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Dust and odour emissions from meat chicken sheds

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Researcher Contact Details
Mark Dunlop
Department of Employment, Economic
Development and Innovation, Queensland
203 Tor Street
Toowoomba QLD 4350
Phone: 07 4688 1280
Fax: 07 4688 1192
Email: mark.dunlop@deedi.qld.gov.au

In submitting this report, the researcher has agreed to the Australian Poultry CRC publishing this material in its edited form.

Research team

Department of Employment, Economic Development and Innovation, Queensland

Mark Dunlop, Erin Gallagher, Dr Jae Ho Sohn, Dr Neale Hudson & Geordie Galvin

Department of Employment, Economic Development and Innovation (DEEDI), Queensland, was the lead agency for this research project. This group was responsible for odour, ventilation, and litter moisture measurement in Queensland and Victoria.

University of New South Wales

Gavin Parcsi, Dr Xinguang Wang and Professor Richard Stuetz

The University of New South Wales (UNSW) was responsible for identification and quantification of non-methane volatile organic compounds present in the air exiting the poultry sheds.

Queensland University of Technology

Dr. Nicholas Meyer, Rob Modini, and Associate Professor Zoran Ristovski

The Queensland University of Technology (QUT) was responsible for measurement of particulate matter number and concentration at all farms.

Department of Primary Industries Victoria

Dr. Ian McCauley and Brett Matthews

Department of Primary Industries Victoria (DPI, Victoria) was responsible for the development and deployment of the in-shed sensor networks. VicDPI staff also assisted with collection of odour, volatile organic compound, litter moisture samples, and airspeed measurements from farms in Victoria.

Foreword by the authors

When this investigation was conceived in 2003–2004, the Australian chicken meat industry was undergoing changes and facing challenges including transition to sheds with tunnel ventilation; rapid growth of the industry with the need for appropriate land parcels to develop new farms; increase in farm size; urbanisation pressures; and the onset of an extended period of drought.

There was a shortage of appropriate odour and dust emission rate data and little understanding of the diurnal, seasonal, batch and inter-farm variability (especially for modern shed designs and management practices but also changes in odour analysis techniques). High quality odour and dust emission rate data was required to improve planning for new and expanding farms by increasing the confidence in odour modelling, improve the calculation of separation distances and respond to community concerns. The measurement of volatile organic compounds (VOCs) was added to the project to improve understanding of the origins of the odour; and the identification of key odorants. In the longer term, these will be required to develop science based, targeted, odour mitigation strategies.

At the inception of the project, there was limited understanding about the many variables that influence the emission of odour and dust from meat chicken sheds and few researchers had extensive practical experience collecting samples from this highly complex biological/mechanical system. Consequently, sampling and analytical methods evolved and were refined during this investigation.

Odour, dust and VOC emissions were measured at a small selection of broiler farm; each managed slightly differently according to prevailing conditions and the preferences of the integrator and farm owner/manager. Shed emissions varied diurnally, seasonally, throughout each batch and between farms and much of the variability could not be readily explained by the conditions recorded on each sampling day. The commencement of extended drought in 2003 potentially introduced another factor into this investigation, which is the use of drought affected feed grains. Whilst impossible to quantify the effect of drought affected grains on odour emissions, it is possible that lower and more variable grain quality may have at times altered the composition of the bird faeces and contributed to feed digestibility problems (and subsequent issues with litter conditions). It would be reasonable to assume that at different farms and different points in time, specific odour emission rates may be different from what we observed. Future measurement of emissions from broiler farms (assuming they are conducted in an appropriate manner) should be considered on their own merits and not automatically tied to the emission rate data included in this report.

Six years after the commencement of this project, and many hundreds of odour, dust and VOC measurements later, the research team are proud to have contributed to advancing knowledge of meat chicken farm emissions and the refinement of associated measurement techniques. It is believed that the findings of this investigation will support the ongoing and sustainable development of meat chicken farms thus ensuring the ongoing supply of quality and affordable chicken meat.

Executive summary

Odour, dust and non-methane volatile organic compound (NMVOC) emissions were measured at tunnel ventilated broiler (meat chicken) farms over several production cycles in Queensland and Victoria. Emission rates were found to vary between farms due to numerous management and environmental factors. The variability in emissions prevented the development of a robust odour emission model; however, the emissions data that has been collected will improve scientific understanding and support improved planning of new broiler farms.

NMVOCs are the building blocks of odour—mixtures of specific odorous NMVOCs combine to form what people recognise as poultry odour—and influence its character and strength. NMVOC composition of broiler odour samples was analysed to provide knowledge that will be vital for the strategic development of odour mitigation strategies and real time monitoring.

Instrumental methods to continuously monitor odour, dust and in-shed environmental conditions were trialled during this project. A prototype artificial olfaction system (AOS) was able to successfully measure in-shed odour concentration and enabled continuous measurement of odour emissions when combined with ventilation rate data. AOS technology could one day form the basis of a continuous odour monitoring system for enhanced research of broiler shed odour emissions. Sensor networks were used to monitor in-shed conditions such as temperature, humidity, ammonia, airspeed and relative concentrations of dust and VOCs were found to be generally unsuitable for use in poultry sheds and further development of sensors, sensor placement and network design will be required.

The successful completion of this project has been made possible through the collaboration of four research teams and co-ordination by the Australian Poultry CRC.

Background

Odour and dust emitted from broiler (meat chicken) farms have the potential to impact on nearby residences, communities and the environment. Impacts due to odour and dust have been recognised by the poultry industries and regulatory authorities as a cause of concern. Consequently, new and expanding farms undergo rigorous assessments to ensure that emissions will not cause unnecessary impacts.

Impact assessments require accurate data for these emissions to enable modelling and prediction of impacts. Most of the published odour emission data for poultry production is no longer relevant due to recent changes in poultry production systems (new building designs, new management practices, new breeds and new diets) and advances in emission measurement practices including new olfactometry and dust measurement standards, improved sample collection methods and advancements in alternative measurement technologies such as electronic sensing arrays and gas chromatography-mass spectrometry/olfactometry (GC-MS/O).

This study has been undertaken to build a database of odour, dust and non-methane volatile organic compound emissions for modern intensive poultry farming in Australia. This data will improve estimation of emissions, improve prediction of impacts and enable improved planning for new poultry farms. Increased knowledge of the chemical composition of poultry odour (through NMVOC assessment) will be critical for identifying the origins of the odour and developing mitigation techniques.

Objectives

The project had the following objectives:
- Development of a database of odour and dust emissions from tunnel ventilated broiler sheds.
- Development of a dust and odour emissions model for representative broiler sheds based upon management factors.

- Examining the relationship between dust and odour emissions, in particular, the importance of dust as a carrier of odour.
- Development and testing of cost effective instrumentation to measure dust, odour and other production factors on commercial broiler farms.
- Application of an artificial olfaction system to continuously monitor odour emissions.
- Identification of specific poultry shed non-methane volatile organic compounds and odorants.
- Quantification and evaluation of specific poultry shed odorants.

Methods

- Eleven tunnel ventilated broiler farms were included in this project. At three of the broiler farms; odour, dust and VOC emissions were measured at approximately weekly intervals. At the remaining eight broiler farms, only odour was measured and only on one day when bird mass in the shed was maximum.

- In total, 434 odour samples were included in the odour emission rate database:
  - 349 samples from broiler farms
  - 85 additional samples from broiler farms for method development (diurnal study, dust and odour relationship, and odour decay)
  - 34 samples were discarded due to excessive olfactometry variability (6.2% of total collected)

- Semi-continuous dust measurements were conducted on 50 separate days at 3 broiler farms.

- The majority of odour, dust and VOC samples were collected from within a temporary flexible duct that was attached to one of the tunnel ventilation fans at each farm.

- Odour concentration was measured using dynamic olfactometry to AS/NZS 4323.3:2001. Two laboratories were used, and comparative testing was conducted between the laboratories to ensure comparability of odour concentration measurement.

- Dust was measured using a DustTrak™ and an aerodynamic particle sizer (APS) and reported in terms of mass concentrations (PM_{10} and $PM_{2.5}$), particle number concentrations and count median diameters (mid-point of the number size distribution). Isokinetic sampling techniques were used.

- VOCs were collected using sorption tubes for subsequent analysis with a GC-MS/O.

- Ventilation rate was estimated by measuring in-shed or fan airspeeds, or by calculating the flow rate through each active fan using manufacturer supplied fan flow rate date (and adjusting for shed static pressure), which was selected as the preferred method.

- Two instrumental approaches were used to monitor in-shed conditions and odour concentration— wireless sensor networks and an artificial olfaction system (AOS).

- The differences in emissions between single use and partially reused litter were assessed at one farm.

- All odour samples were analysed within 8.5 hours of collection.

Results/key findings

Odour emission rates

Odour emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight). Emission rates were normalised according to the number of birds in the shed or the total live weight to enable comparison with published emission rate data.

- Broiler odour emission rates are summarised in the following table.

Units	Full measured range	Range for majority of data
ou/s	2070–135,375	5000–105,000
ou/s/1000 birds placed	68–5187	100–3000
ou/s/1000 birds (while sampling)	86–6335	100–5000
ou/s/kg (total live weight)	0.18–5.13	0.25–2.5

- Broiler farm odour emission rates were highly variable. OER varied by farm, bird age, bird weight, season, time of day, ventilation rate, bird weight distribution and litter moisture. Not all variability could be explained by these factors: consequently other factors were likely to be involved.

- Diurnal variation in odour emission was observed. Changes to temperature, ventilation rate and bird activity (presumably coinciding with light programs) may have contributed to the variable emissions.

- 'Morning flush' of odorants accumulated during the night was not observed.

- OER increased with bird weight up to the day of the first pickup—commonly day 35.

- OER dropped sharply following each pickup.

- There was no clear relationship between OER and shed-average litter moisture content. Odour emission rates measured in this study **did not** increase with increasing moisture content.

- Odour emission rates were observed to vary throughout the day (20 hour continuous period); however the majority of samples were collected between 5:30 am and 2:00 pm, consequently the majority of the measured odour emission rates may not be representative of the daily spread of odour emission rates (evident from the AOS results). Few, if any, olfactometry measurements corresponded with periods of the day when odour emission rates would be minimal. These times are also when poor odour dispersion conditions are most likely to occur.

- Odour emission rates before bird placement (on fresh litter) and after litter removal were found to be lower than when birds were present in the shed. Odour emission rates decreased once birds were removed from the shed.

- Some of the measured odour emission rates were suspected of being unrealistic due to the ventilation rate being manually increased above 'normal' levels (given the ambient temperature and batch age) by the research team while attempting to measure the full range of possible odour emission rates. These data points have been identified in the data set and should be disregarded.

- Odour emission rates tended to be higher during summer, compared to winter, presumably due to greater ventilation requirements.

- Odour emission rates were similar for broiler farms located in Queensland and Victoria; however, this conclusion is based on a very limited number of farms that may not represent other farms in each of the respective states.

- Reusing litter in broiler sheds did not appear to increase odour emissions; however, weather, litter moisture content and stocking density were slightly different between the single use and partially reused batches, which confounded the analysis of the data.

- Odour emission rates measured at eight broiler farms in SE Queensland were found to be slightly different at each of the farms, even though shed design and management were similar. Weather may have been a contributing factor, but it is likely that odour emission rates will be highly variable between farms.

- Odour emission rate measurements from three farms were used while attempting to develop an odour emission model with stepwise regression techniques. Unfortunately, a robust model was not able to be developed.

- Relationships between odour emission and individual factors:
  - In-shed odour concentration generally tended to decrease with increasing ventilation rate, presumably because of dilution.
  - Odour emission rate generally tended to increase with ventilation rate.
  - There was no clear relationship between shed-average litter moisture content and odour emission rate. Maximum odour emission rates tended to occur when shed-average litter moisture content was 26–40%.
  - There was no clear relationship between odour emission rate and live weight density.
  - There were only weak relationships between odour emission rate and ambient temperature, even though ventilation rates tended to increase with ambient temperature.

It is unlikely that any of the aforementioned factors will influence odour emission rate in isolation with other factors. Consequently, variability in odour emission rate must be considered in conjunction with all contributing factors.

Dust emission rates

Dust emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight). Emission rates were normalised according to the number of birds in the shed or the total live weight to enable comparison with published emission rate data.

- Broiler dust concentration and emission rates are summarised in the following table.

Dust fraction	Units	Full measured range	Range for majority of data
PM_{10}	mg/m³ (concentration)	0.04–1.62	0.1–0.8
	mg/s (ER)	1.8–158.5	5–50
	mg/s/1000 birds placed (ER)	0.04–3.90	0.1–1
	mg/s/kg (total live weight) (ER)	$(0.08-2.05) \times 10^{-3}$	$(1-8) \times 10^{-4}$
$PM_{2.5}$	mg/m³ (concentration)	0.001–0.515	0.02–0.14
	mg/s (ER)	0.08–50.3	1–10
	mg/s/1000 birds placed (ER)	0.003–1.24	0.025–0.25
	mg/s/kg (total live weight) (ER)	$(0.02-1.84) \times 10^{-4}$	$(0.4-1.6) \times 10^{-4}$
Particle number	particles/m³ (concentration)	$(0.13-4.34) \times 10^{7}$	$(0.4-2.5) \times 10^{7}$
	particles/s (ER)	$(0.015-2.34) \times 10^{9}$	$(0.1-1.5) \times 10^{9}$
	particles/s/1000 birds placed (ER)	$(0.045-6.3) \times 10^{7}$	$(0.1-4) \times 10^{7}$
	particles/s/kg (total live weight) (ER)	$(0.03-7.45) \times 10^{4}$	$(0.1-3) \times 10^{4}$
Count median diameter (CMD)	μm	1.4–3.4	1.5–2.5

- The concentration of dust in the air exiting the broiler sheds was highly variable. Consequently, dust emission rates from the sheds also varied. Dust emissions varied by ventilation rate, farm, bird age, season, microenvironment, litter management practice and other factors.

- Dust mass concentration and emission rate tended to increase with bird age (or weight). However this was not proven statistically.

- Seasonal differences in dust levels could be partly explained by seasonal differences in ventilation rates; however, this relationship was inconsistent between the farms.

- Dust particle mass and number concentrations and emission rates were generally higher when partially reused litter was employed compared to when single use litter was used. In addition, a greater proportion of fine dust particles (< 1 μm) were generated with partially reused litter.

- When no birds were present in the shed, dust emissions were substantially lower than emissions when birds were present.

- Diurnal variation in dust emission rates was observed.

- 'Morning flush' of dust accumulated during the night was not observed.

Possible effects of methodology on the measurement of odour and dust

- Manually overriding the automatic ventilation system during sample collection may have influenced some of the measured emission rates, producing 'unrealistic' data. The practice of manually controlling fan activity during sample collection was abandoned once this effect was suspected.

- Dust particles collected into odour sampling bags were rapidly attracted to the bag material, excluding them from analysis in the olfactometer; consequently, olfactometry was not an appropriate instrument to assess the influence of dust on perceived odour concentration.

- When using olfactometry to analyse poultry odour, samples must be analysed with 21.5 hours of collection. Divergence in odour concentration was evident 6 hours post sample collection, with significantly different odour concentration measured 21.5 hours post sample collection.

Development of an odour and dust emissions model

It was originally anticipated that data collected by the sensor networks would be suitable for the development of odour and dust emission models. Unfortunately, as the project progressed, it became apparent that the in-shed VOC and dust concentration data collected by the sensor networks did not correlate well with measured odour and dust emission rates and was therefore not suitable for use during model development.

In an attempt to develop an odour emission rate model, stepwise regression methods were applied to the odour emission measurements (olfactometry) using environmental and production factors—season, batch age, ventilation rate, ambient temperature, live weight distribution and litter moisture—to explain the variability in the data. Individual models were developed for the three primary broiler farms; however, not all of the variability in the odour emission rate data could be explained. **Use of these models to predict odour emission rates at other farms is not recommended due to significant differences between the models—especially with different interactions between the various factors—and uncertainty over which of these models should be selected.**

Relationship between dust and odour

The relationship between dust and odour emissions was examined; in particular, the importance of dust as a carrier of odour. During a series of experiments, poultry air samples were filtered using HEPA and glass fibre filters, and compared against unfiltered samples through olfactometry analysis. Also, attempts were made to regenerate odour samples from dust collected on the filters. It was found that the methods used during this project were not able to determine the effect of dust on perceived odour concentration:

- Dust particles collected into odour sampling bags were rapidly attracted to the bag material, excluding them from analysis in the olfactometer; consequently, olfactometry was not an appropriate instrument to assess the influence of particulates on perceived odour concentration.
- Odour could not be reliably regenerated using particulate matter captured on filters.
- Odour and dust measurements (especially PM_{10}) were found to be related; however, it could not be determined whether the relationship was causal or coincidental.
- The influence of dust as a carrier of odour could not be established.

Non-methane volatile organic compound emissions

The gas phase emissions broiler sheds were analysed in three stages: chemical speciation; odorant identification and prioritisation; and NMVOC quantification. The following table lists the chemicals and odorants frequently identified in the NMVOC samples collected. The results of the NMVOC analysis from the broiler houses revealed that there was an impact from the soiling of the litter material within the broiler house. The chemical species that dominated the NMVOC analysis of the broiler house samples were acetone, 2-butanone, 3-methyl-butanal, 2,3-butanedione, 3-hydroxy-2-butanone and acetic acid. Beyond the definition of NMVOC, the presence of sulphide species should not be disregarded. Sulphides present within the results included dimethyl sulphide, dimethyl disulphide and dimethyl trisulphide.

Chemical compounds frequently occurring in poultry house samples

Compound Family	Compounds Identified	Odorants Identified[1]	Odorant Descriptor[2]
Aromatics	Benzene Toluene Xylene (*o-,m-,p-*) Trimethylbenzene Styrene Acetophenone Benzaladehyde Phenol	Toluene	Solvent/Sweet
Alcohols	1-butanol 2-butanol 2-ethyl-1-hexanol	1-butanol	Sweet/Solvent
Aldehydes	Butanal 3-methyl-butanal Hexanal Heptanal Octanal Nonanal Decanal	3-methyl-butanal Octanal	Pungent/malt Citrus/Green/Detergent
Ketones	2-butanone 2,3-butanedione 3-methyl-2-butanone 3-hydroxy-2-butanone	2,3-butanedione	Rancid/fatty/butter
Carboxylic Acids	Ethanoic acid Propanoic acid Butanoic acid		
Terpines	α-pinene β-pinene Limonene Camphene Camphor Carene Eucalyptol	α-pinene β-pinene Limonene Camphene Camphor Carene Eucalyptol	Pine Pine Citrus/Lemon Camphor Camphor Citrus Pine/Eucalyptus
Other Hydrocarbons	Tetradecane Hexadecane Tetrahydrofuran	Hexadecane	Solvent/Plastic/Alkane
Nitrogen	Trimethylamine		
Sulphur	Dimethyl Sulphide Dimethyl Disulphide Dimethyl Trisulphide	Dimethyl Sulphide Dimethyl Disulphide Dimethyl Trisulphide	Smokey Pungent/metallic

[1]*The third column identifies which of the chemicals are also odorants; and*
[2] *provides a descriptor of the odorant*

The results of the quantification of selected NMVOCs revealed that an increase in bird mass will correspond to an increase in NMVOC emissions.

From the results that were obtained from the NMVOC sampling during this project, there was no observed correlation between season or geographical location of the poultry facilities. There was also no observed impact upon the concentration of the NMVOCs analysed as a result of the ventilation rate applied during the collection of samples from the poultry houses. The round robin and diurnal sampling that was undertaken at the broiler sites revealed that the abundances of chemical species varied significantly.

These observations led to the investigation of the composition and emissions of the litter material alone as a primary source of emissions. The increasing accumulation of faeces in the litter material corresponded with a change in the composition of NMVOCs and character of the odour. This suggests that degradation of organic matter in the litter is likely to be the principal mechanism influencing the chemical composition of the overall emission matrix.

Sensor based measurement of dust, odour and in-shed environmental conditions

Wireless sensor networks were found to be useful from an academic perspective for continuously the in-shed environment (in a largely qualitative sense); however they suffered from poor reliability.

Investigation of the sensor data showed that:
- relationships could not be found between the sensor outputs and conventional odour and dust measurements;
- the chosen sensors used for monitoring air quality were not stable and were a limiting factor to the overall performance of the sensor network; and
- the sensors were unreliable and the network occasionally malfunctioned, resulting in extended periods where no data was collected.

Due to these issues, it was not possible to develop robust odour and dust calibration models from the data produced by the sensor networks.

Sensor networks are not ready for deployment into poultry sheds, other than for research purposes.

An artificial olfaction system (AOS) was successfully deployed into two broiler sheds and used to monitor in-shed odour concentration on a semi-continuous basis. When combined with continuous ventilation rate data, the AOS provided a highly detailed record of odour emission rate from the sheds.

The AOS was trained using olfactometry data collected throughout the project. Odour concentration measurements by the AOS correlated well with olfactometry measurements and had relatively small error ranges. The calibration formula was revised several times during the project, resulting in slightly different formulas for different farms; however the refinements were minimal and the AOS could be used at other broiler sheds with reasonable confidence for research purposes.

The AOS measured significant diurnal variation in odour concentration and odour emission rate, presumably due to ventilation trends and other factors that control the production, accumulation, release and transport of odours from the source (litter and birds) to the in-shed air and out of the shed.

Using the AOS, different relationships between odour concentration, odour emission rate and ventilation rate were observed at two different farms. These differences would not have been identified without the continuous monitoring capability provided by the AOS.

The AOS was used to compare the in-shed odour concentration of sequential batches using different litter management practices—fresh litter and partially reused litter. The AOS was well suited to this application and provided significantly more information about odour than infrequent olfactometry odour analysis.

AOS was combined with continuous ventilation rate and on-site weather data to produce a unique data set including odour emission rate and atmospheric stability class—two of the factors that contribute to odour nuisance potential.

While the AOS was used successfully in this project to monitor odour, and produced considerably more detailed odour emission rate data than was possible with olfactometry alone, it is a research tool that is still undergoing development and significant amounts of manual data processing are required to convert the raw sensor responses into odour concentration values—use of AOS by consultants or producers is not currently feasible. Prospective users of alternative instrumental odour sensing systems to measure poultry shed odour need to ensure that the equipment has been thoroughly calibrated and has demonstrated measurement capabilities specifically with poultry shed odour.

Implications

The effect of variability and unpredictability of odour emission rates on industry planning and expansion

Odour emission rates were found to be highly variable, and the variability on each sampling day, throughout each batch, between batches and between farms could not always be explained by the environmental or production conditions recorded by the research team. Additionally, the range of odour emission rates was similar or slightly higher than values reported in literature. Consequently, prediction of odour emission rates by consultants for dispersion modelling purposes is unlikely to significantly change.

Volatile organic compounds in odour

The identification and quantification of non-methane volatile organic compounds (NMVOCs) combined with the prioritisation of odorant species within these NMVOCs will support the development of tailored odour mitigation strategies. By focussing on nuisance odorants, researchers can develop strategies to develop odour abatement and mitigation techniques, with the aim of improving the management of poultry shed emissions. Furthermore the identification of key odorants will support the development of real-time monitoring systems that can be targeted at assessing these nuisance compounds in order to estimate the overall odour emission.

Modelling of dust impacts

Further modelling work (e.g. dispersion modelling) will be required to use the database of dust emission rates obtained in this project to determine dust concentrations downstream of tunnel-ventilated poultry sheds as a function of distance. This information is necessary to determine dust concentrations in the areas surrounding poultry farms.

Recommendations

Measuring odour emissions at poultry farms

- Odour sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because broiler odour emissions are highly variable.

- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, fan details (dimension, manufacturer), mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, litter moisture content, litter depth, litter reuse status (single use or reused litter), lighting conditions and drinker type.
  - Batch information—bird age, bird numbers, bird live weight, total live weight, number of birds placed at the start of the batch, bird breed.

- Daily fan activity should be understood/surveyed for that time of the batch and year. Odour sampling should be scheduled so that samples are collected at a representative ventilation rate or at several ventilation rates over the normal daily range. Efforts must be made to collect odour samples during the night when odour emission rates are lowest (and is also the time when atmospheric conditions are most stable and poor odour dispersion is likely).

- Fan activity **should not** be manually over-ridden, and stabilisation time should be allowed, if possible, following each change in fan activity. If fan activity changes during the collection of samples, it is recommended to record the changes in fan activity and calculate a time-weighted-averaged ventilation rate rather than manually lock-in the number of active fans. By locking in fans, abnormal shed conditions may be produced—especially in terms of temperature, bird activity and odour production/release mechanisms—that will result in the measurement of unrealistic odour emissions.

- Odour samples should be collected and analysed in duplicate to improve olfactometry confidence and accuracy. Samples should be analysed as soon as possible following collection.

- Efforts should be made not to disturb the chickens prior to, or during, sample collection as additional activity may increase the release of odour from the litter and birds.

Measuring dust emissions at poultry farms

- Dust sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because poultry dust emissions are highly variable.

- Continuous, size-resolved dust measurements are necessary for studies that attempt to characterise the mechanisms of dust generation in intensive poultry sheds.

- For studies that integrate dust measurements over extended periods of time (e.g. gravimetric filter analysis), it should be recognized that large variations in dust concentrations are likely to occur during the sample collection period.

- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, litter moisture content, litter depth, litter reuse status (single use or reused litter), lighting conditions, drinker type.
  - Batch information—bird age, bird numbers, bird live weight, total live weight, number of birds placed at the start of the batch, bird breed.

Sampling methodology

Dilution olfactometry analysis

- Odour samples should only be analysed at reputable, experienced olfactometry labs that can demonstrate compliance with AS/NZS 4323.3:2001. Olfactometry labs need to report the accuracy and precision of their laboratory, ensuring that $A \leq 0.217$ and $r \leq 0.477$.

- Odour samples are unstable and must be treated carefully. Odour samples should be analysed as soon as possible (preferably within 12 hours, maximum 24 hours) by:
  - choosing an olfactometry laboratory in close proximity to the test site;
  - transporting the samples to the olfactometry laboratory as soon as possible; and
  - pre-arranging delivery time to ensure the samples are analysed as soon as possible after delivery to the olfactometer.

- Where more than one olfactometry laboratory is used for a single trial, it is recommended that a test be performed to ensure similarity in results from all laboratories.

Ventilation rate measurement

- It is recommended that ventilation rate be estimated using manufacturer's performance data (from certified testing laboratories), number of active fans and shed static pressure. This method is recommended assuming that the following conditions are met:
    - fans are clean, well maintained and in good working order;
    - fan details are recorded including fan diameter, number of blades, blade pitch, blade material, motor manufacturer, motor power, voltage, pulley sizes, grills, shutter description, presence of a cone. A tachometer should be used to check rotational speed;
    - static pressure is recorded at the time of ventilation measurement (changes to fan activity and fluctuating wind conditions will affect the reading);
    - all active fan activity, including duty fans, is recorded;
    - on-farm airspeed measurement inside the shed or across each fan face should ideally be made as a cross reference to the manufacturer's published fan performance data.

- Estimating ventilation rate using manufacturer's performance data is recommended because:
    - ventilation rate can be consistently estimated regardless of duty and tunnel fan activity as well as tunnel ventilation status (internal shed airspeed measurement is unsuitable when mini-vents are open or when duty fans are active);
    - manufacturer's fan performance data is usually obtained using standardised methods and certified laboratories (but you need to check which standard was used);
    - airspeed measurements across each active fan are time consuming and prone to errors due to fluctuating winds as well as non-uniform and turbulent air flow;
    - airspeed measurements across each fan face will be affected by the presence of grills and back-draft shutters; and
    - within the poultry shed environment, it is difficult to achieve the conditions required by AS4323.1:1995 when measuring airspeed inside the shed or across each fan face.

- When airspeed measurements are to be taken inside the shed or across each fan face, measurements must be made according to AS4323.1:1995.

- External fan measurements should be undertaken with caution because of turbulent fan air flow.

- External fan measurements should be avoided during gusty wind conditions.

- If measuring air velocity across the fan face, measurements need to be made at each active fan.

- Internal shed velocity measurements should not be undertaken while mini-vents or duty fans are active.

- Internal shed velocity measurements should be avoided during low levels of ventilation (when airspeed is minimal).

- Be aware that errors of 10–20% are likely regardless of the method used.

Measuring litter moisture content

Litter moisture content can be highly variable across the shed floor area. To adequately survey and quantify the range and distribution profile of moisture content, numerous samples of litter need to be collected across the entire floor area. It is recommended that the profile of litter moisture content be reported rather than the shed-average value, as this will enable identification of wet/dry spots, which may significantly contribute to the total odour emission.

Using the odour emission rate data

- Odour emission rates vary diurnally, seasonally, throughout the batch and will be different at different farms depending on management and infrastructure. **Calculation of daily average, batch average or constant odour emission rate is not appropriate**—unless for a specific purpose.

- Odour emission rates should be presented in terms of total OER (ou/s), OER per 1000 birds placed (ou/s/1000 birds placed) or OER per kg total live weight (ou/s/kg).

Using the dust emission rate data

- Dust emission rates vary diurnally, seasonally, throughout the batch and will be different at different farms depending on management and infrastructure. Selection of a daily average, batch average or constant dust emission rate should be made with extreme care: considerable variation is likely to occur around the chosen average.

- If possible, dust emission rates should be presented in terms of total emission rate (ER) (e.g. mg or particles/s), ER per 1000 birds placed (e.g. mg or particles/s/1000 birds placed) and ER per kg total live weight (e.g. mg or particles/s/kg). This will enable easier comparison between different studies.

Instrumental measurement of air quality in poultry sheds

Application of sensing stations in poultry sheds

- Representative sampling locations need to be determined to enable meaningful and useful measurement of air quality and in-shed environmental conditions. Such sampling locations need to be applicable during both tunnel and mini-vent modes of ventilation.

- The position of sensors, and required mobility, need to be determined to enable selection of power supply (battery or mains power)—can the sensor station be built into the shed (e.g. suspended from the ceiling) or does it need to be mobile?

- Sensor measurements need to be integrated with ventilation rate (e.g. using fan activity) to enable the estimation of emissions.

- Whilst sensor based measurements could not be correlated against conventional measures of dust and odour concentration, they did provide relative measures of dust, ammonia, VOC (surrogate for odour) and airspeed (surrogate for ventilation rate) within the shed.

- Potential users of sensing stations need to identify what *really* needs to be monitored in order to reduce the number of sensors, which will improve power usage, mobility, price and size/handling.

- Use of the AOS should be considered for future assessments of odour in poultry sheds because it produces a more comprehensive record of the highly variable emissions than is possible with olfactometry alone.

- AOS must be calibrated using poultry odour samples, ideally collected from the farm/source of interest.

- Additional research should be directed toward combining AOS with weather data to improve understanding of when odour emissions combine with poor dispersion conditions.

Sensor and network selection

- Select sensors that are robust and suited to the environment within poultry sheds, especially in terms of dust accumulation, high humidity, variable air flow and cleaning requirements.

- Sensor networks should be evaluated for suitability of operation in enclosed spaces, and intermittent interruption in operation to ensure robust transmission of data, and prompt recovery from interruptions.

- Utilise 'off-the-shelf' sensors (in un-modified form) to simplify construction and replacement of faulty/exhausted sensors.

- The design of AOS should include sensors that target NMVOCs identified as being primary odorants; including 2,3-butanedione and dimethyl disulphide.

Future research

- Additional studies to quantify 'typical' odour emission rates from broiler farms measurements need to be made at multiple farms and on multiple days (especially leading up to the first pickup and after pickups); however, significant variability, unexpected and unexplainable odour emission rates—as seen in this project—would be likely. Odour measurements must represent the full spread of 'normal' daily odour emissions, which will require odour samples to be collected at night.

- An artificial olfaction system (AOS) should be used in future odour measuring research activities because the degree of variability and full range of odour emission rates cannot possibly be quantified using olfactometry alone. Research should be directed toward refining the useability, robustness and accuracy of the AOS in detecting the chemicals determined as being the principal nuisance odorants.

- Future research should be directed at quantifying the specific biological, physical and chemical mechanisms that regulate the formation, release and transport of odour and dust within the shed and in the exhaust airstream.

- The effect of litter moisture content on odour formation is still largely unknown—including the delay between wetting and increased emission; changes to microbial community composition and activity; and changes to the litter physical odour release properties due to caking. Further research must investigate these relationships between litter moisture content and odour generation. Techniques to accurately measure the full moisture profile of the litter and to quantify the amount of caking will be required to achieve this.

- Development of robust odour and dust emission models should still be pursued, despite the inability to produce a robust model during this project. The model will need to incorporate the fundamental factors influencing odour emission, and should be formulated from first principles rather than attempting to fit modelling parameters to collected data.

- Future research should be directed at quantifying the conservation/degradation of odorants following emission from the shed (and before reaching receptors). Changes in odorant composition beyond the farm boundary may change the perception of odour by receptors.

- Investigation of the composition and NMVOC emissions from the litter material from the broiler houses would provide useful information relating to the principal odorant emissions from the broiler house.

- Moreover, the investigation of the microbial communities within the litter material and their corresponding NMVOC emissions would enable the elucidation of the species responsible for the key nuisance odorant formation.

Contents

1 Introduction

In Australia, the chicken meat industry annually produces approximately 800,000 tonnes of chicken meat (from 500 million birds). The majority of birds are raised intensively in sheds that are either naturally ventilated, or mechanically ventilated with an automated climate control system to provide the chickens with an optimal growing environment. Aerial emissions from these sheds, including odour and dust, are a normal part of production.

Odour and dust emitted from broiler (meat chicken) farms has the potential to impact on nearby residences, communities and environment. Impacts due to odour, in particular, and dust have been recognised by the chicken meat industry and regulatory authorities as a cause of concern. Consequently, proposals for new and expanding farms undergo rigorous assessments to investigate the likelihood of these emissions causing unnecessary impacts.

Impact assessments require accurate data for these emissions to enable modelling and prediction of impacts. Much of the published odour emission data for poultry production is not relevant due to recent changes in poultry production systems (new building designs, new management practices, new breeds and new diets) and advances in emission measurement practices including new olfactometry and dust measurement standards, improved sample collection methods and advancements in alternative measurement technologies such as electronic sensing arrays and gas chromatography-mass spectrometry-olfactometry GC-MS-O.

This study has been undertaken to build a database of odour, dust and volatile organic compound (VOC) emissions for modern intensive broiler farming. This data will improve estimation of emissions, improve prediction of impacts and support improved planning for new broiler farms. Increased knowledge regarding the chemical composition of poultry odour (through measuring VOCs) is considered critical for identifying the origins of the odour and developing mitigation techniques.

Similarly, detailed knowledge of dust emissions from modern, tunnel-ventilated broiler sheds is required to ensure sufficient separation distances to minimise impacts. Research regarding particle concentrations and emissions from poultry sheds has previously been conducted in the USA, Europe and Australia. There is still a requirement for high quality data to describe the dependence of particle emission rates from Australian tunnel-ventilated poultry sheds on a range of factors including poultry shed type, season, bird weight, bird age and litter moisture content. The dust component of this research program will attempt to fill this gap in knowledge.

1.1 Research objectives

The focus of this research project was quantifying and improving understanding of the emission of odour, dust and VOCs from tunnel ventilated broiler sheds in Australia—achieved by:
- Development of a database of odour and dust emissions from tunnel ventilated broiler sheds—evaluating the influence of geographic location, season, management and environment on emission rates;
- Development of a dust and odour emissions model for representative broiler sheds based upon management factors;
- Examining the relationship between dust and odour emissions, in particular, the importance of dust as a carrier of odour;
- Development and testing of cost effective instrumentation to measure dust, odour and other production factors on commercial poultry farms;
- Application of an artificial olfaction system (AOS) to continuously monitor odour emissions;
- Identification of specific poultry shed non-methane volatile organic compounds and odorants; and
- Quantification and evaluation of specific poultry shed odorants.

Researchers from the Department of Employment, Economic Development and Innovation; Queensland University of Technology; Department of Primary Industries, Victoria; and University of New South Wales collaborated to provide the skills and equipment necessary to undertake this project.

2 Background

Measurement and research of dust and odour emissions from intensive livestock farming has been undertaken internationally for many years. In Australia, impacts by odour emissions, in particular, have been the major driver for emissions research. In other countries, dust and ammonia are the primary interest for researchers due to environmental and health concerns. There is a large quantity of published information about poultry production systems; odour and dust generation in poultry production; odour and dust emissions from poultry; and odour and dust measurement methods. This chapter provides an introduction to these topics.

2.1 The broiler production system

There are two main types of farm involved in meat chicken production; breeder farms, where fertile eggs are produced; and grow-out farms, where the chickens are grown until harvested. In the grow-out phase of production, chickens can be grown in naturally ventilated sheds, mechanically ventilated sheds or on free range farms. In this investigation, only mechanically ventilated broiler sheds were considered, as these represented the majority of the Australian industry.

There are several breeds of broiler chickens, each with unique characteristics and requirements. Three breeds commonly found in Australia include Arbor Acres (www.aviagen.com), Cobb500 (www.cobb-vantress.com) and Ross308 (www.aviagen.com). Specific and detailed management, nutrition and performance information can be accessed via their websites.

The design and management of the production system will have a direct bearing on odour and dust emissions. The brief descriptions provided in the following sections do not address all aspects of the production systems, but provide general information about design and management issues relevant to the generation and emission of odour and dust.

2.1.1 Grow-out cycle

The growing cycle for broilers typically last up to 56 days, which compared to other livestock production systems is relatively short. Such a short production cycle is possible because broiler chickens grow rapidly (see Figure 1 for typical growth rate). Selective breeding, provision for an ideal growing environment and high quality feed are factors contributing to their rapid growth. On average, between days 7 and 56, a broiler chicken will consume 1.52 kg of feed for every 1 kg of added body weight.
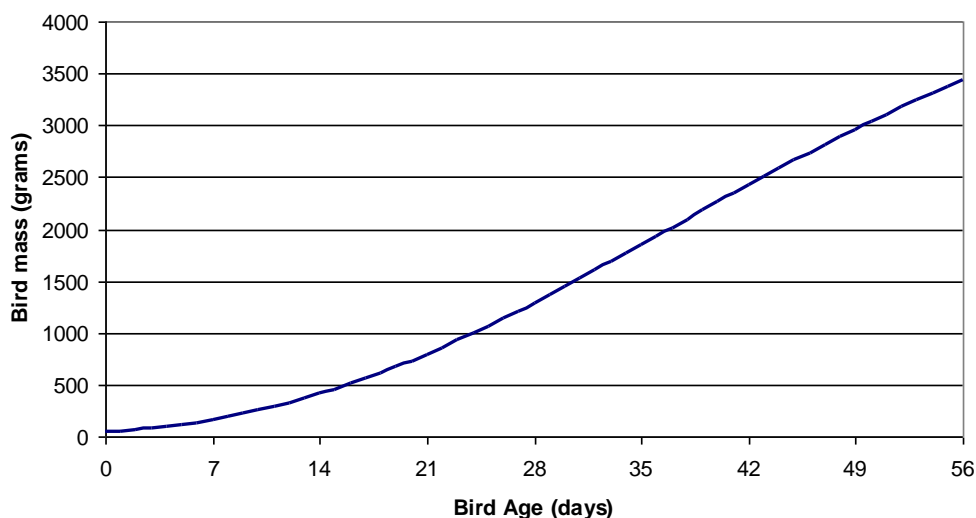
Figure 1:   Indicative broiler growth rate (data combined for Ross 308 and Cobb 500 breeds)

Day old chickens are sourced from a hatchery and introduced to the broiler shed. The birds are restricted to a portion of the shed known as the brooding section, which usually occupies up to half of the broiler shed and is fitted with heaters. As the birds grow, from days 10–14, they are allowed to access more of the shed until they occupy the full shed.

Around day 35, a portion of the birds will be removed for processing (known as the first thin-out or pickup).

Between days 35 and 56, more chickens may be harvested in multiple pickups until ultimately all of the birds have been processed.

The schedule for harvesting birds is determined by market demand for quantities and specification of meat products.

2.1.2 Mechanically ventilated shed design

Mechanically ventilated broiler sheds are designed to provide the birds with a comfortable environment and many design features of modern sheds also contribute to the control of odour and dust emissions. These sheds are typically 100–150 m long and 12–20 m wide, which provides sufficient space for 20,000–50,000 chickens. There will usually be three to ten of these sheds on a typical farm.

The shed floor is usually constructed with compacted earth, road-base or concrete. The roof is usually insulated. Walls are mostly constructed using insulated panelling or impermeable curtains. The selection of wall material depends on the age of the shed and design preference; however, most new farms are constructed with solid, insulated walls.

The ventilation system installed in poultry sheds is very complex and comprises a central control unit, primary ventilation fans, duty ventilation fans, mini-vent inlets, tunnel ventilation inlets, evaporative cooling pads and ceiling baffles (see Figure 2). Large diameter axial fans (1219–1397 mm diameter, called primary or tunnel ventilation fans) are installed on the narrow end of the shed and provide the majority of the ventilation. Maximum ventilation rate is approximately 8–12 m³/h per bird. Additional fans (referred to as minimum ventilation or duty fans) are installed along the length of the shed, on the wall opposite the primary fans or on the roof to provide low levels of ventilation. All fans are fitted with back-draft shutters to prevent fresh air entering the shed through inactive fans. Mini-vent inlets are installed at equal spacing along the walls on each side of the shed. Air is drawn through these vents when low levels of ventilation are required. Tunnel ventilation inlets are positioned on the opposite end of the shed from the tunnel ventilation fans. Air is drawn through these large vents when the shed transitions into tunnel ventilation mode. Evaporative cooling pads are usually installed in front of the tunnel ventilation inlets. When the weather is hot and maximum cooling is required, water runs over these cooling pads, creating a cooling effect as the air passes through them. Foggers— high pressure nozzles designed to atomise water droplets and create a fine mist—may also be installed inside the shed and are activated when additional cooling is required.

Correct ventilation is essential for bird health, efficient production and control of odour and dust emissions.

Tunnel inlets

Duty fans

Ceiling baffles

Mini-vent inlets

Primary/tunnel ventilation fans

Evaporative cooling pads
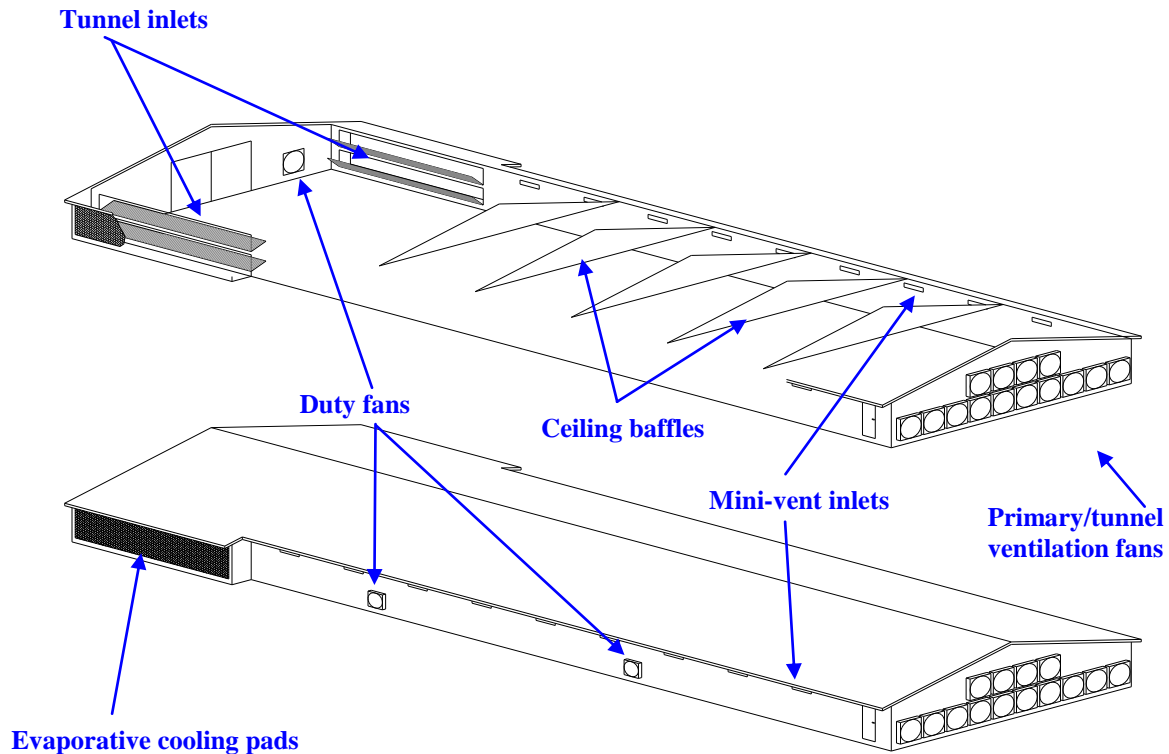
Figure 2: **Components of the broiler shed ventilation system (*top* – inside shed with roof removed, *bottom* – outside shed)**

The sheds are operated under negative pressure (ranging from 0–50 Pa) which draws fresh air into the shed through the inlets. Stale air is exhausted from the shed through the fans. There are primarily three modes of ventilation:

1. mini-vent ventilation;
2. tunnel ventilation without evaporative cooling; and
3. tunnel ventilation with evaporative cooling.

