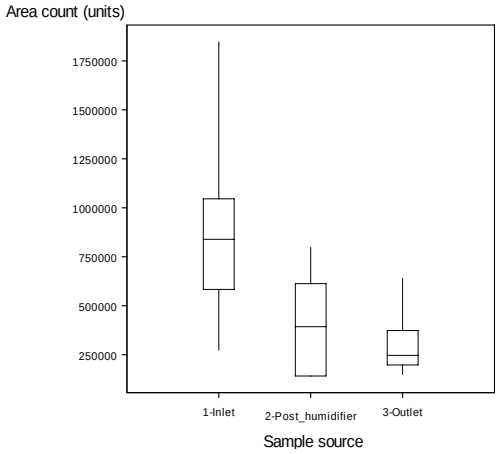

Figure 25. Comparison of relative concentrations of phenol by sample source

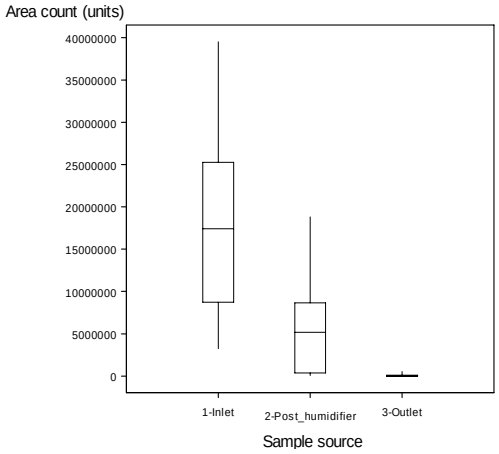

Figure 26. Comparison of relative concentrations of 4-methyl phenol by sample source

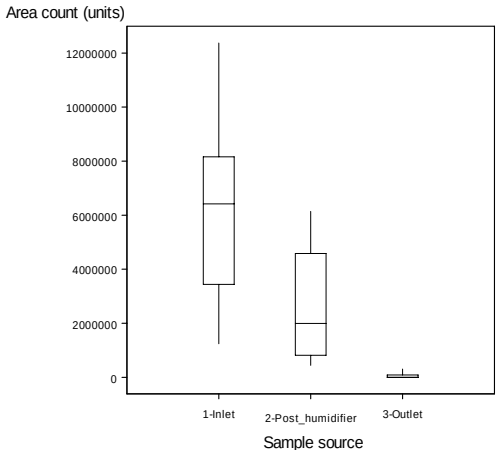

Figure 27. Comparison of relative concentrations of indole by sample source

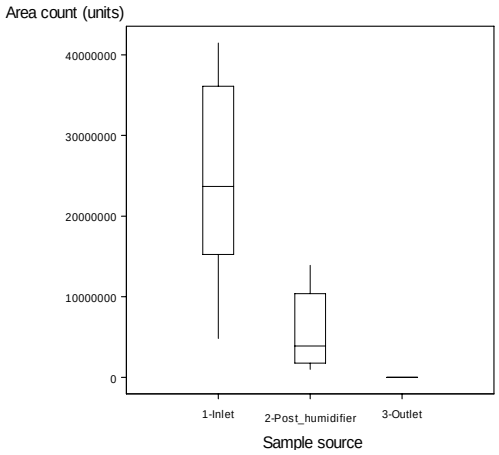

Figure 28. Comparison of relative concentrations of skatole by sample source

The concentration data in Figure 23 to Figure 28 clearly shows that odorous chemicals are eliminated as the air stream passes through the biofilter system. Figure 26 through Figure 28 also show that the humidifier appears to remove a significant amount of the 4-methyl phenol, indole and skatole from the contaminated air stream.

The peak area data for each compound identified in the SIM chromatograms was used to quantify the efficiency with which odorants were removed. Results have been reported separately for the two laboratories that undertook the analyses (Table 5 and Table 6). Table 6 indicates the removal efficiencies for the scrubber only while the removal efficiencies of the complete biofilter system (scrubber plus biofilter bed) are summarised in Table 7.

Table 5. Odorant reduction efficiency for biofilter system (results from QHSS laboratory)

Sample date	Odorant removal efficiency (%)										
	Acetic acid	propanoic acid	butanoic acid	3-methyl butanoic acid	pentanoic acid	3-methyl pentanoic acid	hexanoic acid	phenol	4-methyl phenol	Indole	skatole
16/11/2004	NQ	95	95	95	95	NQ	95	NQ	95	NQ	NQ
10/05/2005	NQ	100	99.9	100	99.5	NQ	95.06	NQ	99.7	NQ	NQ
10/08/2005	NQ	NQ	NQ	NQ	NQ	NQ	100	NQ	88.5	NQ	NQ

Note: NQ = not quantified

Table 6. Odorant reduction efficiency – humidifier only (results from SIS laboratory)

Sample date	Odorant removal efficiency (%)										
	Acetic acid	propanoic acid	butanoic acid	3-methyl butanoic acid	pentanoic acid	3-methyl pentanoic acid	hexanoic acid	phenol	4-methyl phenol	Indole	skatole
2/09/2005	100.0	NQ	100.0	100.0	100.0	NQ	NQ	100.0	100.0	100.0	100.0
2/09/2005	100.0	NQ	100.0	NQ	100.0	NQ	NQ	100.0	100.0	100.0	100.0
2/09/2005	100.0	NQ	100.0	100.0	100.0	NQ	NQ	100.0	100.0	100.0	100.0
2/09/2005	100.0	NQ	100.0	100.0	100.0	NQ	NQ	100.0	100.0	100.0	100.0
9/09/2005	14.6	NQ	-192	-211	-27.7	NQ	NQ	27.8	51.8	-69.9	66.5
16/09/2005	NQ	NQ	86.1	87.1	83.2	NQ	NQ	-15.2	73.4	63.2	74.5
16/09/2005	71.1	NQ	32.6	9.4	68.1	NQ	NQ	51.9	63.9	26.0	55.7
29/09/2005	NQ	NQ	13.8	NQ	100.0	NQ	NQ	48.1	88.8	64.0	79.4
29/09/2005	84.9	NQ	85.5	44.1	100.0	NQ	NQ	69.2	98.4	66.8	81.3
10/10/2005	45.7	NQ	36.9	94.5	-276	NQ	NQ	56.8	52.4	69.5	74.5
Average	**77.1**	**-**	**46.3**	**40.5**	**44.7**	**-**	**-**	**63.8**	**82.9**	**62.0**	**83.2**

Note: NQ = not quantified

Table 7. Odorant reduction efficiency – biofilter system (results from SIS laboratory)

Sample date	Odorant removal efficiency (%)										
	Acetic acid	propanoic acid	butanoic acid	3-methyl butanoic acid	pentanoic acid	3-methyl pentanoic acid	hexanoic acid	phenol	4-methyl phenol	Indole	skatole
29/08/2005	100	NQ	100	NQ	100	NQ	NQ	76.1	100	100	100
29/08/2005	75.6	NQ	100	100	100	NQ	NQ	41.8	99.4	100	100
2/09/2005	100	NQ	100	100	100	NQ	NQ	51.4	100	100	100
2/09/2005	100	NQ	100	NQ	100	NQ	NQ	62.5	100	100	100
2/09/2005	100	NQ	100	100	100	NQ	NQ	100	100	100	100
2/09/2005	100	NQ	100	100	100	NQ	NQ	100	100	100	100
9/09/2005	64.8	NQ	100	100	100	NQ	NQ	56.1	100	96.4	100
16/09/2005	52.7	NQ	100	100	100	NQ	NQ	11.6	96.5	92.8	100
16/09/2005	87.4	NQ	97.2	100	100	NQ	NQ	82	100	98.9	100
29/09/2005	NQ	NQ	100	NQ	100	NQ	NQ	40.7	97.3	100	100
29/09/2005	66.6	NQ	100	100	100	NQ	NQ	56.7	100	100	100
10/10/2005	68.9	NQ	100	100	100	NQ	NQ	69.8	99.8	95.2	100
10/10/2005	90.5	NQ	100	100	100	NQ	NQ	85.7	100	100	100
Average	**83.9**	**-**	**99.8**	**100**	**100**	**-**	**-**	**64.2**	**99.5**	**98.7**	**100**

Note: NQ = not quantified

The efficiencies of removal of eight odorants by the humidifier and by the total biofilter system are summarised graphically in Figure 29. Removal efficiencies of the humidifier range from about 40 % to 80 %. It must be remembered that the humidifier was not intended to be an efficient odour removal device. The primary function was assistance with management of adequate moisture levels in the biofilter bed.

Of the eight odorants, six are removed almost quantitatively by the complete biofilter system, with less efficient removal of acetic acid and phenol by the biofilter system. The presence of acetic acid in the biofilter bed is not surprising. Both aerobic and anaerobic biochemical pathways make extensive use of acetic acid (as acetate or acetate-containing compounds) as an intermediate product. These metabolic processes would be taking place within the predominantly aerobic biofilter bed. Free acetic acid would be stripped from the biofilter bed in low amounts as a consequence of the large concentration gradient between material in the moist biofilm and the air passing through the bed.

Phenol is recognised as a recalcitrant air pollutant. Considerable effort has been expended in identifying biofilter systems able to reduce phenol concentrations. Phenol is quite toxic (i.e. it interferes with metabolism) – as such it is not readily incorporated into microbial metabolic processes. In the context of biofilter efficiency, such recalcitrance appears as poor removal rates. Both Figure 25 and Figure 29 indicate that the humidifier is effectively responsible for most of the phenol removal. In this situation, the humidifier is presumably functioning as a scrubber.

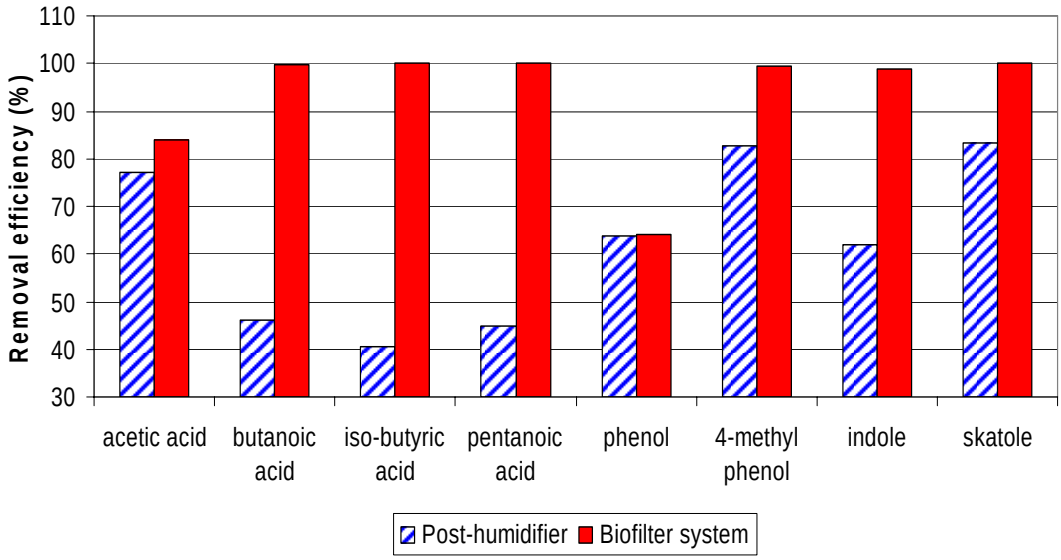

Figure 29. Comparison of removal efficiencies of humidifier only and total biofilter system

3.5 Analysis of humidifier liquid for contaminant accumulation

A short trial was undertaken to investigate the accumulation of contaminants and changes in chemical properties of the humidifier liquid over time. Measurements of pH, electrical conductivity (EC), ammonia nitrogen (NH_3-N), total sulphur, sulphide and total alkalinity were undertaken. Results are displayed in Table 8.

For this trial, the humidifier was filled with fresh water on the first day. Fresh water was only added to the system to replenish water lost through evaporation and liquid sampling. A one litre sample of the humidifier liquid was collected on a daily basis for laboratory analysis. pH and EC were measured on site, immediately after sampling.

The humidifier sump contained a volume of approximately 40 L. It was estimated (using psychrometry) that approximately 20 L of water would have been evaporated daily.

Airflow measurements indicated that contact time in the humidifier was approximately 0.75 s.

Table 8. Results of measurements and analyses of humidifier liquid

	Water quality variables					
Date	pH	EC (mS/cm)	NH3-N (mg/L)	Total S (mg/L)	Sulphide (mg/L)	Total Alkalinity (mg/L $CaCO_3$)
29/08/2005 Supply water	7.4	0.41	0	0	0	86
29/08/2005	8.4	0.69	35.5	7	0.05	172
30/08/2005	8.48	1.812	169	21	0.1	406
31/08/2005	8.24	2.84	240	32	0.17	332
1/09/2005	7.95	4.49	110	36	0.29	288
2/09/2005	7.86	6.94	405	40	0.57	253
5/09/2005	7.59	14.55	1280	50	0.2	456
6/09/2005	7.81	14.82	1110	53	1.43	418
7/09/2005	7.92	15.72	1320	54	0.53	487
8/09/2005	7.72	16.41	1160	56	0.62	514
9/09/2005	7.7	18.33	1190	60	1.04	519
12/09/2005	6.73	16.04	1430	77	0.57	769
13/09/2005	8.07	12.7	1400	78	1.46	549
14/09/2005	7.75	16.65	1320	73	0.63	670
15/09/2005	7.85	17.17	1390	76	0.32	509
16/09/2005	7.43	16.97	1680	78	0.27	563
19/09/2005	7.35	18.49	1770	85	0.14	584
20/09/2005	7.60	18.80	1250	81	2.05	536
21/09/2005	7.57	13.41	1160	81	0.87	460
22/09/2005	7.51	12.46	1100	83	0.67	454
23/09/2005	7.50	11.62	1000	72	1.33	363
26/09/2005	7.48	10.38	601	77	1.2	368
29/09/2005	7.38	10.20	667	91	0.96	358

Of notable interest from the data presented in Table 8 is the accumulation of contaminants, particularly ammonia nitrogen and total sulphur. The accumulation of aqueous ammonia-N and total sulphur are presented in Figure 30. It can be seen in Figure 30 that these chemicals accumulated until they reached a new equilibrium level.

Acidity (measured on pH scale) of the humidifier liquid would regulate the solubility and therefore accumulation of ammonia-N and sulphur compounds in the humidifier liquid. Figure 31 displays the pH measured in the humidifier liquid throughout the course of this trial.