Mini-vent ventilation

Mini-vent ventilation is used when low levels of cooling are required or when no actual cooling is required. It allows stale, moisture laden air to be removed from the shed. Mini-vent ventilation is designed to exchange the air in the shed without creating airspeed or drafts. This is achieved by drawing fresh air into the shed through mini-vents. The amount of opening through the mini-vents is controlled to maintain a slight vacuum in the shed (approximately 20 Pa depending on shed width and inlet design). The negative pressure ensures that an even amount of fresh air is introduced along the entire length of the shed. It also aids the incoming air to be projected along the ceiling, warming the air and increasing its capacity to hold moisture. Fresh air is introduced into the shed in this manner to help prevent excessive litter moisture and condensation.

At the lowest levels of mini-vent ventilation, duty fans will cycle on and off, removing stale air (containing moisture, dust and odour) while maintaining the internal shed environment. As the level of mini-vent ventilation increases, duty fan activity will increase and the primary fans will start to activate. Depending on the number and size of mini-vents and fan capacity, 50–75% of the primary fans can normally be activated before tunnel inlets need to be opened.

Tunnel ventilation with and without evaporative cooling

Tunnel ventilation is used when large amounts of cooling are required. During tunnel ventilation, mini-vent inlets are closed and tunnel inlets are opened. This creates airspeed along the length of the shed,

introducing a wind chill effect for the birds. Wind chill is effective for improving bird comfort during warm weather by reducing the temperature experienced by the birds below the dry-bulb temperature of the air in the shed. Maximum airspeed through the shed will usually be up to 3.5 m/s.

Ceiling baffles are installed in many sheds to reduce the cross-sectional area of the shed, increasing airspeed at a given ventilation rate.

When extra cooling is required during tunnel ventilation, water runs over the cooling pads, creating an evaporative cooling effect. Evaporative cooling is most effective when ambient relative humidity is low.

2.1.3 Optimum temperature conditions

Mechanically ventilated poultry sheds are specifically designed to allow precise temperature control for the birds. Figure 3 displays the optimum temperatures for one breed of broiler (Cobb*500*™). The temperature shown is the effective temperature experienced by the birds following adjustments for humidity and wind-chill. Increased humidity decreases the ability of the bird to dissipate excess heat, which makes the bird feel warmer. Increased shed airspeed creates wind-chill, which reduces the temperature felt by the birds. Consequently, the 16 °C target temperature recommended for 56 day old birds may be achieved with a dry bulb temperature greater than 16 °C, assuming that humidity is low and shed airspeed is high, hence the reason for tunnel ventilation.
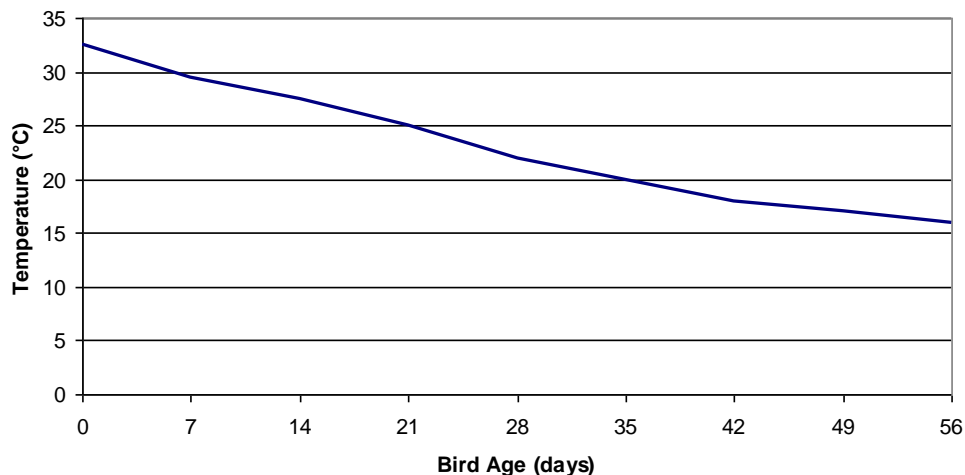
Figure 3: **Target temperature through the broiler growth cycle—RH 50–70% (Cobb-Vantress Inc., 2008)**

2.1.4 Feed and drink supply

Food and water is supplied to the birds through specialised feeding and drinking systems.

Feed is delivered to the farm and stored in silos. An auger system controls the flow of feed into the shed, where it is distributed to the birds using lines of feeding pans (see Figure 4). The composition of the feed in terms of energy, protein and nutrients is changed several times throughout the grow-out cycle to meet the requirements of the birds. Feed is usually always available to the birds.

Water is supplied to the birds using specially designed nipple drinkers (see Figure 5). These drinkers are specifically managed to meet the bird's requirements as they change throughout the grow-out cycle (drinker height and flow rate) and are maintained to prevent leakage. Old drinker designs, known as bell or cup drinkers are rarely used anymore because they were prone to excessive water spillage, resulting in wet litter. Wet litter is recognised as a possible cause of excessive odour generation (see section 2.1.5 below). For this reason, drinker design, management and maintenance are essential to maintain good litter conditions and control odour.

Figure 4: **Picture of a modern feeder pan**

Figure 5: **Picture of a modern nipple drinker (fitted with evaporation cup)**

2.1.5 **Bedding and litter**

Manure, bedding and litter are three commonly used terms. In this report, manure refers to chicken faeces; bedding refers to 'clean' material not containing any manure; and litter refers to a mixture of bedding material and poultry manure. The floor of the broiler shed is covered with bedding. The bedding provides absorbency and insulation. Common bedding materials include saw dust, wood shavings, rice hulls, paper and straw. Previously used litter can be used in lieu of fresh bedding at the start of a batch.

Moisture absorbency is a critical requirement of any bedding or litter material used as a floor covering. Controlling the moisture content of the litter is essential for controlling both odour and dust emissions (McGahan and Tucker, 2003). Moist or wet litter can potentially contribute to increased odour generation whereas dry litter can lead to increased dust generation. Litter can become excessively moist due to leaking drinkers, condensation (moisture laden air inside the shed condenses as cool air enters the shed, especially through cracks or poorly designed inlets) or poor bird health (when excessively wet faeces make the litter wet). Wet litter may be managed by drying the litter with good ventilation practices or replacing patches of wet litter with dry bedding.

Litter may be removed from the shed at the end of a batch (35-56 day production cycle) or retained in the shed for use in subsequent batches. If the litter is kept in the shed, it may be piled or windrowed before being re-spread for the following batch.

2.1.6 **Summary of the broiler production system**

- Shed design, husbandry practices and farm management are likely to have an influence on odour and dust emissions.

- Broiler litter is removed from the shed at the end of the 56 day production cycle. Mechanical ventilation is used to create a comfortable environment (especially temperature) for the chickens, and is also used to remove excessive moisture, which is a contributing factor to odour generation.

- Mechanically ventilated poultry sheds use several modes of ventilation—mini-vent ventilation; tunnel ventilation; and tunnel ventilation with evaporative cooling—which change the in-shed aerodynamics and are therefore likely to influence odour and dust emissions and the measurement of these emissions.

2.2 Odour

2.2.1 Introduction

Odour is a property that gives a substance a characteristic smell. Odorous molecules are formed by combinations of volatile organic compounds (VOCs) (O'Neill and Phillips, 1992), which are often referred to as odorants. When these molecules are inhaled, they are received by the olfactory organ (an area in the upper nasal passage known as the olfactory epithelium) where they react with proteins and activate receptors that send signals to the brain. Within the olfactory region, there are millions of receptor cells that are classed according to their sensitivity to specific odorants (Standards Australia/Standards New Zealand, 2001). There are 100 to 300 classes of olfactory receptor, each of which is more or less sensitive to different odorants, enabling an extremely large number of combinations of odours that can be identified. It is believed that humans can differentiate about 10,000 different odour characters (Standards Australia/Standards New Zealand, 2001).

Odours can be described using four dimensions: detectability (or odour threshold); intensity; quality (or character) and hedonic tone (Standards Australia/Standards New Zealand, 2001). Detectability is the minimum chemical concentration of an odour at which a percentage of the population can sense the odour. Detectability is measured using a dynamic olfactometer (described in more detail in section 2.2.2) and is used to calculate odour concentration. Intensity is the perceived strength of the odour sensation. Intensity allows an odour to be rated as weak or strong. Intensity has a logarithmic relationship to odour concentration (small changes in odour concentration near the detection threshold make a relatively large difference in odour intensity, however at higher concentrations, larger concentration change is required to make small change in odour intensity). Odour quality is a descriptive dimension allowing odours to be described as, for example, floral, rancid, faecal, cardboard, wet socks or any combination of these and many other descriptors. The final dimension of odour description is hedonic tone, which rates the relative pleasantness or unpleasantness of an odour.

Odour is a mixture of many different compounds known as odorants (American Society of Agricultural and Biological Engineers, 2007; Cai *et al.*, 2006; Lacey *et al.*, 2004; O'Neill and Phillips, 1992). Table 1 shows a list of some of the compounds that are produced by the microbial decomposition of manure. It is important to understand these compounds in order to understand how odours are produced. The presence of these compounds in odour will be dependent on the chemistry of the manure and activity of the microbial communities.

Table 1: **Compounds resulting from manure decomposition (American Society of Agricultural and Biological Engineers, 2007)**

Volatile fatty acids	Mercaptans	Sulphides
Acetic	Methylmercaptan	Hydrogen sulphide
Propionic	Ethylmercaptan	Dimethylsulphide
Butyric	Propylmercaptan	Diethylsulphide
Isobutyric		Disulphides
Isovaleric	Esters	
Ammonia and Amines	**Alcohols**	**Nitrogen Heterocyclyes**
Ammonia		Indole
Methylamine	Phenols and Cresols	Skatole
Ethylamine	Phenol	
Dimethylamine	p-Ethyl-phenol	Aldehydes
Trimethylamine	p-Cresol	
Diethylamine		

2.2.2 Biochemical origins of odour

During periods of extended storage and/or treatment within animal housing, in anaerobic ponds, or on feedlot pads, complex wastes are transformed through chemical and microbiological processes to simpler molecules. Three basic steps are involved with the anaerobic digestion of waste materials:

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

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

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

During methanogenesis, the products of fermentation (i.e. acetate, carbon dioxide and hydrogen) are utilised to produce methane. A range of non-methanogenic organisms (acidogens) are responsible for hydrolysis and fermentation. These include *Clostridium spp*, *Bifidobacterium spp*, *Staphylococcus* and *E. coli*. Many other groups are also involved in the process through production of various enzymes.

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

The methanogens and acidogens form a syntrophic relationship in which the methanogens convert fermentation end products to methane and CO_2. The ability of the methanogens to utilise the hydrogen formed during fermentation is critical—if the hydrogen produced is not utilised sufficiently quickly, propionate and butyrate fermentation slows and these volatile fatty acids (and other intermediate metabolic products) accumulate, reducing pH, further slowing the fermentation process. In addition to compromising waste treatment, accumulation of compounds such as butyrate and propionate increases odour emissions. In extreme circumstances, anaerobic treatment fails.

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

- A close association between undigested protein and low molecular weight branched volatile fatty acids, some reduced sulphides and indoles and phenols. Specific amino acids were identified as precursors of key odorants (Hobbs *et al.*, 2004; Mackie *et al.*, 1998);

- Complex carbohydrates in particular were associated with volatile fatty acids (mainly C_2 to C_4, with smaller amounts of C_5 to C_7 acids) (Zhu *et al.*, 1999);

- Deamination of organic N-containing materials present in large amounts in excreta to form ammonia and volatile fatty acids (Mackie *et al.*, 1998);

- Other relationships clearly link specific precursor compounds with odorants, including tyrosine (phenol, 4-ethylphenol), tryptophan (indole and skatole) and phenylalanine (phenyl acetate, phenyl propionate and benzoic acid) (Mackie *et al.*, 1998);

- Assimilatory microbial processes result in formation of cysteine and methionine, breakdown of which releases hydrogen sulphide and mercaptans;

- For dissimilatory processes, sulphate is used as a terminal electron acceptor and is reduced to hydrogen sulphide directly (Mackie *et al.*, 1998);

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

2.2.3 **Key odorous chemicals**

The nature of emissions described generically as odour has been extensively researched, particularly for piggery operations. O'Neill and Phillips (1992) identified 168 separate odorous compounds in pig wastes. More recently, Schiffman *et al.* (2001) identified 331 different volatile organic compounds were responsible for odour from piggery operations. 203 of these chemicals were identified in air samples while 167 were recovered from anaerobic pond liquor samples.

Hobbs *et al.* (1997) proposed that odorants could be separated into four distinct chemical classes – reduced sulphur compounds, volatile fatty acids (VFAs), phenols and nitrogen heterocycles (indoles). Zahn *et al.* (2001a; 1997; 2001b) and Bicudo *et al.* (2002) have extensively researched odour emissions from piggery wastes. They were able to identify a strong correlation between odour intensity and the concentration of 19 volatile organic compounds present in ambient air samples (Zahn *et al.*, 2001a). They refined these findings to show that measurement of the concentration of nine specific odorants enabled an adequate correlation between odorant concentration and odour intensity ($r^2 = 87.6$). The odorants that could be related to odour intensity included VFAs, phenols and indole.

Less intensive research has been undertaken on the specific identity of odorants in cattle wastes. Bicudo *et al.* (2003) measured ambient concentrations of hydrogen sulphide downwind and from the surface of manure storage basins over a 30 day period. Odour samples were collected from the surface of the manure storage lagoon on two occasions. It was confirmed that manure storages were major sources of odour. Emission rates varied between 7 and 10 OU/s.

Baek *et al.* (2003) measured ammonia and hydrogen sulphide (H_2S) fluxes from the pen surface of Texas feedlots. They identified a weak relationship between ammonia emission rates and the pad temperature. They were unable to identify a similar relationship for H_2S following instrument failure. They were able however to identify increases in emission rates of both chemicals following rainfall events. Diurnal variation in emission rates of both variables were also observed, with emission rates peaking at about 13:00 for ammonia and at about 15:00 for H_2S. No odour samples were collected during this study.

More recently, measurement of ambient air concentrations of ammonia, VFAs and other odorants downwind of feedlots in Alberta, Canada were reported (McGinn *et al.*, 2003). A positive correlation between ambient ammonia concentrations and odour intensity was observed. It was concluded that ammonia was an indicator or surrogate for odour and the odour plume, rather than being a major odorant. Concentrations of VFAs measured adjacent to feedlot pens were thought to be high enough to create the potential for nuisance odour conditions. It was also shown that the concentrations of odorants fluctuated throughout the day. It was not clear whether these fluctuations arose from diurnal trends or were in response to atmospheric conditions and dispersion. The authors identified that odour emissions might be managed in part by stocking pens at appropriate rates.

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

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

- Zahn *et al.* (2001a) demonstrated that downwind concentrations of hydrogen sulphide were much lower than the detection threshold. This finding in part explained the previously observed lack of correlation between hydrogen sulphide concentrations and odour concentrations (Hobbs *et al.*, 1999; Hobbs *et al.*, 1998);

- Wright *et al.* (2005) did not detect hydrogen sulphide, dimethyl disulphide or methyl mercaptan in samples collected downwind of a major piggery. They identified 4-methylphenol, 2'-aminoacetophenone, *iso*-valeric acid and 4-ethylphenol as the most significant odorants;

- Trabue *et al.* (2008a) demonstrated that hydrogen sulphide was the dominant sulphur-containing odorant at piggeries, while methanethiol was the principal sulphur-containing odorant in poultry litter (discussed further below);

- Trabue *et al.* (2008b) showed that butanoic acid, 4-methylphenol, 4-ethylphenol, indole and 3-methylindole were the dominant odorants associated with piggery buildings, while butanoic acid, 3-methylbutanoic acid and 4-methylphenol were characteristic of poultry odour.

The work of Trabue *et al.* (2008a) demonstrated that sulphur-containing compounds probably do contribute to intensive livestock odour. They showed that very stringent sampling and storage techniques were required to reduce the impact of moisture on sample composition. By passing the sample through calcium chloride traps, thereby greatly reducing the humidity within the sample, it was possible to detect sulphur-containing compounds within the sample container up to 48 hours after sample collection.

A key outcome of these investigations was identification of the dominant chemical classes responsible for the characteristic livestock odour detected downwind of these operations. Many of the chemicals were polar, water soluble compounds with relatively high boiling points and low vapour pressures.

These chemicals also have low odour detection thresholds. Zahn *et al.* (1997) tabled odour detection thresholds for some of the odorants associated with livestock production, together with what they termed "transport efficiency". The latter term refers to the relative concentrations observed at the source of the odour and 100 m downwind. Selected examples from Zahn *et al.* (1997) are summarised in Table 2.

Table 2:   Transport efficiencies and odour detection thresholds for selected odorants

Compound	Transfer efficiency (%)[a]	Odour threshold ($\mu g/m^3$)[a]
Acetic acid	100	100
Propanoic acid	53	25
Butan-2-ol	89	908
Butanoic acid	76	2.5
Pentanoic acid	37	2.6
Decanol	198	[b]
Hexanoic acid	44	198
Benzyl alcohol	44	[b]
Phenol	12	226
4-Methylphenol	11	8.3

Notes: [a] (Zahn *et al.*, 1997); [b] Odour threshold not available.

More recently, Trabue *et al.* (2008a) tabulated selected chemical properties of a number of odorants. Some of these are reproduced in Table 3.

Table 3: **Physical and organoleptic properties of selected odorants (de Vos *et al.*, 1990; Trabue *et al.*, 2008a)**

Odorant	Molecular weight (g/mol)[a]	Boiling point (°C)[a]	Vapour pressure (kPa)[a]	Odour threshold (µg/m³)[a]
Acetic acid	60	118	2.33[b]	356.3
Propanoic acid	74	140	1.75[b]	108.3
2-methylpropanoic acid	88	155	1.68[b]	70.8
Butanoic acid	88	164	0.15[b]	14.1
3-methylbutanoic acid	102	177	0.07[b]	10.3
Pentanoic acid	102	186	0.04[b]	20.2
4-methylpentanoic acid	116	199	0.0008[b]	22.9
Hexanoic acid	116	205	0.006[b]	60.3
Heptanoic acid	130	222	0.0004[b]	147.4
Phenol	94	182	0.065[b]	424.9
4-methylphenol	108	22	0.017[b]	8.3
4-ethylphenol	122	218	0.029[b]	6.3
4-propylphenol	136	232	0.012[b]	
Indole	117	254	0.002[b]	0.15
3-methylindole	130	266	0.002[c]	3.0
Hydrogen sulphide	34	-59.6	1840[c]	24.9
Carbonyl sulphide	60	-50	1010[c]	135.4
Carbon disulphide	76	115	53[c]	296.4
Methanethiol	48	6.8	205[c]	2.2
Dimethyl sulphide	62	38	45[c]	5.6
Dimethyl disulphide	94	117	3[c]	47.5
Dimethyl trisulphide	126	41	0.8[c]	8.8

Notes: [a](Trabue et al., 2008a); [b] determined at 27 °C; [c] determined at 20 °C

2.2.4 **Odour measurement**

Odour has traditionally been assessed using olfactometry, which determines odour detection thresholds using a combination of gas dilution equipment and trained human assessors. In Australia, odour is assessed according to the Australian olfactometry Standard: AS/NZS 4323.3:2001 *Stationary source emissions - Part 3: Determination of odour concentration by dynamic olfactometry* (Standards Australia/Standards New Zealand, 2001). Odour concentration and emission rates determined using other olfactometry standards may not be comparable to values determined using the Australian olfactometry standard (Department of Environmental Protection, 2002).

While still regarded as the only standardised method for odour measurement, olfactometry is limited when trying to determine the origins and constitution of a particular odour or trying to measure odour in real-time or over an extended period. To achieve these outcomes, technologies such as a non-specific electronic sensor array (sometimes referred to as an artificial olfaction system (AOS) or electronic nose (Sohn *et al.*, 2007a; Sohn *et al.*, 2008)) or gas chromatograph-mass spectrometer-olfactometer (GC-MS-O) are required. The GC-MS-O can be used to identify the chemicals that make up an odour, primarily VOCs, which provides opportunities to identify odour sources and develop specific mitigation techniques. Electronic sensor arrays attempt to replicate the human olfactory response by using multiple sensors, each sensitive to a range of different compounds. By identifying patterns in the sensor responses (magnitude of individual responses and relative difference between sensors), and calibrating these responses against olfactometry measurement (to AS/NZS 4323.3:2001), these sensor arrays are capable of continuously measuring odour concentration in real time with reasonable accuracy.

2.2.4.1 Olfactometry standards

The determination of odour is dependent on the method by which it is analysed and calculated. When reviewing existing odour concentration and emission data, it is critical to understand the method by which the odour samples were analysed, as quite different values will be obtained for the same odour by using alternate methods. Current olfactometry standards also have defined accuracy and precision criteria, which must be met in order for the olfactometry laboratory to be compliant. Similar levels of accuracy and precision were not required by older olfactometry standards.

The Australian/New Zealand Standard AS/NZS 4323.3:2001, is the current standard for dynamic olfactometry. Prior to the development of this standard, several standards had been used in Australia including the Dutch method for olfactometry (NVN2820), the Victorian B2 method and a draft European CEN method, (now EN 13725, *Determination of odour concentration by dynamic olfactometry*).

The Australian and European standards are very similar (with the AS/NZS 4323.3:2001 based on a draft version of the CEN method) and consequently odours measured according to these standards will have comparable odour concentrations and the olfactometers must meet specific accuracy and precision criteria (van Harreveld *et al.*, 2008). The NVN2820 standard defined the odour unit differently to the current Australian Standard, and consequently the odour values measured according to NVN2820 are not directly comparable to odour measurements made according to AS/NZS 4323.3:2001. According to Robertson *et al.* (2002), NVN2820 odour units need to be divided by a factor of approximately two for them to be comparable with the European (and consequently the Australian) olfactometry standards. Demetriou and Bardsley (cited by The Department of Environmental Protection (2002)) found that NVN2820 produced results approximately twice as high as the Victorian B2 method. Consequently, odour measurements made according to the Victorian B2 should be roughly comparable to AS/NZS 4323.3:2001, however comparative testing between the two methods has shown that greater variability occurred when odours were determined with the B2 method (Bardsley, 2002).

2.2.4.2 Odour decay in sampling bags

Odour is a mixture of volatile chemical compounds. Once collected and stored in a sampling vessel, the volatile compounds comprising odour may change over time. To overcome this issue, the olfactometry standard recommends that samples be collected and stored in polytetrafluoroethylene (PTFE, Teflon[®]), polyvinylfluoride (PVF, Tedlar [®]) or polyethylene terephthalate (PET, Nalophan[®], Melinex[®]) bags.

Van Harreveld (2003) investigated the stability of tobacco odour in sample drums and found that odour concentration changed considerably over a 30 hour period. Consequently, it was recommended to undertake olfactometry analysis within 12 hours of collection. Van Harreveld also recommended the use of PET bags over PVF bags for sample storage.

Pollock and Friebel (2002b) undertook a similar investigation as van Harreveld, but used broiler odour. In this investigation, the authors found that odour concentration changed as sample storage time increased, but the changes were dependent on the time of year that the samples were collected, odour laboratory and sample bag. While no firm conclusions were drawn, it was recommended that samples be collected using PVF bags.

Parker *et al.* (2003) and Koziel *et al.* (2004) tested a selection of sample bag materials for suitability to store odour samples. The authors found that Tedlar bags had a background odour due to release of phenol and acetic acid from the bag material, which was sufficient to affect the measurement of odour concentration following 4–24 hours of sample storage. Koziel *et al.* (2004) reported that PET bags (Nalophan[®] or Melinex[®]) provided the best sample recovery of a range of VOCs and semi-VOCs and had no residual interfering compounds that would influence the measurement of odour concentration.

Agreement between the van Harreveld and Koziel *et al.* studies supports the use of PET bags to for the collection of odour samples; however, lack of agreement with the Pollock and Friebel study highlights the need for further research into the stability of odour samples in sample drums for different sources of odour.

2.2.5 Odour and dust relationship

The air in broiler sheds contains a mixture of odorous gases and dust particles. It has been demonstrated that dust particles collected in animal houses carry odorant molecules (Cai *et al.*, 2006; Das *et al.*, 2004; Heber *et al.*, 1988; Lee and Zhang, 2008; Oehrl *et al.*, 2001; Williams, 1989). It is believed that odorants can absorb onto dust particles and produce a much stronger and longer-lasting olfactory response than an equivalent volume of odorous air (Hammond *et al.*, 1981). It has been suggested that odour emissions from animal houses may be reduced by removing dust from the air (Briggs, 2004; Carey *et al.*, 2004; Cargill, 2001; Lacey *et al.*, 2004; McGahan *et al.*, 2002; Ministry of Agriculture and Food, 1999). There is, however, some doubt that removing dust will significantly reduce the detection threshold for odour (Williams, 1989). To date, attempts to correlate dust removal and subsequent odour reduction using olfactometry have been unable to demonstrate any correlation between dust removal and subsequent odour reduction (Simons, 2006; Williams, 1989).

The relationship between dust and odour is very complicated. While it has been confirmed that dust particles carry odorant molecules—adsorbed onto the surface or absorbed into the particle—it is unclear how much of the odour bound to the dust contributes to the total perceived odour emitted from a poultry shed. Olfactometry is unlikely to be an appropriate instrument for resolving this question because the olfactometer instrument almost certainly filters out dust particles—only allowing measurement of odours in the gas phase only, not odours associated with particulates. In addition, Williams (1989) found that dust concentration in odour sample bags quickly diminished due to static attraction of dust to the plastic bag material. It was proposed that particles were electrostatically attracted to the plastic bag material.

A methodology is yet to be developed that will enable the contribution of odour laden dust to the total perceived odour to be quantified.

2.2.6 Broiler farm odours

Odour generation and emission is a normal part of broiler production. Odours are produced in broiler operations primarily from the microbial decomposition of faeces (Jiang and Sands, 2000); some odours may also be emitted from the birds themselves (Lacey *et al.*, 2004). Odours generated in the shed are emitted from the shed through the ventilation fans. The generation and emission of odour is presumed to be regulated by numerous factors relating to: litter properties; moisture content of the litter; temperature; ventilation; dust levels; the birds (age, live weight, activity, health status, stocking density); and weather. The diagram in Figure 6 attempts to demonstrate the complex and intertwined relationship between these factors and odour emission rate. These factors often interact with each other, and some are dependent on each other. These interactions and dependencies make it very difficult to identify the causes of increased odour emission. The generation of odour is usually influenced by factors that will affect microbial activity, while emission rates are affected by odour generation as well as the factors that influence the capture, mixing and transport of odour from the shed.

Odours have the potential to create a nuisance for nearby neighbours. The most effective ways to prevent odour or dust nuisance is to ensure adequate buffer distance between farms and receptors (McGahan and Tucker, 2003) and to prevent excessive odour generation through good management practices. The potential for odour nuisance to occur is investigated during odour impact assessments, and results in the calculation of separation distance between farms and neighbours. Separation distances are determined using either: approved guidelines for recommended distances (Department of Primary Industries - State Government of Victoria, 2009); simple formulas incorporating features of the farm, landscape and receptor (Environment Protection Authority South Australia, 2007); or estimating emission rates and using atmospheric dispersion modelling to predict impacts.

Accurately measuring representative odour emission rates from broiler farms can be challenging. Previous attempts to measure emission rates have demonstrated the influence of the factors shown in Figure 6 on odour emission rates. When reviewing published odour emission rate data, these factors require careful consideration.
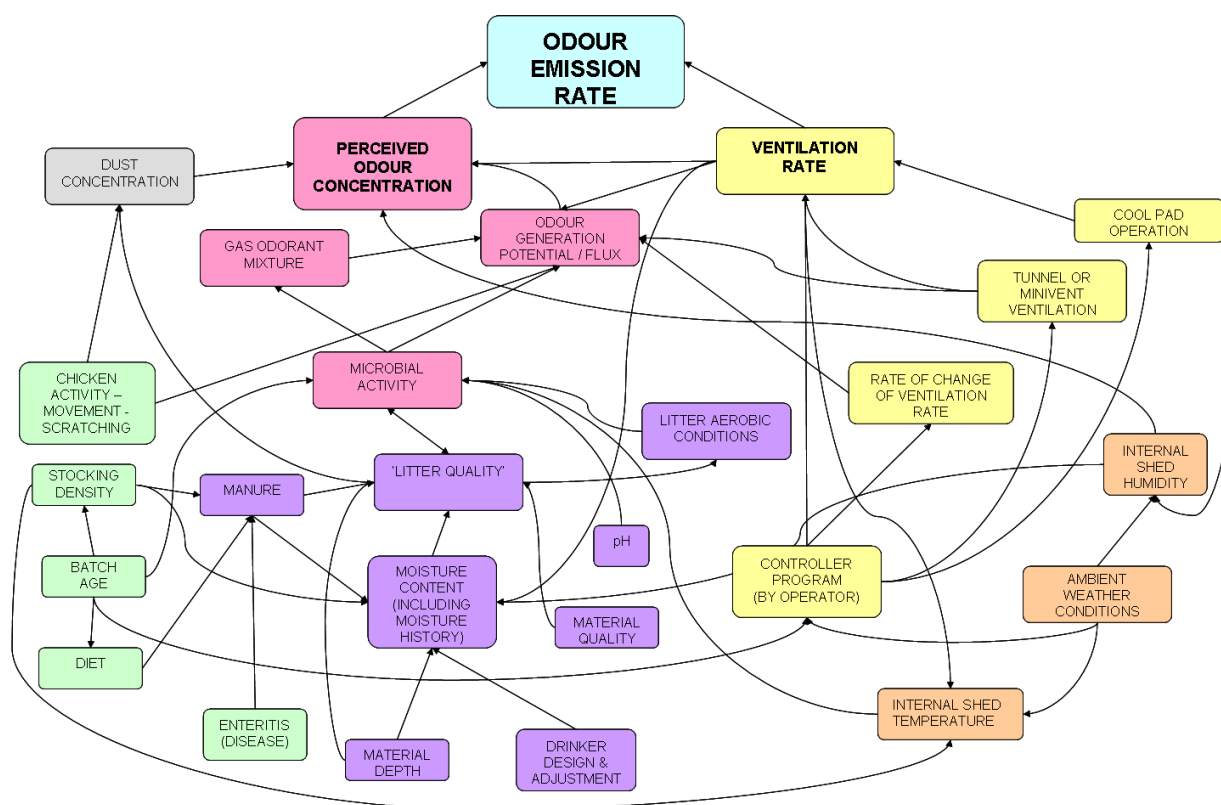
Figure 6: Diagram illustrating the interaction between farm conditions, environmental conditions and odour emission rate

2.2.6.1 Factors influencing odour generation at broiler farms

There are several properties of broiler litter that will influence odour generation including chemical composition, quantity, aeration, pH and moisture content. Conditions that favour microbial activity are likely to increase odour emissions.

Chemical composition of the litter will be influenced by bird diet and stage of decomposition. Gates (cited in McGahan *et al.* (2002)) found that reducing crude protein levels in the diet reduced pH, moisture content and ammonia in the litter, resulting in a reduction of ammonia gas production. Reduction in ammonia may not necessarily equate to a reduction in odour emissions (Briggs, 2004); however, it demonstrates that diet will influence microbial activity and the subsequent generation of gasses during the litter decomposition process. Turan *et al.* (2007; 2009) measured VOC emissions during broiler litter composting and found that VOC emission rates changed significantly over time, as the decomposition of the litter progressed. Consequently, odour emission rates would be expected to change as litter is decomposed.

A review by Cargill (2001) found that live weight density was a cause of increased odour production in poultry houses. Jiang and Sands (2000) also reported that as bird age increased, manure accumulation also increased leading to greater odour generation. Increased live weight density (by increasing bird numbers or bird age) will increase manure deposition leading to increased nutrient and moisture levels and greater physical disturbance of the litter, which combine to increase odour emissions.

Jiang and Sands (2000) reported that odour generation will take place under aerobic and anaerobic conditions. Aerobic decomposition will occur in the presence of oxygen and anaerobic decomposition is more likely to occur in wet, caked litter where oxygen supply is reduced. Anaerobic decomposition is often attributed to the production of highly odorous (and unpleasant) sulphurous compounds, but odorous compounds containing nitrogen will still be produced during aerobic biodegradation (McGahan *et al.*, 2002).

Jiang and Sands (cited in McGahan *et al.* (2002)) reported that pH was an important factor for odour emissions because it influenced the formation of anaerobic conditions; microbial activity; and chemistry within the litter. Moore *et al.* (1995), Moore *et al.* (2006) and Gates (cited in McGahan et al. (2002)) reported changes in ammonia emissions with changes in litter pH.

Possible influence of litter moisture content on odour emissions

Litter moisture content is presumed to be one of the most critical factors affecting odour production in poultry sheds (Carey *et al.*, 2004; Clarkson and Misselbrook, 1991; Jiang and Sands, 2000; McGahan *et al.*, 2002; Scottish Environment Protection Agency (SEPA), 2008). Moisture content is expected to affect odour generation because water acts as a catalyst in the processes of odour generation, transfer and transport (Jiang and Sands, 2000); will increase microbial activity (Carey *et al.*, 2004); and high levels of moisture content will tend to increase anaerobic bacterial activity (McGahan *et al.*, 2002). Excessive litter moisture can occur for a variety of reasons including high ambient humidity; poor ventilation system design or operation; high stocking density; flock health problems; leaking drinkers; leaking shed; seepage of water from outside; or from poor management of evaporative coolers and fogging systems.

It is commonly believed that odour emission rate increases with litter moisture content. Data reported by Clarkson and Misselbrook (1991) (see Figure 7) suggested that odour emission rates increase dramatically once litter moisture content increases above 40%. This data should not be taken on face value because:

- other factors such as bird age and weight increased concurrently with litter moisture content;

- these measurements were taken in early 1989, which is late winter or spring in England. It could be reasonably expected that the weather was warmer at the end of the batch and consequently ventilation rate and emission rate would also be greater;

- the shed involved in Clarkson and Misselbrook's study was ridge ventilated and therefore different to current best practice shed design in Australia; and

- odour measurements were not conducted to a recognised, modern olfactometry standard (which was not available in 1989) and consequently the precision and accuracy of these odour measurements cannot be assured. The highest recorded value was based on a single measurement, and due to the inherent variability in olfactometry, could be an outlier.
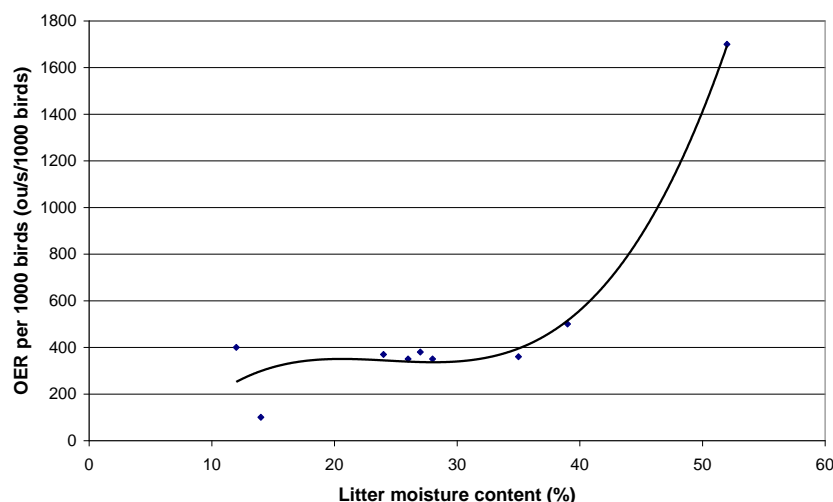
Figure 7: **Increasing odour emission rate with litter moisture content (derived from Clarkson and Misselbrook (1991))**

In contrast to the increase in odour emission with litter moisture content seen by Clarkson and Misselbrook, data presented by Sneath and Robertson (2000) and Simons (2006) (see Figure 8) shows no increase in odour emission rate with increasing litter moisture content.
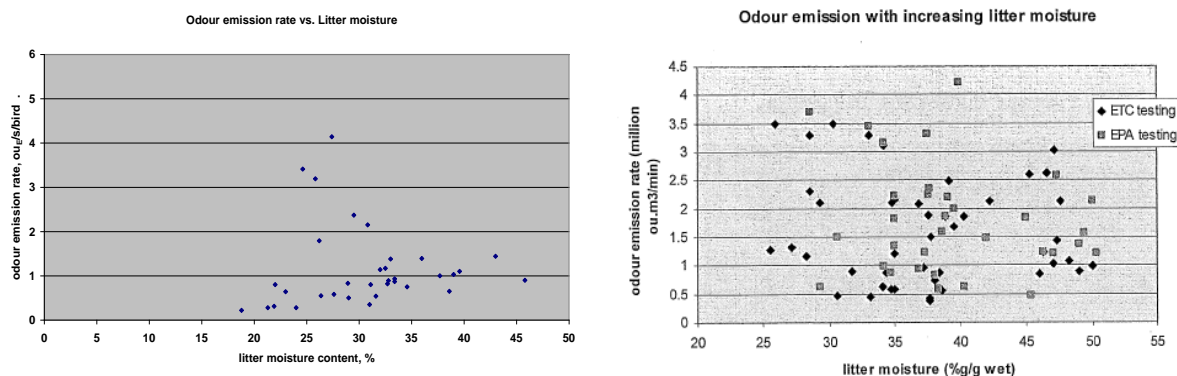
Figure 8: **Odour emission rate versus litter moisture content from Sneath and Robertson (2000) (*left*) and Simons (2006) (*right*)**

While the relationship between litter moisture content and odour emission rate has not been clearly established in these three previous studies, broiler growers work on the presumption, based on their own experience, that high litter moisture content (greater than 40% (McGahan and Tucker, 2003)) leads to increased odour emissions. It is likely that the previous research studies did not observe this relationship because:

- The research studies measured shed-average litter moisture, not range or profile of moisture content throughout the shed or the existence of small areas of wet litter. A small patch of wet litter may emit a strong odour, contributing to the overall shed emission while not significantly increasing the measured shed-average litter moisture content.

- There is likely to be a time delay between wetting of the litter and the increase of odour emission. Lunney and Lott (1995) and Watts *et al.* (1994) reported that feedlot odour emissions peaked approximately one to five days following rainfall. The delay occurs because the microbial community requires time to increase activity, and it takes time for the manure to become anaerobic. In addition, Klieve *et al.* (1995) found that this microbial activity in the wet feedlot manure pad forms a polymer-like sheet on the surface which may reduce evaporation and prolong the manure drying process— which also prolongs the production of odours. Whilst there are differences between the feedlot and broiler situations, odours in both cases are generated through microbial activity. It is therefore likely that there may be a delay between the wetting of poultry litter, and an increase in odour emission. This delay is likely to vary according to temperature, moisture content, microbial activity, litter composition and physical litter characteristics such as litter friability.

- The exchange of odorants from the litter to the air is controlled by complex mechanisms which may be restricted when litter is wet and caked, as explained by Simons (2006). Caking and compaction of the litter prevents the birds from disturbing the litter, which assists the transfer of odorants into the air stream. It may be possible, therefore, that dry, friable litter will increase the transfer of odorants into the air when compared to wet, caked and compacted litter. The understanding of the emission processes is further complicated by the differences in diffusion mechanisms of odorants through pore spaces in dry, porous materials as opposed to through liquids in saturated materials (Hudson *et al.*, 2009).

Further research is required to completely understand the relationship between litter moisture content and odour generation in broiler farms.

Possible influence of ventilation on odour emissions

Ventilation influences odour generation, transfer and transport.

Broiler shed ventilation is primarily controlled to remove heat from the shed, maintaining a comfortable and healthy environment for the birds. As the internal temperature of the shed increases, more fans are activated to remove the heat and maintain the temperature.

Effective ventilation management will contribute to maintaining good litter moisture content (between 15% and 30% wet basis (McGahan and Tucker, 2003)), reducing anaerobic microbial activity and generation of odours (McGahan *et al.*, 2002).

Ventilation is a critical factor influencing odour emissions from broiler sheds. Odour emission rate (OER) is the product of odour concentration (OC) and ventilation rate. Assuming that odour concentration remains constant, changes to ventilation rate will result in proportional changes to odour emission rate.

Ventilation will also influence the transfer or release of odorants from emitting surfaces to the air (litter, building surfaces and the birds). These processes are controlled by physical air movement as well as the concentration of odorants in the air. Hudson *et al.* (2009) and Hudson and Ayoko (2009) demonstrated that emission of odour from area sources—such as poultry litter—are strongly related to wind speed. Therefore, the mass transfer of odorants from the litter is very likely to be primarily controlled by advection processes (driven by wind speed).

Jiang and Sands (2000) explained the relationship between ventilation rate and the emission of odour from the litter using boundary layer theory (as defined by Schilichting and Gersten (2000); and Incropera *et al.* (2007)). Boundary layer theory explains the mass transfer process at the solid/air and liquid/air interface and may be used to relate the rate of evaporation of an odorant to its diffusion characteristics, temperature, air velocity across the surface and the geometric dimensions of the source. Using this theory, the airborne chemical concentration for each odorant is a function of the air velocity across the surface of the litter and the birds.

The concentration of odorants in the shed may also be an important factor for regulating the transfer of compounds from the litter surface into the gas phase, especially when in-shed airspeed is negligible. Gholson *et al.* (1989) and Gholson *et al.* (1991) (in describing the operation of a flux chamber) reported that as the gas phase concentration increases, the liquid/gas phase equilibrium will be affected and the transfer of compounds from the surface to the air will be reduced. The transfer rate will be different for every odorant compound, depending on its Henry's Law constant. This equilibrium theory can be equally applied to poultry sheds where variable ventilation rates will result in different gas concentration within the shed, and presumably the emission rate of odorants from the litter and other surfaces into the air will also vary.

The mechanisms described by Hudson *et al.* (2009) and Hudson and Ayoko (2009), and to a lesser extent Jiang and Sands (2000) and Gholson *et al.* (1989), provide a overall description of the transfer of odorants from emitting surfaces into the airstream, and the importance of ventilation to the odour transfer process. In plain English, odorants produced by microbial degradation (Jiang and Sands, 2000) are adsorbed onto litter surfaces (and moisture contained within the litter), building surfaces and the birds. When the concentration of odorants in the shed is high and airspeed low, the transfer of these odorants into the air will reduce until equilibrium is achieved. When the odorant concentration is reduced or airspeed increases, presumably by introducing fresh air into the shed with increased ventilation, the transfer rate of odorants into the airstream will increase (possibly only temporarily) until a new equilibrium is achieved. Considering the highly variable ventilation activity in poultry houses, it would be expected that the transfer of odorants into the air, in-shed odour concentration, and subsequent emission of odour from the shed will be highly variable.

2.2.6.2 *Previously reported broiler shed odour emission rates*

Accurately measured odour emission rates are essential for providing realistic predictions of impacts using odour dispersion modelling. Only limited odour emission rate data has been published for intensive broiler production. Much of the previously measured odour emission rate data has unfortunately lost relevance due to changes in olfactometry standards and recent changes to broiler farm design and management.

Pollock and Anderson (2004) reviewed the available odour emission rate data that was available and found that most had been collected for research projects (Jiang and Sands, 2000) or by consultants in the

course of collecting data for odour impact assessments (Mirrabooka Consulting, 2002; Pacific Air and Environment, 2003; Pollock and Friebel, 2002a). In this review, data was adjusted for presentation as odour emission rate per thousand birds placed at the start of the batch ($OER_{1000\ birds}$), using units $ou/s_{1000\ birds}$.

Odour emission rate data from Jiang and Sands (2000) is difficult to extract because the dataset is incomplete (especially in terms of ventilation rate). By combining the available data and making assumptions that the ventilation rates are matched to the odour concentration data, the odour emission rate at three Victorian tunnel ventilated farms ranged from 40 to733 $ou/s_{1000\ birds}$. It is important to note that this data was collected between days 29 and 44 of the production cycle, following the harvesting of some birds from the shed. It is therefore likely that the measured odour emissions were lower than they would have been at the peak of the batch, on day 35 prior to the first pickup. Also, ventilation rates reached approximately 75–80% of the maximum available. Odour analysis was performed to the NVN standard, which is different to the Australian Standard AS/NZS 4323.3:2001 and requires the measured emission rates to be approximately halved to be comparable to the current Australian Standard.

Mirrabooka Consulting (2002) measured odour emissions at a broiler farm near Tamworth on a weekly basis throughout a batch. For this sampling, the shed was fitted with cup drinkers, which are not commonly used in modern sheds and are often reported to cause water spillage and consequently higher litter moisture content and stronger odour. Odour samples were collected and analysed according to the Australian Standard AS/NZS 4323.3:2001. Odour emission rates ranged from 66–742 $ou/s_{1000\ birds}$ (see Figure 9). Mirrabooka Consulting (2002) also reported odour emission rates for a broiler shed fitted with nipple drinkers, which ranged from 235–416 $ou/s_{1000\ birds}$.
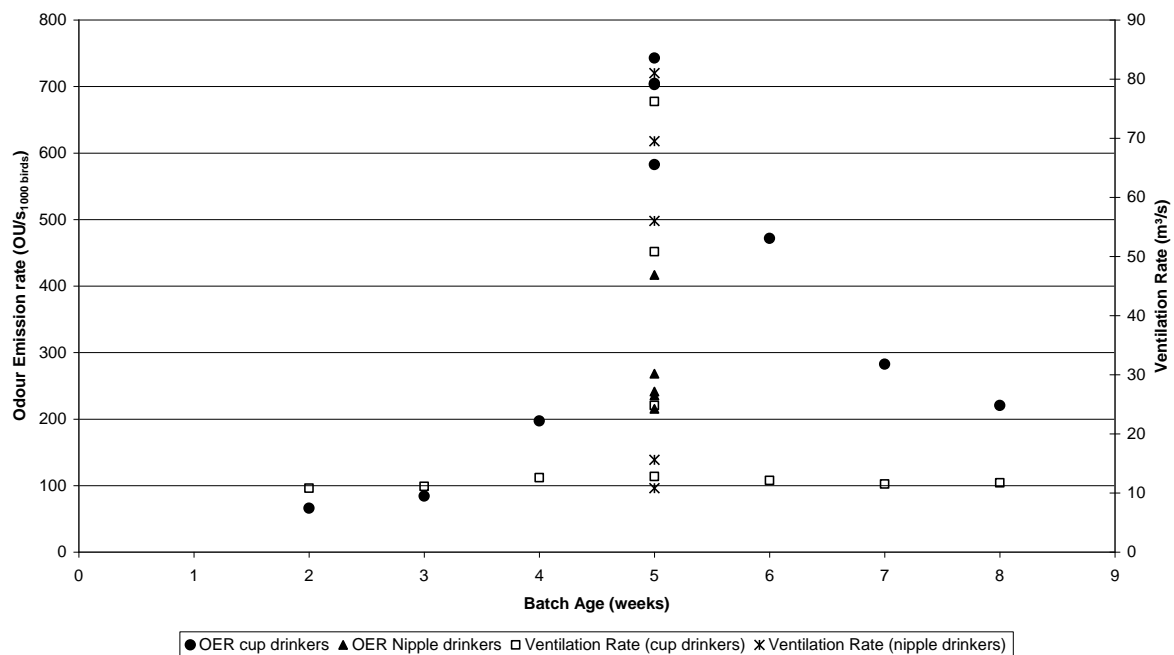
Figure 9: **Odour emission and ventilation rate at a broiler shed (data derived from Mirrabooka Consulting (2002))**

The odour emission rates reported by Mirrabooka Consulting indicated that the use of nipple drinkers may reduce odour emission rates from broiler sheds. Unfortunately, litter conditions in the shed were not reported, and may have been a contributing factor to the reduction in odour emission rate. Another important consideration is that emission rates at both sheds were measured in winter (July and August), when cool conditions dictated that minimal ventilation was required and consequently, most odour measurements were undertaken at 12–15% of the maximum ventilation rate in the shed.

Pollock and Anderson (2004) reported that Mirrabooka Consulting had manually overridden the ventilation system controls (for the week 5 sampling), rather than allowing the system to respond to temperature demands within the shed. This act may have influenced the measured odour emission rates.

Pacific Air and Environment (2003) measured odour emissions at three tunnel ventilated broiler sheds in Queensland. It is stated that the samples were not analysed according to AS/NZS 4323.3, but the method of analysis was broadly compatible. Measurements were made in 1999. Odour emission rates ranged from 380–2300 $ou/s_{1000\ birds}$ at a variety of times throughout the batch and at different ventilation rates.

Ormerod and Holmes (2005) presented a figure comparing odour emission rate ($ou/s/kg_{live\ weight}$) against ventilation rate and used this data to rate the odour potential of a range of farms. Odour emissions ranged from 0.2–1.1 ou/s/kg.

Robertson *et al.* (2002) provided a summary of odour emission rates for broilers and reported that odour emission rates varied from 60–970 $ou/s_{1000\ birds}$ (measured to the European Standard and therefore comparable to the Australian Standard). Samples were collected at a commercial broiler shed housing 34,000 birds, however the shed was not tunnel ventilated instead utilised roof ridge fans.

2.2.7 Summary of background information on odour

Odour in general

- Odour is extremely complex—measured in four dimensions: odour threshold, intensity, character and hedonic tone—and is usually comprised of numerous odorous compounds (odorants).

- Odour threshold is measured using olfactometry. Artificial olfaction systems (AOS) and gas chromatography–mass spectrometry–olfactometry (GC–MS–O) are complementary instrumental methods that can provide additional detail about odour. Odours are analysed according to the Australian/New Zealand Standard AS/NZS 4323.3:2001.

- Odour measurement standards have changed over time so prior odour measurement may not be comparable to current values.

- Odorous gas mixtures are not stable, which can change the nature of an odour and also necessitates timely analysis of odour samples.

- Relationships between odour and dust have been hypothesised, but the effect of dust on perceived odour had not been quantified.

Broiler farm odours

- Odour is produced by the microbial degradation of organic matter (manure).

- Factors influencing odour generation include: chemical composition; manure loading; temperature; litter moisture; aerobic/anaerobic status; litter physical properties and disturbance (influence odour release); ventilation and shed aerodynamics; and many other factors.

- The effects of the above factors on odour generation and emission are extremely complex.

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Previously published broiler odour emission rates

- It has been hypothesised that odour emission rates are influenced by many factors including weather, litter, ventilation, birds (age, mass and number), shed design and farm management practices. **It is therefore likely that odour emission rates will vary between farms, diurnally, throughout each batch cycle and throughout the year.** The emission rate data collected to date does not adequately demonstrate the full range and variability of odour emissions. Maximum odour emission rate typically occurs before the first pickup—usually around day 35.

- Litter moisture has been reported as a contributing factor to excessive odour generation and further research needs to be conducted to quantify the delay between wetting of the litter and increased formation of odour.

- Previously reported broiler shed odour emission rates have not included essential supporting data—odour emission rate data MUST be supported by information including shed dimensions, ventilation system description (including maximum possible ventilation rate), bird age, bird numbers, bird weights, ventilation rate, ambient temperature, odour concentration and preferably litter conditions. This information must be recorded at the time of each odour sample and is required to put the odour emission rates in context with weather conditions and production factors.

- Published odour emission rate data for broiler farms is of limited value—

  Most of the published odour emission rates have been measured using olfactometry methods/standards that are not equivalent to the Australian Standard AS/NZS 4232.3:2001. Consequently, data is not truly comparable. Relationships between the Australian, Dutch NVN2820 and Victorian B2 standards have been published, and can be used to roughly equate data to the Australian Standard; however, caution is required because accuracy and repeatability requirements for the older standards were not as stringent as they are for the current Australian Standard.

  Odour emission rate measurements have not been reported throughout the full grow-out cycle and for the full range of weather conditions experienced on Australian broiler farms. Limited emission rate measurements in cooler weather; at low ventilation rates; and after birds have been removed from the shed, cannot be equated to the emissions from a broiler shed with peak bird weight and maximum ventilation rate.

- Previously reported broiler shed odour emission rates ranged from 40–2300 $OU/s_{1000\ birds}$.

2.3 **Dust**

Dust emissions from broiler sheds occur due to two general processes. Firstly, animal activity or the movement of air causes the mechanical breakdown of mineral and organic material from the litter and birds and entrainment of this material into the air. Secondly gaseous emissions, such as nitrous oxide (N_2O) and ammonia (NH_3), may be converted to the particle phase under the right conditions, adding to the total dust emissions from a poultry shed.

This section will highlight these possible health and environmental impacts and introduce some concepts used to characterise and measure particulates.

2.3.1 Measurement of particle concentrations—mass or number?

Particles suspended in the air can vary in size by many decades from ~10^{-9} m up to ~10^{-3} m. Particles in different size ranges will contribute to different health and environmental impacts. For this reason dust measurements are generally classified by particle size. Airborne particles that are less than ~100 µm in diameter are collectively referred to as total suspended particulate matter (TSP). Particles that are less than 10 µm are defined as PM_{10}. The PM_{10} size fraction is usually grouped into two size categories: coarse particles, with a diameter from 2.5–10 µm, and fine particles, with a diameter of up to 2.5 µm ($PM_{2.5}$). Even smaller size fractions are becoming increasingly important and many studies now report the concentration of particles smaller than 1 µm (PM_1), or even particles smaller than 0.1 µm (ultra-fine particles). The definitions of particle size ranges can vary between countries and particle sampling devices. For example, many European studies of dust emissions from intensive livestock production refer to the 'inhalable' and 'respirable' particles, referring to the particles less than 30 µm and 5 µm, respectively. Although the size ranges do not match exactly, inhalable particles can be compared to TSP.

Particle or dust levels in the air are generally measured as either a mass concentration or number concentration. Mass concentration refers to the mass of PM per unit volume of air and is commonly expressed in units of mg/m³. Number concentration refers to the number of particles per unit volume of air and is commonly expressed in units of particles/m³. Which concentration metric is used in a given environment will primarily depend on the size distribution of particles in that environment. For example if a given sample of air contains a large number of ultra-fine particles (diameter < 0.1 µm) and only a very small number of larger, coarse particles (diameter > 2.5 µm) then the total mass of the particles will still be dominated by the small number of larger particles. To 'see' the ultra-fine particles it would be more appropriate to measure their number concentration. Traditionally, allowable particle concentration levels expressed in air quality guidelines have been expressed as mass concentrations. However with a consensus emerging that fine and ultra-fine particles are more damaging to human health than coarse particles, it is becoming more common to measure particle number concentrations. In many situations it is most desirable to measure both particle mass and number concentration.

2.3.2 Potential health effects of dust

Dust particles can act as a reservoir for bacteria, other disease carrying agents and noxious gasses, such as ammonia. Dust concentrations in intensive animal production sheds can build up to levels that are high enough to adversely affect animal health and productivity. However, there is doubt regarding the specific levels required to induce these adverse effects. In tunnel ventilated poultry sheds, the ventilation rate of air through a tunnel shed is highly variable, with higher rates of ventilation in warm summer weather; and the opportunity for high dust concentrations will also be variable depending on ventilation rate, litter conditions and bird activity. These factors can contribute to amount of dust being emitted from the exhausts of tunnel ventilated sheds into the ambient air.

The effects of dust on health and the environment are dependent on the size of the particles; categorised in terms of TSP, PM_{10} and $PM_{2.5}$. TSP is typically associated with adverse aesthetic effects rather than human health effects because these particles tend to settle out on surfaces causing soiling and discolouration. Larger particles (> 10 µm) are usually trapped in the human nose and throat before being swallowed. PM_{10} particles (particles < 10 µm) travel further down the human airway into the lungs and they are associated with increases in respiratory illnesses such as asthma, bronchitis and emphysema. Particles in the PM_{10} size fraction have been associated with increases in the daily prevalence of respiratory symptoms, hospital admissions and mortality (Pope *et al.*, 1995). The people most sensitive to these conditions include the elderly, children and those with pre-existing heart problems or respiratory diseases. Particulates can accumulate in the lungs after repeated, long-term exposure causing respiratory distress and other health problems. Specific health effects of dust will depend on composition, concentration and the presence of other pollutants.

Particles in the $PM_{2.5}$ size fraction have been associated with health effects similar to those of PM_{10} (Pope and Dockery, 2006). When inhaled, the weak gravitational force felt by these small particles enables them to travel inside the lungs to be deposited in the alveoli.

Particle composition, especially the presence of microbial organisms, can influence the health effects of particulate matter. For example, both harmless and pathogenic bacteria are known to be emitted in the exhaust of tunnel ventilated broiler sheds (Blackall *et al.*, 2008). This study concluded that the pathogenic bacteria were emitted rarely from broiler sheds and concentrations were too low to cause any significant human health effects.

2.3.3 Dust concentrations and emissions from poultry farms

Dust emissions from poultry farms have been studied for at least three decades. However, ongoing research is required due to recent advances in large-scale poultry production and increasing recognition of the potential health effects of particulate matter. In addition, the mechanisms behind dust generation from poultry sheds are not yet completely understood. These mechanisms need to be elucidated in order to design strategies for reducing dust emissions.

Poultry dust consists of a litter materials, feathers, dander, faeces, and crystalline urine. This suggests that dust is generated from birds, manure and litter in poultry sheds. Many interdependent factors can affect poultry dust levels including:
- bird age;
- ventilation rate;
- shed design (type of litter, ventilation system, manure removal system, feeding system);
- in-shed microenvironment (temperature, relative humidity, light levels);
- season;
- time of day;
- stocking density;
- cleaning practices;
- bird handling;
- residual dust levels;
- moisture content of litter and feed; and
- nearby dust sources.

Much of the research concerning dust concentrations and emissions from poultry sheds has been conducted in the USA or Europe, although some has also been conducted in Australia. The results from studies have been tabulated in Appendix 1; and a combined summary of the particulate concentrations and emission rates is provided in Table 4. It should be noted that variations between dust concentrations and emissions measured in different studies could be due to all of the factors listed above, as well as differences in instrumentation and methodologies. As can be seen in the table, studies have been conducted at broiler sheds with natural, mechanical and tunnel ventilation systems. In-shed TSP concentrations range from 0.74–16 mg/m³, although one study reported concentrations as high as 81.33 mg/m³. PM_{10} or PM_5 concentrations are generally lower and vary from 0.1–9.71 mg/m³. Recently, a number of studies have measured the concentrations of the smaller particle size fractions ($PM_{2.5}$ and PM_1) in recognition of the greater health effects of these particles. Results from these studies are included in Appendix 1.

Dust emission rate from a poultry shed is calculated by multiplying dust concentration by ventilation rate. Emission rates are generally expressed in units of mass of PM emitted per unit time. Many studies also calculate the emission rate per 500 kg live weight in order to compare rates between different sheds. Table 4 displays emission rates per 500 kg live weight in square brackets. These normalised rates are converted to the particle emission rate, in units of mg/s, for a hypothetical shed with 40,000 birds at an average weight of 1.8 kg. This is done to enable easier comparison with the emission rates measured during this study, and also to allow a more intuitive understanding of the measured rates.

Only a limited number of studies have been conducted at tunnel ventilated poultry sheds. Redwine *et al.* (2002) measured PM emission rates from four commercial, tunnel ventilated broiler sheds in Texas, USA. During the study, ventilation rates varied from 0.58 to 89 m³/s leading to TSP emission rates up to 3.5 mg/s/500 kg live weight and PM_{10} emission rates up to 0.21 mg/s/500 kg live weight.

Visser *et al.* (2006) performed a study at a tunnel ventilated broiler farm consisting of 7 sheds (each with 26,200 birds) in the USA. Comprehensive $PM_{2.5}$ concentration measurements were taken upstream of the sheds (control); within the sheds at the exhausts; and 30 m, 91 m and 152 m downstream of the sheds. The 24 hr time integrated $PM_{2.5}$ concentration measured within the sheds averaged 0.059 μg/m³, which is significantly greater than the average concentration measured upstream of the sheds, 0.024 μg/m³. However, the 24 hr time integrated average concentrations measured downstream of the sheds (30 m: 0.0241 μg/m³; 91 m: 0.0249 μg/m³; 152 m: 0.0231 μg/m³) were not significantly different from each other or the control. Real-time concentration measurements did hint that $PM_{2.5}$ concentration decreased with increasing distance downstream from the sheds. Importantly, the overall conclusion of the study was that dust emissions from these 7 tunnel ventilated broiler sheds did not significantly affect $PM_{2.5}$ concentrations in the surrounding ambient air.

Bull (2008) performed a study to measure ambient PM_{10} concentrations near a broiler farm in the United Kingdom that housed approximately 250,000 birds. A monitoring station was established and PM_{10} concentration was measured for approximately 7 months over a 12 month period. This study found that daily average PM_{10} concentrations were typically about half of the ambient objective value (50 μg, 24-hour average) and whilst there were a few occasions when the daily average exceeded the objective, occurrence was much less often than what was allowable. The authors concluded that ambient PM_{10} concentrations around broiler farms (at typical receptor distances) are unlikely to exceed the daily mean ambient air quality objective for PM_{10}.

A review of the measurements of dust at Australian poultry farms has been conducted by Pollock and Anderson (2004). The results of studies reviewed by Pollock and Anderson are included in Appendix 1 but they will not be discussed in further detail here.

Table 4: Summary of reported particulate concentrations and emission rates for broilers

| | Ventilation type | Country | Concentration (mg/m³) | | | | | Emission rate, ER (mg/s) [ER per 500kg live weight (mg/s/500kg)] | | | | |
			TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	PM_1	TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	PM_1
Broiler	Mechanical	Australia	4.7–16	1.6–6.3				54–1230 [nr* –8.54]	17–139			
	Mechanical	Overseas	0.7–13.2	0.1–0.7	0.6–9.71	0.024–0.19	0.16	2.8–504 [0.02–3.5]	0.12–30 [0.001–0.21]	24.5–34.6 [0.17–0.24]	2.03 [0.014]	1.65 [0.01]
	Various#	Australia	2.3–8.6		0.3-1.8			85–298 [0.6–2.1]		10–100 [0.07–0.7]		
	Natural	Overseas	1.0–14.0									
	Various#	Overseas	7.1–9		0.8–6.5		0–5.7	158 [1.1]	3.2 [0.2]	20.7 [0.14]		
Not specified	Various#	Overseas	0.02–81.3		0.01–7.73							

#measurements collected from both mechanically and naturally ventilated buildings; or ventilation type not specified
*not reported

2.3.4 Summary of background information on dust

Dust in general

- Airborne dust originates from suspension of mineral and organic materials or by the conversion of gases.

- Dust concentration is measured in terms of mass and/or number of particles.

- Dust is categorised according to particle size ranges (especially TSP, $PM_{2.5}$, and PM_{10}).

- Dust has been linked to health and environmental effects.

Poultry farm dust

- Dust originates from the litter, feed and the birds (skin and feathers particles).

- Factors influencing dust generation include: type of litter; physical litter properties; litter moisture content; bird activity; stage of production (number and size of birds); contribution of feathers; shed design; shed cleaning and management; ventilation; and feed properties.

- Studies have shown that air surrounding broiler farms is unlikely to be significantly affected by dust emitted from the sheds, and ambient air quality objectives for particulates are unlikely to be exceeded.

Broiler dust emission rates

- Previously measured dust concentrations have been highly variable, and categorised according to the various size categories. Refer to Table 4 for summary of reported values.

2.4 Non-methane volatile organic compounds

Odour has traditionally been assessed using olfactometry, which determines odour detection thresholds using a combination of gas dilution equipment and trained human assessors. While still regarded as the only standardised method for odour measurement, olfactometry is limited when trying to determine the origins and constitution of a particular odour or trying to measure odour in real-time or over an extended period. To achieve these outcomes, technologies such as a non-specific electronic sensor array and/or gas chromatograph-mass spectrometer-olfactometer (GC-MS/O) have more recently been applied to the assessment of emissions from intensive livestock operations. GC-MS/O allows the chemical compounds to be separated and identified, with simultaneous identification and characterisation of the odorants according to their perceived intensity and character.

2.4.1 Gas chromatography analysis of odours

Emissions from different intensive livestock operations comprise different chemicals and odorants. Wright *et al.* (2005), Hobbs *et al.* (2004) and Jacobson *et al.* (2006) studied the different compounds that were identified in the emissions for different intensive livestock facilities; the comparisons drawn by Hobbs *et al.* (2004) serve to highlight these differences. As different compounds have different odour detection thresholds, some species that gave an olfactometry response did not always correspond to a response from any other detector, conversely some compounds with large detector responses gave little or no olfactometry response. Speculation is often made as to the identity of the compound based upon it odour characteristic and associated compounds within the matrix.

Studies have been undertaken that focus on particular intensive livestock operations. Studies carried out by Kai & Schäfer (2004), Blunden *et al.* (2005) and Bulliner *et al.* (2006) focussed upon the chemical

analysis of emissions from swine facilities, while Rabaud *et al.* (2003) analysed the emissions from dairy facilities. Work specifically relating to intensive broiler production has primarily focused on the general quantification of the odour emissions and not the identification of the odorants; Hayes *et al.* (2006) and Pescatore *et al.* (2005) reported ammonia emissions from intensive poultry facilities, whilst Williams (1989) reported the relationship between dust and odour from broiler houses.

Table 5 lists recent publications that focussed on the investigation of odorant emissions from intensive livestock operations.

Table 5:   Chemicals reported in different intensive livestock operation emissions

Reference	Chemical Observations
Zahn *et al.* (2001a)	Reported that downwind concentrations of hydrogen sulphide were much lower than the detection threshold.
Wright *et al.* (2005)	Identified 4-methylphenol, 2-aminoacetophenone, iso-valeric acid and 4-ethylphenol as major odorants in piggery emissions.
Trabue *et al.* (2008a)	Reported hydrogen sulphide was the dominant sulphur-containing odorant at piggeries, while methanethiol was the principal sulphur-containing odorant in poultry litter.
Trabue *et al.* (2008b)	Reported butanoic acid, 4-methylphenol, 4-ethylphenol, indole and 3-methylindole were the dominant odorants associated with piggery buildings, while butanoic acid, 3-methylbutanoic acid and 4-methylphenol were characteristic of poultry odour.

2.4.2 **Olfactory-GC-MS analysis of odorants**

Olfactory-GC (GC/O) and GC-MS/O is a well established techniques in other science fields, such as food aromas and taste and odours in drinking water, but has had limited application to environmental odour analysis. In drinking water, taste and odour (or off-flavours) monitoring using GC-MS/O analysis has been successfully applied to the characterisation of common earthy and musty off-flavours compounds such as geosmin and MIB (2-Methylisoborneol) (Hochereau and Bruchet, 2004). These studies have enabled the development of odour wheels for drinking water olfactory assessment (Figure 10) to relate odour descriptors to the chemical composition of odorants (Suffet *et al.*, 1999). Odour wheels are used by water operators and in customer complaint evaluations to determine a cause-and-effect relationship between the water quality and operational failures.

Figure 10: **Taste and odour wheel for off-flavours in drinking water (Suffet *et al.*, 1999) showing the highlighted relationship between earthy – musty odours and compounds, geosmin and MIB (2-Methylisoborneol)**

GC-MS/O applications for the assessment of odorous emissions has mainly focused on the simple qualitative characterisation of odours from various agricultural operations such as swine finishing, dairy processing facilities and poultry sheds (Kai and Schäfer, 2004; Kleeberg *et al.*, 2005; Parcsi and Stuetz, 2007; Wright *et al.*, 2005). Results have shown that emissions are composed of several hundred compounds; some species give intense olfactory responses whereas others give little or no olfactometry response (Figure 11). Additionally, speculation is often made as to the identity of the compound based upon its odour characteristic (Rosenfeld and Suffet, 2004). These studies have shown that GC-MS/O can be successfully used for the analysis and identification of odorous compounds but that more attention needs to directed toward understand the formation of key odorants and their fate in the environment.
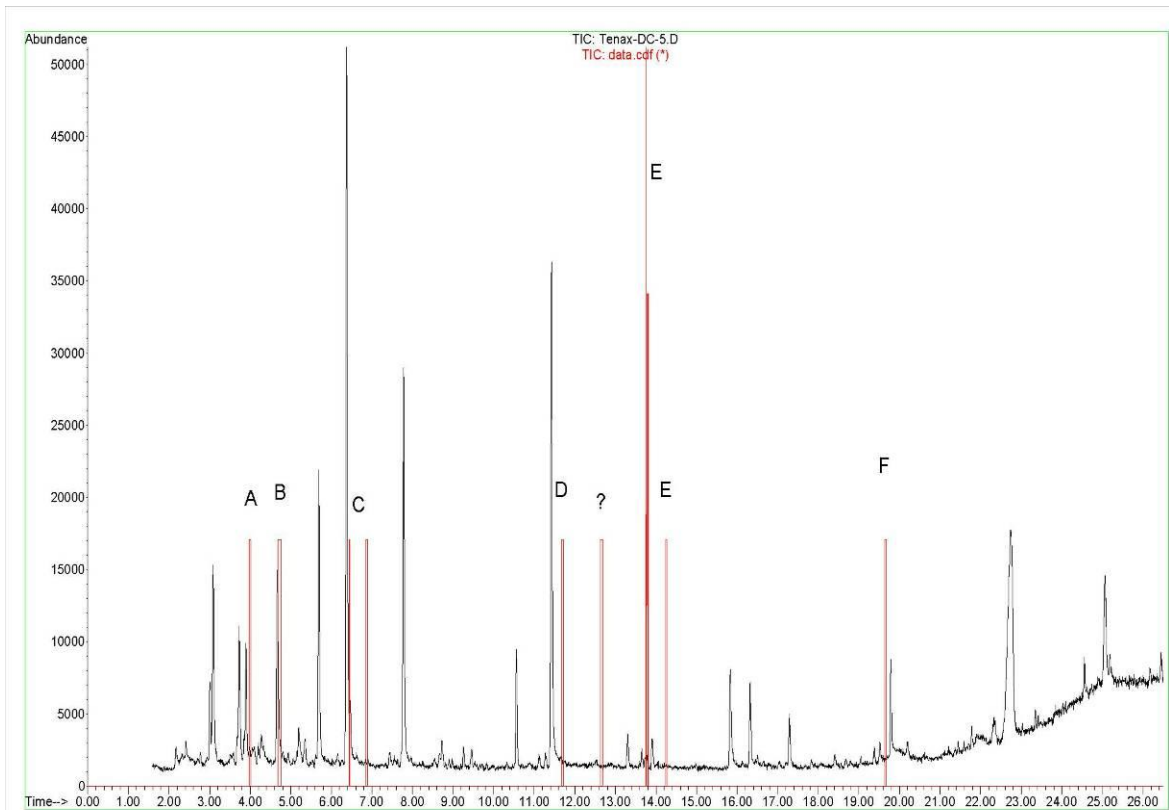
Figure 11: **GC-MS/O analysis showing total ion chromatogram and odour chromatogram (A –
2-butanone, B – 2, 3-butanedione, C – dimethyl disulphide D – 3-hydroxy-2-butanone E –
dimethyl trisulphide and F – acetophenone) (Parcsi and Stuetz, 2007)**

2.4.3 **Summary of background information on Odorant Analysis**

Odorants in General

- Odours are composed of a mixture of odorous and non-odorous compounds

- Odorants identified in intensive livestock operations include 2-butanone, indole, skatole and various sulphides

Poultry house odorants

- Existing work focuses on quantification of chemicals from poultry houses

- Limited information is available on dominant odorants within the emissions from poultry facilities

- Factors influencing NMVOC emissions include: type of litter; physical litter properties; litter moisture content; bird activity; stage of production (number and size of birds); shed cleaning and management; ventilation; and feed properties.

Broiler VOC emission rates

- Previously published material investigated the emissions of ammonia and hydrogen sulphide with little focus on the chemical composition of VOCs with odorant impact.

2.5 Sensor based monitoring of shed air quality

Sensor based air quality monitoring systems are being developed to complement or be alternatives for costly and labour intensive techniques such as olfactometry and instrumental particulate measurement. It is hoped that with refinement, these sensor based systems will offer affordable, reliable, repeatable and continuous monitoring of odour and dust concentration.

Two sensor based systems were trialled in this project to monitor in-shed air quality (especially odour and dust concentration). It was hoped that continuous monitoring would complement the discrete measurements of odour and dust by providing additional data when sampling was not possible. The two techniques included wireless sensor stations fitted with a range of sensors to provide relative information about odour and dust concentration (as well as ammonia, airflow, temperature and humidity) and an artificial olfaction system. Details of these systems are described in the following sections.

2.5.1 Wireless sensor stations for monitoring in-shed air quality

Sensor technologies can be combined with wireless networking to produce a portable environmental monitoring system. Wireless sensor networks have not been applied within broiler sheds, but have the potential to improve monitoring of the in-shed environment and subsequent emissions.

Poultry shed management and in-shed environment pose several challenges for the application of wireless environmental monitoring systems, especially due to:
- dust and ammonia;
- continually varying ventilation rate;
- different modes of ventilation (tunnel, mini-vent and combinations of both of these);
- short production cycles;
- shed cleaning;
- electrical interference from fans, lights, power cabling and other powered equipment; and
- building design.

These conditions:
- necessitate robust sensors and waterproof sensor housings;
- contaminate and degrade sensors;
- interfere with meaningful air-flow measurement;
- require relocation or removal of sensing stations;
- interfere with radio/network communications; and
- increase the difficulty of selecting representative sampling positions.

Therefore, many technical challenges need to be overcome before the use of wireless environmental monitoring systems in poultry sheds can be considered. Activities in this project were aimed at overcoming these challenges and evaluating the value and performance of these systems.

Our hypothesis was that measurement of multiple parameters (odorants, dust, ammonia, temperature, humidity and airflow) at several locations inside a shed would correspond to those made by conventional approaches (e.g. olfactometry) when analysed and processed appropriately.

Selection of 'representative' monitoring locations within broiler sheds is complicated by spatial, seasonal and temporal variability. Wireless sensor networks were utilised in this investigation because they are free from constraints such as power, cabling and, in principle, sensors can be placed in multiple locations and measure microenvironments within a larger system.

Sensors in a traditional wireless sensor network need to have low power consumption and their costs, both capital and recurrent, must be commensurate with the benefits they provide.

In the current project, air flow, odour, dust, ammonia, temperature and humidity sensors were chosen for monitoring air quality, emissions and the in-shed environment.

Temperature and humidity

In the case of temperature sensors, the demands for low power, low cost and durability are readily met by mass-produced microelectronic components. Similar technology is available for humidity sensors, and single chip temperature and humidity sensors are also available at low cost.

Air flow

There are three main types of commercially available anemometers - cup, hot wire and ultrasonic. Ultrasonic sensors are both accurate and have low power consumption, but may be prohibitively expensive for on-farm applications. Hot wire anemometers are accurate and responsive, but their high power consumption makes them unsuitable for continuous, battery powered applications. Cup anemometers consume little power, are moderately accurate, but less sensitive and responsive than the other two types; however, the anticipated flows in the central areas of the shed, particularly during tunnel ventilation events, were expected to fall in the normal operating range of cup anemometers. For these reasons, cup anemometers were selected to measure air flow in these studies.

Dust

Commercial and general research dust monitors use sensors in which the dust particles scatter light from IR LED (infra-red light emitting diode) or laser illumination. The scatter of the light is proportional to the number and size of the particles and, depending on the sophistication of the sensor, signals can be analysed to yield detailed profiles of the dust particles in the sample. These commercial dust sensors can cost $6000 and above, which may be prohibitively expensive for continuous monitoring in broiler sheds. A small range of air quality sensors are available from original equipment manufacturers (OEM) that have the basic sensing optics and electronics of the infra-red dust sensors. *These sensors have a proportional response to dust particles*, although it is not characterised with respect to particle size. These low cost devices (typically less than $200) have potential for measuring dust concentration in the range of 0.02–5.0 mg/m³. Power consumption is moderate as they require either convection heating elements or some form of pump or fan to draw air past the sensor; however, the sensors can be left idle and unpowered between sensing events.

Odour

Sensor based analysis of odour, particularly biological/agricultural odours is difficult. The variety of odorants, the sensitivity of sensors to different odorants, and the relationship to human perceptions are all highly variable. Significant progress in measuring odours by the use of 'artificial olfaction systems' or 'electronic noses' has been achieved (Rock *et al.*, 2008; Sohn *et al.*, 2009a; Sohn *et al.*, 2009b), including the potential for continuous monitoring in animal production facilities (Bell, 2004; Sohn *et al.*, 2008). However, most systems are based on research grade instrumentation and complex analysis, which places these instruments beyond what might be considered commercially feasible for the foreseeable future.

Less complex sensors are available for measuring specific gasses or a range of related gasses. For example, ammonia and hydrogen sulphide can be measured using electrochemical sensors or metal oxide sensors (MOS). Less selective sensors, such as those for volatile organic compounds (VOCs), can measure a range of substances, many of which are odorous. *Using such sensors, the measurements can only be indicative of odour*, and where the nature of the odour changes markedly, the relationship between sensor measurements and odour strength and intensity are weak. Where the nature of the odour is similar or changes slowly, these simple sensors may provide a *relative* measure of odour.

Ammonia

Ammonia is a common odorant in poultry farms although it does not necessarily have a strong correlation with odour. Microbial activity is primarily responsible for the production of ammonia and other odorants, and is influenced by various environmental and biological factors (Jiang and Sands, 2000).

Electrochemical sensors for detecting ammonia are used widely, are sensitive and precise, and use very little power. They are relatively expensive, and have a limited lifespan. MOS for ammonia are available, and have the advantages of low cost and long life. However, they are relatively insensitive, and lack

precision. Metal oxide VOC sensors are readily available, cheap and long-lived, and have adequate range and precision for a monitoring device. The main disadvantage with these sensors is high power consumption and requirement to stabilise for one to four hours prior to taking a measurement. In some applications, this would lead to continuous operation.

2.5.2 Artificial olfaction systems for odour monitoring

Until recently, the human nose and dynamic olfactometry have been the only tools available for the assessment of odours; however, dynamic olfactometry has limitations:

- it is a laboratory-based method requiring a trained human panel;
- it may be unsuitable for routine assessment and management of odour on site because cost and labour requirements are prohibitive (Nimmermark, 2001);
- samples collected for olfactometry analysis are known to be unstable (AS/NZS 4323.3:2001 requires analysis within 30 hours of collection);
- samples need to be collected at times that enable olfactometry assessment within the required period rather than collecting samples at times when odour emissions are problematic, for example at night and/or early in the morning when it is impractical to collect samples and assess them (Guo *et al.*, 2003); and
- samples are collected over a short time period, which may enable quantification of constant emissions, but may not be representative if emission rates are variable.

Artificial olfaction systems (AOS) can help to overcome these issues and provide further opportunities in odour research. Recent advances in sensor technology, signal processing and pattern recognition algorithms have led to the development of AOS utilising one or more non-specific gas sensors. These instruments can be tailored to detect and recognise specific gasses and gaseous mixtures, i.e. odours. They are sometimes referred to as 'electronic noses' because the electronic sensors and integrated data processing systems are designed to mimic the olfactory processes that occur in the human nose and brain.

AOS are particularly useful for continuous monitoring of odours and for discriminating between different odours (e.g. abattoir vs piggery). Calibration using dynamic olfactometry expands the use of the AOS by enabling quantification of odour concentration.

An AOS is an instrument consisting of a gas sampling apparatus and a number of gas sensors interfaced to a computer or other computation device. Overall, the AOS matches the natural olfaction process (i.e. smelling things with your nose), comprising the following stages between detecting an odour and its recognition, namely: interaction, signal generation, processing, and identification, as outlined by the analogy between biological and artificial noses in Figure 12 (reproduced from Hines *et al.* (2003)). In this system, the pattern recognition acts as a signal processing unit like the brain in the biological olfactory system.
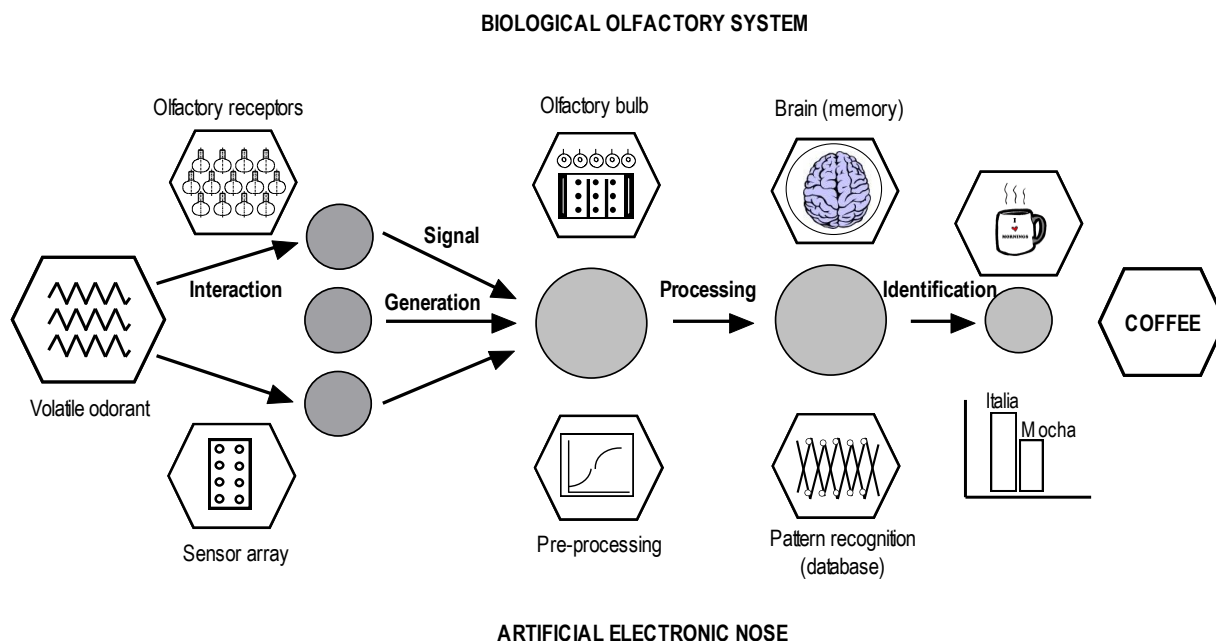
Figure 12:   Basic diagram showing the analogy between biological and artificial noses (reproduced from Hines *et al.* (2003))

The unique feature of the AOS is that its sensor array responds differently to various odours. An odour may contain hundreds, even thousands, of different volatile organic compounds (VOCs). Each odour therefore produces its own 'odour fingerprint'. Classical analytical methods using gas chromatography–mass spectrometry (GC-MS) identify the individual compounds in an odour. In contrast, the AOS examines sensor array response patterns to differentiate odours.

By using computational techniques to recognise response patterns, the AOS can be taught to classify a gas mixture that it has previously been trained to recognise. The AOS can complete tasks such as identification of a gas or odour, classification of odour samples, or quantification of an odour sample using odour units (ou m³), the standard unit for odour measurement.

Previous application of artificial olfaction systems for odour monitoring

Research has been undertaken to improve the capabilities and reliability of AOS and demonstrate suitable applications for its use. In particular, previous research has shown that AOS:

- is a fast, accurate, reliable tool for monitoring odours;
- can reliably quantify odour concentration within the range of 1,000–30,000 ou/m³;
- demonstrates good repeatability for odour measurement;
- can be used for continuous odour monitoring;
- can discriminate between different types of odour, enabling the source of the odour to be identified;
- can assist with predicting odour impacts;
- can be used to identify odour 'events' to assist with mitigation;
- can be set up as a mobile instrument for on-site odour assessment; and
- can be used at rendering, composing, wastewater treatment, biofiltration, piggery facilities and abattoirs.

However, AOS requires training to enable discrimination and quantification of odours; specialised data processing; calibration; and may require pre-conditioning of the sample air. (Boholt *et al.*, 2005; Capelli *et al.*, 2008; Littarru, 2007; Onkal-Engin *et al.*, 2005; Qu *et al.*, 2001; Sironi *et al.*, 2007; Sohn *et al.*, 2009a; Sohn *et al.*, 2009b; Sohn *et al.*, 2006; Sohn *et al.*, 2003)

Application of an artificial olfaction system in this research project

AOS had not been used to monitor odour in poultry houses prior to this research. Application of the AOS in a broiler shed as a preliminary part of this project has been reported by Sohn *et al.* (2008) and Sohn *et al.* (2007b). Important outcomes from the preliminary research have been summarised in this report and recommendations to use the AOS in other broiler sheds during different seasons have been applied with the outcomes from subsequent research activities detailed in this report.

2.5.3 Summary of sensor based measurement of odour and air quality

- There are many sensor options for measuring a range of air quality parameters.

- Wireless networking offers potential benefits over cable communication systems.

- All hardware (sensors and communications) need to be suited to poultry production systems.

- Odour is particularly difficult to measure using sensors and instrumental techniques.

- Artificial olfaction systems have been developed to replicate human perception of smells, but need to be trained to measure particular odours.

- Continuous monitoring of odour, dust and other air quality parameters can be used to supplement conventional, infrequent, measurement techniques—olfactometry and dust measurement—and provide additional data for times when other measurement methods are not feasible (e.g. at night).

- Continuous monitoring is especially well suited to measuring highly variable emission—such as those from commercial poultry farming—and provide greater understanding of the variability than can be achieved with discrete sampling methods.

2.6 Application of background information to this project

- Odours and dust will need to be sampled and measured to the AS/NZS 4323 series of standards.

- Regular sampling will be necessary to quantify odour and dust emission rates throughout the 56 day long production cycle. Emissions are expected to change following pickups, requiring additional measurements.

- Emission measurements will need to be repeated as ventilation requirements change throughout the day.

- Ventilation mode (i.e. tunnel or mini-vent) and rate will need to be recorded while measuring dust and odour emissions.

- Litter moisture content will need to be measured throughout the batch due to the reported effect of this on odour and dust emissions. Moisture content in the days leading up to odour measurements will need to be understood because of delayed effects—increased moisture leads to growth of microbial community (2-5 days) and potentially increased odour generation.

- Dust will need to be measured in terms of mass and particle number and categorised in terms of particle size ranges (i.e. $PM_{2.5}$ and PM_{10}).

- Continuous odour, dust and air quality monitoring should be used to supplement infrequent odour and dust measurements in order to establish the variability in emissions, and provide assistance in identifying ideal sampling times/conditions.

3 Methodology

During the project there were three different sampling campaigns that focussed on measuring odour, dust and NMVOC emissions from broiler sheds.

During the first campaign, samples were collected from broiler facilities in both Queensland and Victoria during both summer and winter. This included an initial series of field samples that were used to verify methods and refine field techniques. Samples were collected at various times during the broiler growth cycle.

The second campaign was undertaken at a broiler farm that re-used a portion of the litter from one batch of broilers to the next. In similarity to the earlier broiler work, samples were collected at various times throughout the growth cycle.

The third and final field sampling campaign took place entirely in Queensland. Odour emissions were measured at seven broiler farms between thirty-one and thirty-six days of age, which is when peak bird mass and peak odour emissions were anticipated.

3.1 Farm selection

3.1.1 Farm selection criteria

Farms were selected for monitoring based on the following criteria:

- Shed age 0–5 years
- Shed tunnel ventilated (not a naturally ventilated shed retrofitted with tunnel ventilation fans)
- Shed to use litter suitable for location (i.e. shavings, rice hulls, etc)
- Drinkers to be nipple (with or without evaporation cup)
- Terrain at tunnel ventilation fan end to be flat enough for attachment of sample duct
- Management practices to be industry standard – no additional procedures taken place that are not part of typical day-to-day management
- Within workable distance to the olfactometry laboratory for odour sample analysis

Farms were selected in Queensland and Victoria in an attempt to ensure that odour, dust and volatile organic compound (VOC) emission measurements would be representative of poultry sheds in sub-tropical and temperate regions.

3.1.2 Farm descriptions

The details of shed design, installed fans, litter management practices, and location for all farms that participated in this study are summarised in Table 6.

Table 6:   Description of farms

Farm Label	Location	Shed Dimensions (m)				Shed Description		Ventilation System				Bird Breed	Management	Litter Type
		Width	Length	Wall height	Baffle height	Shed Walls	Shed Age	Tunnel fans	№	Side/other fans	№			
Farm A	Gatton, QLD	14.8	120	2.6	2.4	Curtain sided	2004	Hired Hand 52.5" (1333.5 mm), with cone	8	Hired Hand 52.5" (1333.5 mm), with cone	1	Arbor Acres	Single Use	Shavings
Farm B	Bendigo, Vic	15.8	91.5	2.4	2.4	Solid walls	2000	American Coolair 1.0hp, 6 blade, MNCFE52L	6	Fancom 1456, 24" (609.6 mm), 0.75hp	7	Ross, Cobb & Arbor Acres	Single Use	Summer Shavings, Winter Rice Hulls
Farm C	Ipswich, QLD	15.5	150	2.7	2.7	Solid walls	2005	SKOV DB1400, 1.0hp	14	SKOV DB1100, 0.5hp AND SKOV DB1400, 1.0hp	2 & 1	Cobb	Partial Reuse	Shavings
Farm F	Caboolture, QLD	13.7	125	2.7	2.4	Curtain sided	2003	Titan 48" (1219.2 mm), 1.5hp, 6 blade	8	Titan 39" (990.6 mm), 6 blade	4	Cobb	Partial Reuse	Shavings
Farm G	Caboolture, QLD	15.5	150	2.7	2.4	Solid walls	2005	Munters EM50, 1270 mm, 1.0hp	16	Munters EM36, 914.4 mm, 0.5hp	3	Cobb	Partial Reuse	Shavings
Farm H	Caboolture, QLD	15	153	2.7	2.4	Solid walls	2006	Munters EC50, 1270 mm, 1.0hp, with cone AND Munters EM50, 1270 mm, 1.0hp	12 & 2	Munters EM36, 914.4 mm, 0.5hp	3	Cobb	Single Use	Shavings
Farm I	Caboolture, QLD	15.3	153	2.2	-	Solid walls	2005	Hired Hand 52.5" (1333.5 mm), with cone	13	Munters EM36, 914.4 mm, 0.5hp	3	Cobb	Partial Reuse	Shavings
Farm J	Esk, QLD	15.24	154.28	2.8	2.4	Solid & Curtain	2006	Munters EM50, 1270 mm, 1.0hp	14	Munters EM50, 1270 mm, 1.0hp	1	Cobb	Single Use	Shavings
Farm K	Ipswich, QLD	15	150	2.7	-	Solid walls	2006	Munters EM50, 1270 mm, 1.0hp	14	Munters EM50, 1270 mm, 1.0hp	2	Ross	Single Use	Shavings
Farm L	Ipswich, QLD	15	150	2.7	-	Solid walls	2006	Hired Hand 52.5" (1333.5 mm), with cone	12	Munters EM36, 914.4 mm, 0.5hp AND Hired Hand 52.5" (1333.5 mm), with cone	3 & 1	Ross	Single Use	Shavings
Farm M	Gatton, QLD	14.8	120	2.6	2.4	Curtain sided	2004	Hired Hand 52.5" (1333.5 mm), with cone	8	Hired Hand 52.5" (1333.5 mm), with cone	1	Arbor Acres	Single Use	Shavings

Note: Farms D and E were layer farms that were included in this research but reported elsewhere.