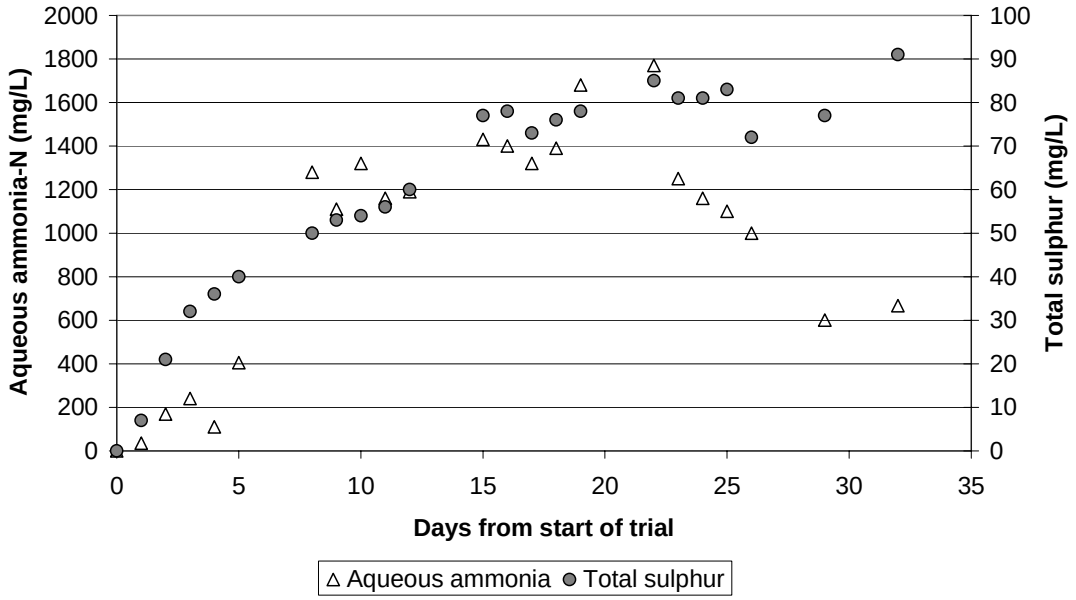

Figure 30. Accumulation of ammonia-N and total sulphur in humidifier liquid

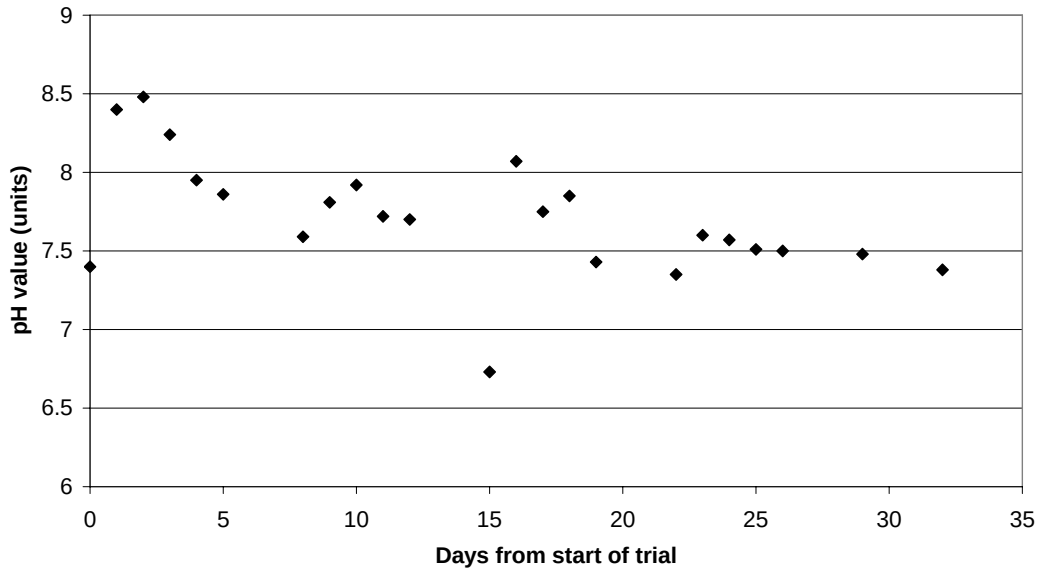

Figure 31. pH in humidifier liquid

One of the reasons for this short term assessment of the humidifier was to monitor the ability of the humidifier to reduce odour and ammonia concentration in air passing through it. Odour concentration was measured on five occasions, and ammonia was measured on six occasions. Odour and ammonia concentrations are displayed in Figure 32 (data already presented in section 3.1 and 3.3).

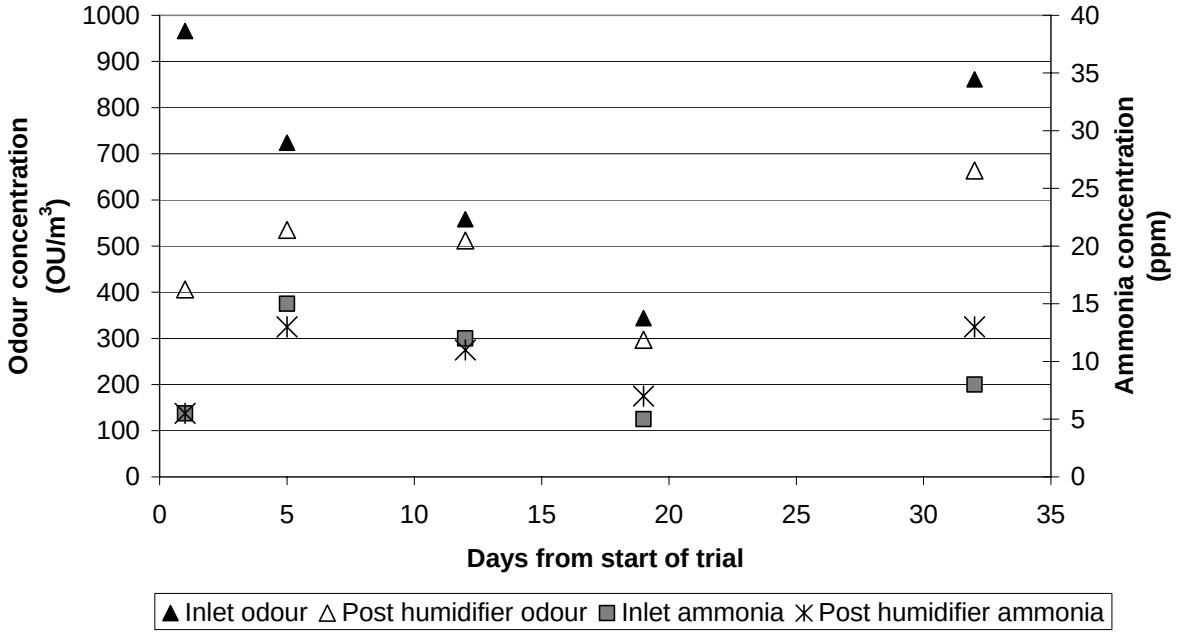

Figure 32. Odour and gaseous ammonia concentration through the humidifier

In Figure 32, it can be seen that the humidifier did not substantially reduce ammonia concentration at any stage of the trial. In fact on two occasions, the ammonia concentration leaving the humidifier was greater than that entering the humidifier. This may have been related to changes in pH, which forced the release of ammonia from the humidifier liquid. Odour reduction across the humidifier was noticeable at the very beginning of the trial. However, once the liquid accumulated contaminants (such as ammonia and sulphur compounds), the efficiency of the humidifier to reduce odour concentration was reduced.

This humidifier was designed to humidify the air, not reduce the concentration of gaseous contaminants. Thus, it was not surprising that reduction of odour and ammonia through the humidifier was insignificant. This is not to say that a humidifier could not be used to scrub specific gaseous contaminants from the airstream. To achieve adequate scrubbing capability, the condition of the scrubbing liquid would need to be strictly controlled (especially pH, and concentration of contaminants) and the contact/treatment time may need to be increased.

3.6 Electronic nose analysis results

The odour samples collected from the biofiltration system (at the inlet, post humidifier and outlet) were also analysed using an AromaScan® A32S (electronic nose). Eighteen odour samples (six per sampling point) were collected between 20 June 2005 and 29 September 2005. Raw results from the electronic nose were pre-processed and then analysed using principal component analysis (PCA) for odour discrimination, and artificial neural network (ANN) analysis for odour quantification.

Odour discrimination using principal component analysis

Raw sensor response data from the AromaScan® was calibrated to compensate for errors caused by relative humidity (RH) as reported in Dunlop et al. (2004). The RH corrected sensor response data was then used to perform PCA.

The PCA is a model based, unsupervised method widely used in the gas-sensing field to extract the main relationship in the data matrix containing the sensor array response. PCA is primarily used to extract information on the ability of the sensor array to differentiate between samples. The PCA results using raw sensor responses without data pre-processing are shown in Figure 33. This figure shows that the AromaScan® was able to discriminate between odour samples collected at the outlet of the biofilter from the inlet and post-humidifier samples.

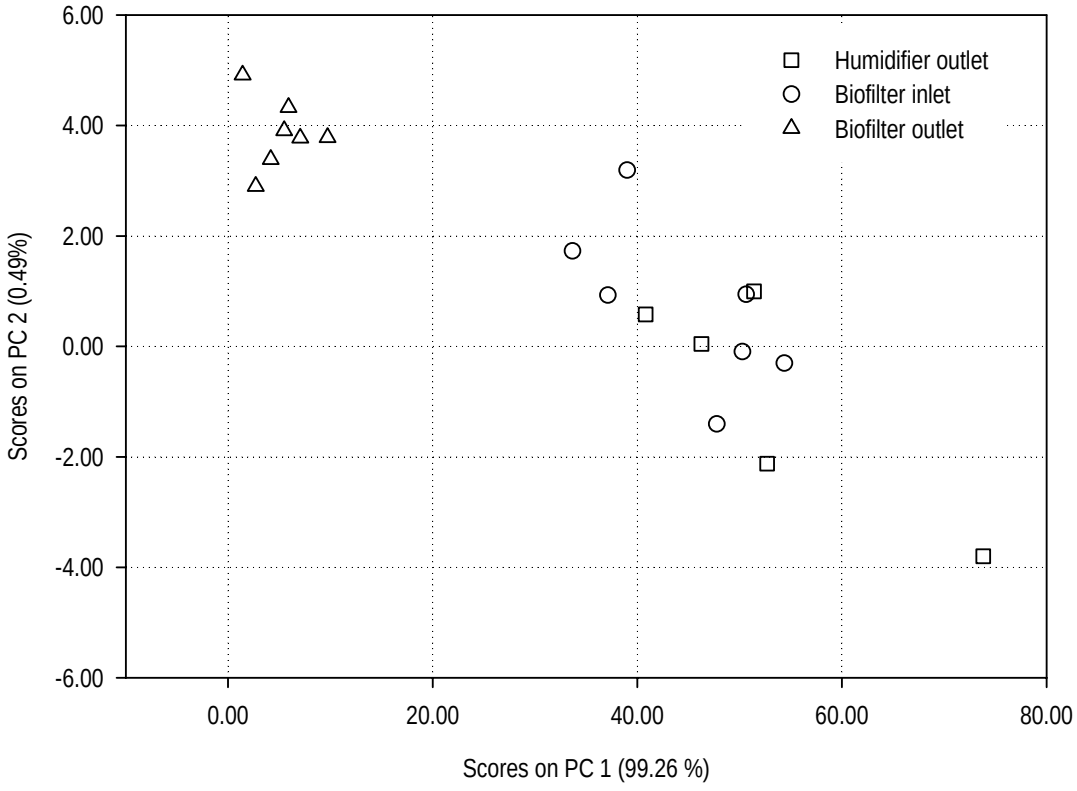

Figure 33. Two-dimensional PCA of raw sensor response data collected from 18 odour samples

To improve the odour discrimination performance of the AromaScan®, the data extracted from the raw sensor responses have to be pre-processed. Techniques used for pre-processing work include weighting, standardising and normalising of the sensor responses.

- Weighting or scaling multiplies each vector by a constant, thus manipulating its influence on the evaluation model.
- Standardising removes weighting that is artificially imposed by the scales of the variables. It can also enhance the noise on sensors that produce little or no signal but are treated as being of equal importance.
- Normalisation reduces the sample-to-sample absolute variability e.g. concentration effect, by forcing the vector length to be one.

The PCA result following application of two pre-processing algorithms (Mean-Centre and *NORMALIZ* function in PLS Toolbox® 3.5 in Matlab® (2004)) is depicted in Figure 34. It shows points belonging to the same odour source plot closely together and are more distinct following normalisation pre-processing.

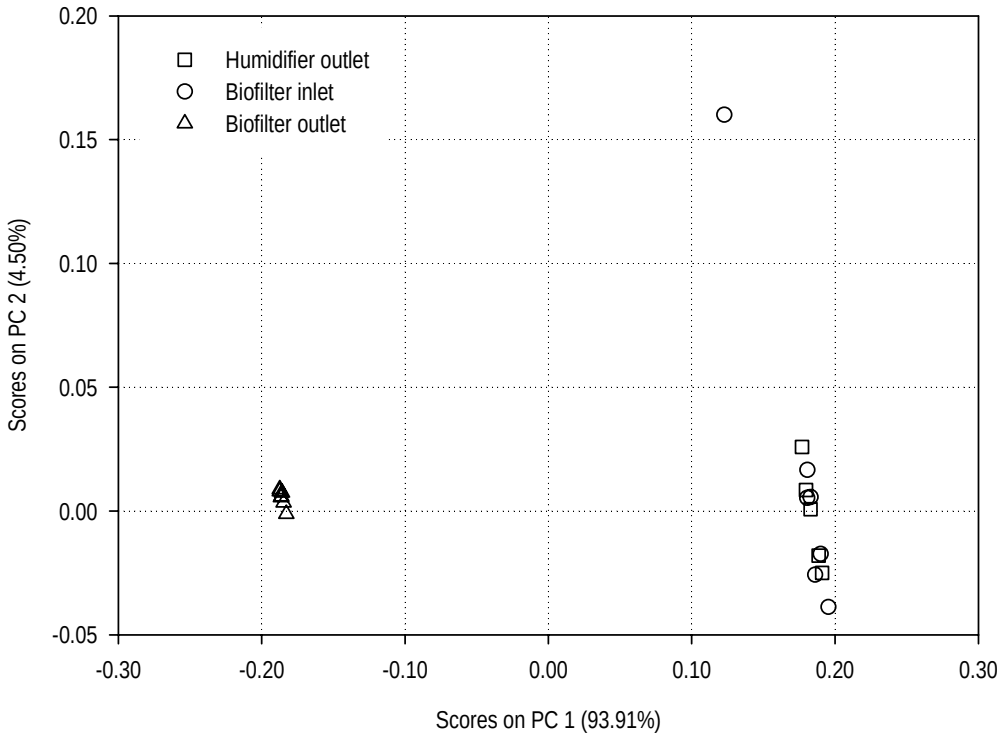

Figure 34. Two-dimensional PCA of pre-processed sensor response data collected from 18 odour samples using *NORMALIZ* function

The points representing samples collected from the biofilter outlet are clustered quite tightly. This means that sensor responses for odour samples collected from the biofilter outlet had similar odour patterns. Thus, it can be concluded that the biofilter system performance was stable over the sampling period.

The points representing samples collected from the inlet ducting and humidifier outlet show looser clustering compared with those of the biofilter outlet. This is mainly due to changes in chemical characteristics of odours emitted from the piggery shed (may be due to variations in feedstuff, pig growing stage, farm management, pit cleaning, and weather conditions etc).

Odour quantification using artificial neural network

Artificial neural network (ANN) analysis was used to predict odour concentration from the sensor responses of the Aromascan®. AromaScan® sensor response and olfactometry data were fed into the ANN following pre-processing using a range of statistical methods and PCA. Data was also corrected for sensor temperature, sample temperature and relative humidity.

The architecture of the ANN used for this work was a two-layer back propagation network, with a tan-sigmoid transfer function in the hidden layers and a linear transfer function in the output layer. It has 20 neurons in the hidden layer. A pre-processing algorithm and an early stopping technique were applied to improve the performance of the ANN.

Seventy six odorous air samples were used to build this odour prediction model. Three sets of sensor outputs were collected from each air sample to minimise noise and errors from the 32 sensors of the Aromascan, giving a dataset of 228 sensor outputs and 76 olfactory results from the 76 air samples. The entire dataset was randomly divided into four subsets, i.e. 25 % for training, 25 % for validation, 25% for testing and 25% for cross-validation. After the network was trained, the unused data sets, i.e. cross-validation set, were presented to the trained ANN to evaluate the prediction capability of the trained ANN model.

The simulations were carried out under the condition of 10^{-10} of mean square error, which was the objective of the network. The ANN showed the best performance at eight epochs using early stopping techniques. At this epoch, the values of the mean square error calculated by cross-validation process and gradient, were 2.99×10^{-5} and 6.3×10^{-2}, respectively.

Figure 35 is a scatter plot showing the actual versus predicted odour concentrations using ANN analysis.

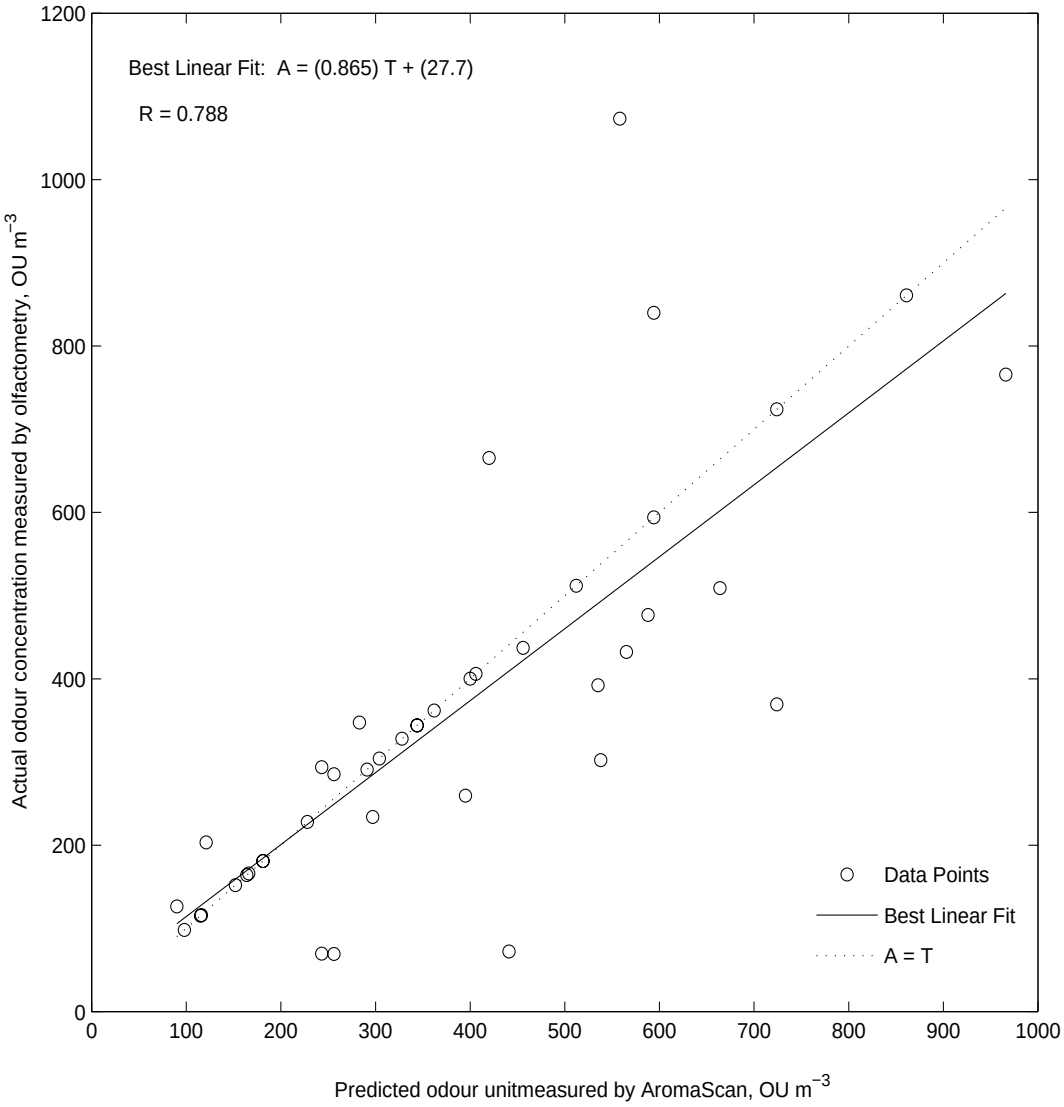

Figure 35. Odour prediction results using ANN work and an AromaScan® A32S

The correlation coefficient (r^2) of the data in Figure 35 is 0.79. Some outliers are observed especially around 500 OUm^{-3}, therefore, some care needs to be taken when using the model for odour prediction work. This limitation is due to the limited number of samples (n=76) used in this modelling work. Usually, hundreds of samples are required to build a robust prediction model using the ANN technique.

4 Guidelines and recommendations for designing biofilters for Korean applications

4.1 General biofilter design principles

There are several applications in Korea where biofiltration could be applied to reducing agricultural odour emissions. These include:

- manure storage tanks;
- aerated (or agitated) liquid fertiliser tanks;
- mechanically ventilated pig housing (especially farrowing and gestation buildings);
- naturally ventilated pig housing; and
- high-rise pig housing.

These have been identified as sources of offensive or excessive odours. In addition, minimal modification to existing facilities would be required for implementation of a biofilter to these sources.

There are some general principles which can be applied when designing a biofilter for agricultural applications. These principles relate to:

- choice of configuration (open or closed bed system);
- ensuring the chosen design will suit new or existing fan systems (flow rate and pressure drop);
- sizing (choice of dimensions particularly bed area and depth);
- efficiently directing odorous air to the biofilter;
- selecting the flow rate to optimise the reduction in odour nuisance;
- using suitable materials (biologically active as well as structural materials); and
- providing the correct conditions for microbial activity.

4.1.1 Choice of biofilter configuration (open bed or closed bed)

Descriptions of open and closed bed biofilter systems were provided in Dunlop & Hudson (2003). These systems have several advantages and disadvantages.

Open bed biofilter

Advantages:

- Considered to be a cheapest option because filter bed does not need to be completely enclosed.

Disadvantages:

- Are open to environmental extremes (drying sun, drenching rains and snow);
- Can require large footprint which can create problems with uniform airflow and maintenance;
- Treated air escapes to the atmosphere which makes it difficult to measure contaminants in the exhaust air for monitoring/evaluation purposes;

- Airflow is generally upward which opposes gravitational water flow;
- Options for maintaining moisture content are limited;
- May not be visually appealing; and
- May require extensive earthworks if filter bed is located in-ground.

Closed bed biofilter

Advantages:

- Treated air is contained and can be monitored for residual contaminants;
- Filter bed is protected from environmental extremes;
- Airflow can be upward or downward;
- Provides more options for controlling moisture content of filter bed (such as by gravitational methods);
- Would possibly require smaller footprint; and
- Fans could be located at the inlet or outlet because housing is sealed.

Disadvantages:

- Higher costs due to complete enclosure of filter bed.

These advantages and disadvantages should be considered when selecting a biofilter for a specific situation. There is no 'right or wrong' selection as these two biofilter configurations have the same operating principle, i.e. contaminated air is passed through a moist porous medium in which microorganisms reside.

4.1.2 Ensuring the biofilter will suit new or existing fan systems

A fundamental requirement for a biofilter is to pass contaminated air through a porous medium. Resistance to airflow will occur in ducting (particularly restrictions, contractions or transitions) and through the filter bed. This resistance will cause a pressure drop through the system, which the supply fan will need to overcome.

Pressure losses through the ducting will increase with airflow velocity due to friction on the sides of the ducting. Narrower ducts will increase velocity for a given volumetric flow. Therefore to reduce pressure losses in ducting, the largest diameter ducting should be used.

Pressure losses through the filter medium will increase with:

- increased velocity through the filter bed (due to friction);
- increased depth of filter bed;
- reduced porosity within filter material (caused by fine materials such as compost or fine woodchips); and
- increased moisture content (due to slight reduction in porosity with pores becoming filled with water).

Fan selection will determine the importance of reducing pressure losses through the biofilter system. Some fans can operate quite comfortably under reasonable static pressure (200 to 1000 Pa) whereas the performance of others is greatly reduced at very low pressures (<50 pa).

In general, centrifugal fans can operate under moderate pressures whereas large diameter, axial fans (commonly used to ventilate intensive animal housing) are able to operate efficiently under relatively low pressures (30-50 Pa). Therefore the size and style of existing fans, or the selection of new fans, will have a significant bearing on the design parameters of a biofiltration system.

4.1.3 Choosing dimensions for the biofiltration system

The overall size of the biofiltration system will be determined by:

- specific volumetric flow rate requirements (either building ventilation rate, minimum ventilation rate, static pit exhaust flow rate or manure aeration rate);
- physical constraints (footprint or height restrictions);
- fan specifications (flow rate vs static pressure relationship); and
- biological requirements for adequate treatment (especially empty bed contact/retention time, EBCT/EBRT).

A 'generic' biofilter design does not exist. A biofilter will need to be designed for each individual situation by addressing specific requirements and constraints.

The process for choosing the dimensions of a biofilter for treating intensive animal and agricultural odours are listed below and presented as a flowchart in Figure 36.

1. Obtain relevant information including:
   - volumetric flow rate;
   - required treatment time (usually 5 to 10 seconds);
   - on-site physical size restrictions (eg. how much room is there for a biofilter?);
   - fan performance information, including flow rate versus static pressure; and
   - aerodynamic properties of the filter medium, especially pressure drop per depth at various flow velocities (these will need to be measured for the particular filter medium selected for the biofilter).
2. Calculate the required volume (m^3) of filter material by multiplying the volumetric flow rate (m^3/s) by the EBCT (s).
3. Choose either the bed depth (m) or the cross sectional area (m^2) of the filter bed.
4. Calculate the cross sectional area (m^2) of the filter bed or the bed depth (m) from the volume of filter material and chosen bed depth or area.
5. Check that the calculated filter bed depth and area are suitable for the location where the biofilter is to be installed (will not exceed physical space limitations). If the calculated dimensions are excessive, it will be necessary to choose another bed depth or area.
6. Calculate the empty bed flow velocity (m/s) through the filter material by dividing the volumetric flow rate (m^3/s) by the cross sectional area (m^2) of the filter bed.
7. Use the empty bed flow velocity, bed depth and aerodynamic property information of the filter material to estimate the pressure drop through the biofilter material.

In the following case studies, pressure drop will be calculated using Equation 2. This equation assumes that the filter bed is a woodchip/compost mix (compost content ranging from 0% to 40% compost by mass), of 60% moisture content (wet basis) with air flow in a vertical direction. This equation was generated using data interpreted from Sadaka et al. (2002), and adjusted to relate to the pressure/velocity measurements undertaken with the pilot scale biofilter used in this trial (described in Dunlop et al. (2004)). The pressure drop calculated using this equation is very dependent on the type of biofilter medium. Different types of woodchip or compost materials could significantly change the value of this equation.

$$p = 4 \times d \times 10^{\left(\frac{\log_{10} v + 0.0032c + 1.9447}{-0.0014c + 0.6187}\right)}$$ **Equation 2**

Where: p is pressure drop (Pa)

d is depth of filter medium (m)

v is velocity through filter bed (m/s)

c is % compost in the filter bed (%)

8. Check that this pressure drop will match the performance of the fan system. If the pressure drop is too great, it will be necessary to reduce bed depth or increase cross sectional area. Making these changes will have a two-fold effect:
    - reducing the empty bed flow velocity (which will reduce pressure drop per depth); and
    - reducing pressure drop by decreasing the depth.

    If the biofilter cross sectional area is already at the maximum, and the depth cannot be reduced, either a new fan system will be required, or the EBCT will need to be reduced.
9. If, at this stage, the cross sectional area and bed depth are suitable and the pressure drop through the filter bed matches the performance of the fan system, then the chosen dimensions are likely to be acceptable.

Table 9 is a spreadsheet (with equations made visible) that was used by the project team to assist in calculating the size and dimensions of biofilters. It was programmed using Microsoft® Office Excel 2003.