3.2 Sample collection

For each farm visit, air quality and environmental conditions were measured and details about farm management were recorded. Information collected is shown in Table 7.

Table 7:   Data collected on each farm visit

Air Quality	Environmental Data	Farm Management
• Odour	• Ambient Temperature	• Bird Age
• Dust	• Relative Humidity	• Average Bird Weight
• Non-methane Volatile Organic Compounds (VOCs)	• 10 m Weather Station Data (where installed)	• Number of Birds Placed
		• Number of Birds Present on Sample Collection Day
		• Internal Shed Temperature
		• Internal Shed Relative Humidity

Air samples were collected either from within a polyethylene duct; within the shed; or from a tunnel ventilation fan. Sections 3.2.3 and 3.2.4 describe the three sample collection methods used.

Specific details for the collection of odour, dust and VOC samples; and measurement of litter moisture, ventilation rate, weather, shed and production conditions are provided in sections 3.2.4 to 3.2.13.

3.2.1 Sampling program

At the commencement of this study, a detailed sampling program was designed so that emission rates would be measured throughout the entire production cycle. This program included the assessment of weather, litter and production conditions known to affect the generation and emission of odour and dust. The sampling program was amended during the course of the project.

The initial sampling program included seven sampling days throughout the production cycle. Odours were to be collected:

1. With the fresh litter in the shed, prior to bird placement
2. Week 3 (where week 1 started on the day when birds were placed in the shed as day old chicks)
3. Week 5 (or just before the first pickup)
4. Week 8 (or just before final pickup)
5. Birds out, used litter still in the shed
6. Litter out, before shed cleaning
7. Litter out, after shed cleaning but before placement of fresh litter

Sampling events 1, 5, 6 and 7 were chosen because there was no available emissions data during these stages of the production cycle. The litter clean out stage of the batch (around the times of sampling events 5 and 6) is often implicated as a time when odour impacts occur. Sampling event 1 was also chosen to provide 'baseline' emission data.

This sampling program was used during the summer sampling campaigns at Farm A and Farm B. Following preliminary analysis of the emissions measured at these farms, significant holes were identified during particular stages of the batch, that made the emission rates measured during weeks three, five and eight difficult to put into context. The data collected during summer at Farms A and B was not adequate to describe the increase in emissions up to week five, nor did it describe the changes in odour emission as birds were sequentially harvested from the shed.

A new sampling program was conceived to address these issues and was used for the winter sampling at Farms A and B. The new sampling program required sample collection at the following times:

1. Day 14 (birds placed in the shed on day 1 as day old chicks)
2. Day 21
3. Day 35 (or just before the first pickup)
4. The day following first pickup
5. Day 42
6. Day 49
7. The day when litter was being removed from the shed. Some samples were collected prior to the litter being disturbed and some were collected while machinery was operating in the shed and removing the litter.

The sampling campaign at Farm C, where the re-use of litter was being assessed, was similar to the winter sampling program used at Farm A and B, **except** samples were collected prior to final bird removal (about day 55) instead of after final bird removal.

For Farms F–M (multi farm round robin), odour and VOC samples were collected on the day of the first pickup, before birds were removed. Peak odour emissions were expected at this time.

3.2.2 **Selection of ventilation rates on each sampling day**

Ventilation rate is known to influence odour emission rates, so measurements were made at different ventilation rates. The initial sampling schedule called for samples to be collected at 25%, 50%, 75% and 100% of the maximum ventilation rate (for the shed).

Collection times for odour samples are constrained by the need to transport and analyse the samples as soon as possible following collection to ensure sample integrity. Samples needed to be delivered to the olfactometer in the early afternoon to ensure they would be analysed on the same day as collection. Consequently, samples needed to be collected in the morning.

Methods for the selection and control of ventilation rates during sample collection changed during the course of this study. At Farms A and B, ventilation was manually controlled. At Farms C and F–M, the ventilation system was left in automatic mode.

For Farms A and B, samples were collected at the pre-determined ventilation rates, manually controlled during collection time. The lowest ventilation rate was sampled at the beginning of each sample day because ventilation requirements were expected to increase throughout the day. If the ventilation rate was higher than 25% when sample collection was set to commence, the higher value would be chosen. The required level of ventilation was then locked in to prevent changes during sample collection. More fans were sequentially turned on for sample collection at higher ventilation rates. Approximately 15 minutes was allowed between any change in ventilation rate and the start of sample collection.

At the completion of the summer and winter sampling campaigns at Farms A and B, there were concerns about manually controlling the ventilation rate. To address these concerns, ventilation control systems were left in automatic mode at the remaining farms (C–M). Samples were collected at different ventilation rates by waiting until the ventilation system automatically turned on more fans. The sampling team usually waited for the number of fans to stabilise before collecting samples. If the number of active fans changed during sample collection (usually only during VOC collection, because odour samples only required 10 minutes for collection), a time weighted average ventilation rate was recorded. At very low levels of ventilation, it was occasionally necessary to manually turn on the fan to which the sampling duct was attached. This was to ensure that the fan did not turn off mid-sample. When this was done, care was taken to match the required ventilation rate at the time (usually required manually turning off one of the fans in the next stage of ventilation).

3.2.3 Location of dust, odour and volatile organic compound sample collection

3.2.3.1 Inside the shed

Air samples for preliminary studies, including odour decay and importance of dust, were collected inside the broiler sheds.

Odour samples were collected from inside the shed near the final ceiling baffle, or approximately 6–10 m upwind from the tunnel ventilation fans where baffles were not installed. The final baffle is the final area in the shed where the air is mixed before exiting the shed, and therefore expected to be representative of the emissions exiting the shed. According to AS 4323.1 (Standards Australia, 1995a), air samples should ideally be collected three diameters upwind from a disturbance (bend, contraction, louvers or fans) which roughly equates to the location of the final baffle.

3.2.3.2 Polyethylene duct

Odour, volatile organic compound and dust samples for the seasonal and location variability studies; diurnal variability study; and the comparison between single litter use and partial litter reuse study were collected from within a polyethylene duct (Figure 13). The duct was manufactured from a transparent polyethylene material (clear Gale Pacific Ltd. Solarweave®Q). The use of a duct enabled air samples to be collected at a sampling plane in accordance with AS 4323.1 (Standards Australia, 1995a). It was especially important in terms of collecting representative dust samples isokinetically.

Ducts were custom designed for each farm to ensure that minimal backpressure was applied to the fan. For fans fitted with a cone, duct diameter was equal to the cone diameter. For fans without cones, the duct was made the same diameter as the fan impeller. Duct length and position of sampling plane was calculated according to AS 4323.1 (Standards Australia, 1995a). Duct length was equal to eleven duct diameters. Samples were drawn from a hole cut in the duct at a distance of eight duct diameters from the fan face.

The duct was suspended from the fan housing or shed wall with ten gauge wire, that was tensioned by a winch supported by a rigid frame (see Figure 13) attached to an adjustable frame to account for minor terrain variability. Sidewards movement of the duct was minimised with steel star pickets covered with polypropylene pipe.

Figure 13: Polyethylene duct attached to tunnel ventilation fan

Duct design varied depending on whether the fan had a square housing or a round cone. For fans with a square housing, a transition section was required to accommodate the circular duct. A galvanised steel square-to-round transition was used (see Figure 14 and Figure 15). The steel transition fitted over the existing fan housing, was secured with screws and supported with wire and star pickets. The steel transition enabled simpler and cheaper ducts to be manufactured, however the transition was difficult to handle and install onto the fans. An integral transition formed as part of the polyethylene duct (see Figure

16) was found to be a more suitable, yet more expensive option.

Figure 14: Galvanised square-to-round transition

Figure 15: Transition with duct attached

Figure 16: Duct with integral square-to-round transition

The use of a duct for sample collection at one farm over multiple days was important for standardisation of the sample collection process, especially for the isokinetic measurement of dust emissions. The use of a duct for one-off collection of air/gas samples requires careful consideration (especially cost/benefit). Successful use of a duct requires planning, appropriate siting and calm weather. Construction of the duct must be planned weeks before the sampling event. The shed and fan must have the structural integrity to support the weight of the duct. A relatively flat, unobstructed area is required beyond the exhaust fans to accommodate the length of the duct. Calm winds are also required during sampling because the duct is very sensitive to strong cross winds, which could damage the duct, sampling equipment, fan or shed.

3.2.3.3 Tunnel ventilation fan face

Collection of odour and organic compound samples from the fan face was used for the round robin study.

Odour and volatile organic compound samples were collected from the external fan face of one tunnel ventilation fan at farms where a duct could not be attached to the shed wall, or where the farm was visited on one occasion only and the cost and time requirements of constructing a duct were not justifiable.

When using this method, care must be taken to prevent side wind interference and dilution of the sample.

3.2.4 **Odour sample collection**

Odour samples were collected according to AS/NZS 4323.3 (Standards Australia/Standards New Zealand, 2001).

Odour samples were drawn into rigid drums lined with a Melinex® bag (polyethylene terephthalate) using a vacuum pump as shown in Figure 18. All bags were preconditioned by filling with odorous air then emptied prior to the sample being collected. All components of the sampling train that were in contact with the poultry odour were manufactured from stainless steel or polytetrafluoroethylene (PTFE). The volume of sample collected in QLD was 120 L (Figure 17), and for Victoria was 15 L (Figure 19). The difference in sample volume was due to the use of different olfactometry laboratories.

Where odour samples were collected from inside the shed, samples were drawn into the drum directly from the fittings on the drum lid as shown in Figure 17. Where odour samples were drawn into the drum from within the polyethylene duct, a stainless steel probe and PTFE tubing were used (Figure 18). Where odour samples were collected from the down-wind side of one of the tunnel ventilation fans, PTFE tubing was used to collect the samples. One end of the tubing was connected to the sampling drums and the other end was carefully positioned within the fan housing and guard (as shown in Figure 20) to prevent crosswind interference.

All odour samples were collected simultaneously into two separate drums, effectively producing duplicate odour samples for individual analysis. Sampling in this manner is recommended by AS/NZS 4342.3 to reduce variability due to olfactometry analysis and improving confidence in the measured concentration.

All drums were filled over approximately ten minutes (sampling flow rate in QLD was approximately 20 Lpm and in Victoria was approximately 3.5 Lpm). Once filled, the drums were sealed and transported to the olfactometry laboratory for analysis. All samples were analysed within 8.5 hours of collection. Each bag was used once and discarded after analysis.

Figure 17: Odour sample collection from within the shed

Figure 18: Odour sample collection from within the polyethylene duct in Queensland

Figure 19: Odour sample collection from within the polyethylene duct in Victoria

Figure 20: Odour sample collection from a tunnel ventilation fan face

3.2.5 **Dust sample collection**

There are two general approaches to measuring dust emission rates from intensive livestock buildings: within the shed, close to the exhaust fans; or outside the shed, in the exhaust airstream. Previous research has shown that dust concentrations within a shed are generally higher than concentrations downstream from a shed (Visser *et al.*, 2006). The objective of this study was to measure representative emission rates. Therefore, dust measurements were conducted in the exhaust airstream, as it was exhausted from the building (within a temporary polyethylene duct designed in accordance with AS 4323.1:1995, see section 3.2.3.2).

Dust samples were obtained by drawing air through an isokinetic sampling probe that was inserted into the polyethylene duct (see Figure 21). The isokinetic sampling probe obtained representative dust samples independently of the particle size distribution. The probe achieves this by ensuring that the air stream entering the particle samplers has a velocity (speed and direction) equal to that of the air in the gas stream just ahead of the sampling probe. This meant that all particles of all sizes entering the sampler have a collection efficiency of unity. The isokinetic probe was designed specifically for this project in accordance with AS 4323.2–1995 (Standards Australia, 1995b).

In this project, particle mass and number concentrations were measured to characterise poultry dust emissions (see section 2.3.1). In addition, particle number size distributions were also measured. PM_{10} and $PM_{2.5}$ particle mass concentrations were measured using two TSI model 8520 DustTraks (www.tsi.com) with appropriate inlets. Particle number concentrations and size distributions were measured with a TSI model 3320 Aerodynamic Particle Sizer (APS). The three particle sampling devices were operated in parallel downstream from the isokinetic sampling probe (see Figure 22).

Figure 21: Isokinetic sampler used for particulate measurement

Figure 22: Isokinetic sampler, APS and DustTraks

3.2.5.1 *DustTrak: TSI model 8520*

The DustTraks were used for on-line, real-time continuous measurements of particle mass emitted from the sheds. The DustTrak is a laser-scattering photometer and thus determines mass loading indirectly by light scattering. It measures particles in the size range from 0.1–10 µm within 0.001–100 mg/m³ load range. The unit is supplied with a cyclone and an inlet kit for measuring particle sizes corresponding to PM_{10}, $PM_{2.5}$ or $PM_{1.0}$ dust fractions.

In this study, two DustTraks sampled in parallel downstream from the isokinetic sampling probe. One DustTrak was fitted with a PM_{10} inlet and the other with a $PM_{2.5}$ inlet. This setup allowed simultaneous measurement of PM_{10} and $PM_{2.5}$ concentrations. Concentrations were logged every 30 seconds during sampling.

3.2.5.2 *Aerodynamic particle sizer (APS): TSI model 3320*

Particle size distributions and number concentrations were measured with the APS. The APS measures particle number size distribution continuously in real time over the size range 0.5–20 µm. The maximum concentration is 1000 particles/cm³ with maximum coincidence error of 6% at 10 µm. The instrument measures the time-of-flight of individual particles in an accelerating flow field. It achieves this by accelerating particles through a nozzle before they are detected by two broadly focused laser beams. A monotonic relationship between time-of-flight and particle aerodynamic diameter is then used to generate a particle size distribution in real time. Integration over the size distribution also yields a measurement of particle number concentration. In this project a particle size distribution was generated every 20 seconds.

3.2.6 **Non-methane volatile organic compound sample collection**

3.2.6.1 *Introduction to methods—sorbent tubes*

Non-methane volatile organic compounds (NMVOCs) were collected to identify and quantify the chemical components of the air exiting the poultry sheds. These can be collected by a variety of different methods; however, in consideration of logistical constraints and the project objectives, sorbent tubes were

chosen because they provide robustness, sample stability, reliability, repeatability, ease of use, cost effectiveness and the ability to quantify NMVOCs.

Sorbent tubes are small inert tubes that come in a variety of sizes (see Figure 23). Markes International Limited (Pontyclun, UK) manufacture sorbent tubes that have been accepted across multiple disciplines involved in volatile and semi-volatile organic compound monitoring as the standard size of 6.35mm outer diameter and 89mm length.

Figure 23: **An example of two sorbent tubes with brass caps—the upper tube is coated in an inert coating to prevent oxidation of highly volatile species during sampling**

Each tube is packed with a measured amount of sorbent that collects and traps the target VOCs as the sample air is drawn through the tube, thus an effective sampling volume in the order of 10 litres may be collected in a tube no larger than a pencil. The tube itself is fabricated from either stainless steel or glass. Stainless steel tubes offered a much higher degree of robustness than glass and were chosen for use in this project.

To ensure that each sample remained free of contamination, inert fittings and sample flow paths were utilised—for example stainless steel sampling manifolds, polytetrafluoroethylene (PTFE) tubing and, most importantly, each tube was sealed with 2-piece brass screw caps with PTFE ferrules prior and post sample collection (Swagelok® caps with Teflon® ferrules: part numbers: B-400-C with T-400-SET respectively).

Sorbent tubes can be sampled and reliably analysed many times as the sorbent bed within the tube can be cleaned with relative ease and have consistently low carry over rates. As the analytes are captured on or within a sorbent they are readily liberated by gentle gas flow and heat. Thermostatically and flow rate controlled devices such as the Markes TC-20 (Markes Int'l. Ltd Pontyclun, UK) allow for sorbent tubes of the same sorbent bed to be batch conditioned simultaneously, providing efficient and timely turn around from analysis to re-deployment for field sampling.

Each sorbent tube is identified with a unique serial number, allowing identification of the sorbent contained within the tube, and when correct quality assurance and quality control strategies are implemented, the sampling, analysis and conditioning cycles that the tube has under gone can be readily recorded. This is of significance as the sorbents within the tube have a finite life and this must be acknowledged in order to have confidence that the results of tube analysis are reliable, precise and provide accurate representation of the NMVOC composition of an air sample.

3.2.7 **Sorbent selection**

The sorbent tubes contain a sorbent of known mass and composition, chosen specifically for the target analytes. During this project, it was decided that the use of sorbents that have been widely documented for other studies of livestock emissions would be ideal to capture the NMVOCs from poultry sheds.

Extensive studies of VOC emissions from bovine and porcine operations have used both carbon molecular sieves and graphitised carbon black sorbents. Carbon molecular sieves are porous materials that collect analytes by trapping them within the pores of the material, capturing analytes smaller than the size of the pore in the material and allowing larger molecules to pass through the sorbent bed. Graphitised carbon black sorbents are generally nonporous materials that collect analytes on their surface by adsorption, thus their strength is considered to be a function of their specific surface area—the area analytes have to bind to—thus a lower specific area corresponds to a lower strength.

Detailed methodologies from the United Kingdom Health and Safety Laboratory (UK HSL Methods for the Determination of Hazardous Substances MDHS-72), the United States Environmental Protection Agency (USEPA Method TO-17) and technical notes available from Markes Int'l Ltd., led to the use of two different sorbent tubes to ensure accurate and reliable representation of the volatile organic compounds found in the gas phase emissions from the poultry houses.

The principal sorbent selected was Tenax TA—a widely used, inert, hydrophobic, weak sorbent, with a specific surface area of ~35m²/g. Tenax TA targets VOCs with boiling points between 100–450 °C or compounds n-C_7 to n-C_{30} for example aromatics, apolar and polar compounds, poly aromatic hydrocarbons and poly chlorinated biphenyls.

The second sorbent was Carbotrap 300, which provides an approximate analyte capture range of ethane (C_2) to n-C_{20} and is a mixture of three different sorbents: Carbopack C; Carbopack B; and Carbosieve SIII (listed in increasing sorbent strength and packing order within the tube). Table 8 lists the properties of these three sorbents.

Table 8: Properties of the three sorbent types within the Carbotrap 300 sorbent tubes

Sorbent	Specific Surface Area	Target Compound Range	Sorbent Strength	Hydrophobic / Hydrophilic
Carbopack C	~12 m²/g	n-C_8 to n-C_{20}	very weak	hydrophobic
Carbopack B	~100 m²/g	n-$C_{5/6}$ to n-C_{14}	medium	hydrophobic
Carbosieve III	~800 m²/g	ethane to n-C_5	very strong	mildly hydrophilic

With the specific targeting of the Tenax TA sorbent tubes and the Carbotrap 300 sorbent tubes, it was anticipated that the significant majority of NMVOCs present in the gas phase emissions from the poultry sheds could be trapped for analysis.

For added redundancy a sorbent tube that contained a mixture of Tenax and Carbograph 1TD was occasionally used. Carbograph 1TD is a moderately weak hydrophobic sorbent with a specific surface area of ~100 m²/g and a target analyte range of n-$C_{5/6}$ to n-C_{14} including alcohols, aldehydes, ketones and apolar compounds.

3.2.8 **Sorbent tube collection methodology**

There are two methods of collecting NMVOCs with sorbent tubes: active sampling using a vacuum pump; and diffusive sampling (also refereed to as passive sampling). Throughout the project, the majority of samples were collected using active sampling; however, diffusive sampling was also occasionally used.

Active sampling was conducted using a calibrated air sampling pump and adjustable low-flow tube holders to draw sample air through the sorbent tube at a known flow rate and for a set duration (SKC Universal Pump 224-PCXR8 and 224-26-01 respectively, SKC Inc., Pennsylvania, USA, see Figure 24). This allows for the total volume of air passed through the sorbent to be recorded and the concentration of the analytes detected during subsequent analysis to be determined.

**Figure 24:   Vacuum pump used to draw the air samples through the
sorbent tubes to collect the analytes**

Appropriate sampling flow rate, duration and total sample volume is essential. An excessive sampling volume may result in the sorbent becoming saturated and VOCs passing through the tube unretained. A flow rate that is too high or too low may similarly result in the VOCs passing through the sorbent without sorption. It is for these reasons that double tubes were collected in series during the initial proof of concept field trials. These series tubes demonstrated that the sampling flow rates and volumes were suitable for the NMVOCs to be retained on the first (front) sorbent tube.

Air samples were drawn through a 1.5 m long, 6.35 mm diameter stainless steel probe that was either within the polyethylene duct as shown in Figure 25, or directly from the tunnel ventilation fan as shown in Figure 20 of section 3.2.4. The probe fed into a stainless steel manifold shown in Figure 26, onto which the sorbent tubes were attached with 60 mm lengths of Tygon® tubing (Saint-Gobain Performance Plastics Corporation Tygon® R–3603 vacuum tubing).

All tubes were individually calibrated using a flow meter (TSI Incorporated Model 4143) and individual low flow tube holders attached to Tygon® tubing. Samples were collected for 30 minutes at a maximum rate of 100 mL per minute.

Figure 25: VOC sampling from duct

Figure 26: Filtered VOC tubes and manifold

In comparison to the active sampling methods, diffusive samples do not require a sampling pump—the leading end of the sorbent tube is opened to the emission source whilst the trailing end of the sorbent tube remains capped (see Figure 27). Specifically designed diffusion caps must be placed over the open end of the sorbent tube to fix the cross sectional area of the sampling surface, and to prevent the ingress of dust, insects and other particulate matter to the tube.

Figure 27: Sorbent tube with diffusion cap in place

3.2.8.1 Filtering of pumped sorbent tubes

Throughout the initial stages of the field sampling a number of comparative samples were collected that were either filtered or unfiltered. This filtering was performed inline by way of a 0.2 µm PTFE disc filter housed within a stainless steel holder (see Figure 28). This inline filter was placed before the sampling manifold so each sorbent tube had one common filter.
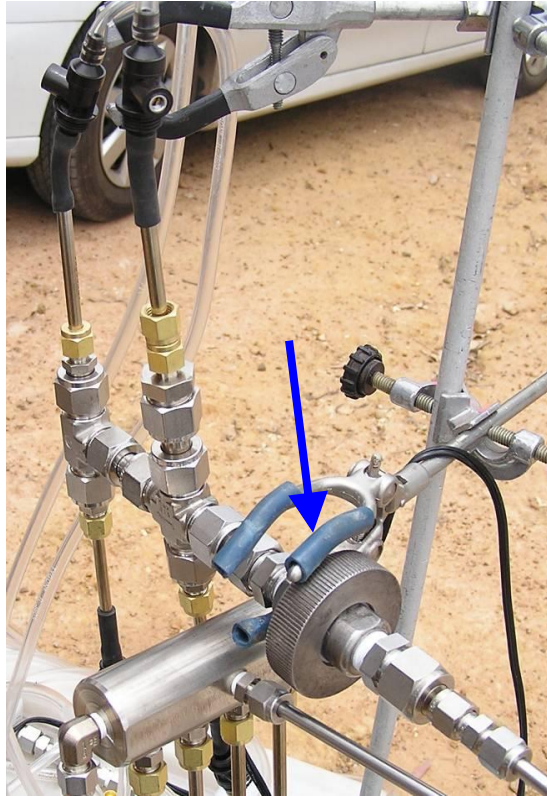
Figure 28: **Sorbent tubes in place collecting filtered samples— arrow pointing to inline filter housing containing a Teflon filter. Lower manifold (obscured) for unfiltered sorbent tubes**

The intention of this filtering was to prevent particulate matter from entering and contaminating the sorbent tube, and to provide consistency within samples by removing any error from differing levels of inadvertently collected particulate matter. After empirical analysis of the results obtained from these initial samples it became evident that there was significant variability within the unfiltered results and henceforth all samples collected would be filtered.

As the project progressed, two other filter materials were used to perform this filtering; mixed nitrocellulose fibre and resin free glass fibre. In difference to the single inline filter for all tubes as with the PTFE filter, the mixed nitrocellulose fibre and glass fibre filters were individually housed in clear polystyrene cassettes (SKC, AirMet Scientific, North Sydney, NSW, Australia). This allowed for investigation of NMVOCs trapped on the particulate matter for each individual sorbent tube.

Upon further detailed analysis of the results and specifically the results of laboratory based tests it was concluded that the use of resin free glass fibre filters provided the most reliable and consistent samples.

The analysis of collected particulate matter was performed in addition, albeit intrinsically parallel, to the gas phase NMVOC analysis to provide greater understanding of the chemical make up of the air exhausted from the poultry sheds and any chemical mechanisms that may be taking place during the transportation of particles.

Furthermore it should be accepted that there is a significant amount of *parasitic static cling* resulting from the movement of air over the various flow paths within the sampling setup, such as the polyethylene duct, stainless steel sampling lines and fittings and other inline features. This will reduce the amount of air borne particulate matter that will actually reach the filter and sorbent tube.

3.2.8.2 *Sorbent tube storage and handling considerations*

Extreme care was exercised throughout all stages of sample collection, transportation, analysis, conditioning, and re-deployment into the field to ensure that the tubes retain their integrity. Care was also taken when handling tubes to avoid contamination from human contact—as the skin contains numerous natural oils—by handling the tube only in the centre of the stainless steel body, well away from the tube openings.

Once a sample had been collected in a sorbent tube, it was immediately and cautiously sealed with its caps and wrapped in clean aluminium foil. The aluminium foil serves to identify the tube as having been exposed, to insulate the tube from rapid changes in temperature and to also act as a secondary contamination barrier.

Each sorbent tube was transported in a clean, translucent plastic container that held up to ten tubes. Aside from being a convenient way to package and ship the tubes, the case gave additional handling protection to the sorbent tubes.

The tubes were stored in refrigerators (between 1-5 °C) to conserve the integrity of the analytes captured on the sorbent. When in the field for sample collection or during transportation from the field locations to the laboratory for analysis, the tubes were kept in portable refrigerators or coolers with ice packs to keep their temperature sub-ambient. Although these measures may be considered superfluous, every attempt has been made throughout this project to guarantee the utmost integrity of the data obtained from the analysis of the NMVOCs collected on these sorbent tubes.

3.2.9 **Ventilation rate measurement**

Ventilation rate was measured by three methods throughout the project: inside the shed; at the fan face with a hot wire anemometer; or calculating ventilation rate from manufacturer's fan performance data, fan activity and shed static pressure.

3.2.9.1 *Internal shed*

Airspeed was measured inside the broiler shed at a cross section under the final baffle before the tunnel ventilation fans. Where baffles were not in place, measurements were taken between final mini-vent and the tunnel ventilation fans. Using AS 4323.1 (Standards Australia, 1995a), a grid pattern with 32 measurement points was formulated (Figure 29). Airspeed was measured inside the shed using a hot wire anemometer (TSI Incorporated VelociCalc® Model 8386–M–GB). Each point was measured over ten seconds, with the average value recorded. An average of the 32 measurement points was used to calculate the average airspeed (m/s). Ventilation rate (Q) was calculated by multiplying the average airspeed by the shed cross-sectional area (see Equation 1).

$$Q \text{ (m}^3\text{/s)} = \text{average airspeed (m/s)} \times \text{internal shed cross sectional area (m}^2\text{)} \qquad \textbf{Equation 1}$$
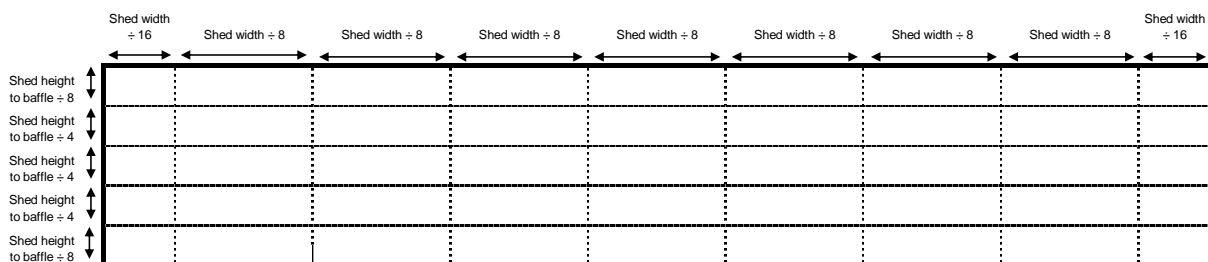
Figure 29: Internal shed airspeed measurement grid pattern

3.2.9.2 External fan face

Airspeed measurements were taken in two perpendicular transects across the external face of each fan using a hot wire anemometer (TSI Incorporated VelociCalc® Model 8386–M–GB) as shown in Figure 30. Each transect consisted of 12 points, which were each measured over 2 s. The spread of measurement points over the fan face was calculated using AS 4323.1 (Standards Australia, 1995a). A 2 m length of small diameter PVC (polyvinyl chloride) pipe was marked with measurement points and attached to the fan housing with either clamps or metal hooks during airspeed measurement (see Figure 30). An average of all measurements from all active fans was used to calculate the shed ventilation rate. Ventilation rate (Q) was calculated by multiplying the average airspeed (m/s) by the fan cross-sectional area by the number of active fans (see Equation 2).

$$Q \text{ (m}^3\text{/s)} = \text{Average airspeed (m/s)} \times \text{fan cross–sectional area (m}^2\text{)} \times \text{no. active fans} \qquad \textbf{Equation 2}$$

Figure 30: Measurement of airspeed at fan face (External)

Figure 31: Measurement of airspeed at fan face (Internal)

Where fan shutters were on the outside of the fan, measurements were taken from the internal fan face (Figure 31).

3.2.9.3 Fan activity, static pressure and manufacturer's performance information

Shed ventilation rate can be estimated using fan performance data (Dunlop and Duperouzel, 2008; Wilhelm *et al.*, 2001). Flow rate for each active fan was estimated using performance data provided by the fan manufacturer or from an independent testing laboratory (for example the BESS Laboratory at the University of Illinois http://www.bess.uiuc.edu/). Ventilation rate was calculated by multiplying the number of active fans by the estimated flow rate through each fan.

Calculating ventilation rate with this method assumes that the fan performance data is accurate and that the fans are clean and in good condition. It is essential that the fan performance data exactly matches the fans installed at the farm. It is therefore necessary to record details including; fan manufacturer; model number; number of blades; blade pitch (if adjustable); motor size and manufacturer; and pulley sizes. It is also advisable to supplement the estimation of flow rate through each fan with physical measurement of the velocity profile using techniques described above in Section 3.2.9.2.

Fan performance data was sourced from fan manufacturers or suppliers. Figure 32 displays the fan performance data for the fans installed on farms involved in this study. It can be seen that flow rate reduces as the magnitude of the static pressure increases (inside the shed is lower pressure than outside). The fan performance curve equations (see Table 9) were calculated using Microsoft® Excel 2003 by fitting a polynomial trend line to the flow rate data at different static pressure values.

For this method to be successful, it is essential to measure the shed static pressure at the time of ventilation measurement. Temperature and barometric pressure should also be recorded to enable the air

flow to be adjusted to match the conditions under which the fans were evaluated and then, for the purposes of calculating emission rates, adjusted to match standard temperature and pressure conditions (see section 3.2.9.4).

Fan Performance Curves
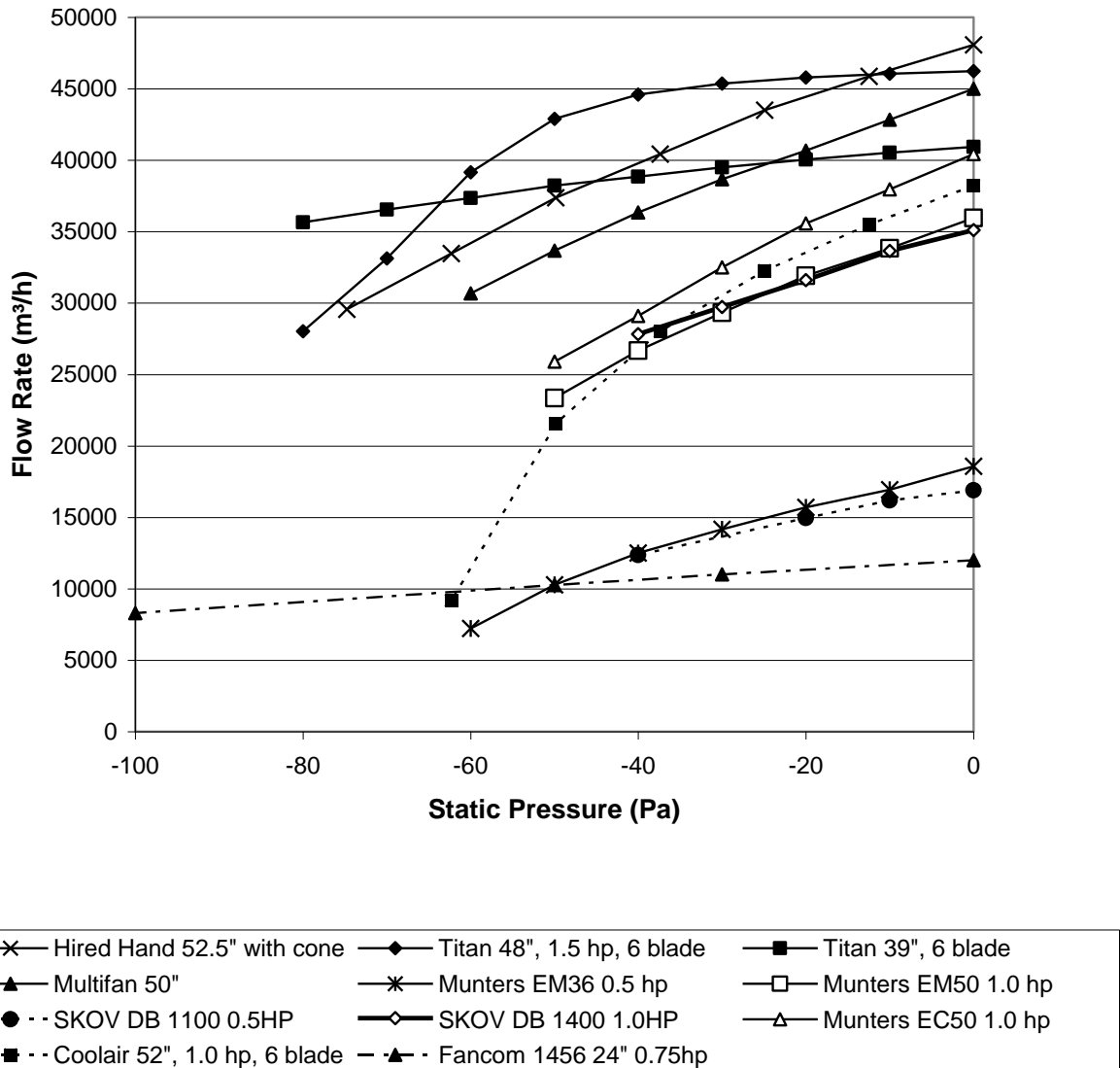
Figure 32: Fan performance curves as supplied by manufacturer

Table 9:   Fan performance equations

Fan	Fan Performance Equation*
Hired Hand 52.5" (1333.5 mm) with cone (Hired Hand, 2004)	$Q = 0.00023969p^3 - 1.2363p^2 + 155.37p + 48062$
Titan 48" (1219.2 mm) 1.5hp, 6 blade (Titan Fan Products Australia Pty Ltd, 2006)	For pressure between 0 and (equal to) -20Pa: $Q = -0.295p^2 + 15.65p + 46231$ For pressure between -20 and (equal to) -40 Pa: $Q = 0.1018p^3 + 7.535p^2 + 226.97p + 48410$ For pressure less than -40Pa: $Q = -11.45p^2 - 885.5p + 27250$
Titan 39" (990.6 mm) 6 blade (Titan Fan Products Australia Pty Ltd, 2006)	$Q = -0.0005p^3 - 0.4229p^2 + 35.287p + 40928$
Multifan 50" (1270 mm) (Vostermans Ventilation B.V., 2004)	$Q = 0.023p^3 + 1.1965p^2 + 228p + 45000$
Munters EM36 (914.4 mm) 0.5hp (Munters Europe AB, 2005)	$Q = 0.0412p^3 + 2.25p^2 + 175.45p + 18561$
Munters EM50 (1270 mm) 1.0hp (University of Illinois Department of Agricultural Engineering BESS Lab, 2002b)	$Q = 0.0234p^3 + 0.173p^2 + 201.77p + 35937$
SKOV DB 1100 (1092.2 mm) 0.5hp (Farmmark Pty Ltd, 2008)	$Q = -0.0617p^3 - 4.5p^2 + 32.167p + 16900$
SKOV DB 1400 (1371.6 mm) 1.0hp (Farmmark Pty Ltd, 2008)	$Q = -0.5036p^2 + 164.61p + 35173$
Munters EC50 (1270 mm) 1.0hp (University of Illinois Department of Agricultural Engineering BESS Lab, 2002a)	$Q = -1.3679p^2 + 223.65p + 40418$
Coolair 52" (1320.8 mm) 1.0hp, 6 blade, MNCFE52L (University of Illinois Department of Agricultural Engineering BESS Lab, 1999)	$Q = 0.00005p^5 + 0.0053p^4 + 0.2387p^3 + 3.0252p^2 + 227.78p + 38227$
Fancom 1456 24" (609.6 mm) 0.75hp (Patarker Pty Ltd, 2008)[##]	$Q = -0.0444p^2 + 32.618p + 12004$

This was a variable speed fan. The corresponding equation was for the maximum flow rate. In the absence of measured ventilation rate for this fan, the maximum value was assumed.

*   Where: Q = ventilation rate, in m³/hour, and
                         p = internal shed differential pressure, in Pascals (Pa).

3.2.9.4 Adjustment of ventilation rate for standard conditions

According to AS/NZS 4323.3 (Standards Australia/Standards New Zealand, 2001), the ventilation rate used to calculate an emission rate is to be standardised to standard temperature and pressure conditions (0 °C, 101.3 kPa). Each fan manufacturer was contacted, and details were recorded as to the temperature and pressure conditions under which the fans were tested. As a result, the flow rate of the fans was altered according to Equation 3 (sourced from Appendix G of AS/NZS 4323.3).

$$V_{R,0} = V_s \times \frac{(273+0)}{273+t} \times \frac{P_s}{101.3}$$

Equation 3

Where $V_{R,0}$ = volume flow at standard conditions
P_s = absolute pressure during fan performance testing, in kPa
V_s = measured flow rate
t = temperature during fan performance testing, in °C

3.2.9.5 Continuous monitoring of fan activity

At two of the farms included in this study (winter batch at Farm A and the partially reused litter batch at Farm C), ventilation rate was continuously monitored using fan activity sensors. The method used to monitor fan activity was similar to that used by Dunlop and Duperouzel (2008). The following section summarises the important components of the ventilation monitoring system.

Fan activity

Fan activity data, combined with fan performance data and other data such as shed static pressure and inlet vent positions, was used to continually estimate actual ventilation rate.

Mercury tilt switches were attached to the fan back-draft shutters to monitor fan activity, similar to the approach used by Wilhelm *et al.* (2001). The use of tilt switches was selected over other techniques due to low cost (sensors cost approximately $3.00 per fan), availability of components, expected reliability (when compared to more complex systems) and unobtrusiveness. The potential problems foreseen with the use of tilt switches included the possibility for false positive readings if the shutters did not close when the fan turned off. Additionally, if a wire broke during cleaning operations or through fatigue caused by repeated opening and closing of the shutter, a false positive reading would also be returned.

Mercury tilt switches were fitted onto an angled aluminium plate, which was then riveted onto the fan back draft shutters of every fan on the shed (see Figure 33 and Figure 34). The purpose of the angled plate was to avoid hysteresis issues associated with the switch only just (or just not) reaching a true horizontal position when the fan turned on and the shutter opened. The angle ensured the tilt switch passed beyond the horizontal position, whenever the louvers opened, so the switch would always activate.

Figure 33: Mercury tilt switch with fan turned off (shutters closed, switch closed)

Figure 34: Mercury tilt switch with fan turned on (shutters open, switch open)

Inlet vent opening

Inlet vents are an integral part of the ventilation system in a tunnel ventilated poultry shed. The mode of ventilation (tunnel or mini-vent), was determined by monitoring the position of the mini-vents and the fan activity.

To detect when mini-vents were open or closed, a Hall-effect sensor was used. A Hall-effect sensor is a digital semiconductor switch which responds to the presence of a magnetic field. To create a magnetic field, a magnet was fastened to the mini-vent shutter (see Figure 35). The voltage output of the Hall-effect sensor changed as the strength of the magnet moved away from the sensor and was recorded by the data logger. An assumption was made that if the mini-vents were open, the shed was operating in mini-vent mode. On the other hand, if the mini-vents were closed and a reasonable percentage of the fans were active, it was assumed that the shed was operating in tunnel ventilation mode.
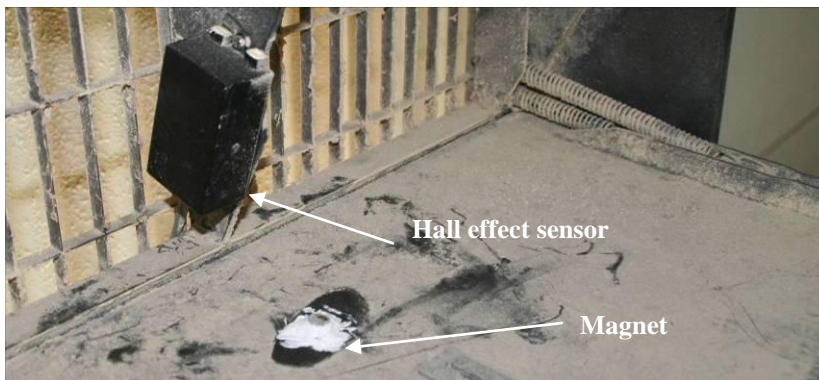
Figure 35: Mini-vent opening sensor (mini-vent in open position)

Shed static pressure

The differential pressure between the inside and outside of the chicken shed affects the performance of the ventilation fans. Chicken sheds will normally have a differential pressure in the range of 0 Pa to -40 Pa relative to the outside. This differential pressure is often referred to as static pressure. The static pressure will vary due to the number of active fans, inlet vent position and by external forces such as wind. Consequently, the static pressure will fluctuate constantly. The ventilation controller monitors the static pressure and adjusts the inlet vents to maintain a suitable pressure. Because static pressure affects fan performance, it was essential to monitor the static pressure to allow calculation of ventilation rate with reasonable accuracy.

A differential pressure sensor (Setra brand model 264, ±63 Pa range, see Figure 36) was used to measure the pressure difference between the ambient environment and the internal shed environment. The reference pressure for the pressure sensor was the pressure measured inside a weatherproof box (which was vented, but protected the sensor from strong wind pressures) or from within the control room of the poultry shed.

Figure 36: Setra ultra low differential pressure transducer used to measure the shed static pressure

Measurement frequency of each sensor

A data logger (dataTaker® DT500, dataTaker® Pty Ltd) was programmed to monitor and record the output of each sensor at specified intervals. Table 10 lists the monitoring and recording frequency for each of the sensors.

Table 10: Frequency of monitoring and recording for each sensor

Sensor	Monitoring Frequency	Recording Frequency
Fan activity (mercury tilt switches)	Six second	6 minute average; on change in fan activity
Mini-vent switches (Hall effect sensors)	Six second	6 minute average, on change in fan activity
Shed static pressure (differential pressure sensor)	Six second	6 minute average, on change in fan activity

3.2.10 Litter collection

Litter moisture content was monitored by collecting litter samples on each day that air samples were collected. In each shed, a grid system was developed so that litter samples would be collected at equal intervals across the entire floor area. For sheds approximately 100 m in length, six transects were used; and for sheds approximately 150 m in length, nine transects were used. For each transect, five samples were collected across the width of the shed at:

- Sample A – between drinker line and wall

- Sample B – between first feeder line and second drinker line

- Sample C – shed centre

- Sample D – between fourth drinker line and fourth feeder line

- Sample E – between fifth drinker line and wall

Figure 37 depicts the location of litter collection points.
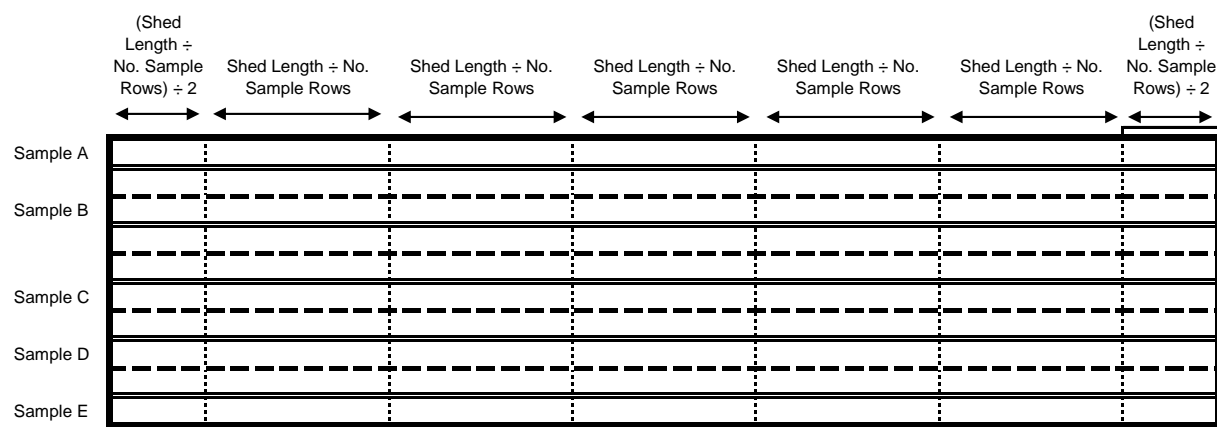
Figure 37: Litter sample collection grid pattern
Note: Double line represents a drinker line and dotted line represents a feeder line.

Samples were collected to full depth using a steel scoop or shovel, and stored in individually marked Nasco WhirlPak® bags (710 mL, 0.076 mm thickness), as shown in Figure 38. Samples were stored in the laboratory and analysed within 7 days in accordance with AS 4454-2003 (Standards Australia, 2003).

Figure 38:   Filling sample bag with litter (at sample point A)

3.2.11 **Measurement of weather conditions**

Weather conditions were monitored at Queensland sites (Farms A and C) with a 10 m portable automatic weather station (AWS) (See Figure 39).

Figure 39:   Weather station used for this project

Weather information collected during the trials is displayed in Table 11. All data (except rainfall) was collected every second then averaged and reported every six minutes. Hourly and daily averages (and totals) were calculated during post processing. Specific information for the weather station sensors is displayed in Table 12.

Table 11: Weather information collected during the trials

Parameters measured by the AWS	
2 m wind speed	10 m wind speed standard deviation
2 m wind direction	2 m temperature (2 sensors)
10 m wind speed	2 m relative humidity
10 m wind direction	10 m temperature
2 m wind direction standard deviation	Total radiation
10 m wind direction standard deviation	Barometric pressure
2 m wind speed standard deviation	Rainfall

Table 12: Weather station sensor information

Sensor/Parameter	Brand	Model Number	Sensitivity	Range
Data Collection	DataTaker	DT500 (version7)	0.11% for Voltage 0.21% for Current	0-2500 mV 0.25-25 mA
Temperature (2 m)	Vaisala	50Y Humitter	±0.6°C at 20 °C	-10 to +60 °C
Temperature (2 m & 10 m)		PT100		-50 to +250 °C
Relative Humidity (RH) (2 m)	Vaisala	50Y Humitter	±3% at 90% RH	10 to 90%
Wind Speed	Gill Windsonic	1405-PK-040 Option 3	±4% at 20 m/s	0 to 60 m/s
Wind Direction	Gill Windsonic	1405-PK-040 Option 3	± 3° at 20 m/s	0 to 359°
Total Radiation	Li-Cor	LI200SZ	0.2 kW/m²/mV	
Barometric Pressure	Vaisala	PTB101B	±0.5 hPa at 20 °C ±2 hPa at 0-40 °C	600 to 1060 hPa
Rainfall	Hydrological Services	TB3	one tip/0.2 mm rain	0 to 700 mm/hr

The AWS was located and managed by DEEDI according to AS 2923–1987 (Standards Australia, 1987) wherever possible. It was not always possible to locate the weather station in strict accordance with the standard at some of the sites due to vegetation or geographical landforms. In these cases, the weather station was positioned as close as possible to the trial site, which occasionally meant small compromises in relation to these obstacles.

Data from the AWS was able to be used to calculate atmospheric stability class, described using Pasquill-Gifford stability categories. Stability class was calculated using the σ_A method (wind turbulence based method using wind direction standard deviation) as described in USEPA (2000).

3.2.12 Measurement of ambient and shed temperature and humidity

Ambient and in-shed temperature and relative humidity were measured with three instruments. During in-shed ventilation rate measurement, the hot wire anemometer (TSI Incorporated VelociCalc® Model 8386–M–GB) was used to measure temperature and relative humidity.

Ambient temperature and relative humidity were monitored with a Kestrel® Pocket Weather Tracker (Nielsen–Kellerman model 4500, see Figure 40). The Kestrel was suspended from DEEDI's sample collection trailer out of direct sunlight and influence from air exiting the shed. Readings were recorded every minute.

Temperature of the air exiting the shed was monitored from within the polyethylene duct using a Cox Tracer® (Cox Technologies, Inc., see Figure 41). The logger contains two temperature sensors, one inside the green body, and the other external sensor in the steel probe. The probe was suspended inside the duct for the duration of the sample days. Readings were recorded every minute.

Figure 40: Kestrel® Pocket Weather Tracker

Figure 41: Cox Tracer® Temperature Recorder

For measurement of ambient temperature and relative humidity, as mentioned in section 3.2.11, a 10 m weather station was used. It is possible to measure ambient conditions using portable instruments such as the Kestrel® and Cox Tracer®. However, it is important that the measurement point is located away from any interference from the air exiting the poultry shed. Figure 42 shows how ambient temperature measured with a Kestrel or Cox Tracer compared to ambient temperature measured at 2 m from DEEDI's weather station. Sixty-five percent of the portable instrument readings were within one degree Celsius and 34% of the readings were between 1.5 and 4 degrees Celsius above that measured by the weather station. The use of portable temperature instruments is good for measuring internal shed temperature, but care must be taken when measuring ambient temperature near the tunnel ventilation fans. The use of a weather station will reduce the possibility of these errors.
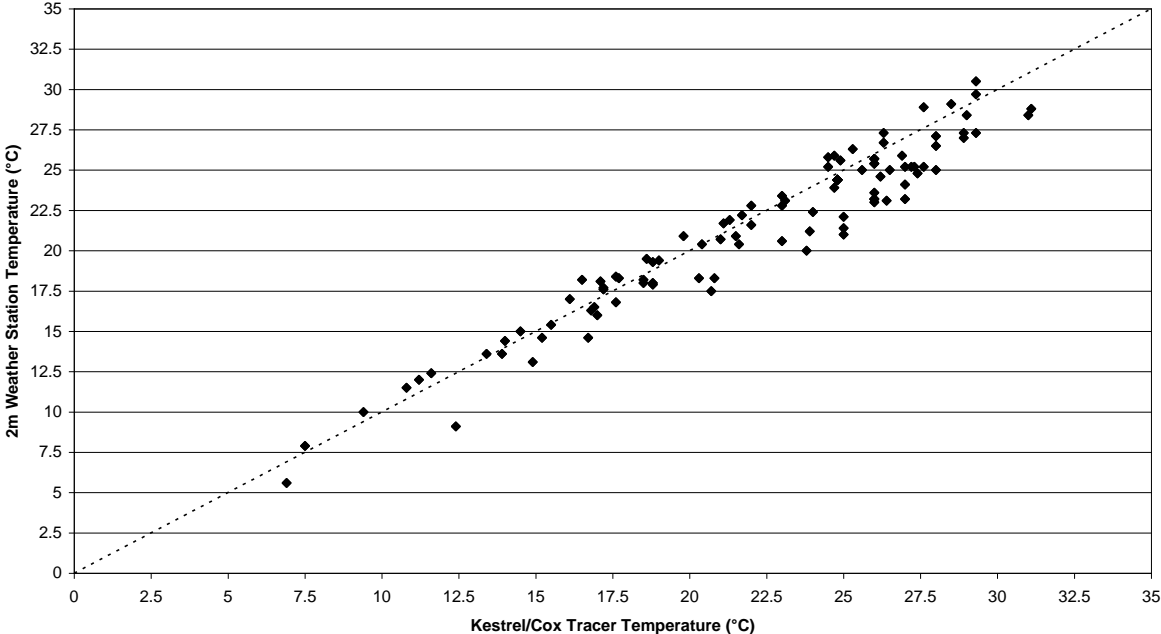
Figure 42: Comparison between weather station (2m) and Kestrel/Cox Tracer temperature

3.2.13 **Production parameters**

Production information was provided by the farm manager and integrator. Number of birds placed, number of birds present on each sample collection day, and average daily live weight were supplied, and average live weight density was calculated accordingly. These parameters were assessed for their ability to influence air quality.

3.2.13.1 Bird weight

Details of bird weight were supplied by the producers using the weekly average weight and the integrator at collection for slaughter.

3.2.13.2 Bird numbers

The number of birds placed and number of birds removed at each pickup were supplied by the integrator. All other data regarding the number of birds present was provided by the producer. The number of birds present on each day of the batch was estimated using the number of birds placed; number of birds collected at each pickup; and estimated or measured mortality rate.

3.2.13.3 Live weight density

Live weight density (LWD) was calculated by using Equation 4:

LWD (kg/m²) = No. birds in shed × av. bird live weight (kg) ÷ shed floor area (m²)   **Equation 4**

3.3 **Analysis techniques**

3.3.1 **Olfactometry – odour concentration analysis**

3.3.1.1 *Department of Employment, Economic Development and Innovation (DEEDI) Olfactometer*

Odour concentration from all Queensland farms was determined using the eight panellist, triangular, forced choice dynamic olfactometer developed by the Department of Employment, Economic Development and Innovation (DEEDI), which has been described previously (Nicholas *et al.*, 1999; Zeller *et al.*, 2002). This olfactometer was constructed and operated to comply with the Australian/New Zealand Standard for Dynamic Olfactometry AS/NZS 4323.3:2001 (Standards Australia/Standards New Zealand, 2001).

During a typical odour sample assessment routine, each panellist was first screened with the reference gas (n-butanol) to ensure that his or her detection threshold was within the required concentration range of 20–80 ppb (v/v). Thereafter, the odorous sample was diluted and presented to the panellists in one of three ports, while the other two ports emitted clean, odour-free air. The panellists were required to sniff from the ports and determine whether they could detect a difference between the three ports. Each panellist was allowed a maximum of 15 seconds for this assessment. The panellists indicated via a keypad whether they were certain, uncertain or guessing that one of the ports was odorous, as well as from which port the odour (if detectable) was emitted.

This process was repeated, doubling the concentration of odorous air of the previous presentation each time, until each panellist had entered a "certain and correct" response for two consecutive presentations. Each panellist's individual threshold estimate ($\overline{Z}_{ITE}$) was then determined by calculating the geometric mean of the dilution at which the panellist did not respond with certainty and correctly and the first of the two dilutions where the panellist did respond with certainty and correctly. A complete dilution series is defined as a round. Three rounds were completed for each sample provided sufficient sample was available.

At the end of the three rounds, the results of the first round were discarded in accordance with AS/NZS 4323.3. The results from rounds two and three were then geometrically averaged ($\overline{Z}_{ITE}$). The ratio between Z_{ITE} and $\overline{Z}_{ITE}$ is defined as ΔZ. The calculation of ΔZ is presented in the following equations:

$$if\ Z_{ITE} \geq \overline{Z}_{ITE},\ then\ \Delta Z = \frac{Z_{ITE}}{\overline{Z}_{ITE}} \qquad \textbf{Equation 5}$$

$$if\ Z_{ITE} \leq \overline{Z}_{ITE},\ then\ \Delta Z = \frac{\overline{Z}_{ITE}}{Z_{ITE}} \qquad \textbf{Equation 6}$$

If ΔZ is greater than ± 5 then all $\overline{Z}_{ITE}$ values of the panel member with the largest ΔZ were excluded from the data set. The screening procedure was then repeated, after re-calculation of $\overline{Z}_{ITE}$ for that measurement. If a panel member again did not comply, the results for this panel member (with the largest ΔZ) were omitted. This was repeated until all panel members in the dataset had an acceptable ΔZ value. The last value of $\overline{Z}_{ITE}$ was then defined as the odour concentration and expressed as odour units per cubic metre (ou m³).

3.3.1.2 Emission Testing Consultants (ETC) Olfactometer

The ETC olfactometer was designed and built to comply with the performance and design criterion of the Standard.

Six odour panellists were used to assess odour samples. Each odour panellist had two ports (left and right) in which odour samples were presented. One port always contained odour free air (reference air) and the other diluted sample air. The olfactometer was designed so that the reference air and the diluted sample air could be swapped randomly from one port to the other.

All odour panellists were screened to ensure their sensitivity to a reference odorant (*n*-butanol) was between 20 and 80 ppb. Odour panellists were assessed on a continuous basis to ensure they complied with the criterion for sensitivity and consistency stipulated in the Standard.

The olfactometer was calibrated on an annual basis using a NATA certified tracer gas (carbon monoxide) and assessed against the performance criterion of the Standard.

3.3.1.3 Compliance of olfactometers with accuracy and repeatability criteria

To be compliant with AS/NZS 4323.3:2001 (Standards Australia/Standards New Zealand, 2001), olfactometers must meet or exceed assessment criteria for accuracy and repeatability. Accuracy is a measure of how closely the olfactometer can measure the true value of a reference gas (40 ppb Butanol) and is defined by accuracy test variable A_{od}. Olfactometer must achieve $A_{od} \leq 0.217$ for compliance. For olfactometer precision (measured in terms of repeatability), olfactometers must achieve a value of $r \leq 0.477$ (resulting in $10^r \leq 3$). In plain English, this value implies that the difference between two single measurements, performed on the same material, in one laboratory, will not be greater than a factor of 3 in 95% of cases. An assumption is then made that this repeatability is transferable to unknown samples (Standards Australia/Standards New Zealand, 2001; van Harreveld *et al.*, 1999).

During this study, two olfactometry laboratories were used: DEEDI laboratory in Queensland and ETC in Victoria. DEEDI olfactometer accuracy ranged from $0.052 \leq A_{od} \leq 0.121$ with an average value of $A_{od} \approx 0.082$. Repeatability ranged from $0.259 \leq r \leq 0.318$ ($1.46 \leq 10^r \leq 2.08$). ETC olfactometer accuracy ranged from $0.098 \leq A_{od} \leq 0.216$. Repeatability ranged $0.251 \leq r \leq 0.465$ ($1.78 \leq 10^r \leq 2.92$).

3.3.1.4 *Round robin testing of olfactometry laboratories*

All odour samples could not be analysed by the same olfactometry laboratory. As farms in Queensland and Victoria were included in the study, it was not logistically possible to analyse the Victorian samples in Queensland within the required time frame. Hence an olfactometry laboratory was used to analyse the Victorian odour samples. To ensure comparability between laboratories, all participating olfactometry laboratories took part in an international round robin test in 2005.

An independent laboratory (OLFAtec GmbH, Honigsee, Germany) distributed gaseous samples to all participating laboratories. The samples were analysed on one day within a specified week determined by OLFAtec. Each laboratory calculated their odour concentration results and forwarded the results to OLFAtec, where odour threshold results were calculated. The results were then analysed by OLFAtec to determine the accuracy of each olfactometry laboratory.

The odour concentration and odour threshold results are shown in Table 13. The terms 'pass' and 'fail' indicate whether the concentration calculated by the laboratory fell within the set limits of accuracy.

Table 13: Olfatec 2005 round robin test results for DEEDI and ETC

Test №		Odour concentration (ou/m³)		Odour threshold (µg/m³)	
		DEEDI	ETC	DEEDI	ETC
1.	1–Butanol	378 (pass)	340 (pass)	95.24 (pass)	105.88 (pass)
2.	1–Butanol	1166 (pass)	900 (pass)	101.3 (pass	130.89 (pass)
3.	Tetrahydrothiopen	3158 (pass)	3800 (pass)	2.37 (pass)	1.97 (pass)
4.	SFREE – ethylacrylate, methylacrylate and 2–ethyl 3–methylpyrazine	7061 (pass)	8100 (pass)	0.14 (pass)	0.12 (pass)

The odour concentration and odour threshold results for the DEEDI and ETC olfactometers are shown in Figure 43 and Figure 44 respectively.
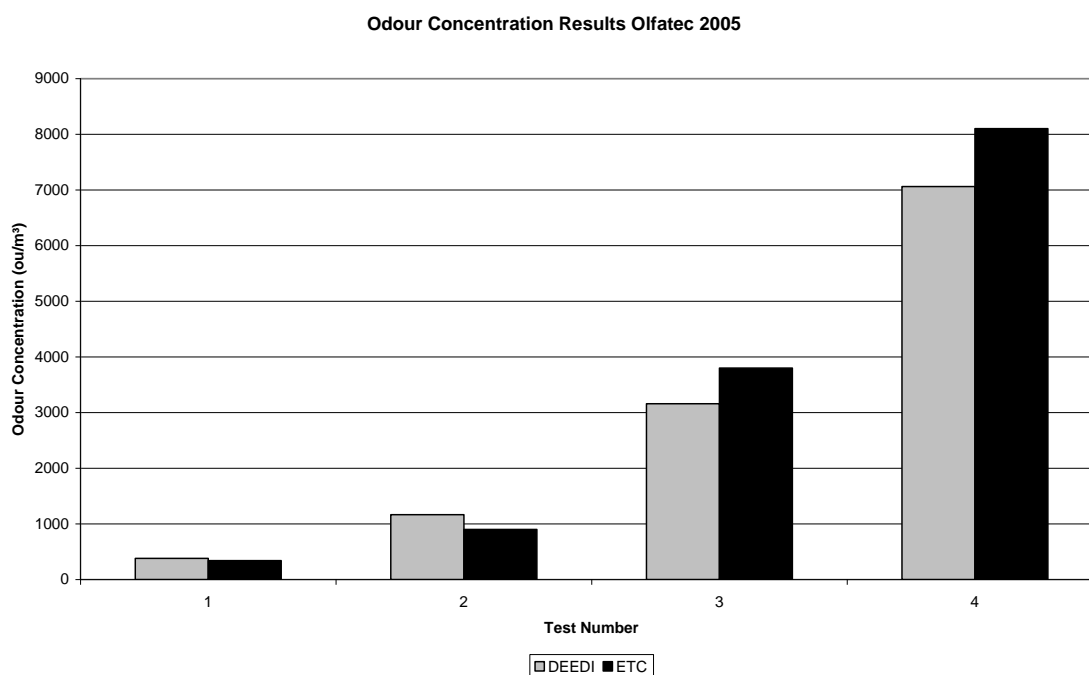
Figure 43: Odour concentration results for Olfatec Test 2005

Odour Threshold Results Olfatec 2005
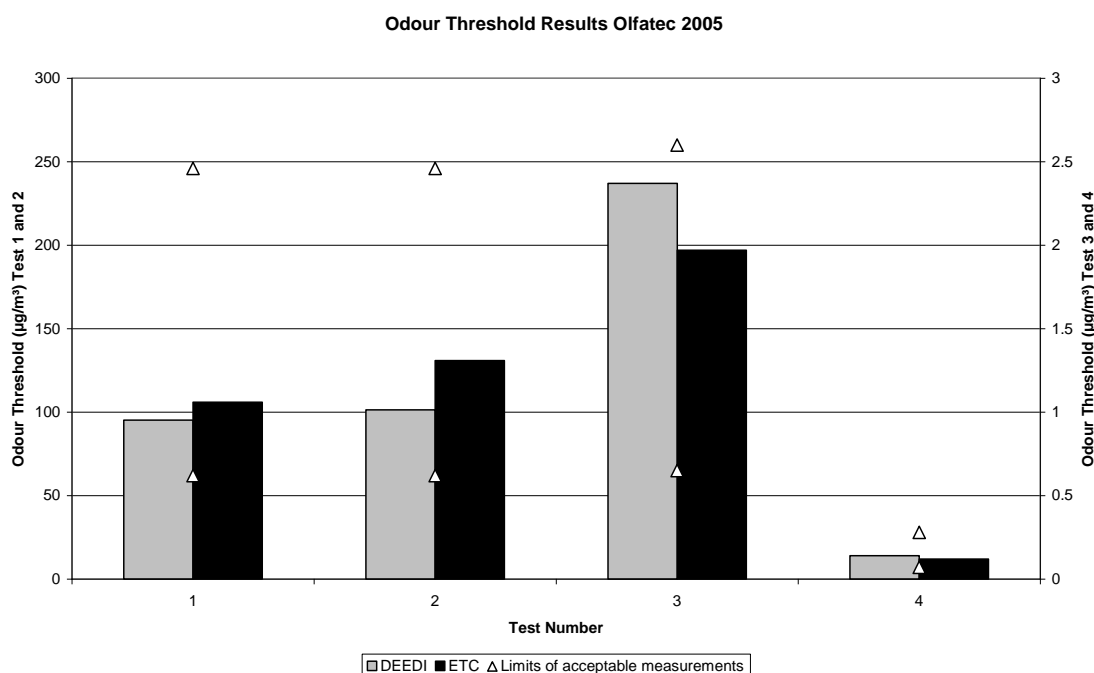
Figure 44: Odour threshold results for Olfatec Test 2005

Summary of round robin testing

The two olfactometry laboratories used during this project—ETC and DEEDI—were assessed using an international round robin compliance test conducted by OLFAtec and both laboratories passed each of the four assessment included with the test. Similar results by both olfactometry laboratories in this independent testing event demonstrated that odour measurements by both labs were comparable—when using standard gas mixtures. Consequently, assessment of poultry odour samples by either ETC or DEEDI olfactometers would also be expected to be comparable.

It is recommended that where more than one olfactometry laboratory is used for a single trial, that:

- a test be performed to ensure similarity in results from all laboratories; and
- all laboratories conform to AS/NZS 4323.3:2001 (Standards Australia/Standards New Zealand, 2001).

3.3.2 Dust analysis

Particle mass concentration (for PM_{10} $PM_{2.5}$ fractions) and particle number concentration were measured in the exhaust stream from broiler sheds. These variables had units of mg/m³ and particles/m³ respectively. The data analysis procedure was identical for both concentration measurements. Concentrations were first corrected for dilution during the sampling process. Dilution with particle-free air during sampling was necessary to maintain isokinetic conditions. Particle number or mass emission rates were then obtained by multiplying average corrected concentrations by average ventilation rate, which was expressed in units of m³/s, producing emission rates in units of mg/s or particles/s. These rates represent the number or mass of dust particles emitted per second from the broiler sheds. For comparison between different broiler sheds, emission rates were normalised to emission rate per kg of live bird weight, and emission rate per 1000 birds placed, using the appropriate production parameters.

During the sample collection periods, continuous dust concentrations were recorded at the majority of farms. Therefore a choice had to be made regarding the time period over which concentrations were averaged. Two approaches were taken. Firstly, to directly compare dust and odour emission rates, particle mass and number concentrations were averaged over the times that odour samples were collected.

Secondly, to investigate the relationship between dust emission rate and ventilation rate, concentration measurements were averaged over the times when ventilation rate was relatively constant (i.e. when the number of active fans was constant).

Particle size distributions were also measured throughout this project. A very large number of size distributions were recorded at each farm so to easily represent this information a single parameter, Count Median Diameter, (CMD), was calculated for each distribution. The CMD represents the mid-point diameter of a particle number size distribution.

3.3.3 Non-methane volatile organic compound and odorant analysis

The laboratory analysis of the sorbent tubes for non-methane volatile organic compounds (NMVOCs) and odorants was performed in three unique and sequential stages:

1. Using a thermal desorber (TD) to liberate the analytes from the sorbent tube, focus and inject the NMVOCs;

2. Using a gas chromatograph (GC) to separate the NMVOCs on a chromatographic column; and

3. Using a mass selective detector (MSD)—alternatively known as a mass spectrometer (MS)—and olfactometry detection port (ODP) to detect, identify and quantify the NMVOCs and odorants.

The instrument series is frequently referred to as TD-GC-MS/O—the MS/O segment indicating that these two stages happen simultaneously. Figure 45 show the TD-GC-MS/O instrument setup as used in this investigation.
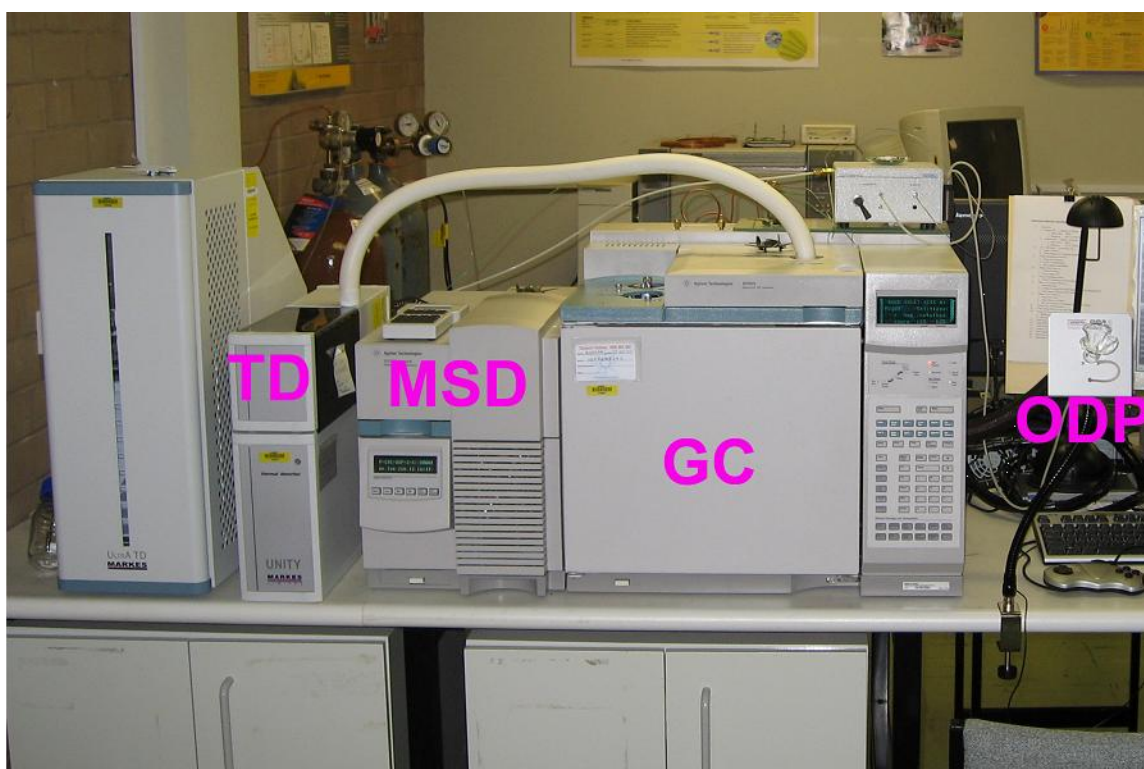
Figure 45:   The instrument setup for the analysis of the thermal desorption tubes. *From left to right: Markes UltrA Autosampler, Markes Unity Thermal Desorber, Agilent 5973N Mass Selective Detector, Agilent 6890N Gas Chromatograph and Gerstel ODP2 Olfactory detection port*

The gas chromatograph-mass spectrometer (GC–MS) combination is one of the most powerful analytical tools available to most modern analytical chemists. The selectivity, flexibility, and sensitivity of GC–MS

lend itself to the analysis of environmental samples, owing to the wide variety of analytes that are found within a particular matrix.

The chemical characterisation of the NMVOCs within the poultry shed emissions was performed using an Agilent 6890N gas chromatograph coupled to an Agilent 5973N mass selective detector (Agilent Technologies, Nth Ryde, Sydney, Australia).Varying different operating parameters during the course of the research enabled an optimum method to be established for the efficient speciation of the analytes captured on the sorbent tubes.

The separation of the chemical species allows for their identification, numerous detectors are commercially available for integration into a chromatographic system; however, the mass selective detector has the benefit of providing rapid and flexible chemical speciation. For the purpose of characterising the odorants within the NMVOCs, an additional olfactory detection port is necessary. It is the combination of the mass spectrometer and the odour detection port that provide the unique data set for the characterisation of the NMVOCs and the odorants present within the gas phase poultry shed emissions.

The methods for each piece of analysis equipment are explained in the following sections. A summary of the NMVOC laboratory analysis equipment and operating parameters used throughout the project is provided in Appendix 2. The term volatile organic compound (VOC) refers to any organic compound that under normal conditions will be of sufficient volatility to enter the atmosphere; where normal conditions are typical atmospheric pressure (101.325 kPa) and temperature (~300 K). Correspondingly, NMVOC are all volatile organic compounds with the specific exclusion of methane (CH_4). For the purpose of this document the terms NMVOC and VOC have been used interchangeably; however, it should be expressly noted that where VOC is written, it is implied that it is the non-methane volatile organic compounds (NMVOC).

3.3.3.1 *Thermal desorption—operation and control parameters*

The initial stage of the laboratory analysis procedure, that of the thermal desorption, was performed with a Markes Unity Thermal Desorber (Markes Int'l. Ltd Pontyclun, UK). This instrument performs a series of sample preparation steps, focuses the volatile organic compounds and then injects them as an analyte slug into the GC. Clean, rapid injection of the analyte slug must be executed to enable the VOCs to be separated effectively by the chromatographic column. This is achieved using cryogenic trapping (also known as cryogenic focussing), which precipitates the volatiles into a liquid that can be injected onto the chromatographic column. In fundamental difference to the use of cryogenic fluids (LN_2) the Unity Thermal Desorber contains a narrow sorbent trap, known as the *cold trap*, which employs a Peltier device to maintain a desired temperature to focus the analytes from the sorbent tube. This cold trap is held at either ambient (25~30 °C) or sub-ambient (-10 °C) temperature whilst the analytes are thermally liberated from the sorbent tube. The use of a temperature controlled sorbent trap negates the use of cryogenic temperatures and the corresponding cryogenic fluids.

The operation of the TD is governed by numerous parameters controlled either by software or manual adjustment. There is a number of different modes of operation under which the TD can function—for the analysis of NMVOCs from sorbent tubes, the Standard 2(3) stage desorption is selected. Figure 46 illustrates the graphical user interface of the Markes Unity software that is used to control the different temperatures and times of the TD. The gas flow rates are controlled by needle valves on the instrument and verified by the flow rates reported on the GC.
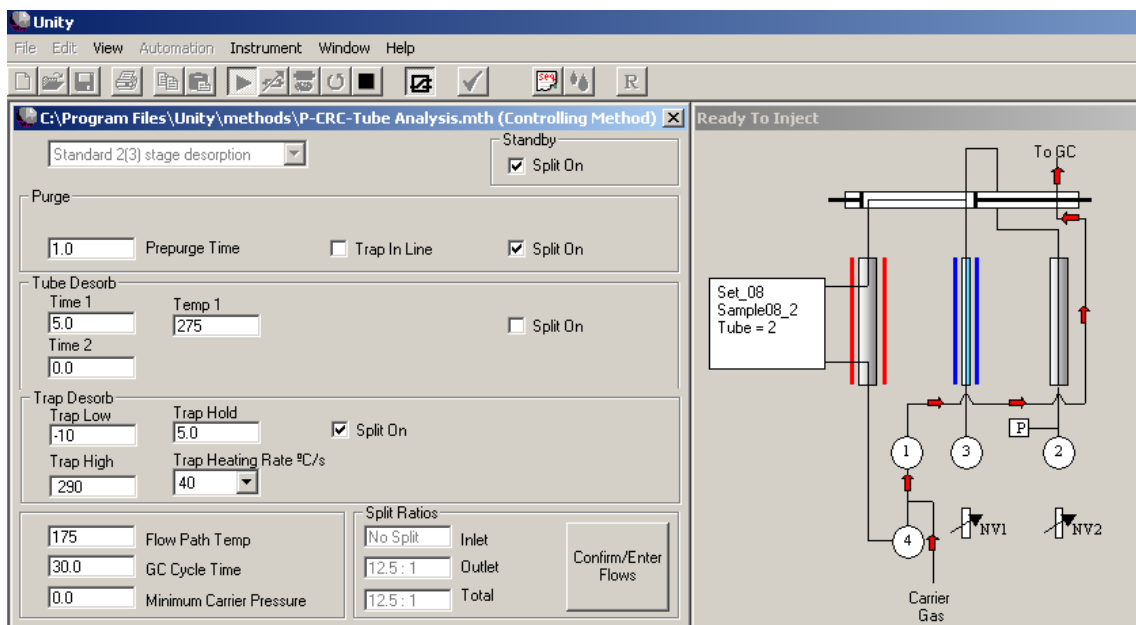
Figure 46: Markes Int'l. Unity software screen capture. *The left portion is the controlling method and the right portion illustrates the current flow path and instrument status (tube loaded, waiting to desorb)*

The Unity thermal desorber has three stages of operation:

1. tube purge;

2. tube desorb; and

3. trap desorb (including a default trap purge).

Tube purge

The tube purge is a critical component of the sample preparation, as it removes undesirable contaminants such as oxygen and water from the sorbent. This is vitally important when sampling from humid environments such as poultry sheds—if any moisture is passed to the cold trap and injected into the GC it can result in damage to the column and the detector as well as interfering with the signal from the detector. The presence of oxygen in the sorbent tube will result in oxidation of the volatiles within the sorbent tube upon heating.

The presence of both oxygen and water vapour in the sorbent tubes is unavoidable as they are collected from the atmosphere, thus careful sample preparation must be employed to minimise their harmful effects on the analysis. It should be recognised that thermally labile compounds may degrade during the heating stages of the thermal desorption; however, the use of gentle temperature ramps and effective pre-purging should minimise the risk.

During the tube purge, the tube is held at ambient temperature, the cold trap is kept at the trapping temperature (*trap low)* and the carrier gas is passed though the sorbent tube at a flow rate equal to that during the tube desorb stage, which is set by the needle valves. The time that the tube is purged for is set by the *prepurge time* and can optionally be captured inline (*trap in line*) by the cold trap and/or have some of the flow diverted into the recapture tube (*split on*). If the prepurge is not trapped in line it is passed through to the solvent vent of the gas chromatograph.

Tube desorb

Upon conclusion of the prepurge the tube desorb stage commences, with an electric heater (the *oven*) heating the sorbent tube to a preselected temperature (Temp 1) and maintaining this temperature for the preset time (Time 1). During this stage the carrier gas continues to flow through the sorbent tube and

through to the cold trap where the analytes are captured and focussed. This stage thermally liberates the analytes from the sorbent tube and collects them on the cold trap. The flow from the sorbent tube can either have all the sample passed onto the cold trap or split a certain ratio to the recapture tube for additional analysis with the *split on* function selected.

There can either be one or two temperatures to which the oven is heated, depending upon the characteristics of the NMVOCs that have been collected. The cold trap is maintained at its Trap Low temperature during the tube desorption stage in order to effectively capture all the NMVOCs from the flow.

Trap desorb—including trap purge

The conclusion of the tube desorb stage commences the trap purge, which is in essence identical to the tube purge and further ensures that there is minimal unwanted moisture or oxygen contamination within the analytes that have been captured on the cold trap before the heating of the trap is instigated. The cold trap is a narrow sorbent tube that acts as a cryogenic trap; the sorbent is contained in a quartz tube that can rapidly be heated by the Peltier device.

The sorbent contained within the cold trap should be selected based on the analytes that are to be focussed. The *trap low* temperature is the temperature at which the cold trap is maintained during standby, tube purge, tube desorb and trap purge. As indicated in the preceding text, this temperature is either ambient (25~30 °C) or sub-ambient (-10 °C) depending on the characteristics of the sample. The cold trap is designed to provide a focussed analyte *slug* that can quickly and cleanly be injected into the GC and this is achieved through rapid (*ballistic*) heating. The cold trap is heated from the *trap low* temperature to the *trap high* temperature in a matter of seconds—this heating rate can be customised to preserve sample integrity. As with the other two stages the complete sample can be injected into the gas chromatogram or a portion can be split into the recapture tube for additional analysis.

Miscellaneous parameters

The split ratio is controlled by the needle valves on the TD; however, the software contains a dialogue box pertaining to this ratio setting. The user must enter the flows as indicated by either the gas chromatogram or as measured with an accurate flow meter. In this way the amount of sample that is passed to the gas chromatogram or to the recapture tube can be calculated.

The sample flow path through which that the NMVOCs flow, most significantly along the transfer line, is also controlled from the TD software. The *flow path temp* is selected based upon the volatility of the compounds—a temperature that is too low may cause some of the analytes to condense along the flow path before reaching the GC, conversely a temperature too high may result in thermal degradation of the sample.

During automated operation (i.e. when the UltrA Autosampler is attached) the cycle time must be set according to the total run time of the GC and the time required for the oven to return to the initial temperature.

As mentioned in the preceding text, the cold trap of the TD is similar to a sorbent tube, although of a much narrower bore to allow the analytes to be rapidly released upon the ballistic heating. In similarity to the selection of sorbents for the sorbent tubes, the properties of the sorbent contained within the cold trap can be selected to best suit the analytes being assessed. During this project, a general purpose graphitised carbon sorbent was selected—suitable for the NMVOCs that were repeatedly detected in the tubes. In a similar method to the conditioning of the sorbent tubes, a cold trap can be conditioned if it becomes apparent that there is an undesirable level of carry over contamination between samples; however, this is not frequent as the higher trap desorb temperature than the tube desorb temperature ensures that all analytes released from the sorbent tube will be released from the cold trap upon heating.

Thermal Desorption Methods

During the initial sampling and method development stages of the project, the thermal desorption methods underwent minor revisions to accommodate the two different sorbent tubes that had been selected for the field sampling. The moderate hydrophilic Carbotrap 300 sorbent captured far more moisture during sampling then the Tenax TA tubes and this had a marked impact on the experimental results. Two different methods were used to thermally desorb the analytes from the sorbent tubes, as seen in Table 14.

Table 14: **Instrument controlling parameters for the thermal desorption of the Tenax TA and Carbotrap 300 sorbent tubes**

Parameter	Tenax TA	Carbotrap 300
Purge (min.)	1.0	5.0
Tube Desorb Time (min.)	5.0	5.0
Temp. (°C)	250	250
Trap low (°C)	-10	+30
Trap High (°C)	290	300
Trap Hold (min.)	5.0	5.0
Trap Heating Rate (°C/s)	MAX	MAX
Flow Path Temp (°C)	150	150
Splits (Purge/Tube/Trap)	Y/N/Y	Y/N/Y

As the project developed and the sampling techniques were refined, the thermal desorption parameters were refined until one method was developed that was appropriate for both the Tenax TA and Carbotrap 300 sorbent tubes. As can be seen in Figure 47, it has been influenced strongly by the initial Tenax TA method; however, has been optimised for efficient analysis of Tenax TA, Carbotrap 300 and dual sorbent Tenax TA and Carbograph 1TD sorbent tubes.
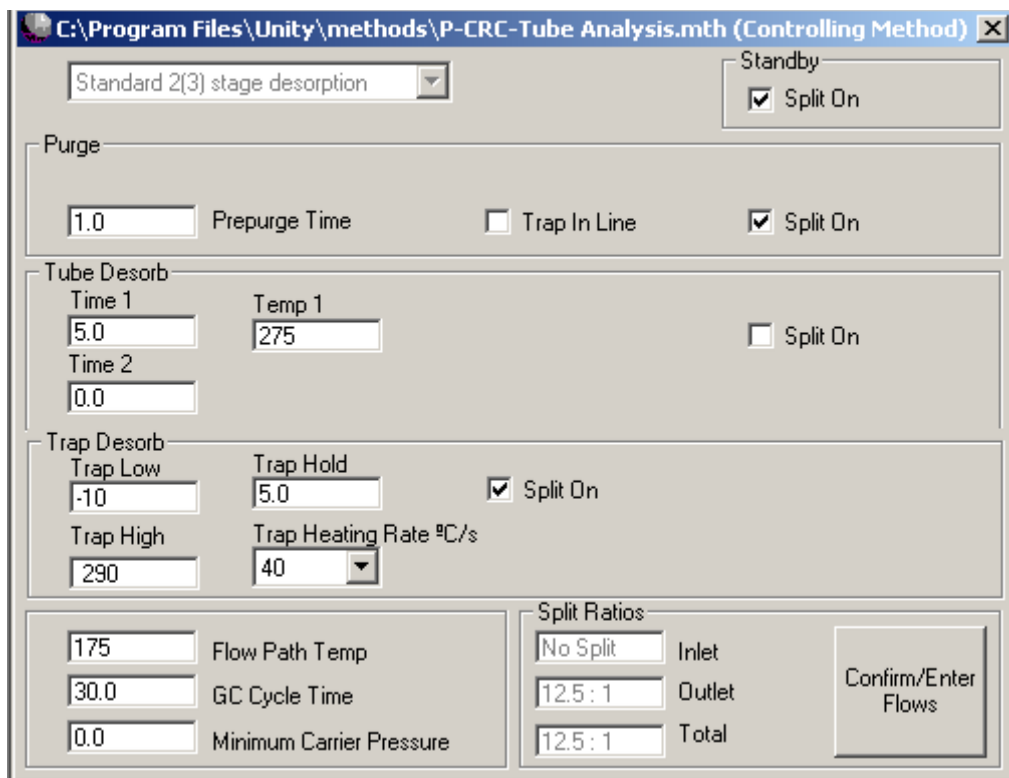
Figure 47: Screen capture of the TD software illustrating the final thermal desorption parameters that were used for all sorbent tube samples

3.3.3.2 *Gas chromatograph operation and parameters*

The unknown facets of the speciation lead to the use of very general GC operating parameters for the initial sample analysis; however, once the quantity and variety of compounds was understood, this method was refined to an optimal level to reduce total sample analysis time and increase peak separation.

Carrier Gas

The GC was supplied with ultra high purity helium carrier gas (He - 220G, BOC Gases, Sydney, NSW Australia). The electronic pneumatic control module of the GC controlled the gas pressure though the TD and through the GC. Helium has been extensively used in gas chromatography due to its very low molecular (cf. atomic) mass, inertness and non-polar properties.

Column type

The use of fused silica capillary columns in gas chromatography has resulted in increased accuracy and lower detection limits for trace level analysis. These columns are available in different polarities—the analyte mixture that is being separated will determine whether a polar, non-polar or an intermediate polarity column will be selected. The interactions of the analytes within the sample are responsible for the retention time of the particular molecule, and these interactions are physical more so than chemical—with adsorption/desorption (or simply sorption) and porous layer open tubular (PLOT) columns, the affinity for the chemical species is governed by the size, surface charge and van der Waals forces. Combining these factors determines the retention time and therefore elution order of the chemical species.

For the initial sampling, a general purpose (5%-Phenyl)-methylpolysiloxane (HP-5ms, Agilent Technologies, North Ryde, NSW Australia) column was used. This non-polar column is suitable for semi-volatiles, alkaloids, drugs, fatty acid methyl esters (FAMEs), halogenated compounds, pesticides and herbicides. It allowed for the initial identification of the varieties of species within the samples; however, as the results of the initial sampling became clear, and the characteristics of the species being detected were established, a column with a significantly higher polarity was installed.

The polar column that was subsequently chosen was a polyethylene glycol column (HP-INNOWax, Agilent Technologies, North Ryde, NSW Australia)—suitable for alcohols, aromatics, essential oils and solvents. This column was far more suitable to the low molecular mass mildly polar species that were consistently being detected in the samples and allowed for separation of the co-eluting peaks—leading to increased reliability and improved identification of odorants when used concurrently with the olfactory detection port.

During different sampling campaigns, replicate samples were collected in order to analyse them on different columns to ensure that polar column in use was most suitable. These duplicates were analysed on moderately polar columns (DB-VRX, J&W Scientific, and HP-624, Agilent Technologies) with essentially identical stationary phases.

The vast majority of the samples were analysed on the polar (HP-INNOWax) due to the late acquisition of the considerably more suitable DB-VRX column. Time restrictions did not permit repeat sampling or quantification of the DB-VRX data sets; however, it is strongly recommended that all future work would be carried out on this column.

Injection Method

One advantage of fused silica capillary columns over traditional packed columns is the small injection volumes that can be directly injected onto the column. This ensures that all the analytes within the sample matrix will pass to the detector ensuring the accurate representation of the emission source. With the use of the thermal desorber, a split-less injection was performed to ensure that all the analytes within the sample were injected onto the column to maximise the number of compounds identified within the samples.

Flow rate

The retention time and elution order of analytes within a given sample result from the interaction of the analytes and the stationary phase of the column. The flow rate of the carrier gas can influence the elution time but not the order of elution—considerations must be given to the operation of the detector that is being used. This is of significance to the use of a MSD, which is under high vacuum—if the carrier gas flow rate is too high, the pumps of the MSD will not be able to create and maintain the level of vacuum required for proper operation.