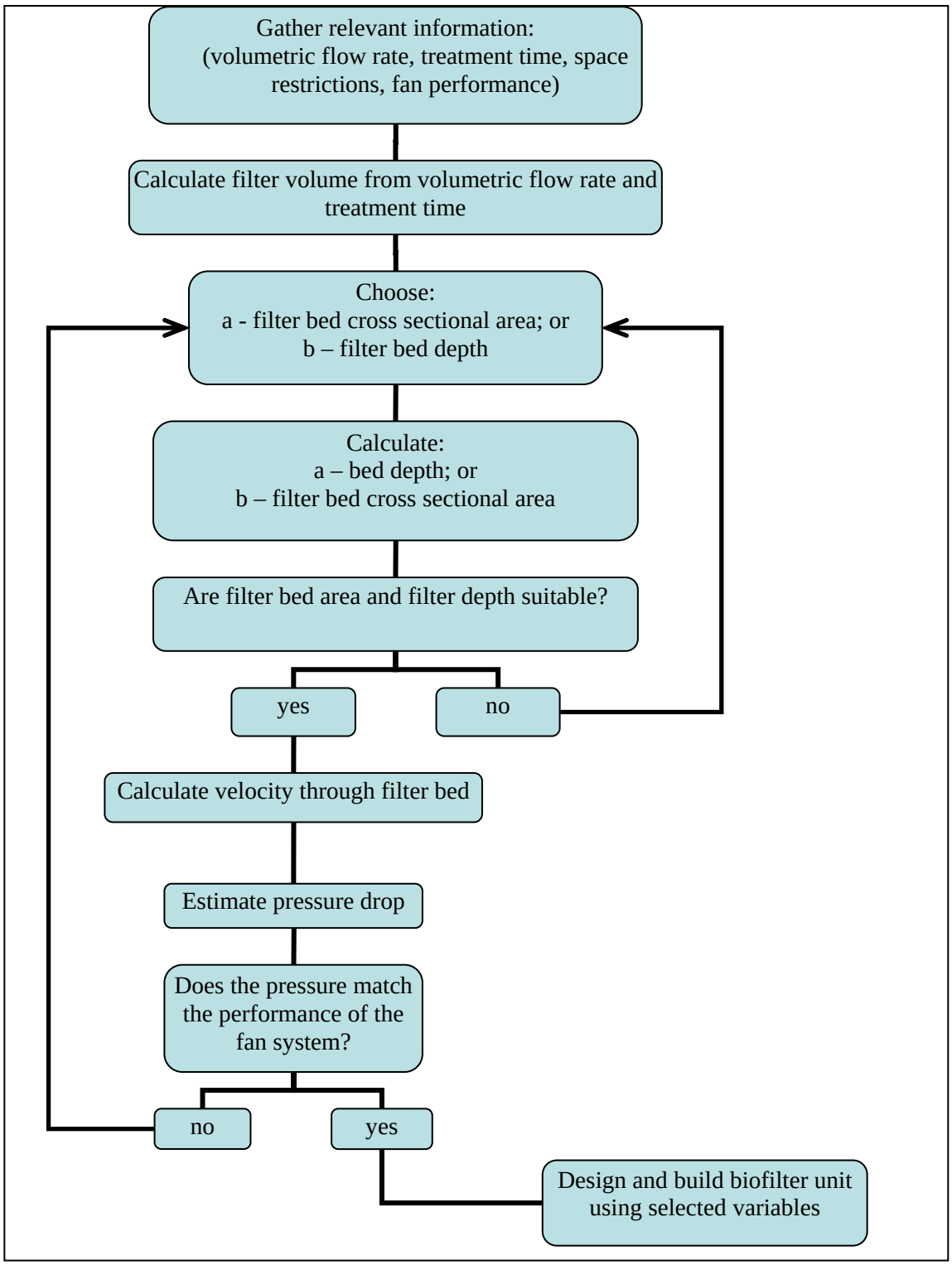

Figure 36. Flow chart for selecting the dimensions of a biofilter

Table 9. Spreadsheet to assist in sizing a biofilter

	A	B
2	**Biofilter Sizing Calculator**	
3		
4	To use this spreadsheet, enter three of the values in the yellow section (rows 14 to 17). The fourth number will be calculated in the blue section (rows 20 to 24). Enter this fourth value into its corresponding yellow cell. All of the other information including flow velocity, filter bed volume, actual retention time (given porosity of filter bed and EBCT) and physical sizing will all be calculated).	
5		
6		
7		
8		
9		
10	Bed Material	Woodchip-compost mix
11	% Compost (by mass)	
12	Approximate Porosity	
13		
14	EBRT/EBCT (s)	
15	Bed Depth (m)	
16	Flow Rate (m^3/hr)	
17	x-sectional area (m^2)	
18		
19	**Calculated Performance**	
20	**EBCT/EBRT** given depth, x section, flowrate **(s)**	=B15*B17/B16*3600
21	**Bed Depth** given EBCT, flow rate, x section area **(m)**	=B14*B16/3600/B17
22	**Flow Rate (m^3/h)**	= B15*B17*3600/B14
23	**X Section Area** given EBCT, flow-rate, bed depth **(m^2)**	=B16*B14/B15/3600
24	**Flow Velocity through filter bed ($m^3.s^{-1}.m^{-2}$)**	=B16/3600/B17
25		
26	corresponding diameter (m)	=SQRT(4*B17/PI())
27	corresponding square width (m)	=SQRT(B17)
28	**Flow Velocity (m/s)**	=B16/B17/3600
29	**Filter Bed Volume (m^3)**	=B17*B15
30	**Actual retention time (s)**	=B14*B12
31		
32	Approximate pressure drop through filter medium (Pa)	=4*(10^((LOG(B24,10)+0.0032*B11+1.9447)/(-0.0014*B11+0.6187))*B15)

4.1.4 Efficiently directing odorous air to a biofilter

Designing a biofilter to treat odorous air is only half of the solution to reducing odours from intensive animal housing. In order for a biofilter to reduce odour emissions, odorous air must preferentially be directed to the biofilter. There are several ways to achieve this depending on whether the building is naturally or mechanically ventilated, and if the waste system is a liquid flushing system, static pit system or deep litter system.

Animal houses do not naturally lend themselves to biofiltration because ventilation rates are normally governed by temperature requirements, not air quality issues. This will lead to odours being diluted by large volumes of fresh air (required to remove heat from the building). Biofiltration is more suited to smaller volumes of air with higher odorant concentration.

Naturally ventilated buildings

Naturally ventilated buildings are not immediately suitable for application of biofilter systems. Firstly, installation of a fan system would be required to draw air from the housing and deliver this odorous air to the biofilter.

Naturally ventilated housing are typically open during warm weather. While the building is open, odours are not contained within the building and natural airflow removes odours from the housing to be dispersed into the atmosphere in an uncontrolled manner. These odours are therefore not contained and would be unavailable to a biofiltration system.

Naturally ventilated housing are usually closed during cool weather. Under these conditions, small vents and minimum ventilation fans operate to remove contaminated air from the housing at a rate that maintains healthy conditions for the animals. Under these conditions, the ventilated airstream would be relatively undiluted. Due to the low ventilation rate, this entire airstream could be captured for biofiltration.

Another option for sourcing odours from naturally ventilated housing would be to attempt to draw the majority of odours directly from their source. An assumption could be made that the majority of odours originate from manure on the floor and from static pits below the slats. Collecting this highly odorous air could be achieved by enclosing the dunging area (Feddes et al. 2005; Feddes et al. 2001; Lemay et al. 2000) or drawing air from the manure pit headspace at a rate which caused down-drafting through the slats (Nicolai and Hoff, 2003). In the case of slatted floor housing, these techniques should minimise the exchange of air across the slats and could be used whether or not the building is open (in warm weather) or closed (during cool weather).

Mechanically ventilated buildings

Mechanically ventilated housing are perhaps more immediately suited to application of biofilter systems because ventilation air movements are controlled. However, as with all animal housing, ventilation rates will usually satisfy temperature requirements rather than air

quality, resulting in the emission of large volumes of diluted air. Typical ventilation rates for a grower/finisher pig housing would range from 20,000 m^3/h to 150,000 m^3/h (depending on size, number of pigs and climatic conditions). With an assumed EBCT of 5 seconds, a biofilter to treat these airflows would need to have a filter bed volume of 27 m^3 to 210 m^3. Coupled with the assumption that most mechanically ventilated animal buildings use large diameter axial fans (which have very limited ability to operate effectively with any appreciable static pressure), a biofilter designed to treat the entire ventilation airstream would be quite large (i.e. large cross sectional area and shallow bed depth).

It would make sense, as with the naturally ventilated buildings, to preferentially collect odours at their source. Assuming once again that most odours originate from manure on the piggery floor or from the static manure pit beneath the slats, odorous air could be sourced from beneath the slats or from enclosed dunging areas. There is a requirement to confirm this assumption and demonstrate that it could be done.

4.1.5 Selecting the flow rate to optimise the reduction in odour nuisance

The primary reason for attaching a biofiltration system to an intensive animal housing is to reduce odour nuisance to nearby neighbours. The relationship between odour emission (from animal housing) and odour nuisance (at a receptor) is very complex. The magnitude of odour nuisance experienced by neighbours will be dependent on odour emission rate at the source, atmospheric dispersion and the amount of turbulent mixing due to surface roughness between the source and receptor.

Odour emission rate

Odour emission rate is calculated by multiplying odour concentration by the ventilation rate. Therefore the odour emission rate can be reduced by decreasing the odour concentration and/or the ventilation rate. Biofiltration helps to reduce odour concentration, thereby reducing odour emission rate.

Ventilation rates cannot usually be reduced because adequate ventilation is required to maintain animal health and comfort. Ventilation rates do however vary diurnally and seasonally. Generally speaking, summer ventilation rates will be higher than winter ventilation rates. Also, higher ventilation rates will be required in the middle of the day, afternoon and early evening compared to during the night and early morning.

Ventilation rates will also have an influence on internal odour concentration. During minimum ventilation conditions, odorants can accumulate within the housing, leading to higher odour concentrations. Under maximum ventilation, large volumes of fresh air can dilute odorous air, reducing odour concentration within the building.

Atmospheric stability

Atmospheric stability will influence the rate at which odours are dispersed once they are emitted from the animal housing. Atmospheric conditions are generally more stable at night and early morning, tending toward unstable during the day and afternoon. During periods of

stable atmospheric conditions, odorous plumes will tend to resist dispersion and vertical plume rise. The odour plume will therefore not disperse and will persist at high concentration for significant distances. This can lead to significant odour nuisance for large distances downwind. During periods of atmospheric instability (unstable conditions), odorous plumes will tend to rapidly disperse and significant plume rise will occur, potentially reducing the opportunity for odour nuisance.

Turbulent mixing

The distance and roughness of the surface between the source and receptor will significantly influence odour dispersion and therefore odour nuisance. Increasing the distance between the source and receptor will enhance mixing, dilution and dispersion of the odour plume, reducing the chances of odour nuisance. Factors that increase surface roughness include obstacles (such as tree belts or screens) and significant natural landforms (such as hills). As with increasing distance, increased surface roughness will enhance dispersion and mixing of odorous plumes, which will reduce odour concentration at nearby receptors.

Combined effect of odour emission rate, atmospheric stability and separation distance

The combination of odour emission rate, atmospheric stability and separation distance forms a complex relationship with significant implications for the design of biofilter systems. Additional site-specific information, such as the time of odour nuisance, will also be required when designing a biofilter.

With regard to choosing the design flow rate through a biofilter system, the combined influences of site specific information and localised odour dispersion may significantly influence the required size of a biofilter. A common approach to sizing biofilters is to calculate the maximum ventilation rate and design a biofilter to suit this. A more sensible approach would be to examine when odour nuisance is occurring, determine the atmospheric stability and ventilation regimes at these times, and size a biofilter accordingly.

Guo et al. (2003) found that the majority of odour annoyance occurred during the morning and early evening, coinciding with stable and neutral atmospheric conditions. Only a small amount of odour nuisance occurred during the middle of the day. Additionally, these authors reported that the majority of odour nuisance occurred under conditions of low wind speed. At low wind speeds, turbulent mixing (and dilution of odour plumes) will be minimal compared with higher wind speed situations, leading to poorly dispersed, high concentration odour plumes. Turbulent mixing is also enhanced by increased surface roughness.

If the findings of Guo et al. (2003) are combined with the ventilation regimes, it may be found that the animal housing ventilation rate is not at its maximum level during the early morning and evening, when odour nuisance may be greatest. Therefore, it may be possible to design a biofilter to treat this reduced ventilation rate in order to alleviate the majority of odour nuisance. Naturally, this would need to be put into a site specific context. If it is important to completely reduce odour nuisance all of the time, the biofilter may very well need to be designed for the maximum ventilation rate.

4.1.6 Selection of materials suitable for use in biofilters

Materials to be used in biofilters can be separated into three categories:

1. construction materials;
2. filter bed structural materials; and
3. active biological materials (used in the filter bed).

Construction materials.

High levels of moisture and salts combine to create a highly corrosive environment within the biofilter. It is therefore essential to select materials which are corrosion resistant or can be coated in order to protect them from corrosion. Materials which resist corrosion include plastics (eg high density polyethylene), fibre composites and stainless steel. The use of ferrous alloys (such as steel) should be avoided where possible unless they can be coated or galvanised to prevent corrosion. The choice of appropriate materials will be highly dependent on the size of the biofilter to be constructed, available budget and local availability.

Biofilter bed structural materials

A range of biofiltration media were reviewed by Dunlop and Hudson (2003). Materials such as soil, saw dust, peat, coconut fibre and straw should not be used in biofilters because they rapidly degrade and compact, requiring high maintenance and large fans to overcome high airflow resistance. Woodchips and bark were identified as suitable materials because of reasonably low airflow resistance and slow decomposition. These materials provide some nutrients to microorganisms, hold moisture and maintain a suitable structure, which resists compaction. Synthetic materials, such as plastic packing, can be used in a biofilter bed. Whilst these synthetic materials have poor water holding capacity and provide no nutrients to the microorganisms, they offer stable structural integrity that would probably provide more consistent airflow performance, minimising compaction and replacement requirements.

Biofilter bed biologically active materials

The materials listed above are usually combined with rich organic matter such as compost (up to 40% by mass). This organic matter introduces microorganisms to the biofilter and provides nutrients. Biologically active materials are listed in Dunlop and Hudson (2003).

4.1.7 Providing conditions to optimise biological activity

Conditions required for adequate biological activity were discussed in Dunlop and Hudson (2003). Optimal temperature and moisture conditions were considered the most crucial for efficient biofiltration. Avoidance of undesirable conditions, which could be toxic to microorganisms, is also important.

Temperatures between 20 °C and 40 °C are considered optimal whilst temperatures below 10 °C and above 65 °C decrease microbial activity. Suitable temperatures will occur during normal summer conditions in tropical and temperate regions of the world. In cooler regions, and during winter in non-tropical regions, temperatures may fall to unsuitably low levels. Where this occurs it may be necessary to provide heating to the inlet airstream, insulate the biofilter and ducting, or both. Consideration will need to be given to the moisture application

system to ensure that water does not freeze in hoses, restricting water application to the biofilter. Where the intensive animal housing is well insulated, air warmed by the animals may be sufficient to prevent freezing in the biofilter or retardation of biological activity, particularly if the biofilter and ducting are insulated.