Whilst the initial sample analysis only employed the MSD, the later sampling employed a second detector—the olfactory detection port (ODP) (Gerstel ODP2, Gerstel GmbH & Co., Germany) which consequently required the effluent from the GC column to be split between the two detectors. This dictated that the carrier gas flow provided sufficient pressure at the end of the column in order to maintain positive flow to the ODP, whilst preserving the vacuum of the mass selective detector. If this balance is not correctly maintained, the MSD could be effectively open to the atmosphere, creating an air leak and potentially damaging the instrument.

Oven Temperature Program

As mentioned in the introduction the GC section, the initial sample analysis employed a very general method—the oven temperature profile was initially a single temperature ramp from 50 °C to 250 °C, with a total run time of 44 minutes. Initial temperature (50 °C) was held for 2 minutes before the temperature was increased at 5 °C/min to the final temperature of 250°C which was held for 2 minutes. This programme appeared to be suitable for the elution of the compounds; however, there was a significant amount of free space (dead time) during which no compounds were eluting. Consequently the temperature programme was modified, to include two temperature ramps, and a lower final temperature. The initial temperature was kept at 50 °C and the first temperature ramp 5 °C/min to 125 °C, then a second temperature ramp of 10 °C/min to 200 °C, which was held for 2 minutes. The first allowed for the elution of the closely related n-C_4 compounds with adequate separation, and also gave enough time for the elution of the higher polarity (cf. higher boiling point) species to elute.

3.3.3.3 Mass selective detector (mass spectrometer) operation and parameters

The mass selective detector (MSD) provides chemical speciation as well as quantification; it is a flexible detector capable of characterising complex samples efficiently for a wide range of chemical compounds. The operating parameters are controlled by the ChemStation Software, and there are two modes of operation in which the MSD can operate; *scan* and s*elected ion monitoring* (SIM). Scan operates the MSD as a continuous scan from a preset range, whilst in SIM mode, the MSD is programmed to target specific m/z ions during specific time windows. The SIM mode is best when the composition of the samples that are being analysed is vaguely understood. This was not the case with the majority of the poultry samples; consequently the use of the scan mode was engaged for all the samples.

Manually controlled operating parameters

The scan parameters were initially set to 50–550 m/z, which was a basis for the initial results; however, upon the further interrogation of the preliminary results, it was determined that the scan range should be increased to detect the lower m/z fragments of many of the compounds. To avoid influence from any traces of air and moisture that may be present during the elution of the compounds, a lower m/z of 35 was chosen. This would allow for many of the n-C_4 fragments in the 40–50 m/z range to be detected and thus increase the reliability of the matches to the mass spectral databases.

Automatically configured operating parameters

The operating parameters pertaining to the stable function of the MSD were controlled automatically by the ChemStation (Agilent Technologies, North Ryde Sydney Australia) software, tuning the instrument allowed for the correct voltages to be configured to ensure the system functioned properly.

Databases, spectral matching and compound identification

Two databases were used for the identification of the compounds eluting from the samples: NIST02 database and Wiley275 database. The former is issued by the National Institute of Standards and Technologies and the other is produces by the science publishing house Wiley InterScience. Once a reliable spread of compounds had been positively identified, several neat standards were purchased to provide retention time matches and also to perform the quantification of the method.

3.3.3.4 The olfactory detection port operation and parameters

The olfactory detection port (ODP) (see Figure 48) was operated in tandem to the MSD and allowed for the simultaneous identification of the odorants that were present among the suite of NMVOCs.
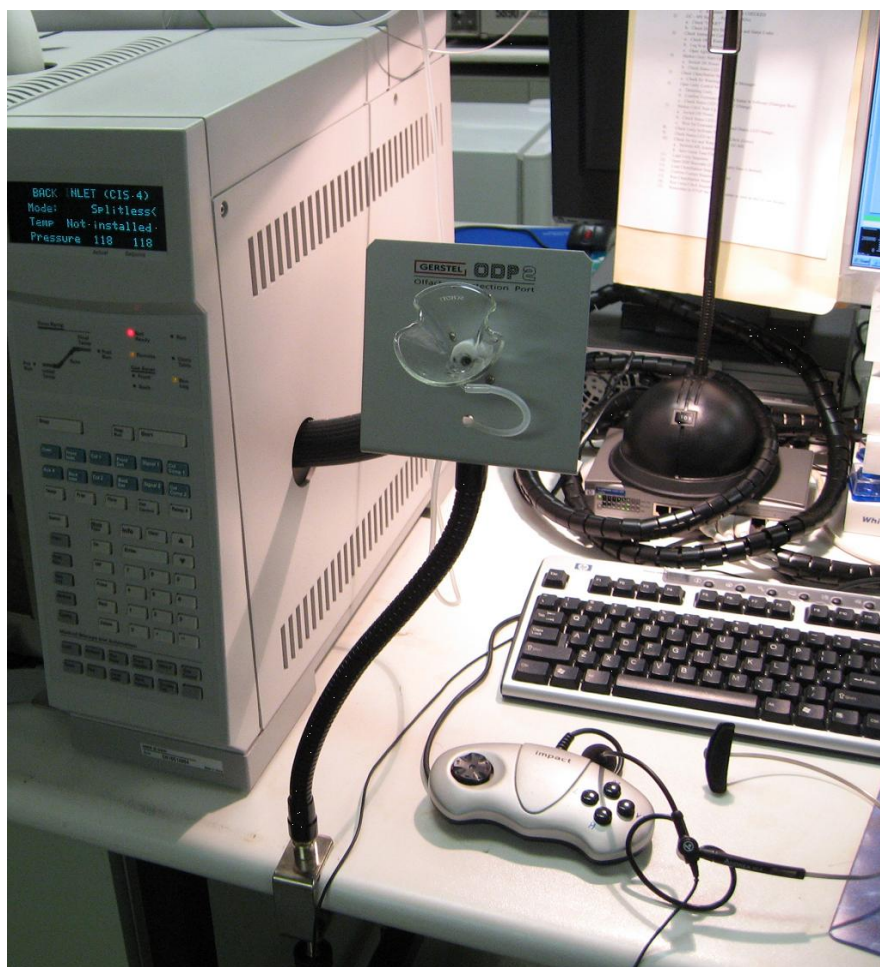
Figure 48: Gerstel olfactory detection port connected to the Agilent 6890N GC. *Seen in the lower frame is the Odour Input Device (OID) consisting of the control pad and headset microphone*

The function of the ODP, as implied by its name, is to detect compounds that promote an olfactometric response from an *operator*. This detection can occur as a presence/absence result or a relative quantity of odour—the quantity of which is described by five discrete levels: absence (0), barely detectable (1), easily discernable (2), significantly odorous (3) and highly odorous (4). The results are recorded using the Gerstel ODP Recorder which integrates with the Agilent ChemStation to provide chromatographic spectra for both the total ion chromatogram and the odorant profile chromatogram.

An additional function of the ODP is the ability to record an odorant descriptor to qualitatively characterise the odour, in similarity to recording a hedonic tone. This descriptor can be used to identify closely eluting peaks or empirically to global impact on the whole odour. Descriptors are used either to classify or specifically identify the odorant, the operator records a comment for later playback that describes the characteristic of the odour. As both the strength of the odour is recorded and the characteristic of the odorant, this is an empirical method to establish which of the compounds within the overall matrix may have the most impact on a receptor.

During the analysis of the samples, a small capillary splitter (Figure 49) diverted a calculated amount of the sample to the ODP, whilst the remainder of the flow continued to the MSD. This split ratio was calculated at the initial temperature of the oven. As the temperature of the oven increased, the volumetric flow rate was kept constant by the electronic pneumatic control module of the GC. This allowed for the flow rate of each of the effluent flow paths to be maintained at the desired ratio.
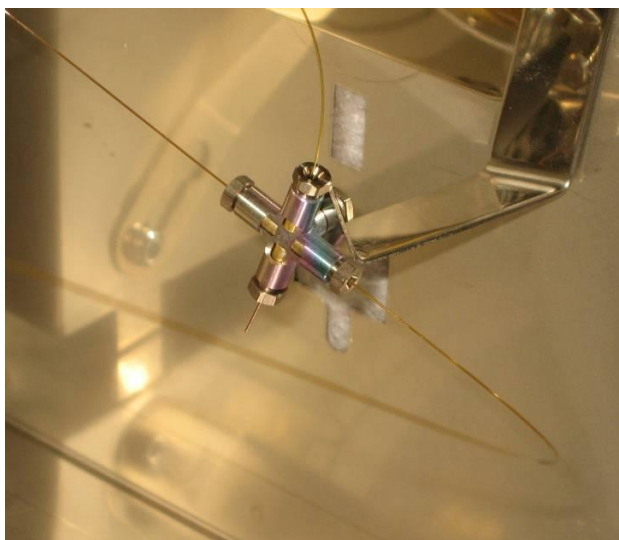
Figure 49: Capillary splitter; low volume cross piece

Although there is a calculated delay between the arrival of the compound at the MSD and the ODP, their respective detection times will differ. The calculated delay is substantiated by the flow of fluids through different capillaries, which are known, to the respective detectors; however, there is a secondary influence on the detection time of a given odorant at the ODP and that is the operators' response. This *operator delay* results from a combination of physiological factors including respiration rate, neural response times and reflex speeds.

The operator records their response to the odour using the odour input device (see Figure 48). Whilst recording their response, the operator can also record a descriptor of the odorant. This can be used to identify the compound from neighbouring non-odorous peaks in the total ion chromatogram, and it can also determine whether the compound is likely to contribute to the overall characteristic of the odour.

3.3.3.5 *Quality assurance and quality control—blank samples*

Consistent documentation of all samples collected, coupled with instrumentation logs, allowed for the scrutiny of the results. Of particular significance was the use of blank tubes to ensure the samples analysed were free from or contained minimal uncertain contamination. Each sorbent tube that was sampled in the field or the laboratory was thermally conditioned to the manufacturer's specifications and then analysed to confirm all traces of analyte had been removed before the sorbent tube was sampled. Additionally, field blanks, ambient samples and laboratory blanks were also collected. Field blanks being tubes that were transported with the actual samples but remained sealed during the return trip from the laboratory to the field. Ambient samples were pumped sorbent tubes collected from the ambient air stream immediately upwind of the poultry shed ventilation inlet. Laboratory blanks were sorbent tubes that remained sealed in the laboratory whilst the balance of the tubes were in the field. All of these blank tubes were analysed under identical conditions when the field samples were analysed. The importance of the collection of field blanks was the ability to determine what compounds were present in the ambient air entering the shed; to enable discrimination of compounds produced in the shed.

3.3.4 **Litter moisture analysis**

Litter moisture content was determined using Australian Standard 4454–2003 (Standards Australia, 2003).

A proportion of each sample (approximately 50 g) was placed in an individually identifiable 100 mL ceramic evaporating dish. Each dish was dried at 105 °C and weighed before the addition of litter. The litter was immediately weighed to ascertain a wet sample weight. All samples were dried in an oven at 105 °C overnight. After cooling in a desiccator cabinet, the dry litter samples were weighed. To calculate wet basis moisture content, Equation 7 was used.

$$\% Moisture\ content = \frac{m_2 - m_3}{m_2 - m_1} \times 100\%$$

Equation 7

Where m_1 = mass of the dish (g)
m_2 = combined mass of the dish and litter (g)
m_3 = combined mass of the dried dish and litter (g)

All samples collected were analysed individually in order to assess intra-shed variability of moisture content.

Contour plots were drawn using Surfer® version 7 (Golden Software Inc. Colorado USA) to visually assess moisture content differences.

3.4 **Data processing**

3.4.1 **Olfactometry data processing**

3.4.1.1 *Averaging of duplicates*

Odour samples were collected into two drums (duplicate odour samples) and each drum was analysed independently by the olfactometer. The odour concentrations values for these duplicate samples were averaged using their geometric mean, producing a single odour concentration value for each sampling time.

Collection and analysis of duplicate samples is recommended by the AS/NZS 4323.4:2001 because it reduces variability in the measured odour concentration and improves confidence in the olfactometry result. Analysis of duplicate samples also provides one way to identify the amount of variability in olfactometry results. If the detection threshold for duplicate samples is measured to be exactly the same, it is reasonably likely that the olfactometer has measured the true result of the sample. However, if the detection threshold for duplicate (and assumed to be identical) samples is found to be quite different, confidence in the results may be reduced.

3.4.1.2 *Removal of duplicates with excess variability*

AS/NZS 4323.3:2001 (clause 8.3.2) requires calculation of repeatability and accuracy for an individual olfactometer. The olfactometer needs to comply with these requirements, which are measured using a reference testing material (40 ppb *n*-butanol gas). The assumption is then made that these repeatability and accuracy measurements are transferrable to the measurement of unknown samples. Accuracy defines the ability of the olfactometer to determine the 'true' result of an odour sample. Repeatability defines the ability of the olfactometer to measure the same sample multiple times and obtain the same result.

Exclusion of data from olfactometry analysis due to excessive variability is not covered in the Standard. However, if the ratio between duplicate odour samples was greater than the repeatability ratio of the olfactometer (given $r = 0.318$ and $10^r = 2.08$ for the DEEDI olfactometer) then we believe that the detection threshold for the duplicate samples was questionable, and it would be reasonable to exclude

both duplicate results on the basis that they do not fit the 95% confidence band. Consequently, we applied this filtering rule to the olfactometry data analysed by the DEEDI olfactometer and 6.2% of the total number of duplicate samples analysed during the project were excluded from further analysis. The duplicates discarded are shown in Appendix 3.

For the ETC olfactometry, variability between duplicates was within the repeatability value for the olfactometer, and within the Australian Standard requirements, and consequently no results were discarded.

3.5 **Sensor based monitoring of shed air quality**

Wireless air quality monitoring stations were installed at Farms A, B and C during batches corresponding with dust and olfactometry odour measurement. The purpose of the stations was to monitor air flow, temperature, humidity, ammonia, dust and VOCs within the shed on a continuous basis over the entire batch. Sensor data was compared with the conventional odour and dust measurements to evaluate whether or not the continuous data could be used to supplement conventional, infrequent odour and dust measurements.

In-shed monitoring stations carried the full range of sensors, mounted on a cross arm 1.6–1.9 m above the ground and supported by a custom-built tripod stand (see Figure 50). The external station included only temperature and humidity sensors, which were mounted on a commercially available weather station stand (Davis 7716, Kilsyth, Australia) (see Figure 51).
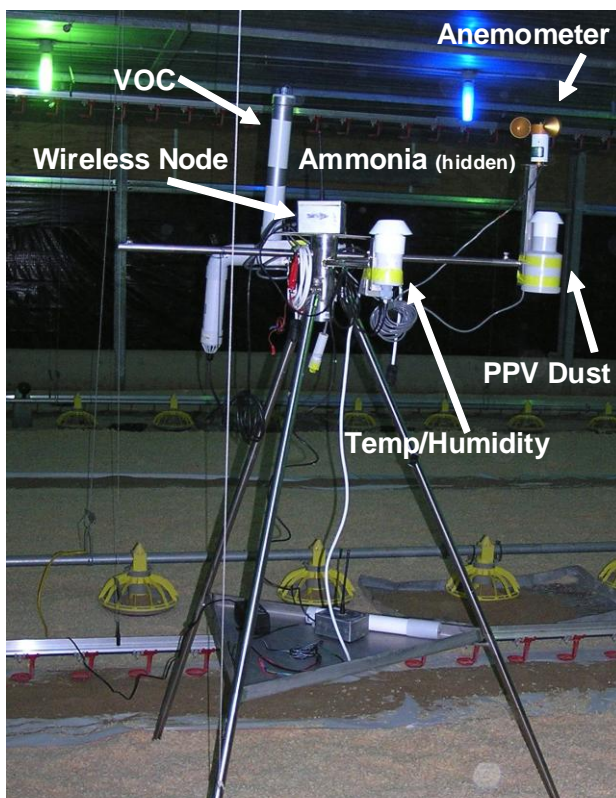
Figure 50: Indoor sensor station deployed with sensors attached

Figure 51: Outdoor sensor station (*note:* station was not installed in this location—for photographic purposes only)

Indoor sensor stations were placed as close as possible to the centreline of the long axis of the shed, at approximately 25%, 50% and 75% of the length of the shed. The station at the cooling pad end of the shed was denoted the 'Door node', the centre of the shed denoted the 'Mid-shed node' and the node nearest the tunnel ventilation fans the 'Fan node'. During the second phase of the litter reuse study at Farm C, a floor to ceiling curtain (brooding curtain) was located about halfway along the shed for the first

two weeks with the birds brooded in the end nearest the fans. The mid shed node was placed on the fan (and brooder) side of the partition.

Monitoring commenced just before birds were placed in the shed and generally continued until pickup events. Depending on the site, pickups usually required the nodes to be temporarily turned off and removed to prevent them becoming obstacles for the catchers. Monitoring resumed as soon as practicable after each pickup.

3.5.1 Wireless system network

A schematic of the typical deployment is shown in Figure 52. The sensing stations transmitted sensor data wirelessly to a 'base node' where it was recorded at 15 minute intervals on a laptop computer. The laptop was connected to a GSM modem, allowing it to be accessed remotely for data downloading and system checking.
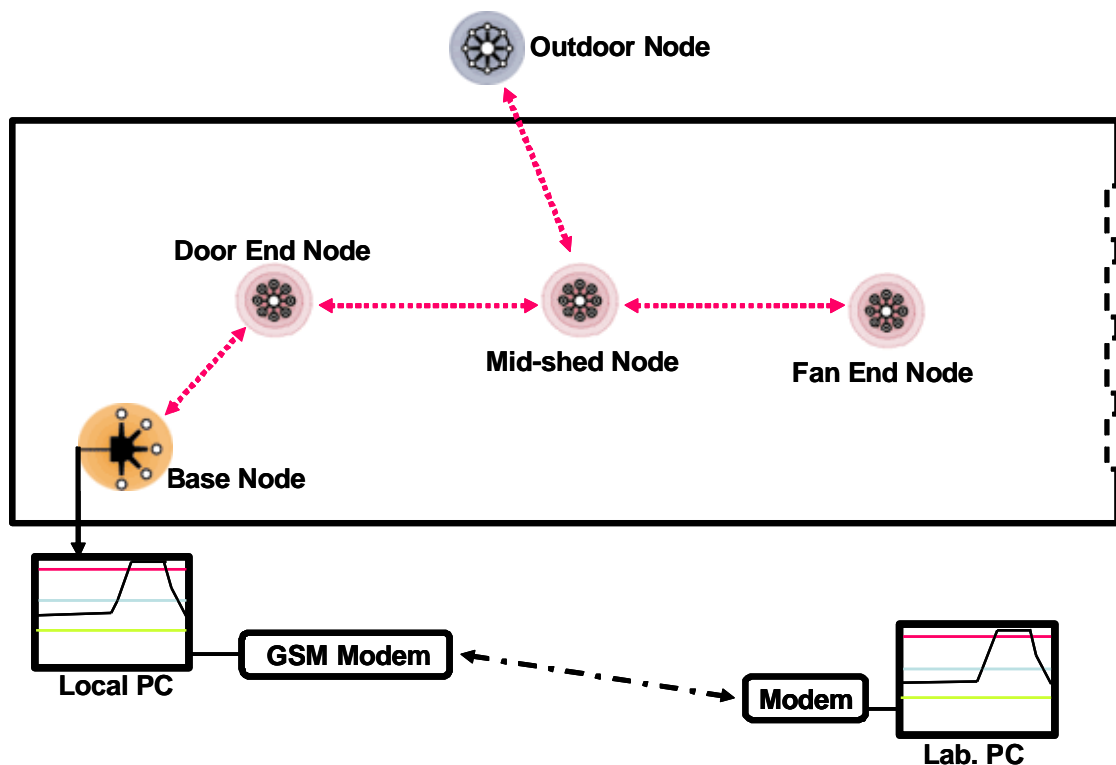
Figure 52:   Schematic of typical WSN deployment in broiler shed

3.5.2 Sensors

Details of the sensors used to monitor air flow, temperature, humidity, ammonia, dust and VOCs are provided in Table 15. Most of these sensors could be considered as 'base level components' and require signal conditioning electronics and customised mounting hardware. Because most of these sensors are not 'ready to use', the manufacturers do not provide detailed recommendations on the best way to mount and use the sensor; instead, users must work these details out for themselves based on their own experience.

Table 15:   Air quality monitoring station sensor information

Sensor/ Parameter	Brand	Model Number	Sensitivity	Range
Temperature	Yellow Springs (OH, USA)	YSI44201	±0.2 °C	-80–100 °C
Humidity	Honeywell (Freeport, IL, USA)	HIH 3610	±2% (<90%RH)	0-100%
Airspeed	Texas Electronics (Dallas, TX, USA)	TV-4	±0.9 m/s (starting threshold 0.6 m/s)	0–45 m/s
Dust	Shinyei Kaisha (Kobe, Japan)	PPD20V	Unspecified, qualitative response in the range of 0–30,000 particles/L	
Ammonia	City Technology (Portsmouth, UK), mounted on a body by Monitor Sensors (Brendale, Qld)	7NH CiTicel	±1 PPM	0–200 PPM
VOC	Synkera Technologies (Longmont, CO, USA)	VOC-707	qualitative response to a range of VOCs (1–100 PPM)	

Of these sensors, the dust and VOC sensors were known not to not provide quantitative sensor responses using recognised units and therefore warranted further investigation to understand how they might respond in the broiler shed environment.

The dust sensor was compared with a DustTrak™ 8520 (TSI Incorporated) under laboratory conditions. While the dust sensor did not provide quantitative measurements of dust concentration, it did respond in a similar way to the DustTrak™ when dust concentration changed. For this reason, it was considered suitable for trial use in broiler sheds to provide general feedback on in-shed dust concentrations.

The VOC sensor responds to a range of organic compounds with minimum sensitivities in the 1–100 ppm range (see Figure 53 for known responses to a selection of VOCs). Consequently, the strength of the signal response from the VOC is related to exposure to a mixture of VOCs (which may or may not be odorous) and therefore it was considered likely that the VOC sensor response might loosely reflect odour concentration in the shed.
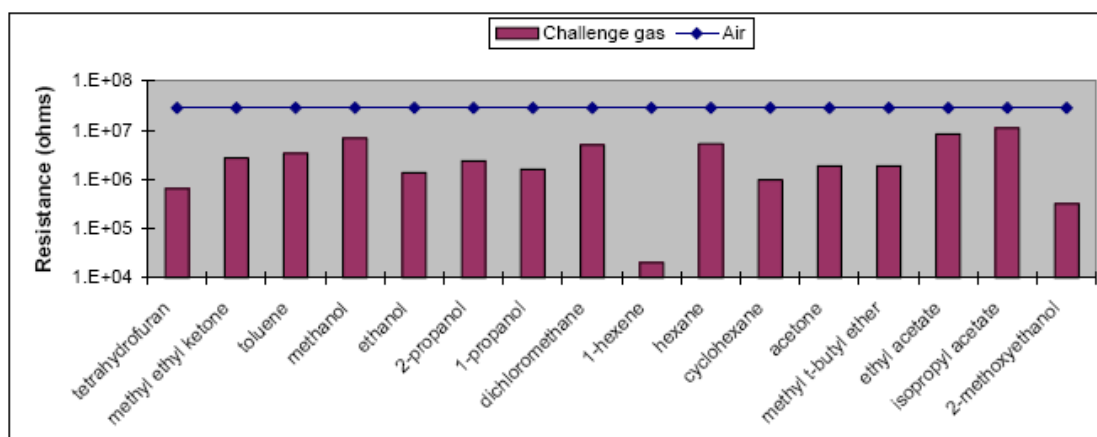
Figure 53:   Typical sensor response to 100 ppm of a range of VOC (data supplied by manufacturer)

The VOC and ammonia sensors were mounted in a customised housing designed to prevent the sensors being covered by dust but still enabling the sensors to be exposed to the in-shed air (see Figure 54). While providing some protection form large dust particles, the housing did not provide complete dust protection and the addition of the fan increased power requirements for the sensor stations.
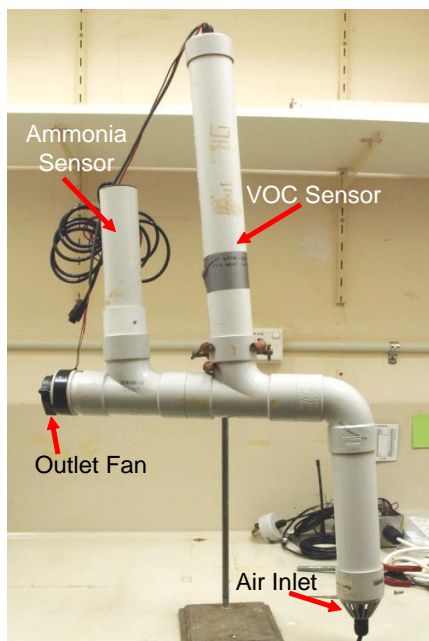
Figure 54: **Ammonia and VOC sensor housing**

The stations were originally intended to run on battery power but unfortunately the combined power requirements of the node electronics, sensors and fan was approximately 3.3 W. This necessitated connection to a mains power source to provide reliable power for the duration of the batch.

3.5.3 Sensor station data analysis

At the end of each study, data was exported from the Sensicast database into Excel spreadsheets and all sampling times were adjusted to the same 15 min time datum. Data was assessed manually for quality and obvious outliers or sensor failures were removed from the dataset. Completeness of the data record was determined based on the total amount of sample intervals possible over the period while birds were in the shed, and the number of valid readings left after removal of outliers and failures.

Each of the seasonal/site experiments was analysed for correlation between sensor response and conventional odour measurements. These analyses were conducted for the individual seasonal and reuse studies, as well as the complete data set. These measurements were analysed by correlation and regression methods, and partial least squares analysis. The full dataset was also used to develop a model relating sensor measurement to conventional odour measurements using artificial neural network techniques.

3.6 Measuring odour emissions using an artificial olfaction system

An artificial olfaction system (AOS), developed by DEEDI, was used to measure poultry shed odours. The AOS co-analysed odorous air from within the sample drums collected for olfactometry analysis (Queensland only), and was installed at two broiler farms to semi-continuously measure odour concentration using air drawn directly from the shed. The primary purpose of co-analysing the olfactometry samples was to 'train' the AOS for recognition and quantification of poultry odour. Semi-continuously monitoring poultry shed odour emissions with the AOS on a one minute sampling interval provided a more thorough record of poultry emissions than was possible with infrequent olfactometry.

The AOS operates by the process outlined in Figure 55. A sample of poultry shed air is introduced to a sensor array, which produces a series of electrical responses that are recorded using a data logger. The data is then processed using calculations that have been developed during the training of the AOS, after which an odour concentration is reported.

```
┌──────────────────┐     ┌──────────────────┐     ┌──────────────────┐     ┌──────────────────────┐
│ Poultry Shed Air │ ──▶ │   Sensor Array   │ ──▶ │  Data Processing │ ──▶ │  Odour Concentration │
└──────────────────┘     └──────────────────┘     └──────────────────┘     └──────────────────────┘
```
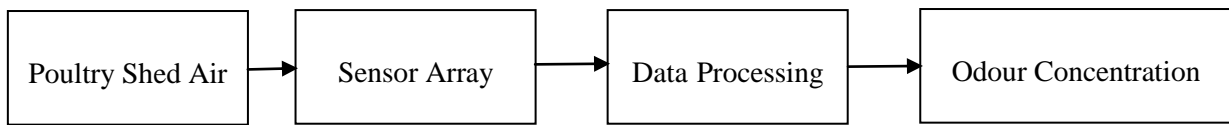
Figure 55:   Process diagram of odour concentration measurement using the AOS

3.6.1 Training of the artificial olfaction system using olfactometry

The AOS needed to be trained to allow the electrical responses from the sensor array to be converted into an odour concentration. This is achieved by exposing the sensor array to numerous odour samples of known odour concentration, as determined using dynamic olfactometry, and recording the pattern of electrical responses from each sensor within the array (see Figure 56). The odour samples need to be from the same source (or similar source such as other broiler farms) because changes to the composition of the odour will produce a different response from the sensor array, even though the odour concentration may be the same. This is why the AOS is calibrated by co-analysing odour samples; because there are no 'standard' calibration gases for broiler odour.
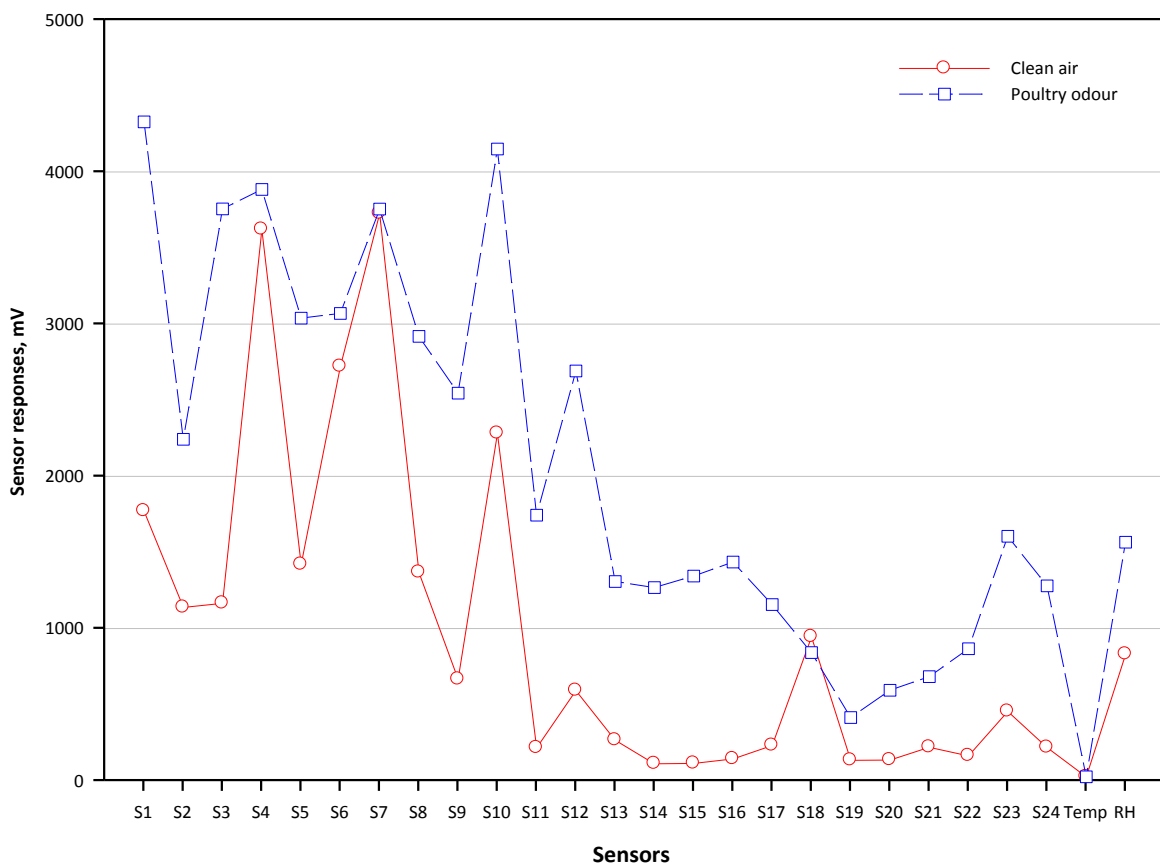
Figure 56:   Example of the 'pattern' or 'fingerprint' of electrical responses from the sensor array

The odour samples collected from similar sources are used to establish a data-set for further data analysis (i.e. odour classification based on the sensor array pattern or odour quantification). An example of odour classification using the AOS is presented in Figure 57. A data-set was established using odour samples collected form the different emissions sources including a poultry shed (A), a biofilter in a piggery (B) and a piggery effluent pond (C). The sensor response to clean instrument grade air from a cylinder is included as the control (D). Data points that plot close together on the map indicate a similar odour

pattern and can, therefore, be classified as a similar odour type. As shown in Figure 57, the entire dataset can be classified into four distinctive odour groups. This result demonstrates that the AOS is able to discriminate between samples collected from different sources.
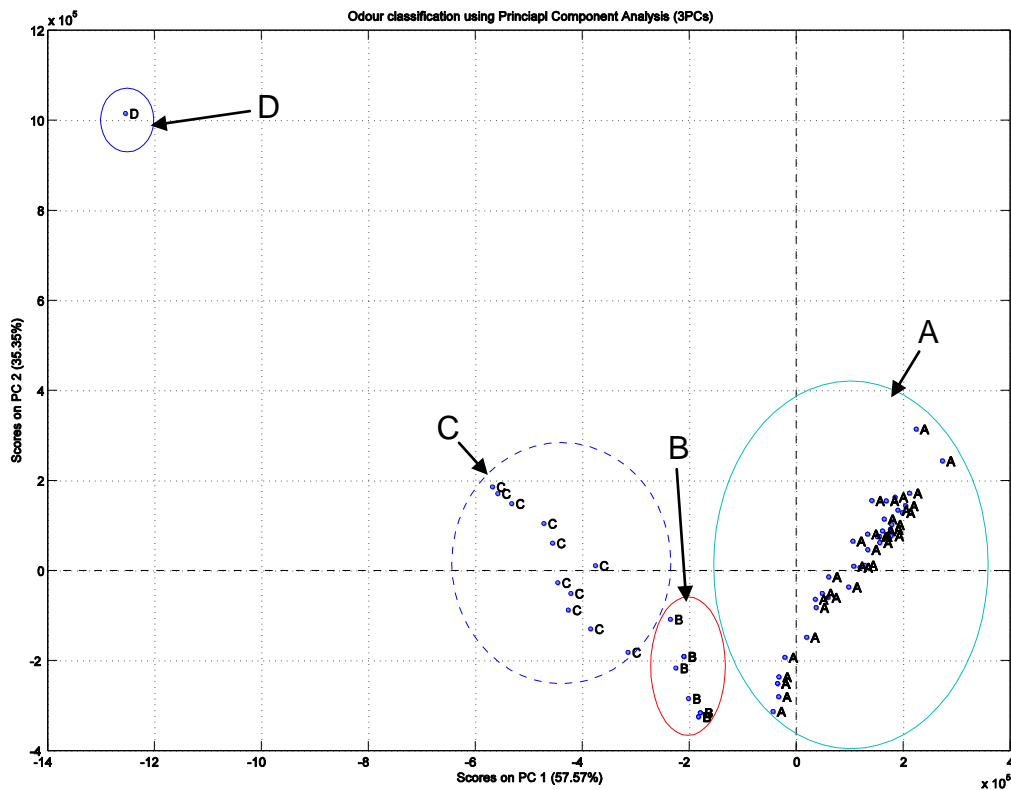
Figure 57: Example of odour classification using AOS. *Two-dimensional odour mapping using principal component analysis from odour samples collected at various agricultural odour emission sources including poultry shed (A), biofilter (B), piggery effluent pond (C), and clean air (D)*

During this research project, odour samples from Farm A were presented to the AOS directly from the odour sample drums that were collected for olfactometry analysis; while at Farm C, the AOS was installed and operated at the farm which allowed odour samples to be drawn directly from the shed concurrent with collection of the samples for olfactometry. A total of 174 samples were analysed from Farm A and 76 samples from Farm C during the calibration process.

The calibration formulas developed for Farms A were fine tuned for the odour concentration measurement at Farm C by using the corresponding olfactometry results.

The pattern and magnitude of sensor response is what enables the AOS to measure odour concentration, but additional data processing is required. The sensor outputs of the AOS were pre–processed using principal component analysis for the purpose of dimensionality reduction and outlier handling. Sohn *et al.* (2007b) provides greater detail of how PCA was used to simplify the data from Farm A.

Once the response from the sensor array had been pre-processed using PCA, partial least squares (PLS) regression in chemometrics was used to develop a calibration formula enabling it to report odour concentration. Matlab™ statistical packages and the Partial Least Squares (PLS) Toolbox 3.5™ for Matlab™ were used for pre-processing and development of the calibration formula.

The performance of the calibration formula was validated using two statistical measures: the root-mean-square error of calibration (RMSEC) and the root-mean-square error of cross-validation (RMSECV). The RMSEC is a measure of how well the model fits the calibration data. In contrast, the RMSECV is a measure of a model's ability to predict new samples.

The AOS, using the developed calibration formulas, was used to continuously monitor odour concentration within broiler sheds at Farm A and Farm C over an entire production cycle.

3.6.2 Continuous odour measurement at Farm A and Farm C

Odour concentrations during three batches of broilers (a batch directly after the winter batch at Farm A, and two consecutive batches at Farm C), were monitored using the AOS.

The AOS was housed in an insulated 20-foot shipping container at Farm A and a control room attached to the shed at Farm C. Each was air conditioned to maintain a clean, temperature-controlled environment (see Figure 58).

A system to draw odorous air from within the broiler shed and deliver it to the AOS sampling port was built using 110 mm diameter polyvinyl chloride (PVC) stormwater pipe. A sub sample of the air in the delivery pipe was then drawn into the AOS using a customised sampling port. The length of the air delivery pipe was approximately 30 m from the pipe inlet to the AOS at Farm A and 25 m at Farm C. At both Farms, the air collection point was located half way across the shed, 10 m upwind from the tunnel ventilation fans and 1 m above the litter (see Figure 59). Sample air was drawn through the PVC pipe at a velocity of 6.25 m/s using an axial fan (Fantech® TD-500/150 mixvent series axial fan).
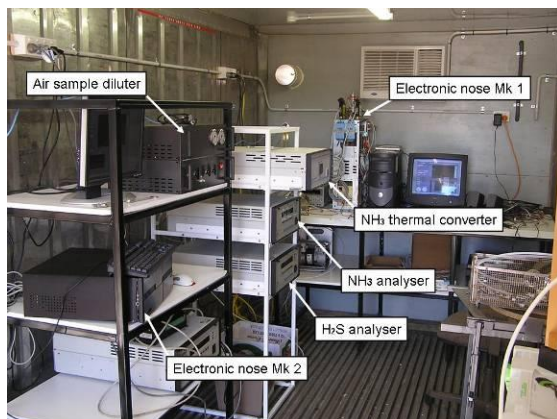
Figure 58: Mobile laboratory interior at Farm A   **Figure 59: Point of sample collection, shed interior**

The AOS consisted of 24 different metal oxide sensors (MOS). Signals from all sensors were collected at a sample rate of 60 Hz using a DT800™ data logger (dataTaker®, www.datataker.com). The temperature, relative humidity and sensor responses were monitored and stored using a real-time data logging program developed using Labview 7.1™ (National Instruments, Austin, Texas, USA).Odorous air samples were presented to the AOS at a flow rate of 500 mL/min.

3.6.3 Combining artificial olfaction system data with ventilation rate and weather data

Odour concentration data continuously recorded by the AOS was combined with ventilation rate and weather data (see sections 3.2.9.5 and 3.2.11 respectively). The combination of these data sets enabled calculation of odour emission rate throughout the batch and also allowed odour emission rates to be correlated with weather conditions and atmospheric stability conditions, which is likely to have a substantial influence on the emissions and the potential for odour nuisance. While assessing the potential for odour impacts was beyond the scope of this research project, the opportunity to present the combined data was useful for demonstrating a potential use for AOS.

Continuous odour emission rate records are presented in Chapter 11.

3.7 **Summary of methodologies**

- Eleven tunnel ventilated broiler farms were included in this project. At three of the broiler farms; odour, dust and VOC emissions were measured at approximately weekly intervals. At the remaining eight broiler farms, only odour was measured and only on one day when bird mass in the shed was maximum.

- The majority of odour, dust and VOC samples were collected from within a temporary flexible duct that was attached to one of the tunnel ventilation fans at each farm.

- Odour concentration was measured using dynamic olfactometry to AS/NZS 4323.3:2001. Two laboratories were used, and comparative testing was conducted between the laboratories to ensure comparability of odour concentration measurement.

- Dust was measured using a DustTrak™ and an aerodynamic particle sizer (APS). Isokinetic sampling techniques were used.

- NMVOCs were collected using sorption tubes for subsequent analysis with a TD-GC-MS/O. Sampling and analysis techniques, including the selection of sorbents, were refined during the project, resulting in the development of an improved method for measuring NMVOC emissions from poultry sheds.

- Ventilation rate was estimated by measuring in-shed or fan airspeeds, or by calculating the flow rate through each active fan using manufacturer supplied fan flow rate date (and adjusting for shed static pressure), which was selected as the preferred method.

- Two instrumental approaches were used to monitor in-shed air quality, micro-climate and odour concentration—wireless sensor networks and an artificial olfaction system (AOS).

4 Odour emissions

From November 2005 to May 2008, 349 odour measurements were made at eleven broiler farms, located in Queensland and Victoria, during different times of the year and at different stages of the production cycle. Data for each of these measurements is provided in Appendix 5 to Appendix 11, and is summarised below in Figure 60 to Figure 61. Each of these figures displays the data using different units of emission rate, which are useful for different purposes. These figures show a wide spread of ventilation rates. This spread is due to samples being collected at different farms during different ventilation, weather and production conditions. While some trends in the data may be visible, each emission rate measurement must be considered on its own, and in conjunction will all of the supporting information provided in the appendices.

Some of the emission rates presented in these figures require further consideration because the specific methodology used on particular days may have influenced the result. These points are for Farm A (especially days 18 and 27 and 31) and Farm B (especially days 13 and 32). Further analysis of these data points is provided in Section 4.4.

(Note: Farms D & E were layer farms and their emissions have been reported separately.)