Moisture content is a critical factor for effective biofiltration. This is because moisture provides a pathway for gaseous contaminants to move from the gas phase to a liquid phase, where microorganisms can consume and convert these contaminants to less offensive compounds. Microorganisms also need adequately moist conditions to survive. Moisture content of the filter medium needs to be maintained at approximately 66% (wet basis) (Dunlop and Hudson, 2003). If the moisture content falls below this level, biological activity will decline. If the moisture content rises above this level, pores can be blocked which will create anaerobic zones and restrict airflow. Methods of managing water application are discussed in section 4.1.8.

Avoiding toxic conditions is important to ensure the health of microorganisms within the filter bed. These toxic conditions could include presence of extremely high levels of gaseous contaminants, or incorrect pH within the biofilter material. Kim et al. (2002) found that nitrifying bacteria still effectively removed ammonia at concentrations of 150 ppm and sulphur reducing bacteria still effectively reduced H_2S at concentrations of 200 ppm. However, when H_2S concentrations rose above 200 ppm, the activity of the nitrifying bacteria was reduced. This showed that high levels of H_2S were toxic to nitrifying bacteria. Easter et al. (2005) reported that the pH of the biofilter medium should be maintained at or near neutral to maximise microbial activity.

4.1.8 Methods for controlling filter bed moisture content

Precisely managing the moisture content in a biofilter bed is a major challenge facing designers of biofiltration systems. Moisture can be controlled using timers, gravimetric methods (estimating moisture content by mass) or monitoring moisture content. There are also some proprietary products which attempt to measure the actual filter bed moisture content with specially designed instruments. Unfortunately, most of these techniques don’t control the moisture content precisely, are prohibitively expensive, or are not practical for large biofilters. There are however some methods which are used, and currently form the basis for biofilter moisture management.

Timer system

The simplest water management system incorporates a timer system and sprinklers. Using this system, a timer is used to initiate application of water at certain times of the day for a defined duration. Timer systems have the advantage of low cost and simplicity. However, timer systems have several major disadvantages. Some of these include:

- There is no feedback control to the timer indicating the current moisture content of the filter bed, and therefore the requirement for water application. This can lead to significant under watering or over watering.

- Watering applications will need to be in excess of actual biofilter requirements to ensure that the biofilter is receiving sufficient water. Excessive watering will unnecessarily waste water and create a waste stream as excess water drains from the biofilter.
- Timer systems do not take into account changes in water requirements for different seasons.
- The same amount of water is applied each day regardless of ambient temperature and humidity (factors controlling evaporative drying) or precipitation.

In short, timer systems will apply water to the biofilter. However, the amount of water applied will not match the actual requirements of the biofilter, leading to drying or saturation of the biofilter bed and reduction of biofilter performance.

Gravimetric control of moisture content

Gravimetric control of moisture content is achieved by firstly determining the dry weight of the filter material and then weighing the biofilter (eg. load cells) to determine the amount of water in the filter bed. A microprocessor is required to manage application of water to maintain a specified amount of moisture in the filter bed. Gravimetric methods provide possibly the best measurement and control of moisture content because the mass of the filter bed is constantly monitored and this information forms part of a feed-back loop to the microprocessor.

Gravimetric moisture control was used to manage the moisture content in the pilot scale biofilter used during this investigation. Gravimetric control has been used in other biofilter research (Classen et al. 2000; Sheridan et al. 2002) because, in a research situation, it offers accurate measurement of moisture content and allows precise application of water to specifically address the water requirements of the biofilter.

One drawback of gravimetric systems is cost. Good quality load cells are required to maintain long term accuracy in weight measurements. Microprocessors are also required to provide the control to the water application. Additionally, part or all of the filter bed needs to be completely supported using load cells. For a small biofilter, this is easily achieved. For a large biofilter, however, this could be very expensive. Other drawbacks with gravimetric systems may include load cell drift (change in load cell accuracy over time) and natural changes to filter bed mass due to accumulation of dust (which may or may not be negligible depending on the odour source).

Monitoring air moisture content

These techniques make use of psychrometry (the relationship between temperature and relative humidity) and are still under development. Adequate control will require stable and sensitive relative humidity and temperature sensors. These techniques are still under development and as yet have not formed the basis for an accurate moisture application system.

4.2 Examples of applications of biofiltration to Korean situations

4.2.1 Manure storage tanks

Some piggeries utilise large tanks to store liquid manure slurries for periods up to several months. Anaerobic decomposition of the stored manure slurry emits small volumes of highly odorous air that could be treated using biofiltration to reduce odour concentration and offensiveness.

Conditions required for application of biofiltration to manure storage tanks.

- The tank would need to adequately sealed to prevent fugitive emissions from the tank.
- Ducting would need to be installed to draw odorous air from the headspace in the tank.
- Since no heat is generated in the tank, heating and insulation of the biofilter may be required during freezing weather. If however the stored manure freezes, odour emission would cease, thus negating the need for biofiltration.

Yoo (2005b) reported that NH_3 concentration of gas emitted from manure storage tanks was 180 ppm. H_2S concentration was reported as 15 ppm. These concentrations should not be toxic to the microorganisms in a biofilter.

Biogas yield from swine manure storage was measured by Zhang et al. (2000). These researchers found that the rate of biogas generation was related to temperature and volatile solids loading rate. They found that biogas production rate ranged from approximately 2 L/L/day to 6 L/L/day for volatile solids loading rates of 1 gVS/L/day to 4 gVS/l/day (at a temperature of 35 °C). Manure storage tanks are not gradually loaded, rather, they are completely filled in one go. This may have the effect of greatly increasing biogas generation at the start of a batch. It will be assumed for the purposes of the following example that biogas generation rate is 10 L/L/day.

Example 1: Applying biofiltration to a manure storage tank.

Scenario:

- 200 m^3 manure storage tank, with sealed lid;
- biogas generation is 85 m^3/hour (airflow);
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 15 seconds (this time is greater than the value recommended for general agricultural sources due to the high concentrations of odorants);
- a fan will be required for this application;
- insulation and heating may be required during freezing weather conditions; and
- humidification should not be required because headspace air should be reasonably humid.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{85}{3600} \times 15 = 0.36\,m^3$$

Step 2: Choose bed depth

bed depth = 0.75 m

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = 0.48\ m^2$$

This cross sectional area corresponds to a square with sides 0.7 m
or a circle of diameter 0.78 m.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{85}{3600 \times 0.48} = 0.05\, m/s$$

Step 5: Estimate pressure drop

With an extremely low velocity of 0.05 m/s and a bed depth of 0.75 m, pressure drop through a woodchip-compost filter medium should be less than 100 Pa (but would need to be confirmed prior to purchasing a fan). This value assumes that only very short, low restriction ducting is used to link the biofilter to the storage tank. Additional pressure losses through ducting would need to be added to the estimated pressure loss through the filter bed.

Step 6: Select a fan

Due to the relatively low flow (85 m^3/hour) and static pressure (100 Pa), a small diameter axial fan such as the Fantech mixvent series TD-350/125 (240 V, 60 W, 125 mm diameter mixed flow design, 350 m^3/hour max flow rate) should be sufficient. The fan should be mounted on the biofilter outlet to prevent contact of high concentration ammonia and hydrogen sulphide gases with the fan components.

Summary of this example (see Figure 37 for illustration)

From this example, it can be seen that only a very small biofilter (bed volume 0.35 m^3) is required to treat the exhaust air from a manure storage tank (subject to confirmation of assumptions). Owing to the small size, the bed area could be increased to reduce the bed height and pressure drop, possibly allowing a smaller fan to be used. Air entering the biofilter could potentially be diluted by allowing fresh air into the headspace of the manure storage tank. This action may increase emission rates from the liquid manure, and increase overall loading on the biofilter. The EBCT may need to be altered, depending on the performance of the biofilter, and the conditions under which it is operated.

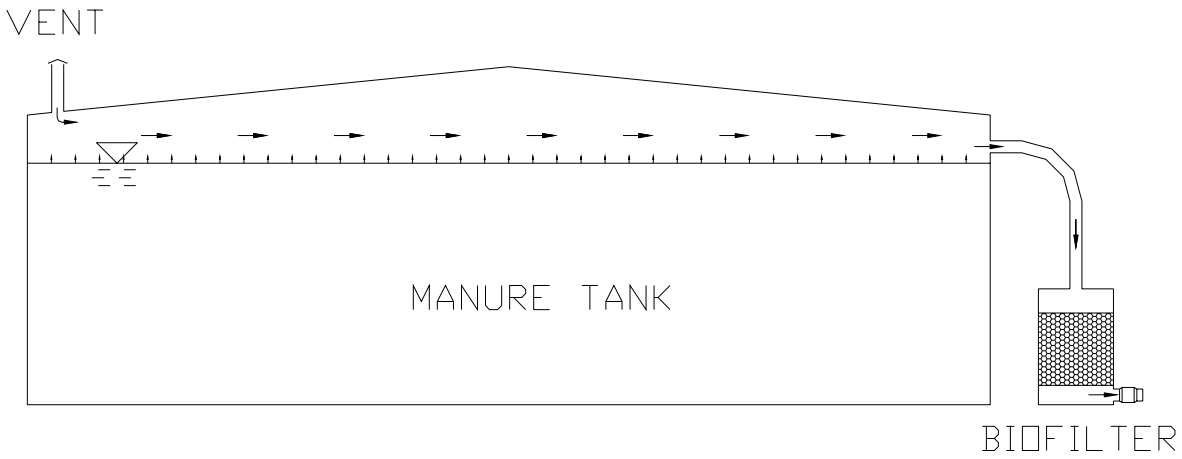

Figure 37. Example of applying biofiltration to a manure storage tank

4.2.2 Liquid fertiliser tanks (aerated)

In Korea, stored liquid manure is treated prior to land application as a fertiliser. This treatment usually involves agitation or mechanical aeration and is designed to reduce the nitrogen content of the manure. In the case of agitated treatment, a biofilter similar to that described in section 4.2.1 would be acceptable, however, a longer retention time may be required to accommodate higher emission rates at the beginning of the treatment process. For aerated treatment, flow rate through the biofilter would be a combination of the aeration rate and biogas yield.

Yoo (2005b) reported that aeration rate for liquid fertiliser treatment was about 2.5 m^3/h/tonne (2.5 m^3/h/$m^3_{(liquid)}$). It will be assumed that the biogas generation rate will be similar to that used in section 4.2.1 (10 L/L/day).

Example 2: Applying biofiltration to an aerated liquid fertiliser tank

Scenario:

- 200 m^3 liquid fertiliser tank, with sealed lid;
- aeration rate is 500 m^3/hour;
- biogas generation is 85 m^3/hour (airflow);
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 15 seconds (this time is greater than the value recommended for general agricultural sources due to the high concentrations of odorants);
- a fan may be required for this application; and
- insulation and heating may be required during freezing weather conditions.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(85+500)}{3600} \times 15 = 2.5 m^3$$

Step 2: Choose bed depth

assume bed depth = 1.5 m

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{2.5}{1.5} = 1.67\,m^2$$

This cross sectional area corresponds to a square with sides 1.3 m
or a circle of diameter 1.45 m.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{585}{3600 \times 1.67} = 0.1\,m/s$$

Step 5: Estimate pressure drop
Using Equation 2, the pressure drop through the biofilter bed is estimated to be 380 Pa (but would need to be confirmed with actual biofilter bed material). This value assumes that only very short, low restriction ducting is used to link the biofilter to the liquid fertiliser tank. Additional pressure losses through ducting would need to be added to the estimated pressure loss through the filter bed.

The estimated pressure (380 Pa) is equivalent to 38 mm H_2O head pressure (or an additional 38 mm depth of liquid fertiliser in the tank). Therefore the aeration compressor could possibly be used to force air through the biofilter. Additionally, a small fan could be applied to the biofilter to overcome pressure drop caused by the filter bed and ducting.

Step 6: Select a fan
Due to the flow (585 m^3/hour) and static pressure (380 Pa), a small diameter axial fan such as the Fantech mixvent series TD-800/200 (240 volt, 140 watt, 200 mm diameter mixed flow design, 800 m^3/hour max flow rate) should be sufficient. The fan should be mounted on the biofilter outlet to prevent contact of high concentration ammonia and hydrogen sulphide gases with the fan components

Summary of this example (see Figure 38 for illustration)
From this example, it can be seen that a reasonably compact biofilter (bed volume 2.5 m^3, bed depth 1.5 m, bed diameter 1.45 m) is required to treat the exhaust air from an aerated liquid fertiliser tank (subject to confirmation of assumptions). If space was limited, the bed area could be reduced to increase the bed height. This would increase the pressure drop, necessitating a fan capable of operating under higher static pressures (such as a centrifugal fan). If the fertiliser tank headspace can be perfectly sealed, the aeration pump could possibly be used to push the air through the biofilter (additional pressure would need to be considered on the aeration pump's performance). The EBCT may need to be altered, depending on the performance of the biofilter, and the conditions under which it is operated.

One issue with applying biofiltration systems to liquid fertiliser tanks would be the shock loading to the biofilter. Biofilters perform best under stable loads or gradually altered conditions. If the fertiliser tank is left empty, then suddenly filled, it may take the microbial population in the biofilter several weeks to build up sufficient strength to adequately treat the odorous gasses emitted from the fertiliser tank. A procedure may be required to adequately prepare the biofilter prior to filling of the fertiliser tank.

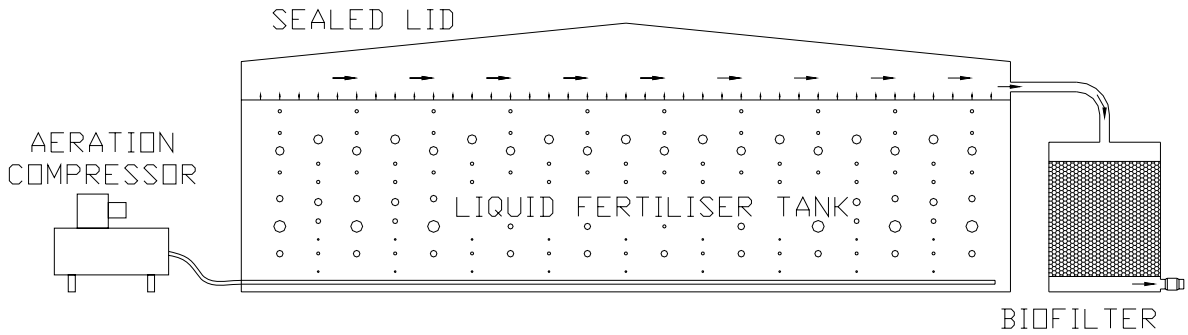

Figure 38. Example of applying biofiltration to an aerated fertiliser tank

4.2.3 Mechanically ventilated pig housing

Biofiltration systems could be applied to mechanically ventilated pig housing in Korea. The size and style of biofilter would be very dependent on the size of the housing, and the source of the odours. It will be assumed in this section that mechanically ventilated pig housing have a static waste pit or flushing system underneath a partially slatted floor.

In mechanically ventilated animal housing, large diameter, axial fans are generally used to generate the required airflow. These fans typically need to operate under low static pressures (less than 50 Pa) in order to maintain reasonable performance. This performance characteristic will have a large bearing on the size and style of a biofiltration system.

Several scenarios will be addressed, including:

- farrowing building (full airflow available for biofiltration);
- nursery building (full airflow available for biofiltration) ;
- growing/finishing building (full airflow available for biofiltration); and
- growing/finishing building (airflow drawn from beneath slats).

Rates of ventilation used in these case studies were provided by Yoo (2005a).

Example 3: Applying biofiltration to a farrowing building (full airflow available for biofiltration)

Scenario:

- 4 m long, 10 m wide, 2.4 m high;
- air flows across the shortest building dimension (largest cross sectional area) at 0.18 m/s;
- Summer ventilation rate is 15 500 m^3/hour;

- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 5 seconds;
- air flow will be provided by an existing fan; and
- insulation and heating should not be required because heat from the growing area should be sufficient for biofiltration activity.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(15500)}{3600} \times 5 = 21.52\, m^3$$

Step 2: Choose bed depth

assume bed depth = 0.3 m

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{21.52}{.3} = 71.7\, m^2$$

This cross sectional area corresponds to a square with sides 8.5 m,
a circle of diameter 9.6 m, or rectangle 10 m by 7.2 m.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{15500}{3600 \times 73.5} = 0.06\, m/s$$

Step 5: Estimate pressure drop

By applying Equation 2, the pressure drop through this biofilter should be approximately 35 Pa (which of course would need to be checked with actual biofilter material).

Step 6: Select a fan

The estimated pressure drop (35 Pa) would create a noticeable increase in static pressure on the ventilation fans, causing a decrease in flow rate. If this pressure were too high, the bed depth would need to be decreased accordingly. Additionally, if the flow through the fan were decreased by the increasing static pressure (assuming that the reduction in flow rate is acceptable from a ventilation point of view), the required biofilter size would decrease slightly. This size reduction cannot be estimated without specific fan performance information.

Additional booster fans would enable the bed depth to be increased, decreasing the footprint. Obviously, running costs would increase due to the additional fans.

Summary of this example (see Figure 39 for illustration)

From this example, it is shown that if pressure drop through the filter bed needs to be minimised, a reasonably large filter bed area is required (71.7 m^2 with bed depth 0.3 m). If the

pressure drop could be increased, the biofilter dimensions would change as shown in Table 10 and alternative fans may be required

Table 10. Changes in biofilter size with increasing pressure drop (note: values calculated using Equation 2)

Pressure drop (Pa)	Bed area (m^2)	Square bed width (m)	Bed depth (m)
35	71.7	8.5	0.3
100	48	6.9	0.45
200	35	5.9	0.6
500	25	5	0.85

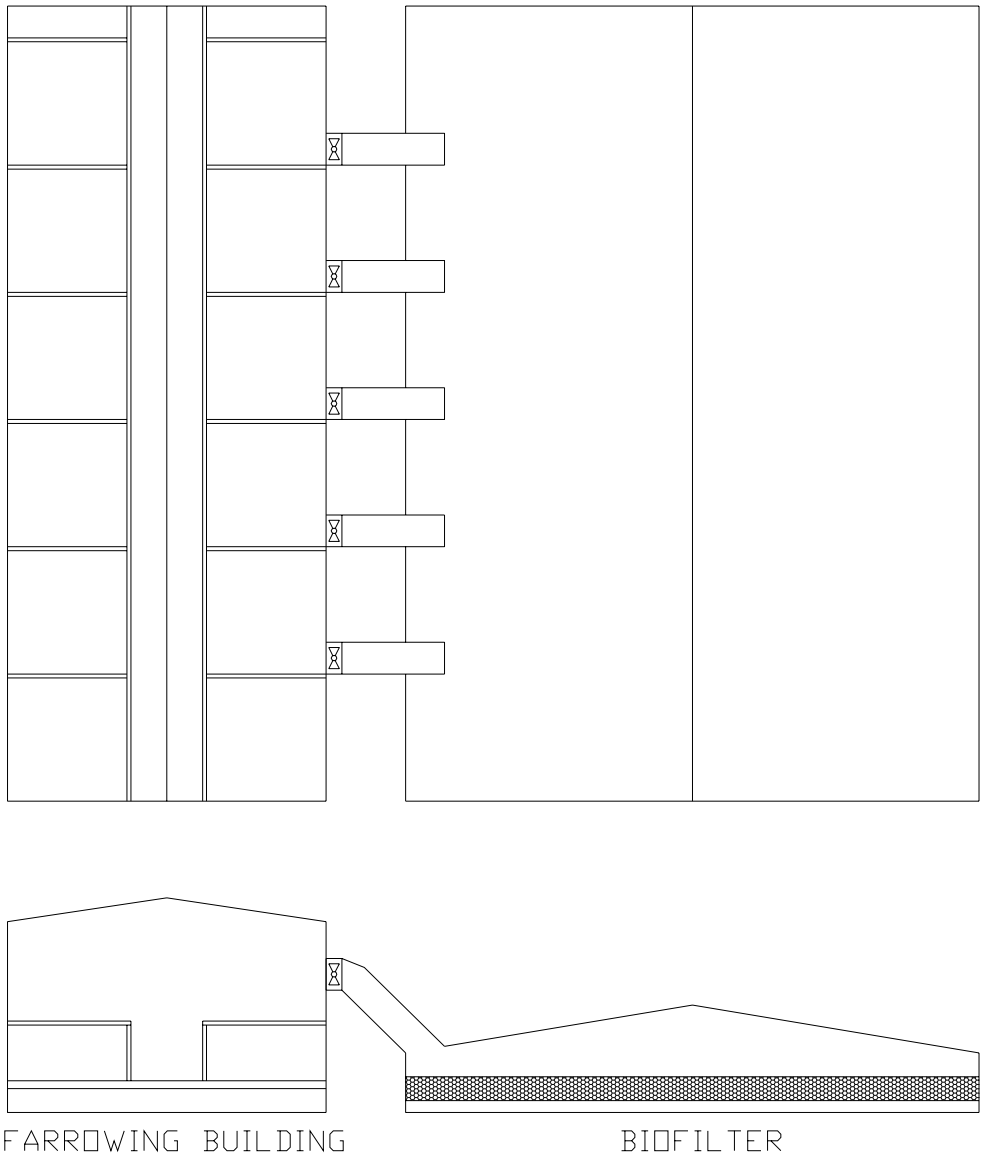

Figure 39. Example of applying biofiltration to a farrowing shed (full ventilation rate)

Example 4: Applying biofiltration to a nursery building (full airflow available for biofiltration)

Scenario:

- 4 m long, 10 m wide, 2.4 m high;
- air flows across the shortest building dimension (largest cross sectional area) at 0.09 m/s;
- summer ventilation rate is 7775 m^3/hour;
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 5 seconds;
- air flow will be provided by an existing fan; and
- insulation and heating should not be required because heat from the growing area should be sufficient for biofiltration activity.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(7775)}{3600} \times 5 = 10.8\,m^3$$

Step 2: Choose bed depth

assume bed depth = 0.3 m

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{10.8}{0.3} = 36\,m^2$$

This cross sectional area corresponds to a square with sides 6 m or a circle of diameter 6.8 m, or single rectangle 10 m by 3.6 m, or two rectangles each 10 m by 1.8 m.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{15500}{3600 \times 73.5} = 0.06\,m/s$$

Step 5: Estimate pressure drop

By applying Equation 2, the pressure drop through this biofilter should be approximately 35 Pa (which of course would need to be checked with actual biofilter material).

Step 6: Select a fan

The calculated pressure drop and flow rate would need to be checked against the performance characteristics of the ventilation fans installed on the nursery house.

Summary of this example (see Figure 40 for illustration)

From this example, it can be seen that the required biofilter has a filter bed cross sectional area of 36 m^2 and a bed depth of 0.3 m. Depending on fan performance characteristics, these dimensions could be altered to optimise space requirements or fan performance.

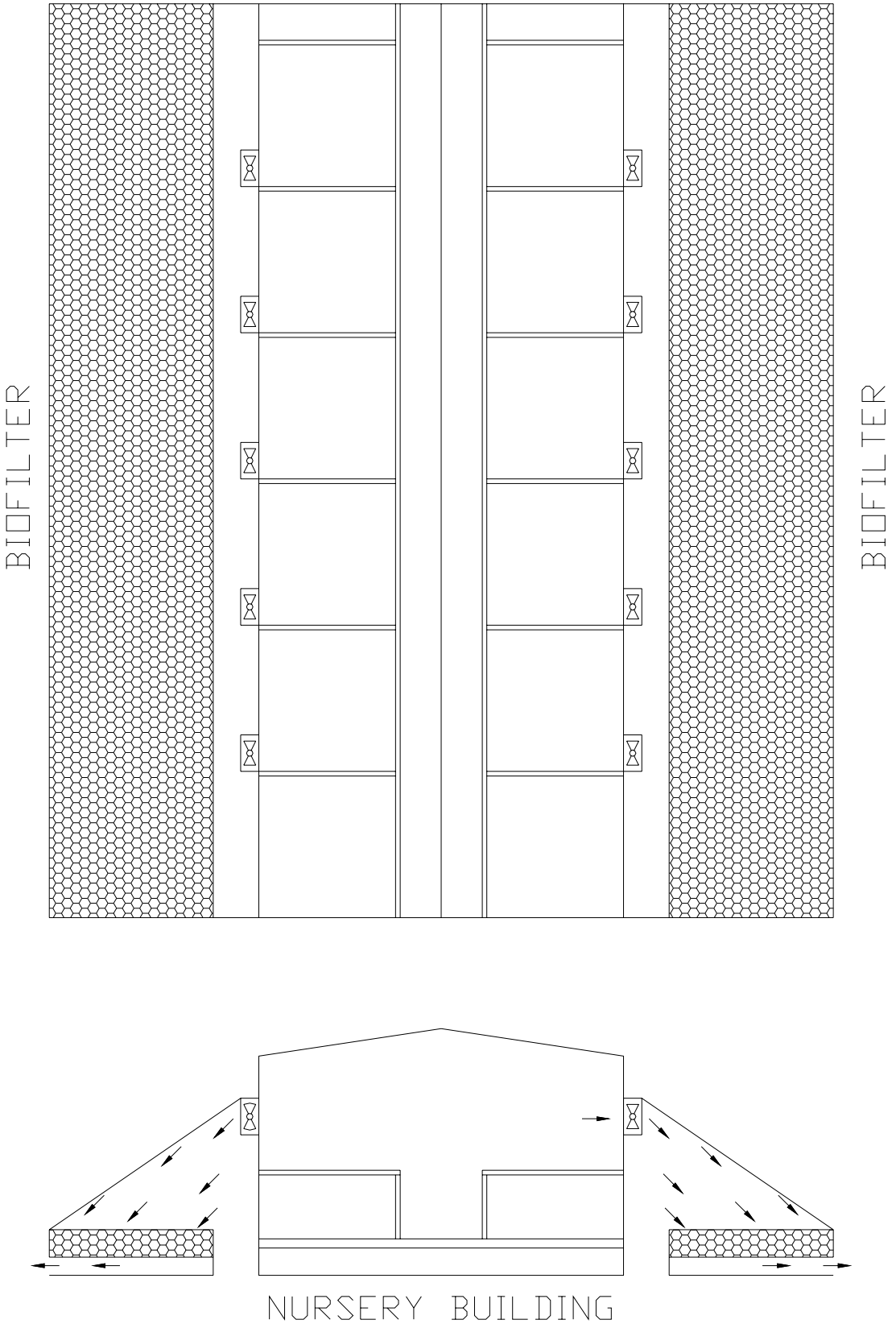

Figure 40. Example of applying biofiltration to a nursery building

Example 5: Applying biofiltration to a growing/finishing building (full airflow available for biofiltration)

Scenario:

- 20 m long, 42 m wide, 2.4 m high;
- air flows across the shortest building dimension (largest cross sectional area) at 0.24 m/s;
- full summer ventilation rate is 87000 m^3/hour;
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 5 seconds;
- air flow will be provided by existing large diameter axial fans; and
- insulation and heating should not be required because heat from the growing area should be sufficient for biofiltration activity.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(87000)}{3600} \times 5 = 120\, m^3$$

Step 2: Choose bed depth

assume bed depth = 0.3 m

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{120}{.3} = 400\, m^2$$

This cross sectional area corresponds to a square with sides 20 m.
or two biofilter beds each 42 m long and 4.75 m wide.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{87000}{3600 \times 400} = 0.06\, m/s$$

Step 5: Estimate pressure drop

By applying Equation 2, the pressure drop through this biofilter should be approximately 35 Pa (which of course would need to be checked with actual biofilter material).

Step 6: Select a fan

The calculated pressure drop and flow rate would need to be checked against the performance characteristics of the ventilation fans installed on the nursery house.

Summary of this example (see Figure 41 for illustration)

From this example, it can be seen that a large biofilter is required to filter the complete ventilation flow. An open bed style of biofilter would probably be required due to the large size.