4.1 Emission rate data for all broiler farms

Figure 60 displays the emission rate data using units of odour units per second (ou/s), which is the total emission rate from the shed. Emission rates varied from 2070–135,000 ou/s. There is an obvious increase in odour emission rate for each farm to approximately day 35, which for most farms was just prior to the first pickup. After this time, emission rates appeared to decline as more birds were harvested from each shed. The relationship between odour emission rate and bird weight is explained further in Section 4.8.2.3.
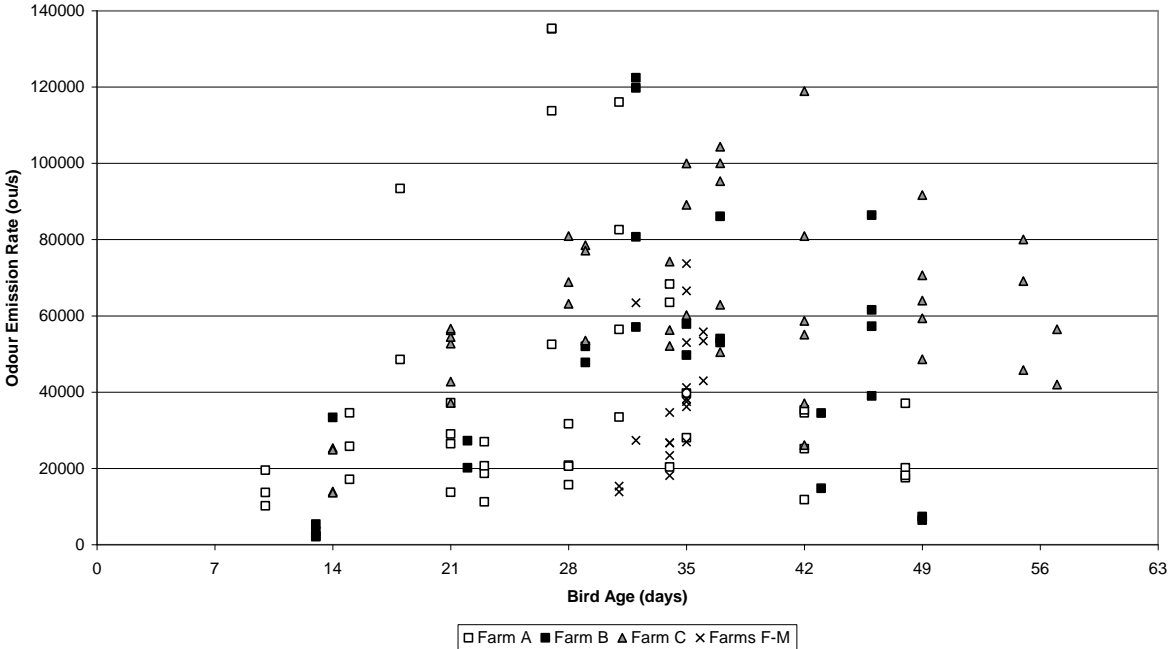
Figure 60:   Odour emission rate for broiler farms

Figure 61 displays the emission rate data using units of odour units per second per 1000 birds in the shed at the time of sample collection (ou/s/1000 birds). Emission rates varied from 86–6334 ou/s/1000 birds, with the majority of data between 100–5000 ou/s/1000 birds. Emissions up to the first pickup will be very similar to the odour emission per 1000 birds placed (only a small adjustment for mortalities). However, the emission rates per 1000 bird increase rapidly following each pickup, due to dividing the emission rate

by a much smaller number of birds. It is very difficult to compare different farms using this measure of emission rate, because knowledge of bird numbers and pickup times are essential for interpreting the data.
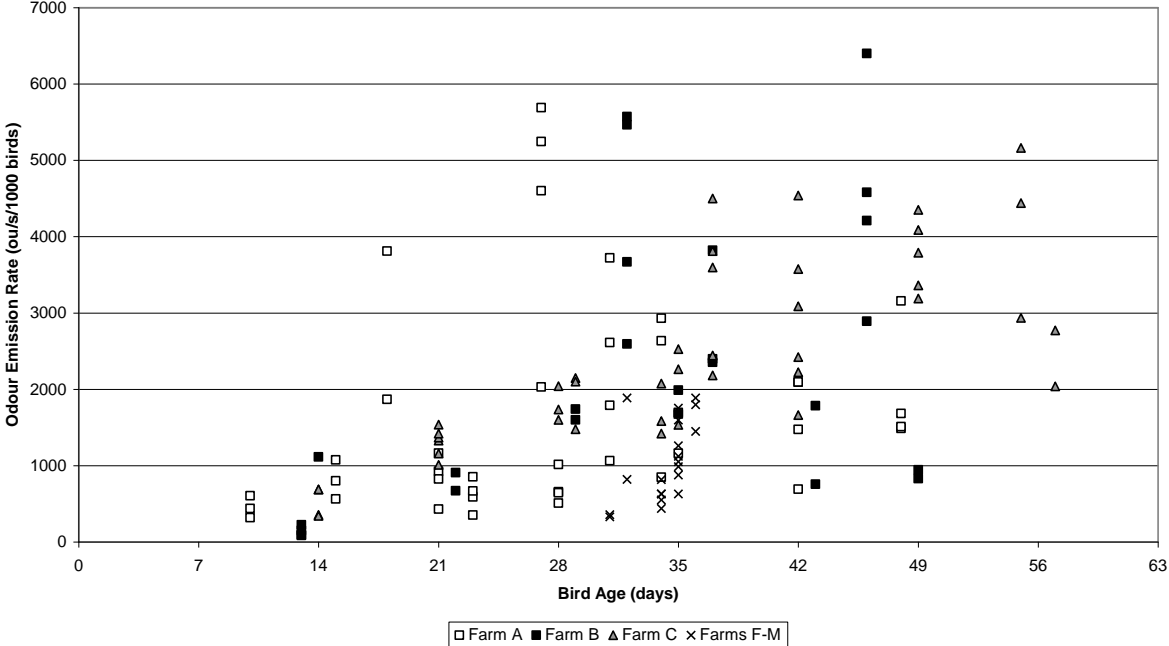
Figure 61: Odour emission rate per 1000 birds for broiler farms

Figure 62 displays the emission rate data using units of odour units per second per 1000 birds placed at the start of the batch (ou/s/1000 birds placed). These units for emission rate are very useful for comparing emission rates from different sized sheds. Emission rates varied from 68–5186 ou/s per 1000 birds placed, with the majority of data between 100–3000 ou/s per 1000 birds placed.
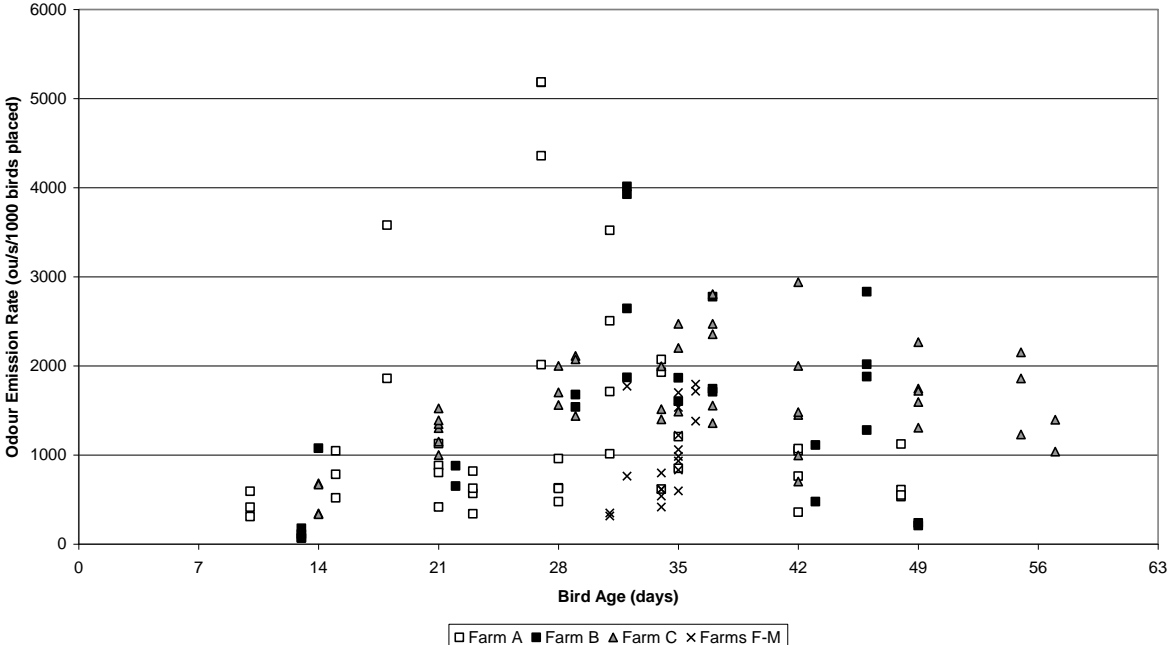
Figure 62: Odour emission rate per 1000 birds placed for broiler farms

Figure 63 re-presents this data (odour emission rate per 1000 birds placed at the start of the batch) using a box and whisker plot to more clearly demonstrate variability throughout each sampling day (primarily due to changes in ventilation rate), between sampling days and between farms. In box and whisker plots, the extent of the whiskers represent the maximum and minimum values, the upper and lower values of the box show the 25th and 75th quartile values and the line inside the box represents the median value. The labels on the x-axis describe the farm, season/batch and the bird age on that particular sampling day.

Note that the data corresponding to Farm A-summer-day 27 should be viewed with caution as the odour emission rate is likely to have been influenced by the research team manually over-riding the automatic ventilation control system (described further in section 4.4).
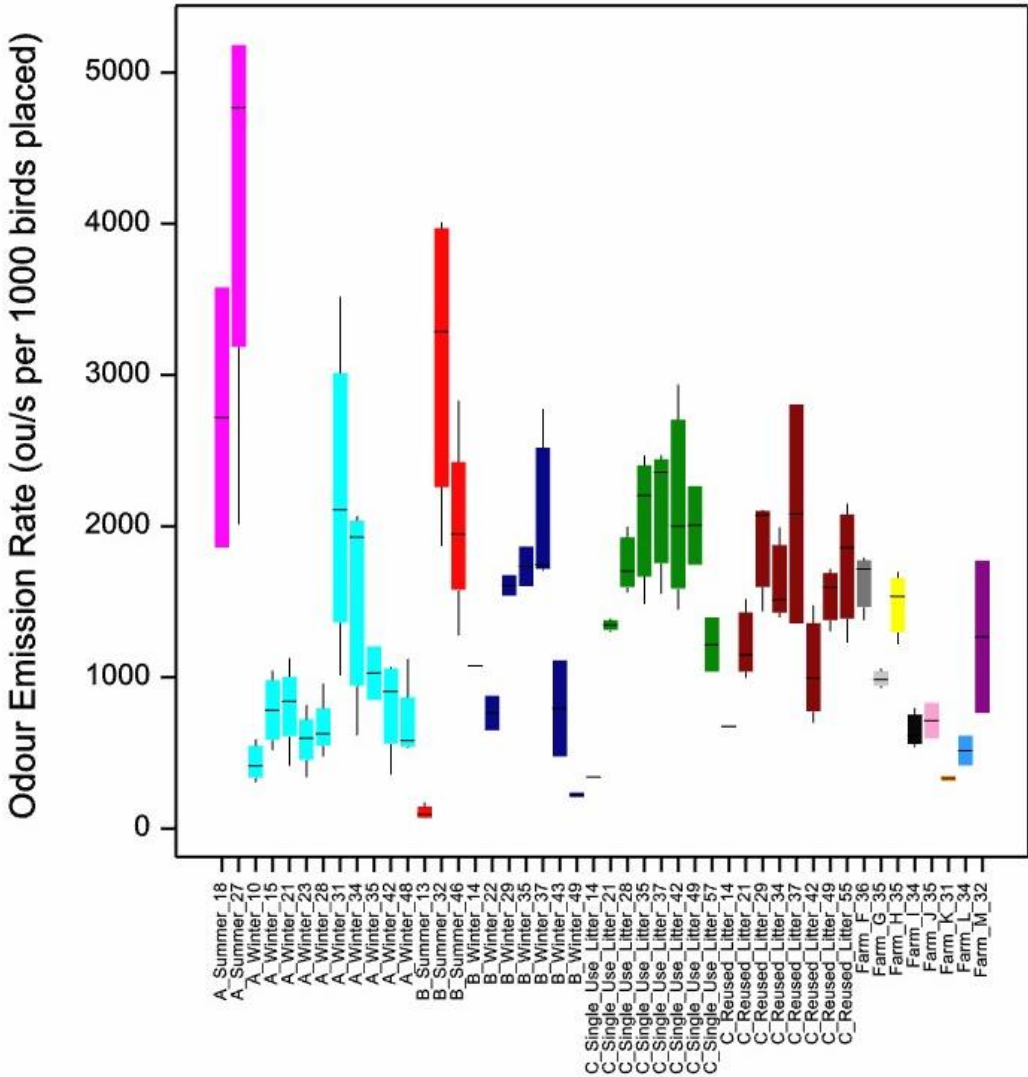
Figure 63: **Box and whisker plot of odour emission rate per 1000 birds placed for broiler farms clearly highlights the variability of emissions on each day and between farms**

Figure 64 displays emission rates in terms of odour emissions per kilogram of birds present in the shed at the time of sampling (units ou/s/kg). Apart from some spikes in the data set (requiring further explanation given in Section 4.4), adjusting the emission data for live weight appears to have a levelling effect. The majority of the emission rates were within the range of 0.25–2.5 ou/s/kg.
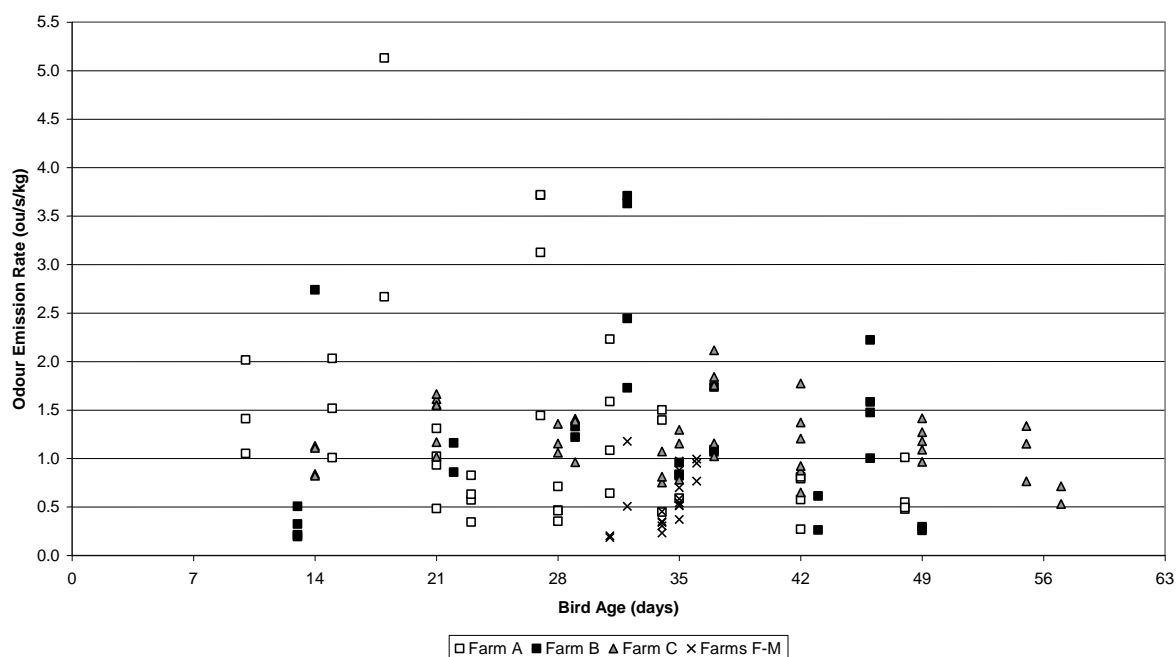
Figure 64: Odour emission rate per kilogram for broiler farms

Regardless of the units used to display odour emission rates, there is an obvious spread of data on each day at each farm. This observation supports the conclusions from the diurnal study (section 4.2) that emission rates vary throughout each day. One consequence of this observation is that in order to accurately describe emissions on a particular day of the batch, it is essential to measure emissions more than just once.

4.2 Diurnal variation of broiler shed emissions

Diurnal variability of emissions from broiler sheds was measured at Farm A in June 2007. Emissions were assessed over a 20 hour time frame during the winter batch of broilers, commencing in the afternoon and finishing at midday the following day. Odour concentration, volatile organic compound, particulate size and concentration and ventilation rate were measured at four predefined steps in the ventilation program. Using the fan monitoring equipment, daily trends with ventilation activity were examined and recurrent periods with different levels of ventilation were identified. Data recorded by the AOS was also used to examine changes in odour concentration over time. A decision was made to collect samples at the following times:

- afternoon (1600)
- evening (1830)
- night (2330)
- early morning (0600)
- mid morning (0900)
- midday (1230)

The olfactometry odour emission data is shown in Figure 65. In terms of odour concentration, measurements during the night were less than those measured during the day. An increase was observed at the early morning measurement time, but the odour concentration did not exceed those measured during the evening. A purge of the night's build-up of odour was not clearly observed. The decrease in odour concentration at mid morning may have resulted from dilution as the ventilation rate ramped up for the day.

As for odour emission rate, the values measured during overnight, early and mid morning were relatively stable and lower than those measured in the afternoon and evening.

Odour concentration and emission rate values measured using the AOS are also shown in Figure 65 alongside the olfactometry measurements. Both data sets showed similar trends throughout the sample collection period. After nightfall, the AOS odour concentration and odour emission rate values remained relatively stable. The increase in concentration shown at midnight may have been caused by bird activity due to the use of lighting during sample collection. After sunrise, the odour concentration and emission rate began to increase from the values measured during the night. As with the olfactometry data, there was no apparent emission purge in the early morning.
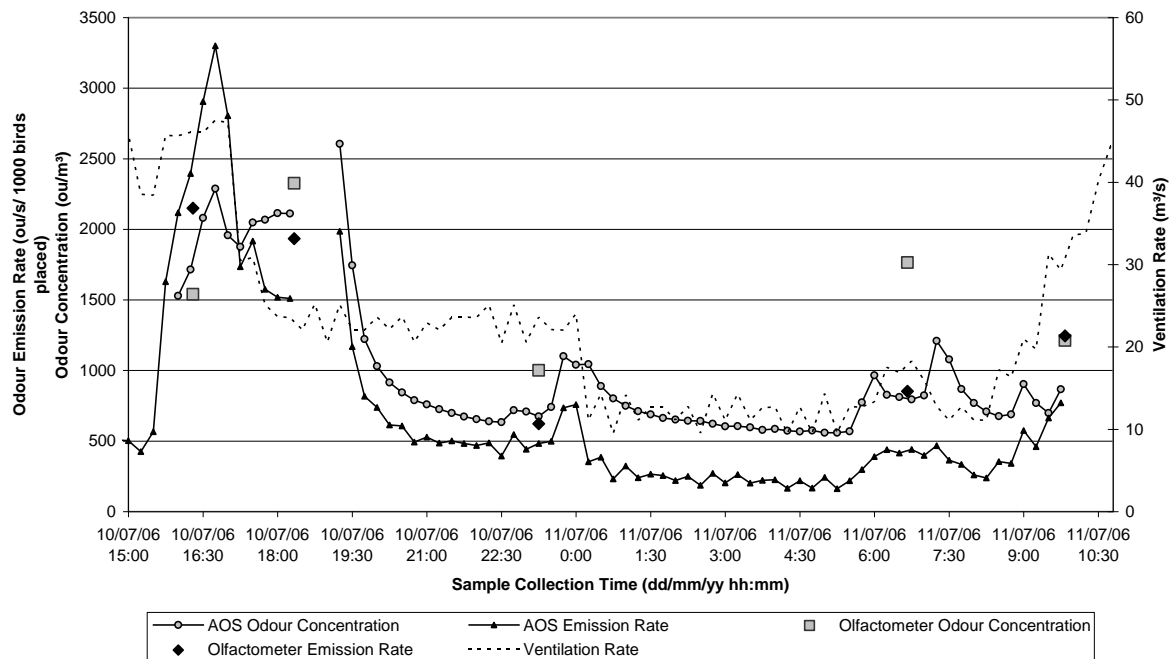
Figure 65: Diurnal olfactometry and AOS concentration and emission rate data

4.2.1 **Summary of diurnal odour emissions**

Poultry odour concentration appeared to vary over a 20 hour time frame. During the evening and night, when ventilation rates were lowest, the in-shed concentration was lower relative to the afternoon values.

Continuous monitoring of ventilation rate over the 20 hour collection period was useful for providing insight into the relationship between concentration and emission rates. Because emission rate is the product of concentration and ventilation rate, it was not surprising that night time and morning emission rates were lower than in the afternoon. This was due in part to the reduction in concentration values (possibly because of lower temperature and bird activity) but the large reduction in emission rate appeared to be influenced primarily by ventilation rate.

The 208 sets of duplicate odour samples analysed for this project were collected between 05:28 and 14:05, with a mean collection time of 09:57. **By collecting all of the samples in the morning, it was not possible to measure the full range of odour emission rates throughout each day of the batch. Care must be exercised when examining the data because the average value of the samples collected on each day will NOT be equal to the daily average emission rate.** For accurate prediction of emissions for planning purposes, diurnal influences must be accounted for.

The results indicate that where repeated measurements are to be taken over one or multiple batches of chickens, samples should collected at approximately the same time of the day and when ventilation requirements are similar. By varying sample collection time, variation in results will almost certainly occur due to diurnal variability.

4.3 Odour emission rates – with and without birds

At Farm A and B, odour emissions were measured before placement of the birds and after removal of the birds. This was primarily an academic exercise to collect odour emission rate data under these conditions because from a practical point of view, ventilation is typically minimal when birds are absent (or naturally driven in the case of curtain sided sheds). Odour emission from the shed were measured (explained in Section 3.2.1):

- after fresh bedding was placed in the shed;
- the day after the birds were removed (used litter);
- during removal of the litter;
- after the litter was removed; and
- after the shed had been washed down and fumigated.

While birds are absent from the shed, it is not normal practice to operate the ventilation fans; however, to enable measurement of emission rates at these times, ventilation fans were manually operated. Odour measurements were taken across the full range of ventilation rate (25%, 50%, 75% and 100%; except on the occasion when odour emissions were measured during litter disturbance and removal when half of the fans were turned on). **Consequently, these odour measurements may not be representative of the real situation and caution should be exercised if using this data.**

Figure 66 displays the odour emissions at these stages of the batch compared to odour emissions while birds were present. Odour emissions measured before placement and after removal of the flock were generally much lower than while the birds were present. Low odour emission rates, especially on the *day following bird removal, highlight the contribution of the flock to the mechanisms controlling* odour emissions.
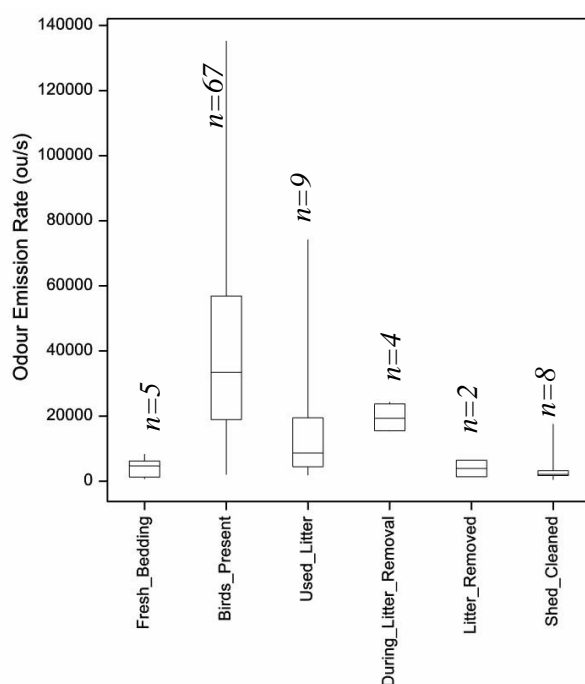
Explanatory note for interpreting box and whisker plots: the extent of the whiskers represent the maximum and minimum values; the upper and lower values of the box show the 25th and 75th quartile values and the line inside the box represents the median value.

Figure 66: Comparison of odour emissions with and without birds (*note: n values are the number of data points*). *Care should be exercised if using this data because ventilation conditions were artificially controlled by the research team.*

4.4 Identifying unrealistic data

At the beginning of this study, the sampling schedule was prepared so that emission rates would be measured at 25%, 50%, 75% and 100% of the maximum ventilation rate on each sampling day. To achieve this, the automatic shed ventilation system was manually over-ridden, with a specified number of fans locked in for each sampling period (of approximately 30–60 minutes to allow VOC samples to be collected). Approximately 15 minutes was allowed between locking fans in and the start of sample collection.

Setting the ventilation rate at the pre-arranged values was not possible on every day depending on weather conditions and the age of the birds. In general, ventilation rate was never lower than that determined by the ventilation control system (which may have caused the birds to overheat); however, the ventilation rate was occasionally increased above the automatic level when the farm manager determined that it would pose no risk to the birds.

The practice of manually overriding the ventilation system was applied at Farm A (summer and winter) and Farm B (summer). **This practice was discontinued at the remaining farms because of the potential for adversely affecting the emission rate measurements, and because the specified ventilation rates (25%, 50%, 75% and 100%) do not actually occur on each day of a batch. Consequently, some of the emission rates that were measured are unlikely to ever occur.**

When samples were collected at Farm B (winter), Farm C and Farms F–M, the ventilation system remained on its automatic setting. Occasionally, the number of fans was locked in, but usually the ventilation system was operated in automatic mode. If the ventilation rate changed during the collection of an odour sample, the number of active fans was recorded and a time-weighted averaged ventilation rate was calculated for the sample collection period.

Figure 67 shows the ventilation rates during each sample collection in units of ventilation rate per 1000 birds placed; ventilation rate per 1000 kg live weight; and the percentage of maximum fan activity. Examination and cross-referencing between these charts highlighted several data points, especially toward the start of the batch, that were relatively and unusually high and *occurred only because the research team manually overrode the automatic ventilation system*. These correspond to Farm A (summer) days 18 and 27 and Farm B (summer) day 13.
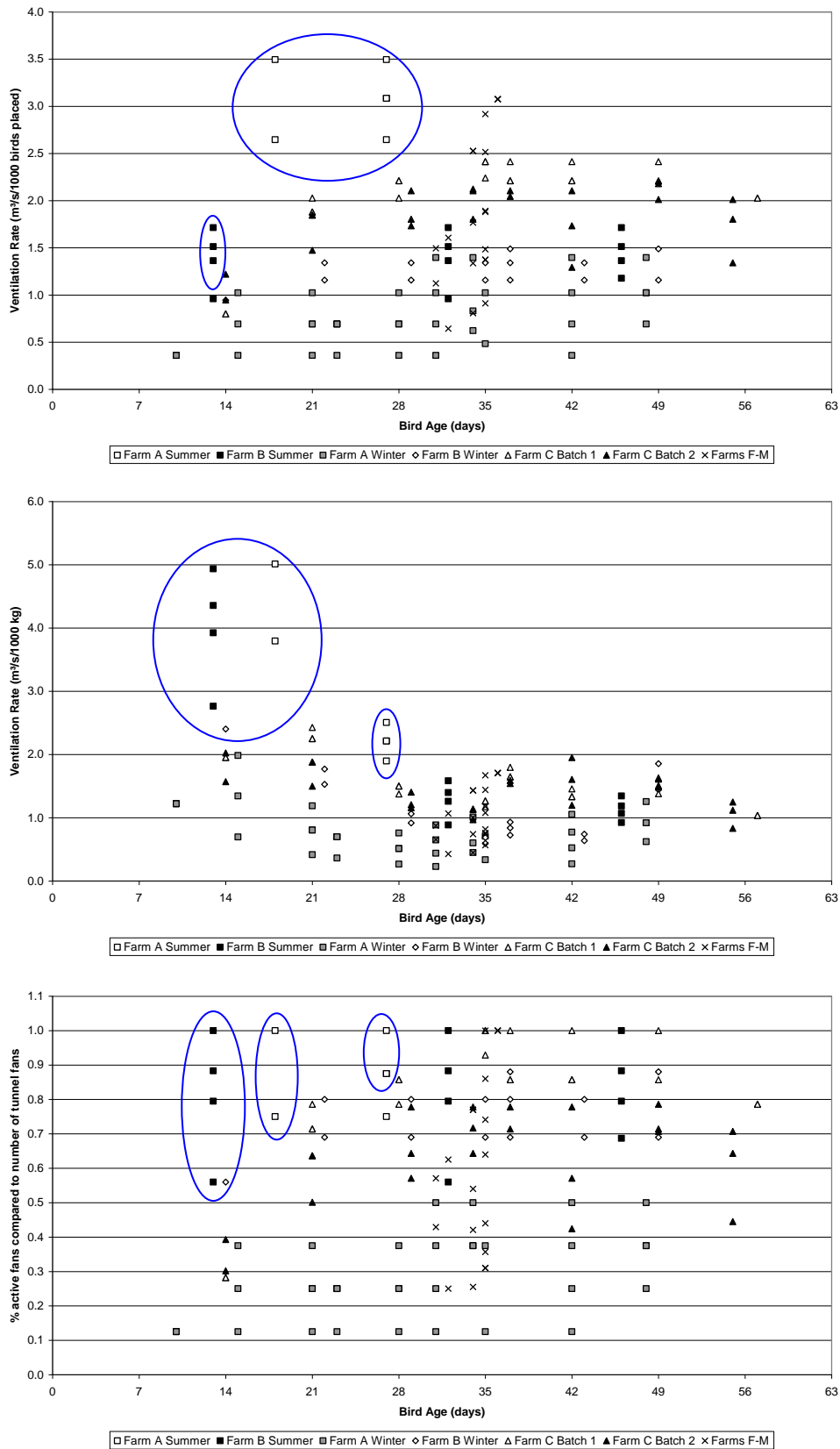
Figure 67: Summary of ventilation activity at all broiler farms – blue circles indicate ventilation rates that appear unusually high, and occurred due to the sampling methodology of overriding the automatic fan controller
Top – ventilation rate per 1000 birds placed
Middle – ventilation rate per kilogram
Bottom – % of maximum fan activity

Examination of the data in Figure 67 was useful for determining unusually high ventilation rates during summer; however, relatively high ventilation rates from winter batches were not so obvious even when the ventilation control system was manually over-ridden and higher than normal fan activity was selected. By making an adjustment for temperature, some of the winter ventilation rates appeared to be relatively higher (see Figure 68). These data points occurred at Farm A (winter) on day 15 and Farm B (winter) on days 14 and 22.
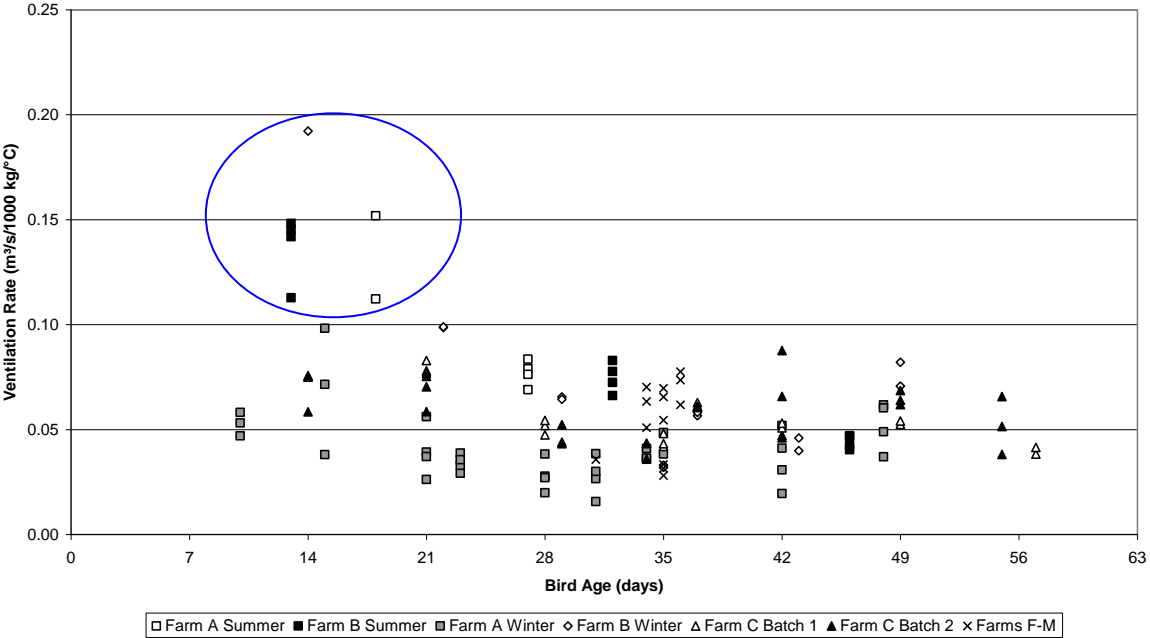
Figure 68: **Summary of ventilation activity at all broiler farms – blue circles indicate ventilation rates that appear unusually high, and occurred due to the sampling methodology of overriding the automatic fan controller – ventilation rate per 1000 kilograms per °C**

Ventilation rates were continuously monitored at Farm A (June to July 2006) and at Farm C (April to June 2007). Daily minimum, maximum and average ventilation rates were determined for each day. Figure 69 displays the ventilation rates for Farm A. The dots correspond to the ventilation rate during sampling. The lines indicating ventilation rates were from the continuous monitoring system (with data from manually over-riding the control system omitted). Presentation of the data in this manner demonstrates that on days 15 and 21, the manually selected ventilation rate exceeded the normal value determined by the ventilation controller. Consequently, the odour emissions measured on these days should be viewed with caution.
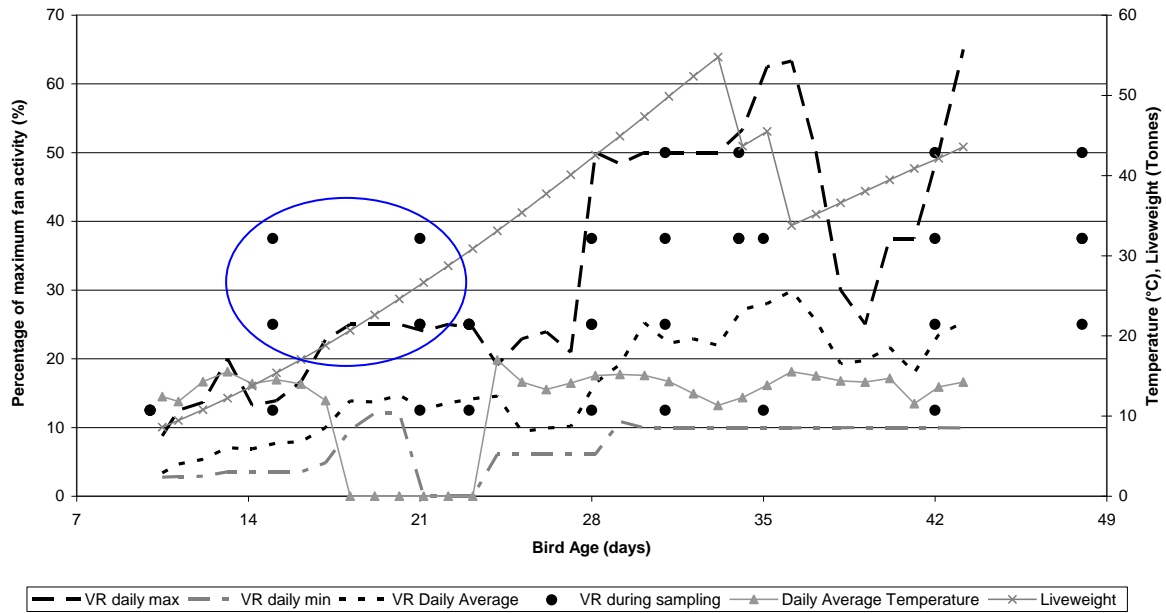
Figure 69: **Ventilation activity measured at Farm A 16 June to 19 July 2006 – blue circle indicates data that appears abnormally high, and occurred due to the sampling methodology of overriding the automatic fan controller (gaps indicate missing data)**

In contrast with Farm A, Figure 70 displays the ventilation rates for Farm C (partially reused litter batch). This figure shows that the ventilation rates during sample collection were within the normal daily range.
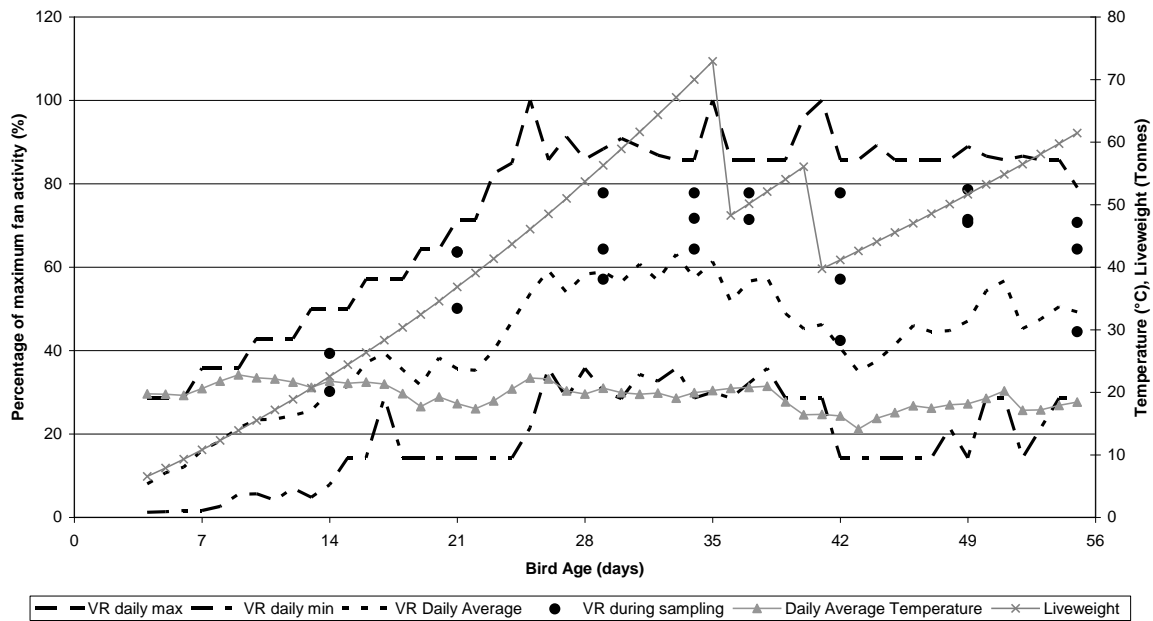
Figure 70: **Ventilation activity measured at Farm C (10 April to 4 June 2007)**

The data identified in Figure 67 to Figure 70 as being abnormally high should be considered unrepresentative of normal conditions. Consequently, the odour emission rates corresponding to these ventilation rates should also be treated with caution, and potentially ignored, because the sampling methodology created abnormal conditions. In addition to these specific data points, odour measurements performed at Farm A and Farm B (summer) were undertaken while manually controlling ventilation. While most of the odour measurements were undertaken at ventilation rates that were likely to be within the normal range of ventilation rates for that day of the batch, the ventilation rate was often increased above the normal level for that time of day, potentially affecting the results. Despite this data being identified as potentially unrepresentative, it was not omitted from the data analysis because the

actual influence of changing ventilation rates on measured odour emissions is unknown and the effects have not been thoroughly investigated or published.

4.5 Broiler single litter use seasonal and location variability

Seasonal variability of emissions was assessed at two broiler farms, one located in southern Queensland (Farm A), the other located in central Victoria (Farm B). One batch of chickens was monitored in summer (November–January in QLD and February–April in Victoria) and winter (June–July in QLD and August–September in Victoria). A review of the summer emission rate data from Farm A revealed that the regularity of data collection was not sufficient to identify trends in emission rates, and the data collected would not allow an assessment of bird removals on emission rates. In addition, several odour measurements from this batch were discarded due to excessive olfactometry variability (see Section 3.4.1.2 for further description); and unscheduled removal of birds prevented measurements on day 35 of the batch and day 47, prior to final bird removal. To address these issues, odour measurements from Farm C were included to supplement the emission rates representing 'Queensland summer'. Monitoring at this farm occurred from January–March 2007.

Each shed was assessed for odour; volatile organic compounds (VOC); particulate concentration and number; and litter moisture content. A maximum of 4 replicates were conducted on each sample day, with each replicate coinciding with a change in ventilation rate. Ventilation rate was subsequently measured at each change.

Frequency of emission measurement throughout the batch was described previously in section 3.2.1.

4.5.1 Odour emissions from individual summer batches

Odour emission rates measured at Farm A, B and C during summer are displayed in Figure 71, Figure 72 and Figure 73 respectively. Litter moisture content has also been included in these charts, as this factor is implicated in the generation of odour. The ventilation rate at the time of each measurement is essential for interpreting the odour emission data, and is provided in Appendix 5, Appendix 7 and Appendix 9 for Farms A, B and C respectively.

Figure 71 shows odour emissions for only two days during the batch at Farm A. Measurements scheduled for later in the batch were not undertaken due to unscheduled removal of the birds (with insufficient warning for the project team to re-schedule sampling times). The average shed litter moisture content ranged between 20–30% on sampling days. The emission rates measured on days 18 and 27 would be considered high when compared to other reported emission rates; however, these emission rates may not be representative of normal production for the reasons described in Section 4.4 (manual control of ventilation during sampling and unrealistic ventilation rates). Insufficient measurements were undertaken to enable the complete range of odour emission rates to be described throughout the batch. The wide spread of emission rates on each day is due to measuring at different ventilation rates and different times of the day; but clearly demonstrates that odour emission rates are not constant throughout the day.
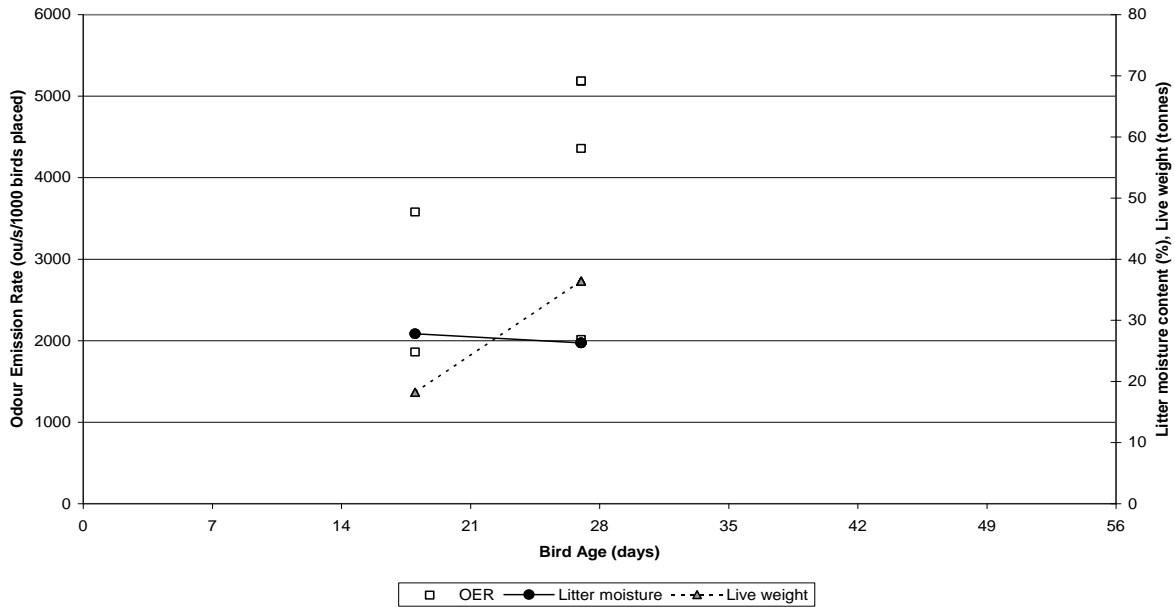
Figure 71: Odour emission rate, shed-average litter moisture content and total live weight for Farm A (summer)

Figure 72 shows the odour emission rates on three days at Farm B. There is clearly an increase in odour emission rate between days 13 and 32 with increased live weight, age and shed-average litter moisture content. Following the first pickup, shortly after day 32, the odour emission rate appeared to decrease and is lower on day 46. Odour emission rate on each day varied considerably between the minimum and maximum values. As with Farm A, this demonstrates that odour emission rates vary considerably throughout each day coinciding with changes in ventilation rate. The ventilation rates measured on day 13 may not be considered normal; because the ventilation system was manually controlled and higher than normal ventilation rates were chosen (see section 4.4). Emissions on this day were relatively low regardless of the ventilation rate. The highest emissions measured on day 32 may not be truly representative because ventilation was manually increased at a faster rate than the normal daily increase in ventilation rate, and may have influenced the measured odour emission rate.
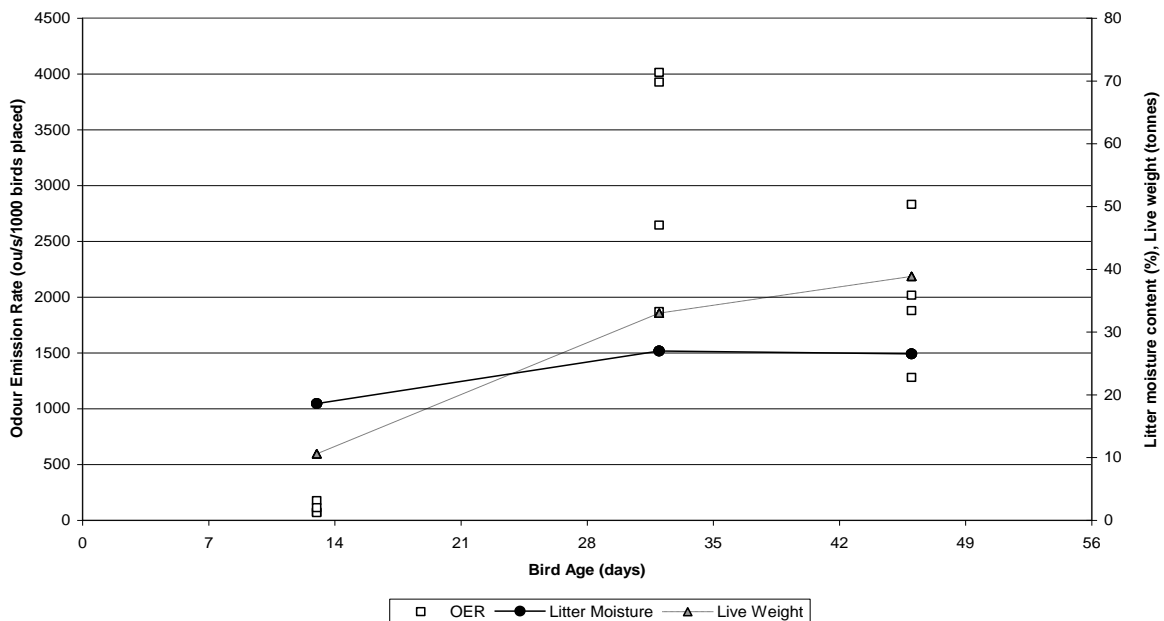
Figure 72: Odour emission rate, shed-average litter moisture content and total live weight for Farm B (summer)

Figure 73 displays the odour emissions measured at Farm C (late January to late March). Odour emission rates peaked on days 35 and 37. Emission rates varied on each day because samples were collected at different times, and at different ventilation rates. The shed-average litter moisture content reached a maximum around day 35 and then decreased until the end of the batch. Reductions in shed live weight occurred due to pickups on day 36 and shortly after day 42. Despite live weight reaching a maximum on day 57, odour emission rates on this day were lower than on day 35, although maximum ventilation rate was also lower on this day. Peak odour emissions reached a maximum on day 42.
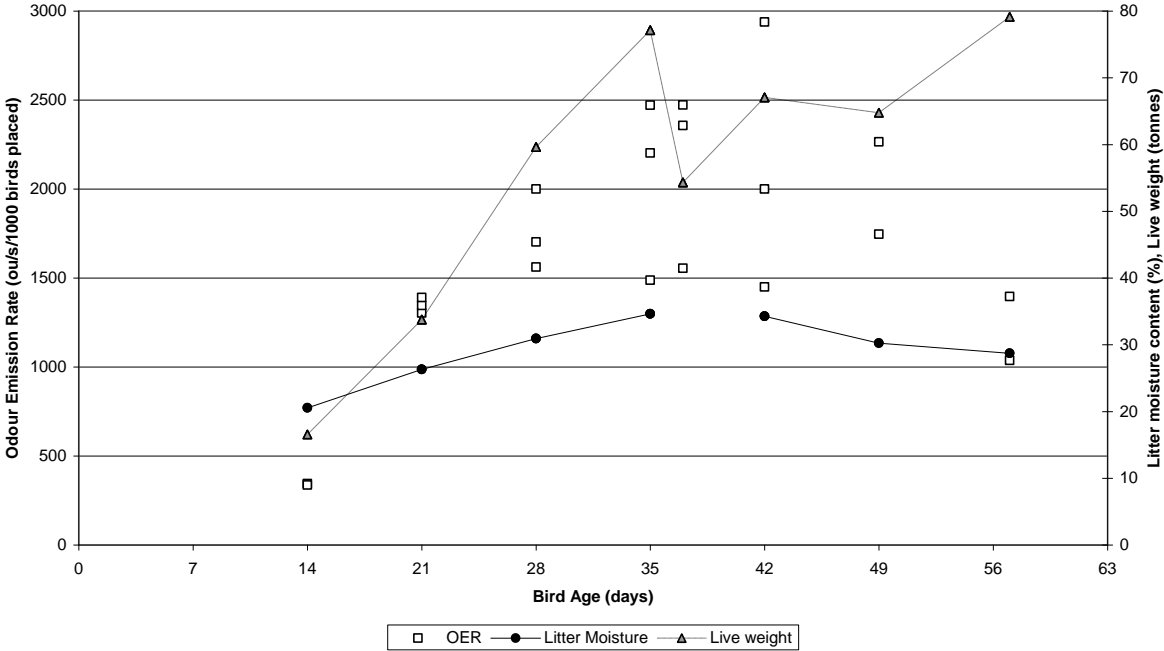
Figure 73:   Odour emission rate, shed-average litter moisture content and total live weight for Farm C (summer)

4.5.2 **Odour emissions from individual winter batches**

Odour emission rates for Farms A and B during winter are shown in Figure 74 and Figure 75 respectively. Corresponding data for winter can be viewed in Appendix 6 and Appendix 8.