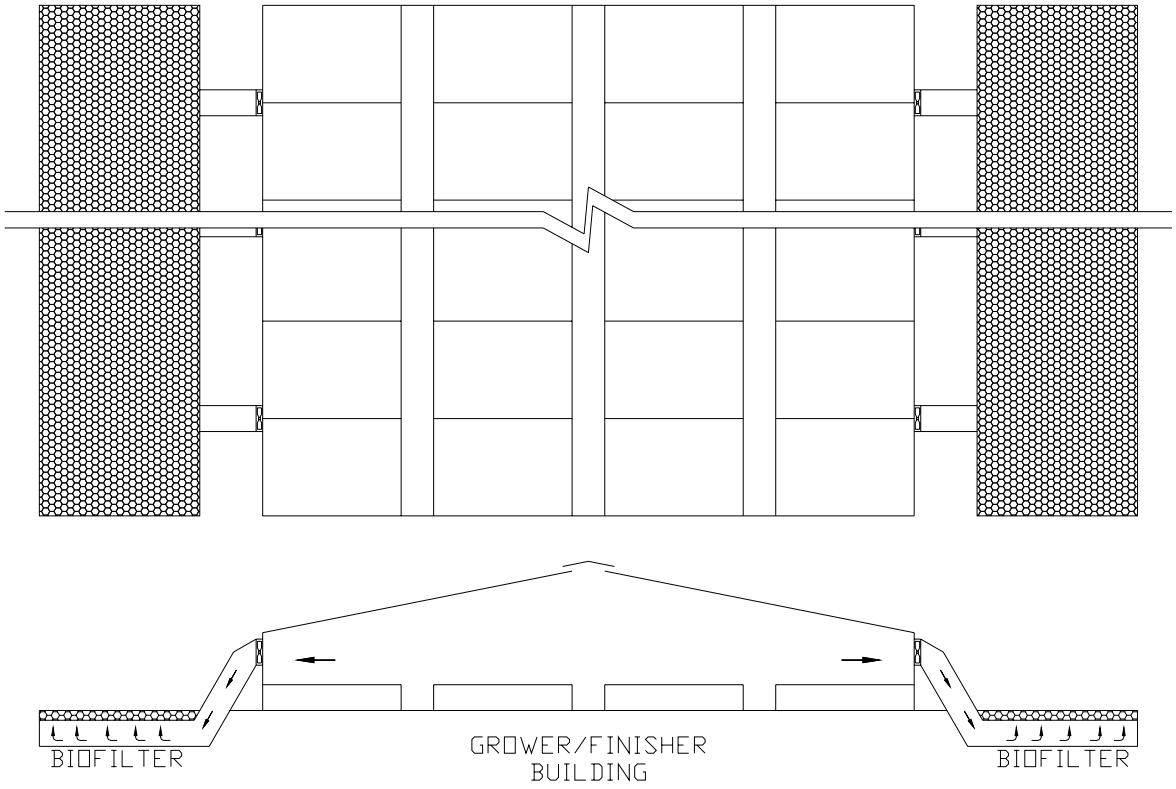

Figure 41. Example of applying biofiltration to a grower/finisher building

Example 6: Applying biofiltration to a large growing/finishing building (airflow drawn from static pit headspace beneath the slats).

Scenario:

- 20 m long, 42 m wide, 2.4 m high (840 m^2 floor area);
- floor area is 40% slatted, with 14% slat opening;
- floor area open to the pit headspace is (840 x 40% x 14% = 47 m^2);
- airflow is calculated as per recommendations by Nicolai (2003); (Velocity of approximately 0.25 m/s through the open slat area is required to prevent pit up-drafting.) $flowrate = area \times velocity = 47 \times 0.25 = 11.75\, m^3/s = 42300\, m^3/h$
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 5 seconds;
- air flow will be provided by existing pit ventilation fans, otherwise, new pit ventilation fans will need to be installed; and
- insulation and heating should not be required because heat from the growing area should be sufficient for biofiltration activity.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(42300)}{3600} \times 5 = 59\, m^3$$

Step 2: Choose bed depth

assume bed depth = 0.3 m

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{59}{0.3} = 197\,m^2$$

This cross sectional area corresponds to a square with sides 14 m,
or one rectangle 42 m long by 4.69 m wide, or
two rectangles, each 42 m long by 2.3 m wide.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{42300}{3600 \times 197} = 0.06\,m/s$$

Step 5: Estimate pressure drop

By applying Equation 2, the pressure drop through this biofilter should be approximately 35 Pa (which of course would need to be checked with actual biofilter material).

Step 6: Select a fan

The calculated pressure drop and flow rate would need to be checked against the performance characteristics of the ventilation fans installed on the nursery house.

Summary of this example (see Figure 42 for illustration)

From this example, it can be seen that quite a large biofilter is required to filter the pit headspace gases. However, it is approximately half the size required to treat the full volume of air required to ventilate the entire building (see the previous example). Additionally, this method of drawing gases directly from the static pit will prevent the concentrated pit gases from mixing with the air above the slats.

Shape of the biofilter could be chosen to suit the building dimensions. For example, if the biofilter were divided into two and installed either side of the building (each being 47 m long), each bed would only be 2.1 m wide.

Nicolai (2003) identified some issues regarding the success of this ventilation method under minimum ventilation conditions (during cold weather). The required flow rate to prevent pit up-drafting is greater than the minimum ventilation rate. Therefore under minimum ventilation conditions, some pit gases may escape into the pig housing. However, even at reduced flow rates, the practice of drawing odorous gases directly from the pit headspace for biofiltration will considerably reduce odorous emissions from the animal housing. At the minimum ventilation rate, EBCT will increase, ensuring adequate treatment time.

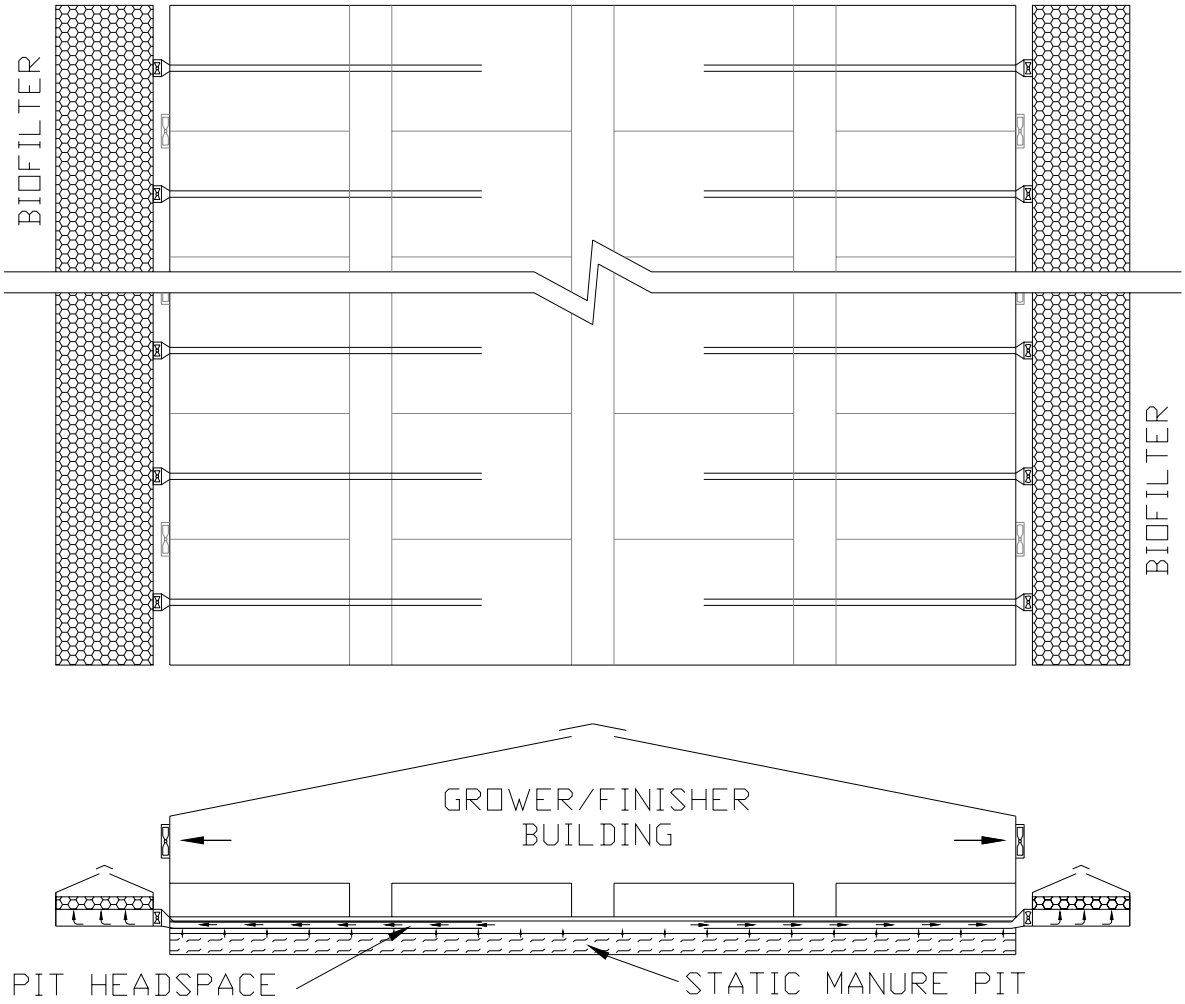

Figure 42. Example of applying biofiltration (pit ventilation) to a grower/finisher building

4.2.4 Naturally ventilated pig housing

Naturally ventilated buildings are managed so that during warm weather, the building is opened to prevent the animals suffering from heat stress, and during cooler weather, the building is completely closed apart from a small vent or fan. This small vent or fan is designed to remove gaseous contaminant at a rate which maintains animal health but minimises excessive cooling/heat losses.

Biofiltration could be applied to naturally ventilated pig housing in Korea. Two methods could be adopted:

1. extracting odorous air for biofiltration under minimum ventilation conditions when the building is closed; and/or
2. drawing odorous air from static pit headspace for biofiltration.

Example 7: Applying biofiltration to a naturally ventilated, small farrowing building (to draw minimum ventilation air when building is closed)

Scenario:

- farrowing building (8 sows);
- 10 m long, 4 m wide, 2.4 m high;
- minimum ventilation rate is 35 m^3/h/head (American Society of Agricultural Engineers, 2003);
- ventilation rate therefore for 8 sows is 280 m^3/h;
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 5 seconds;
- air flow will be provided by existing minimum ventilation fans; and
- insulation and heating should not be required because heat from the growing area should be sufficient for biofiltration activity.

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(280)}{3600} \times 5 = 0.4\,m^3$$

Step 2: Choose bed depth

assume bed depth = 0.3 metre

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{0.4}{0.3} = 1.3\,m^2$$

This cross sectional area corresponds to a square with sides 1.16 m.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{280}{3600 \times 1.3} = 0.06\,m/s$$

Step 5: Estimate pressure drop

By applying Equation 2, the pressure drop through this biofilter should be approximately 35 Pa (which of course would need to be checked with actual biofilter material).

Step 6: Select a fan

The calculated pressure drop and flow rate would need to be checked against the performance characteristics of the minimum ventilation fans installed on the farrowing house.

Summary of this example (see Figure 43 for illustration)

From this example, it can be seen that only a very small biofilter is required to treat the minimum ventilation exhaust from a small farrowing building. The downside of filtering only

the minimum ventilation air is that odorous emissions would still be emitted from the building when the building is opened during warm weather.

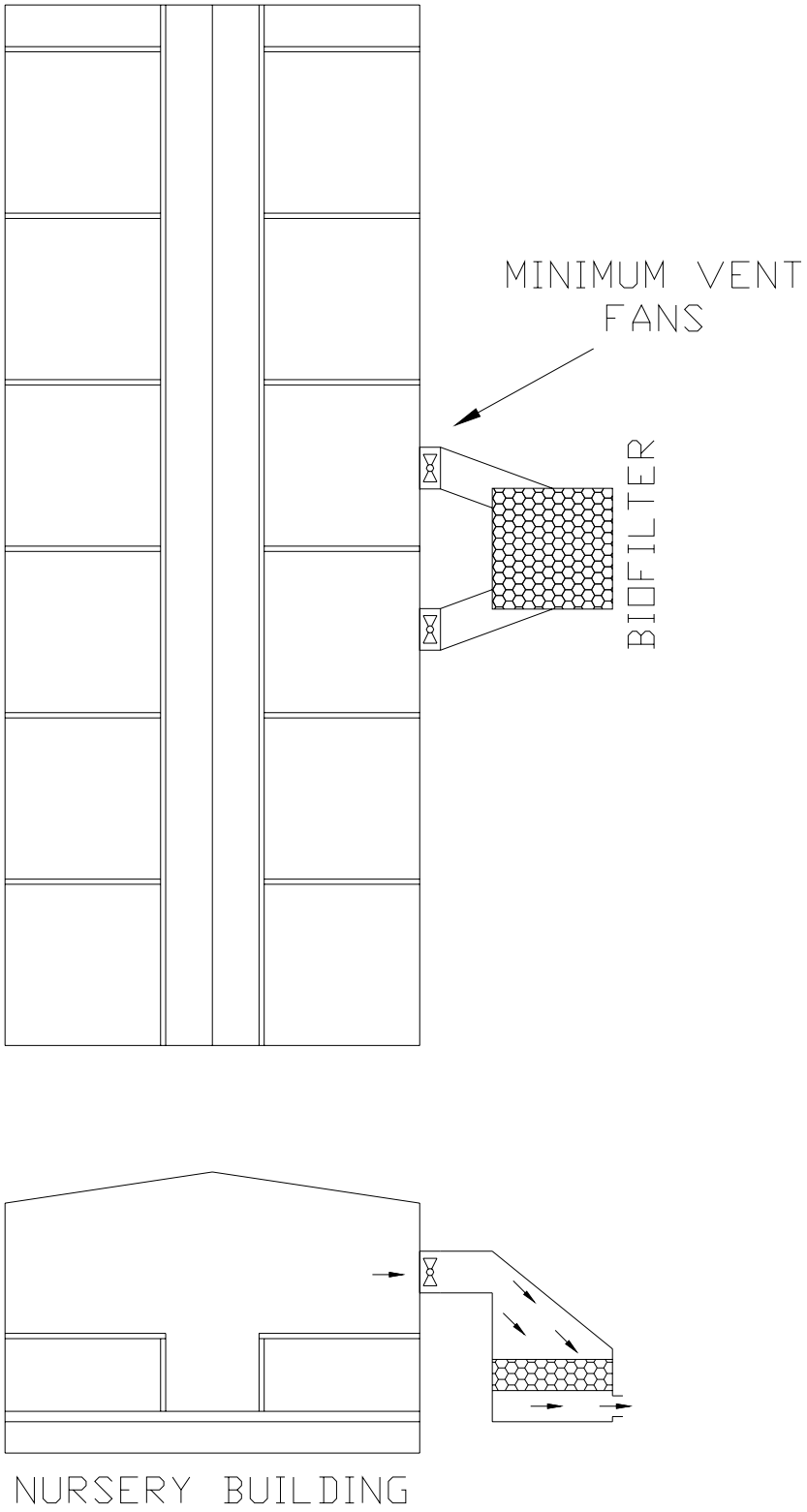

Figure 43. Example of applying biofiltration to nursery building minimum ventilation fans

Example 8: Applying biofiltration to a naturally ventilated medium sized grower/finisher building (air flow drawn from static pit headspace beneath the slats)

Scenario:

- 14 m long, 36 m wide, 2.4 m high (504 m^2 floor area);
- floor area is 40% slatted, with 14% slat opening;
- floor area open to the pit headspace is (840 x 40% x 14% = 28 m^2);
- airflow is calculated as per recommendations by Nicolai (2003);
  (Velocity of approximately 0.25 m/s through the open slat area is required to prevent pit up-drafting.) $flowrate = area \times velocity = 47 \times 0.25 = 7\,m^3/s = 25200\,m^3/h$
- biofilter medium will be woodchip-compost (70:30 by volume);
- EBCT 5 seconds;
- air flow will be provided by existing pit ventilation fans, otherwise, new pit ventilation fans will need to be installed;
- Insulation and heating should not be required because heat from the growing area should be sufficient for biofiltration activity

Step 1: Calculate filter bed volume

$$volume = airflow \times EBCT = \frac{(25200)}{3600} \times 5 = 35\,m^3$$

Step 2: Choose bed depth

assume bed depth = 0.3 metre

Step 3: Calculate cross sectional area

$$area = \frac{volume}{depth} = \frac{35}{0.3} = 117\,m^2$$

This cross sectional area corresponds to a square with sides 14 m, or
one biofilter 36 m long by 3.25 m wide, or
two biofilters 36 m by 1.63 m wide.

Step 4: Calculate empty bed velocity

$$velocity = \frac{airflow}{area} = \frac{25200}{3600 \times 117} = 0.06\,m/s$$

Step 5: Estimate pressure drop

By applying Equation 2, the pressure drop through this biofilter should be approximately 35 Pa (which of course would need to be checked with actual biofilter material).

Step 6: Select a fan

The calculated pressure drop and flow rate would need to be checked against the performance characteristics of the ventilation fans installed on the nursery house.

Summary of this example (see Figure 44 for illustration)
From this example, it can be seen that a large biofilter is required to filter the pit headspace gases for this medium sized grower/finisher building.

Shape of the biofilter could be chosen to suit the building dimensions. For example, if the biofilter were divided into two and installed either side of the building (each being 36 m long), each bed would be only 1.7 m wide.

Under minimum ventilation conditions, when the critical pit ventilation rate cannot be achieved, some pit gases may still be released from the static pit headspace up through the slats. However, a significant amount of odour will be treated by the biofilter, reducing the overall odour emission from the animal building.

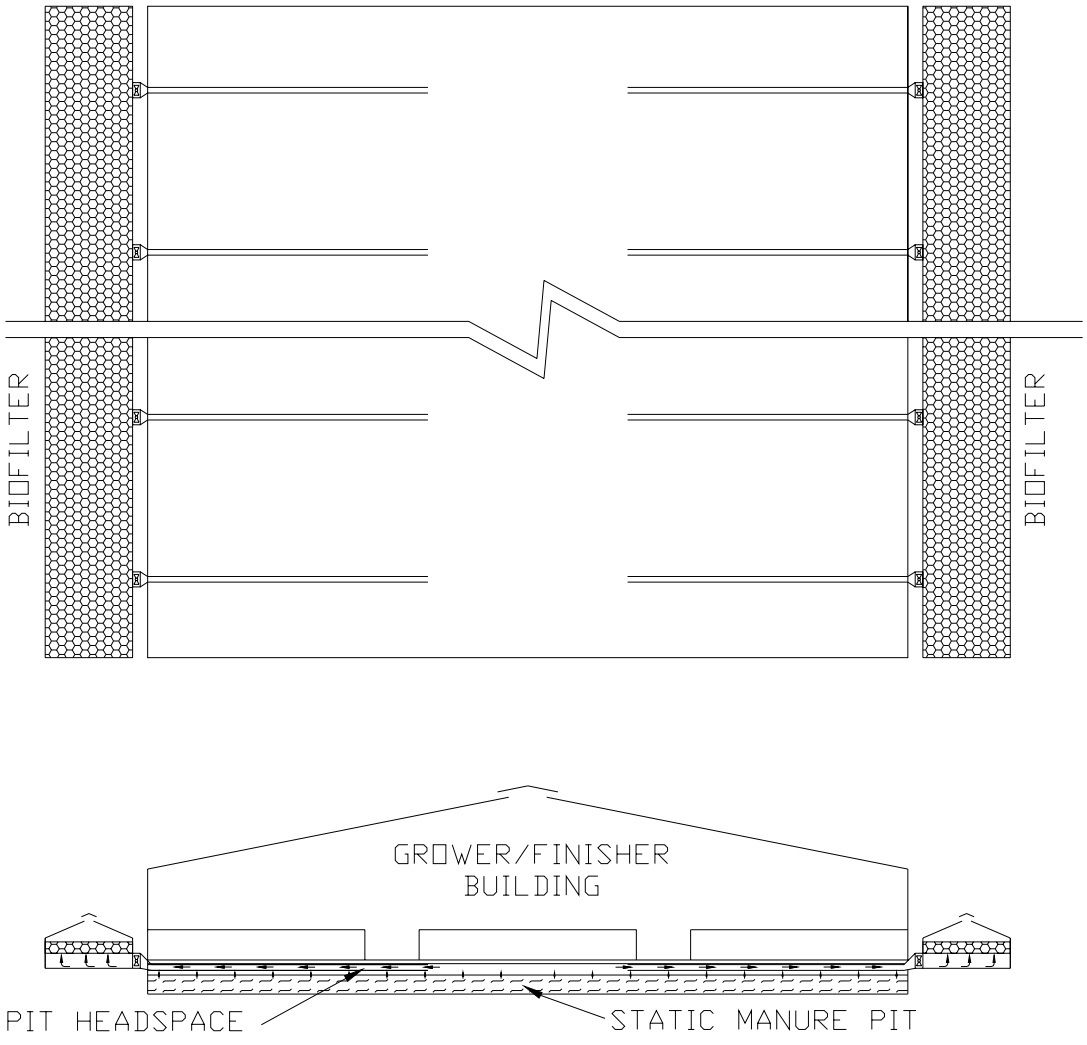

Figure 44. Example of applying biofiltration to a naturally ventilated, medium sized grower building

4.2.5 High rise pig housing

High rise pig housing are designed with the animal living space located above a deep manure space. Ventilation air is drawn across the pig living space as well as down through the slats.

For the air drawn across the pig living space (see Figure 45), a biofilter could be designed using similar principles to those demonstrated in Example 3, Example 4 and Example 5.

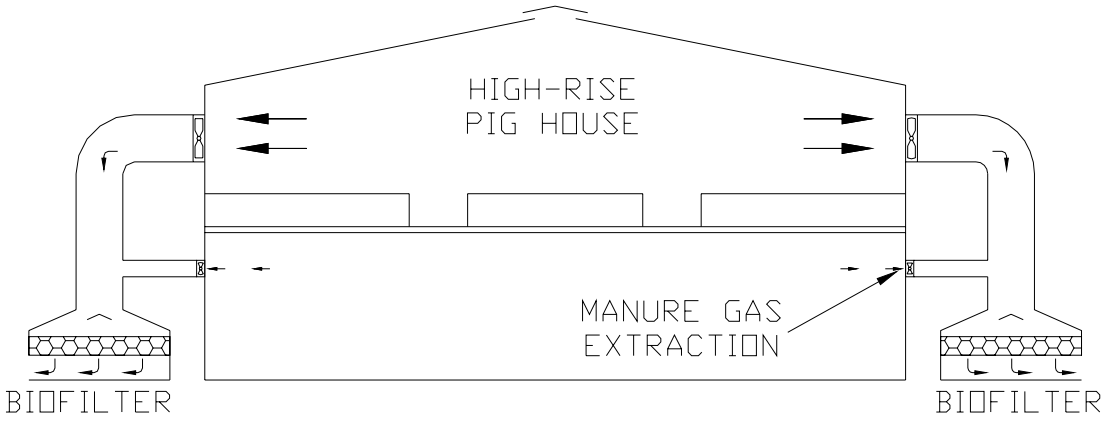

Figure 45. Example of applying biofiltration to a high rise pig house with cross flow ventilation

For air drawn down through the slats (see Figure 46), a biofilter could be designed using similar principles to those demonstrated in Example 6 and Example 8.

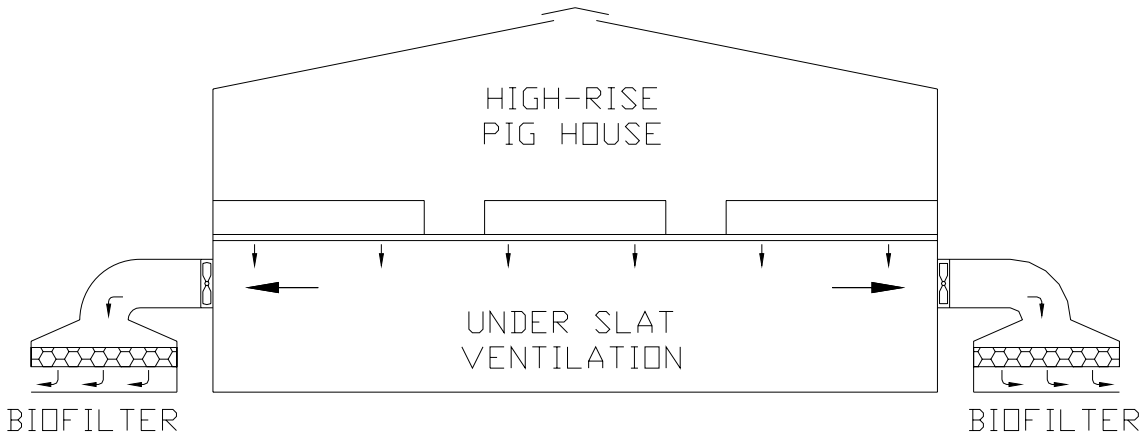

Figure 46. Example of applying biofiltration to a high rise pig house with under slat ventilation

5 Summary

The biofiltration system

A biofiltration system was used to treat odorous air derived from a small piggery building, located near Toowoomba, Queensland, Australia. This was a modular system comprising an inlet ducting system, humidifier and closed bed biofilter. It also included a monitoring and water application system. The inlet ducting system was installed beneath the slatted portion of the pig building floor and airflow was generated using an economical and efficient axial fan. Air was directed through a custom-built humidifier that added moisture to the airstream prior to it entering the biofilter. The closed bed biofilter was constructed from a 2700 litre polyethylene rain water tank and was partially filled with an organic medium of wood chips and pig manure screenings. Odorous air entered the biofilter at the top of the tank and was pushed downward through the filter medium where it was treated microbiologically.

The water content of this biofilter medium was strictly controlled using load cells to determine the total mass of the biofilter. Water was automatically applied to maintain the moisture content of the medium within user defined limits. This was done gravimetrically by continually measuring the weight of the biofilter using load cells and a logger. This system provided very accurate and precise moisture control.

Performance evaluation

The biofilter system was evaluated using:

- dynamic olfactometry (to AS 4.323.3) to measure odour concentration;
- gas detection tubes to measure ammonia concentration;
- electronic nose (e-nose) system; and
- Gas chromatography – mass spectrometry (GC-MS) techniques to measure volatile organic compound (VOC) concentrations.

Olfactometric assessment indicated that the biofilter system was able to reduce odour concentration by about 42% to 43% provided the moisture content of the filter medium was maintained at 66%. If the moisture content of the filter bed declined, odour reduction also declined. Addition of the humidifier did not appear to have any long-term influence on the ability of the biofilter to reduce odour concentration. Unfortunately, olfactometry was unable to measure the hedonic tone or offensiveness of the odour at the inlet or outlet of the biofiltration system. The project team did however observe that the odour of the air exiting the biofilter was less offensive than the air entering the system. The air exiting the biofilter smelt like moist grass or earth, whereas the air entering the system had a distinctive piggery smell.

Gas detection tubes were used to measure the ammonia concentration at the inlet and outlet of the biofilter. The inlet concentration ranged from 5 ppm to 19.5 ppm. The outlet concentration was generally below the detection limit of the tubes (2 ppm). Ammonia removal efficiency ranged from 80% to 95% when the moisture content of the filter bed was maintained at 66%.

E-nose analysis indicated that the biofilter outlet air was different to the air at the inlet of the system and after the humidifier. In order for the e-nose to reliably predict the odour concentration, more odour samples would be required to improve the training of the odour - prediction algorithms.

The GC-MS techniques proved very useful in quantifying the performance of the biofiltration system. Measurement of specific odorants indicated that the removal efficiency of the biofilter system was approximately 84% for acetic acid, 64% for phenol and nearly 100% for butanoic acid, 3-methyl butanoic acid, pentanoic acid, 4-methyl phenol, indole, skatole, propanoic acid and hexanoic acid. Some of these compounds form the basis for the distinctive piggery smell evident at most piggeries. These results help to confirm the observations of the project team which indicated that the outlet air from the biofilter no longer smelt like piggery air.

Recommendations for designing biofilters for intensive livestock applications

The requirements for effective biofiltration, as well as the requirements for matching a biofiltration system to intensive livestock housing, have been summarised in this report. These recommendations address issues such as:

- choice of configuration (open or closed bed system);
- ensuring the chosen design will suit new or existing fan systems (flow rate and pressure drop);
- sizing (choice of dimensions, particularly bed area and depth);
- efficiently directing odorous air to the biofilter;
- selecting the flow rate to optimise odour reduction;
- using suitable materials (filter medium as well as structural materials); and
- providing the correct conditions for microbial activity.

A step-by-step procedure for sizing a biofilter for application to intensive animal housing has been provided, as well as a spreadsheet calculator to streamline the calculation process. The step-by-step procedure for sizing a biofilter has been applied to a range of specific piggery and manure storage scenarios including:

- manure storage tanks;
- aerated (or agitated) liquid fertiliser tanks;
- mechanically ventilated pig housing (especially farrowing and gestation buildings);
- naturally ventilated pig housing; and
- high-rise pig housing.

The results of these scenarios are displayed in the examples in Section 4.2.

Conclusion

This report concludes three years of research into biofilter systems for the purpose of reducing odours from intensive animal production. A pilot-scale biofilter was designed, constructed and evaluated to determine its performance. As a result of this research, a number of recommendations regarding the application of biofilter systems to intensive animal housing have been developed and are presented in this report.

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