Figure 74 shows the odour emission rate peaking with maximum live weight around day 31. Litter moisture was relatively high at the start of the batch, but following day 21, began to drop and remained just over 30% for the remainder of the batch. As in summer, changes in ventilation on each sampling day resulted in a range of odour emission rates occurring on each day. Ventilation rate never exceeded 50% of the maximum ventilation rate during the sample collection times, yet peak odour emission rates were comparable with summer levels. The practice of manually controlling fans during sampling periods may have influenced the measurement of emission rates (as explained in section 4.4), so the peak emission rates in particular should be viewed with caution.
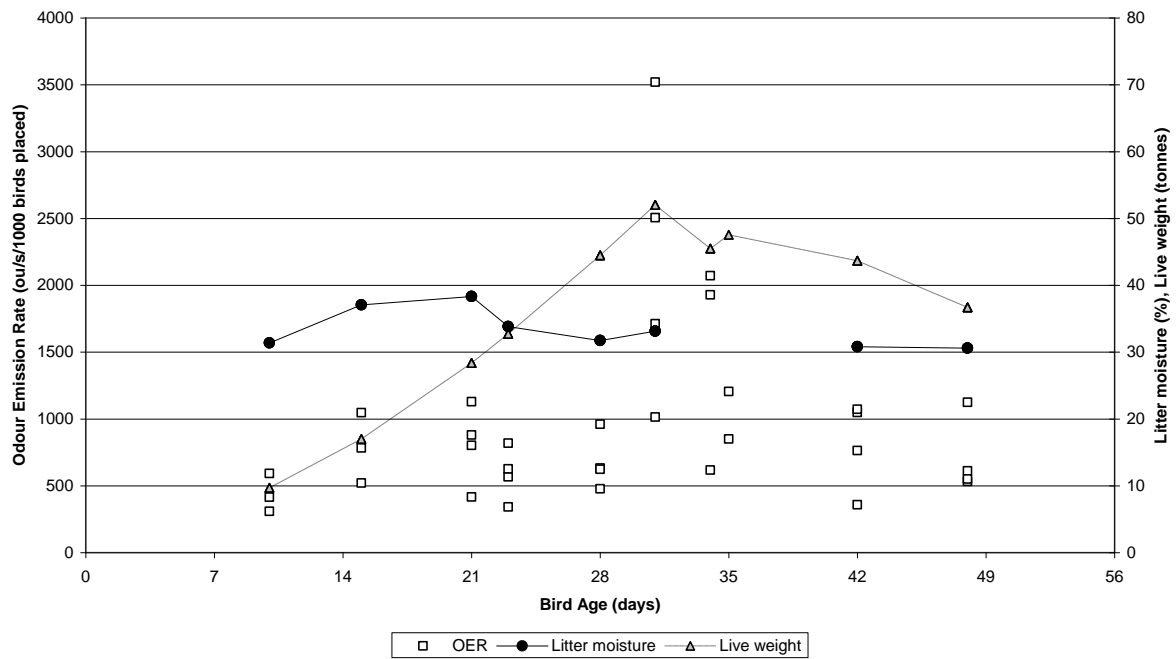
Figure 74: **Odour emission rate, shed-average litter moisture content and total live weight for Farm A (winter)**

Figure 75 shows the odour emission rates at Farm B. Odour emission rates tended to follow the live weight in the shed. Litter moisture content also peaked around day 35, when live weight peaked. The maximum odour emission rate was measured on day 37 of the batch. As with Farm C in summer (see Figure 73), there were no obvious reasons for this.
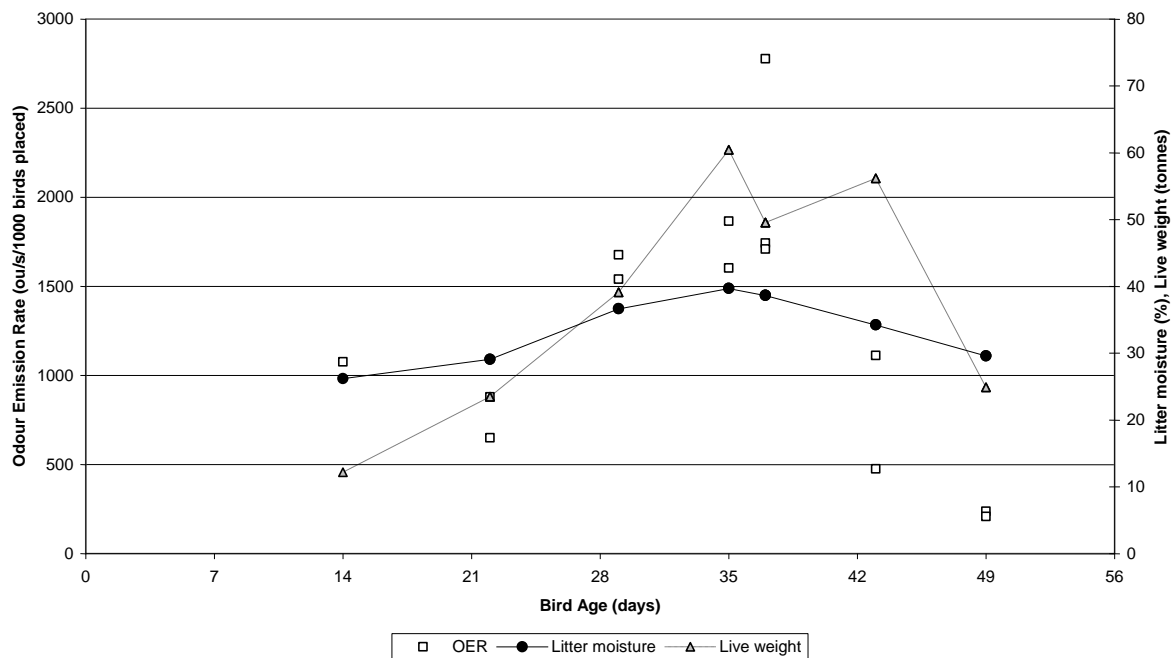
Figure 75: **Odour emission rate, shed-average litter moisture content and total live weight for Farm B (winter)**

4.5.3 **Odour emission rate – summer vs winter**

Figure 76 shows a direct comparison between the odour emission rates measured in summer and winter. Around day 35, daily peak odour emissions measured during this study were similar in both summer and winter. Odour emission rates appeared to remain high following the first pickup in summer, whereas in winter the emission rate decreased following the first pickup (about 35 days).

Throughout the batch, daily minimum OER values were lower in winter than summer. This is likely to have implications on the total daily emission of odour, which in turn will influence the potential for odour impacts.

Displaying all of the data into just two categories has the effect of blending all of the data. For practical use of the odour emission rate data, each odour emission rate needs to be considered independently with associated weather, production, ventilation and litter conditions.
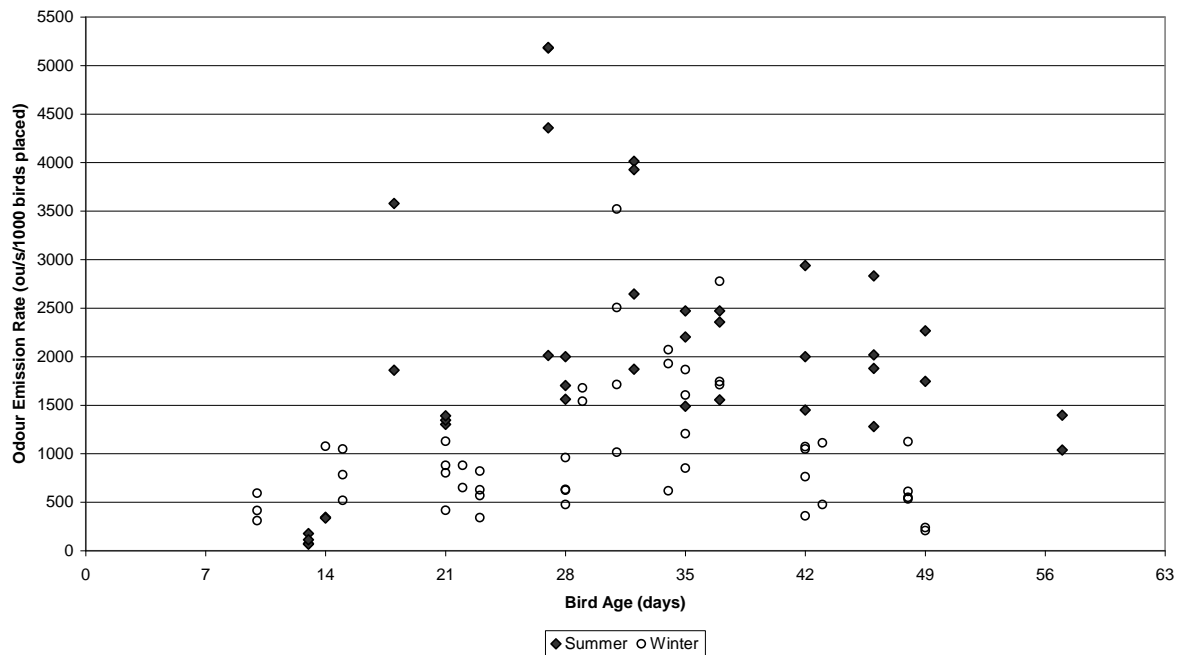
Figure 76: Odour emission rates for broiler farms in summer and winter

The disparity between summer and winter odour emission rates is influenced by ventilation rate. Figure 77 displays odour emission rate plotted against ventilation rate. There is an approximately linear increase in maximum daily odour emissions with ventilation rate; however, minimum odour emission rates appear to be independent of ventilation rate.

In general, winter ventilation rates dominate the lower half of the spectrum, whereas the upper levels of ventilation rate occurred mostly during summer. This was not unexpected, but serves as a reminder of the importance of ventilation rate on odour emission rates; and ventilation requirements need to be clearly understood when measuring or predicting odour emission rates at broiler farms.
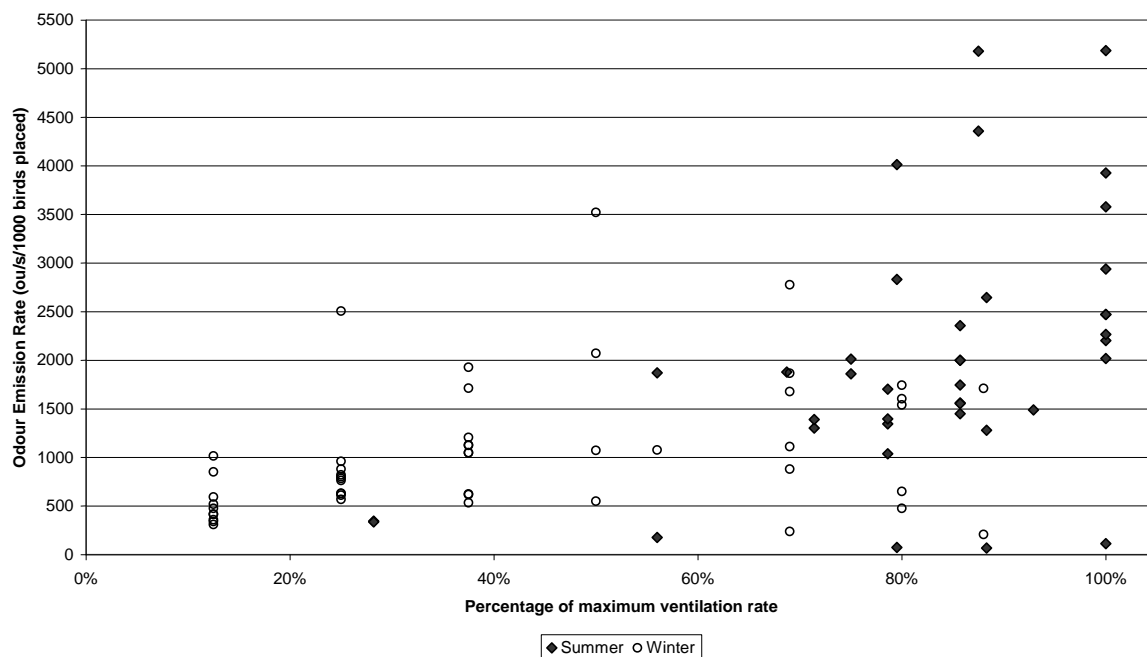
Figure 77: Odour emission rate versus ventilation rate in summer and winter

Statistical analyses were performed on log transformed odour emission rate per 1000 birds placed data using the REML technique. For Farm A, analyses focussed on day 27 and day 28 of the summer and winter batches, respectively. These days were used in an attempt to directly compare both batches. The odour emission rate for Farm A was found to be significantly different, indicating that there were differences between the summer and winter results. For Farm B, day 35 and 32 of the summer and winter batches, respectively were used for analysis. No significant difference between summer and winter emissions was found.

4.5.4 **Odour emission rate – Queensland vs Victoria**

Odour emission rates were measured at broiler farms in Queensland and Victoria to determine if localised differences in litter material, litter management, feed constituents or climate would significantly affect odour emission rates. Figure 78 shows, with the exception of some very high emission rates recoded in Queensland, that the majority of odour emission rates appeared to be similar in both Queensland and Victoria.
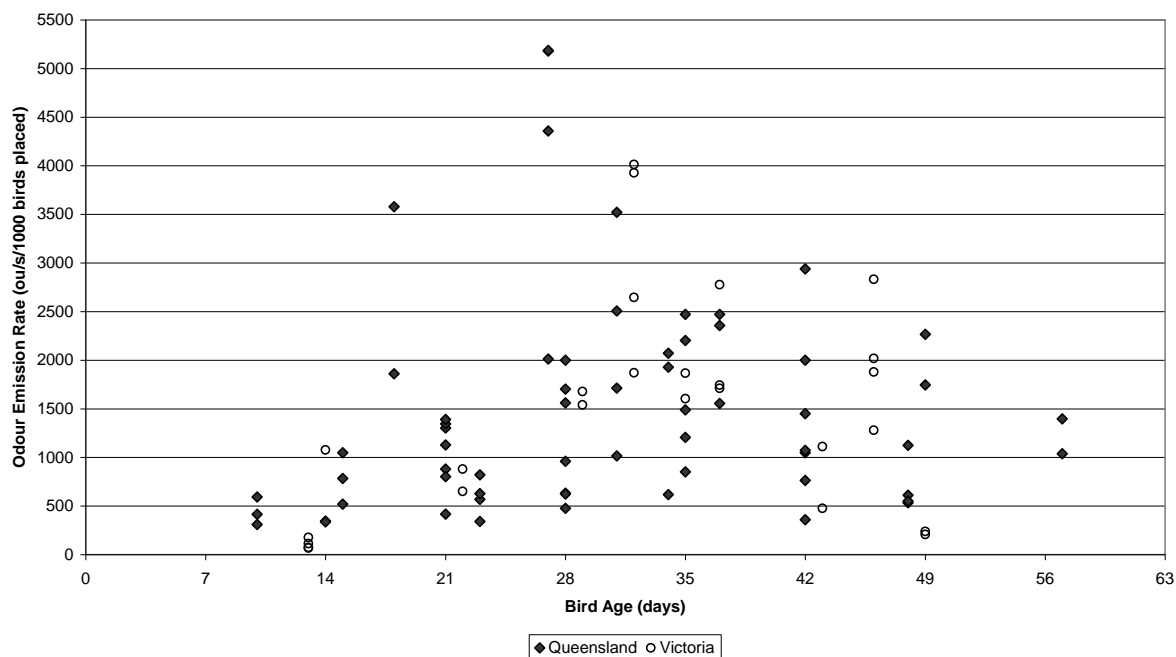
Figure 78: Odour emission rates versus bird age for Queensland and Victorian farms

4.6 Comparison of emissions from single use litter and partial litter reuse

Odour emissions were measured from a farm that partially reused litter to assess whether this litter management process produced different emissions when compared to single litter use. One farm (Farm C) was chosen that partially reused litter. Two batches of chickens were monitored in sequence from one shed—the first batch with single use litter, the second batch grown on partially reused litter. Odour, volatile organic compounds, particulate concentration and number, and litter moisture content were monitored at approximately weekly intervals.

Odour emission rate per 1000 birds placed is shown in Figure 79. For the single use batch, measurements ranged from 337–2939 ou/s per 1000 birds placed, whereas for the partially reused batch, measurements ranged from 669–2806 ou/s per 1000 birds placed. The geometric mean OER measured during the single use and partially reused batches was 1505 and 1393 ou/s/1000 birds placed respectively. The general trend for both batches was of steady increase in OER up to day 35, after which emissions plateaued or fell slightly. There were only minor observable differences in emissions when comparing single use and partially reused litter.
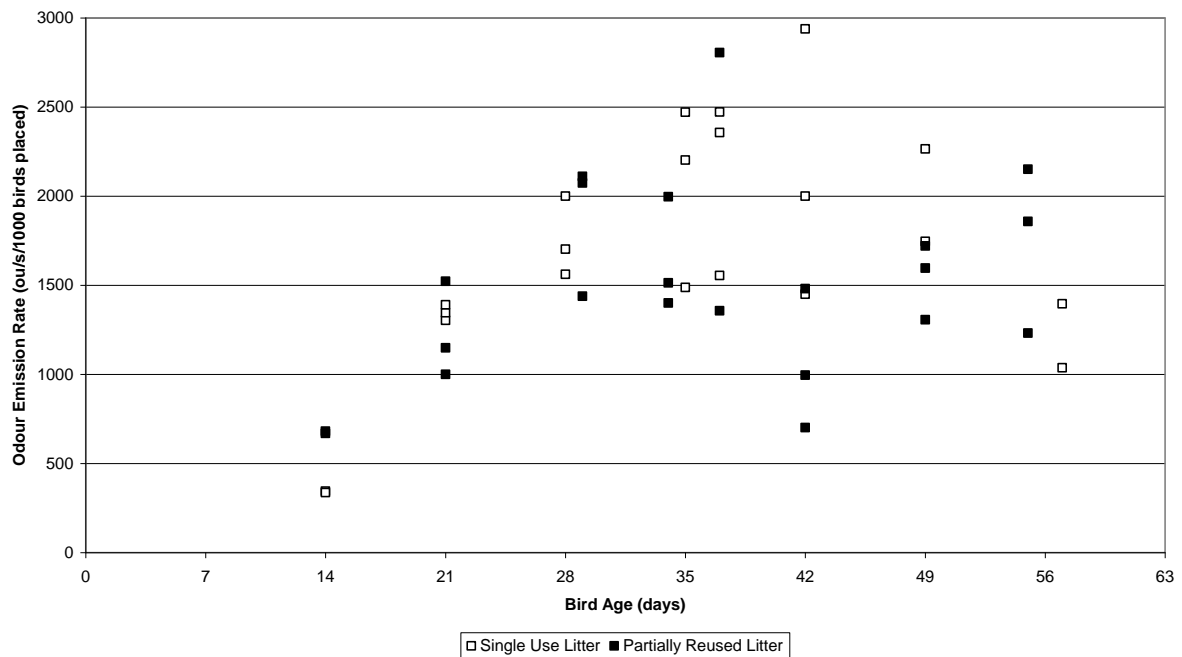
Figure 79: Odour emission rate per 1000 birds placed comparing fresh and partially reused litter

Odour emission rate per kg is shown in Figure 80. For the single use batch, measurements ranged from 0.53–1.84 ou/s per kg, whereas for the partially reused batch, measurements ranged from 0.65–2.12 ou/s per kg. The geometric mean OER measured during the single use and partially reused batches was 1.22 and 1.14 ou/s per kg respectively. Emission rates were relatively constant for both batches. There were few observable differences in emissions when comparing single use and partially reused litter.
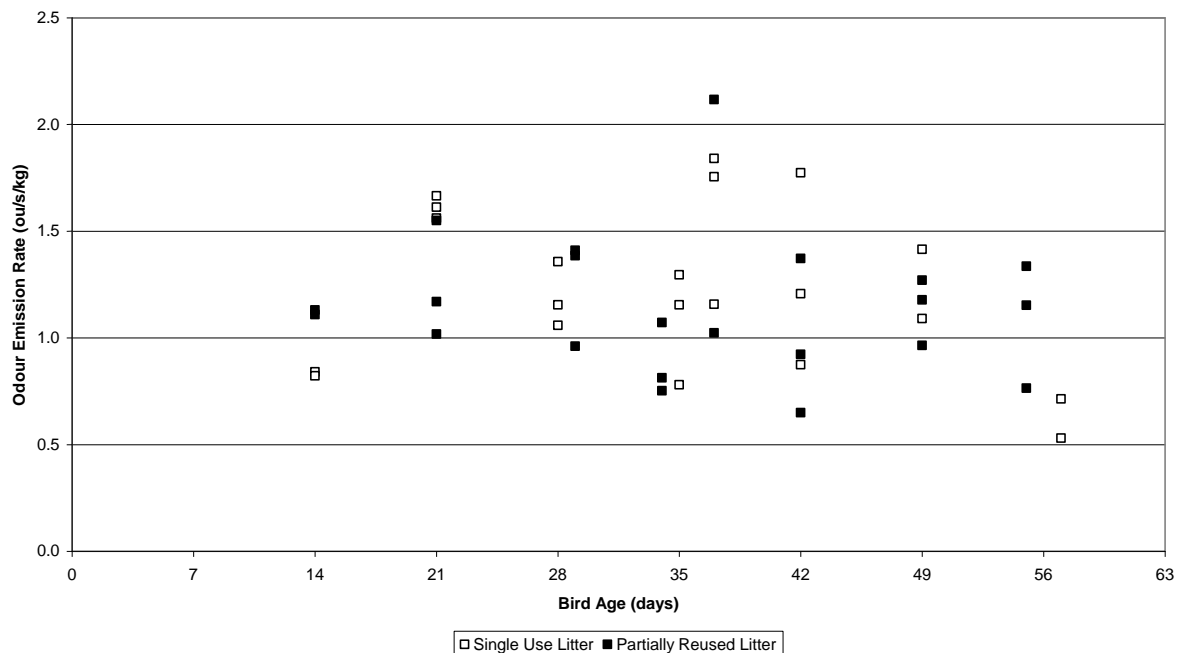
Figure 80: Odour emission rate per kilogram comparing fresh and partially reused litter

On face value, that the odour emissions measured during both batches at Farm C showed that odour emissions did not increase when litter was partially reused; however, there are a number of differences in the single use and partially reused litter batches. Firstly, the single use batch was grown between 30/1/07 and 30/3/07 (summer/autumn), whereas the partially reused batch was grown between 10/4/07 and 6/6/07 (autumn/winter). As shown in Figure 81, ambient temperature measured during the partially reused batch

was lower than the temperature measured during the single use batch. The reduction in ambient temperature would have resulted in reduced ventilation rates, which directly influences odour emission rate.
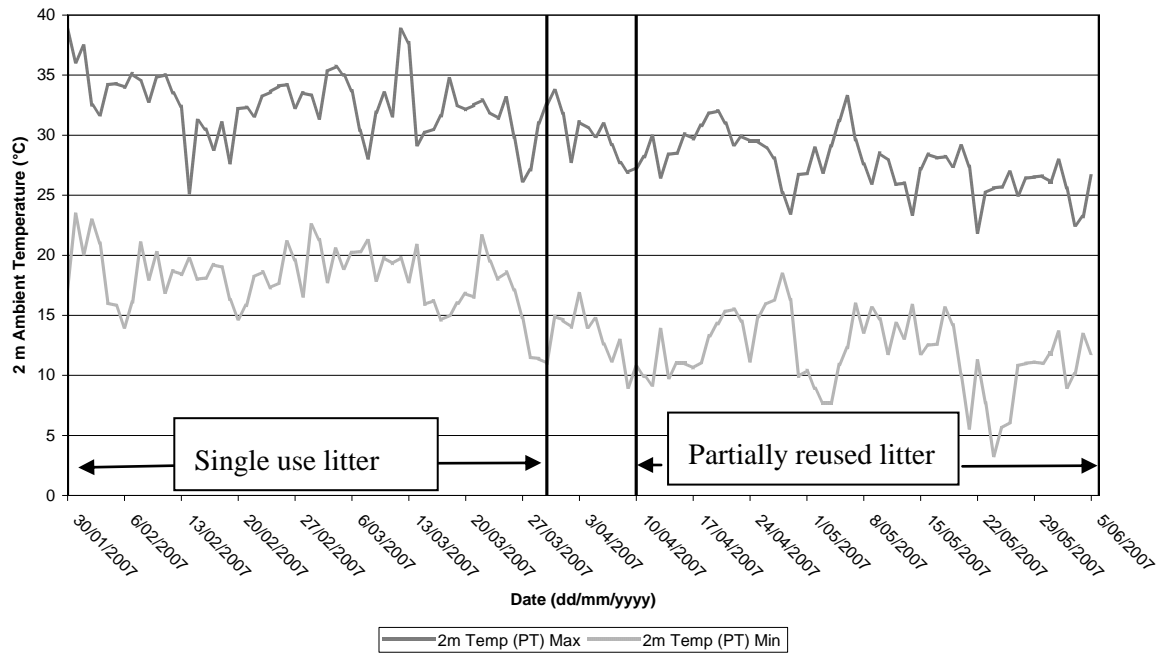
Figure 81: Daily minimum and maximum 2 m ambient temperature for Farm C

Secondly, the number of birds placed during each batch was not identical. The partially reused batch stocking rate was 8% less than the single use batch. It is difficult to identify the impact this difference had on odour emission; however, greater exposure of floor area for interaction between air flow and litter, and less manure deposition may result in reduced odour emissions. We can speculate on the effects, but they cannot be quantified.

Thirdly, average litter moisture content was consistently lower for the partially reused batch (apart from the measurement at day 14) (see Figure 82). As discussed later in Section 4.8.2.2, litter moisture content appeared to have an effect on odour emission rate.
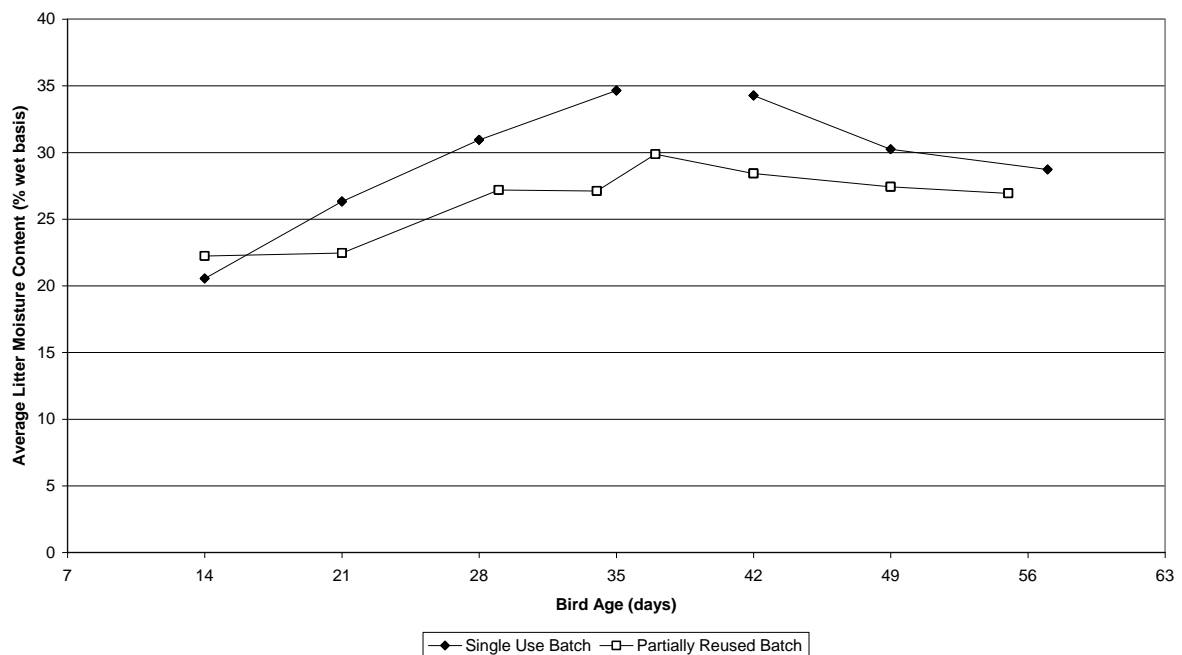
Figure 82: Shed-average litter moisture content (wet basis) for both batches at Farm C

In light of the differences between the single use and partially reused batches measured at Farm C, statistical analyses were performed to assess whether there were any significant differences between the two management practices. Using a linear fixed effects model, the measured odour emission rate per 1000 birds placed was assessed against bird age (Figure 83). A log transformation was performed on the OER data to normalise the values. Neither bird age nor litter management practice significantly affected odour emission rate. However, as the measurements relating to management are completely confounded with other factors (such as ambient temperature, ventilation rate, live weight density), this limited the analytical value. Apart from the environmental and production differences between the two measured batches, it can be seen in Figure 83 that the use of single use or partially reused litter at Farm C did not significantly influence odour emission rate.
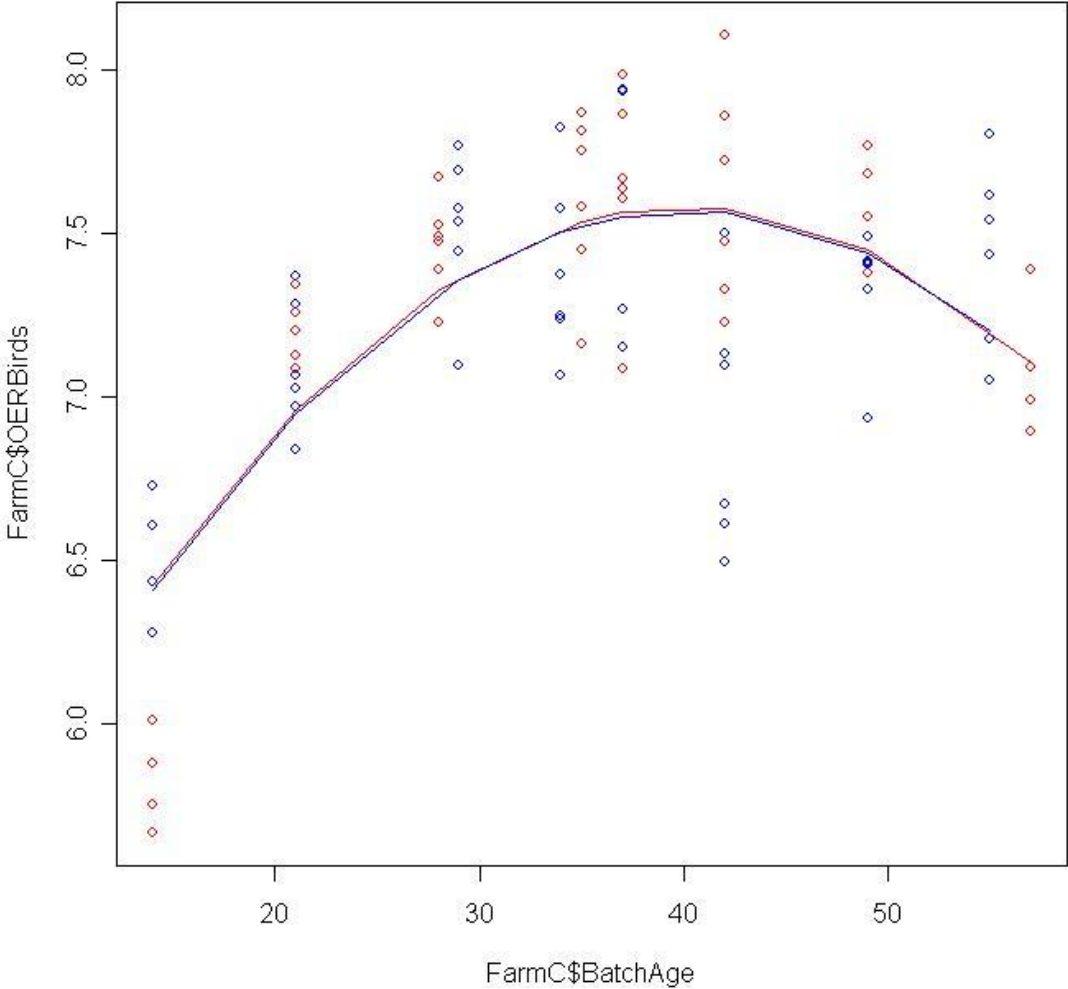
Figure 83: Linear mixed effects model for single use and partially reused litter

4.7 Round robin of Queensland farms

Variability in emissions between farms was assessed at eight broiler farms located in south-east Queensland. Each farm was monitored only on the day before the first pickup for odour, volatile organic compounds, ventilation rate, and litter moisture content. Dust measurements were not undertaken because a duct was not constructed for each of these farms.

The odour emission rate results are shown in Figure 84 for Farms A, C and F–M. The odour emission rate per 1000 birds placed ranged from 315–1794 ou/s for Farms F–M. The comparative emissions for the day before first pickup for Farms A and C ranged from 1014–5187 ou/s and 1400–2471 ou/s respectively.
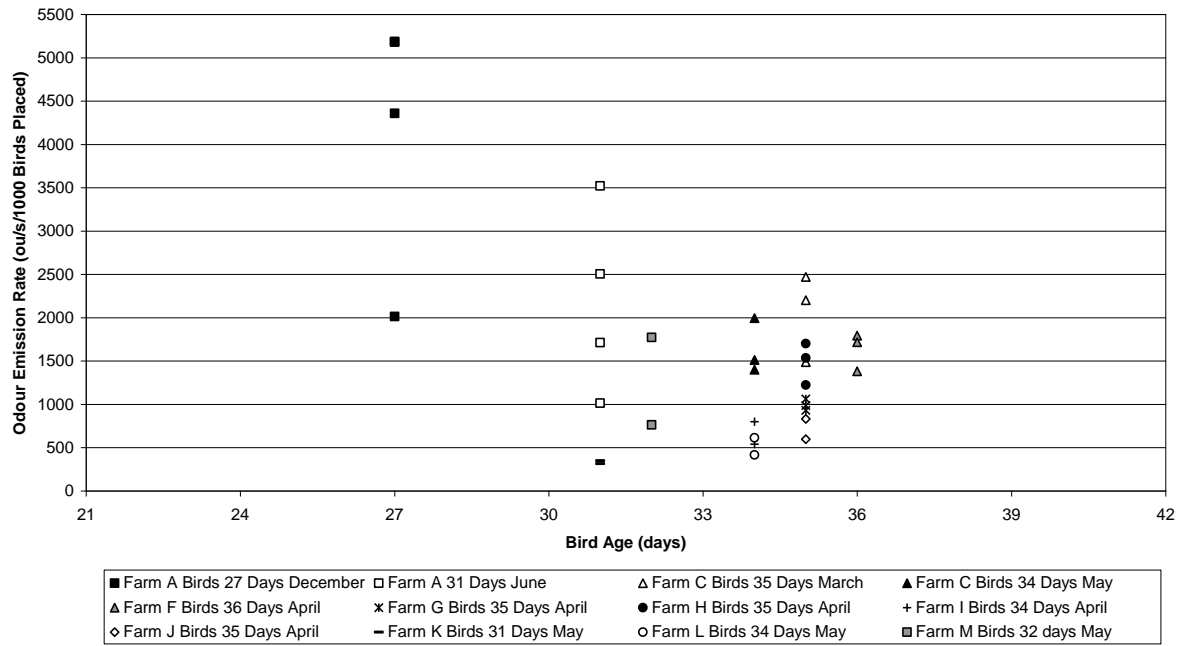
Figure 84: Odour emission rate per 1000 birds placed for QLD farms at peak bird density

The results for Farm A are comparatively higher than the other farms. This may be due to the manual overriding of fans and consequently, the three highest recordings for Farm A should probably be excluded (as explained in Section 4.4). After excluding these measurements for Farm A, the range of odour emissions for the 10 farms located in south-east Queensland was 315–3520 ou/s per 1000 birds placed (see Figure 85—data presented using a box and whisker plot).

Explanatory note for interpreting box and whisker plots: the extent of the whiskers represent the maximum and minimum values; the upper and lower values of the box show the 25th and 75th quartile values and the line inside the box represents the median value.
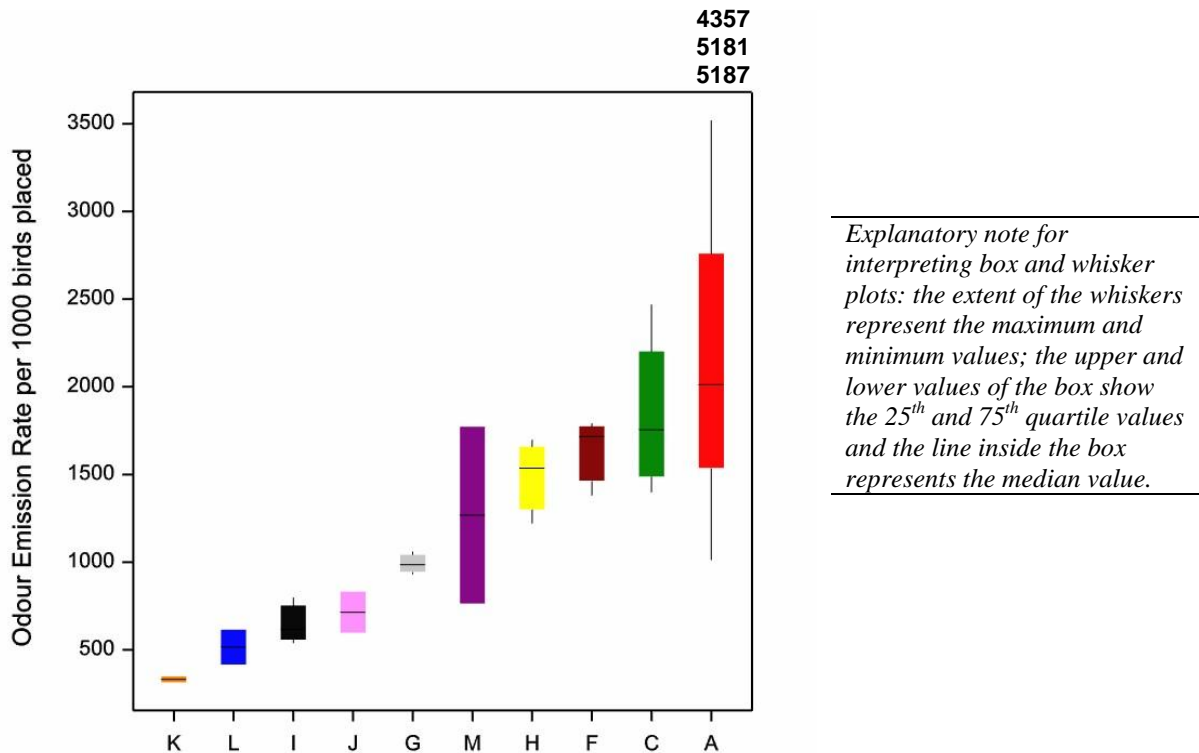
Figure 85: Comparison of odour emission rate for all Queensland broiler farms at peak density. (*note:* the three values above the chart represent three data points from Farm A, Summer, that were removed to improve presentation of the remaining data and because these three values are likely to be unrealistic due to the research team manually over-riding the fan controller).

It can be seen in Figure 85 that there is variability between the farms, with some farms having lower odour emissions than others. Reasons for inter-farm variability could not be determined from the conditions recorded on each sampling day. Much of the variability seen at each farm was due to changes in ventilation rate.

In terms of litter management, Farms I, G and F partially reused litter (as well as some of the data points for Farm C), whereas the remaining farms practiced single litter use. Figure 85 shows that there is no obvious trend in odour emissions when comparing litter management practice. For example, Farm I is similar to Farms L and J; Farm G is similar to Farms J and M; and Farm F is similar to Farms M and H. There are no trends that suggest that partial litter reuse will generate higher odour emissions compared to single use management practices (at peak of bird density).

4.8 Odour emission rate relationships

4.8.1 Development of odour prediction models

The data was analysed to identify any relationships that may exist between odour emission rate and other variables measured on-farm. A stepwise regression in both directions was used to determine the most appropriate model to estimate odour emission. The model development process iterates through steps, testing all factors in the model for possible inclusion or exclusion based on the significance of the factor to the model. A final model is selected with the least number of significant factors while still producing an acceptable fit to the data, qualified using AIC (Akaike's Information Criterion) (Akaike, 1974).

The models chosen included the factors shown in Table 16, which were found to significantly influence odour emission rates from Farms A, B and C. A single model could not be produced because of differences between the three farms; however, individual models were able to be developed for each of the three farms.

The models are comprised of a constant (intercept), singular factors and factors with two way interactions. Two way interactions (where two variables are listed in one row) mean that the second variable significantly influences odour emission only during the time when the first variable significantly influences odour emission. For example, for Farm A, ventilation rate significantly influences odour emission rate when season was also a significant influence. The coefficients in the models are multiplied by the factors and added together to estimate the odour emission rate per bird placed as shown in Equation 8.

$$OER \ per \ bird \ placed \approx intercept + \sum (factors \times coefficients) \qquad \textbf{Equation 8}$$

A worked example for the Farm C model is provided in Appendix 12.

Table 16:   Stepwise regression coefficients for factors influencing odour emission for Farms A, B and C

Factors	Unit	Model coefficients		
		Farm A	Farm B	Farm C
Intercept	–	-9.3497907*	-3.291484	17.0451417*
Season (indicates season where estimate applies)	–	3.9382325 (winter)*	2.192325 (winter)	0.8127175 (summer)*
Batch age	Days	0.0315003	–	-0.0569523
Ventilation rate	m³/s	0.0614428*	0.141079*	0.0377881*
Ambient temperature	°C	0.1480233	-0.140341	-0.7846743*
Live weight density	kg/m²	-0.0553451	-0.042130*	-0.4675131*
Litter moisture	% wet basis	0.1281601*	0.117204*	-0.4117151
Season: Batch age		–	–	–
Season: Ventilation rate		-0.0834111*	-0.131991*	–
Season: Ambient temperature		–	–	–
Season: Live weight density		–	–	-0.1023154*
Season: Litter moisture		–	–	–
Batch age: Ventilation rate		–	–	–
Batch age: Ambient temperature		-0.0072937*	–	-0.0028754
Batch age: Live weight density		0.0036354*	–	0.0055347*
Batch age: Litter moisture		–	–	–
Ventilation rate: Ambient temperature		–	-0.002791*	–
Ventilation rate: Live weight density		0.0029953*	–	-0.0009478
Ventilation rate: Litter moisture		–	–	–
Ambient temperature: Live weight density		–	–	0.0162404*
Ambient temperature: Litter moisture		–	0.005838*	0.0234855*
Live weight distribution: Litter moisture		–	–	–

Notes for applying the models:

- For the 'Season' factor – when the coefficient is listed as winter, the factor has a value 1 when it is winter and a value of 0 when summer. When the coefficient is listed as summer, the reverse is true. For Farm C, 'summer (= 1)' is related to the first batch (fresh litter) and 'not-summer (= 0)' is related to the second batch (partially reused litter)
- When applying two-way factors – multiply the two factors' values and the coefficient.

OER data produced by the models correlated well with the OER data measured at Farms A, B and C, producing r^2 values of 0.91, 0.92 and 0.87 respectively. Figure 86 shows the correlation between the measured and modelled data for each of the three farms.
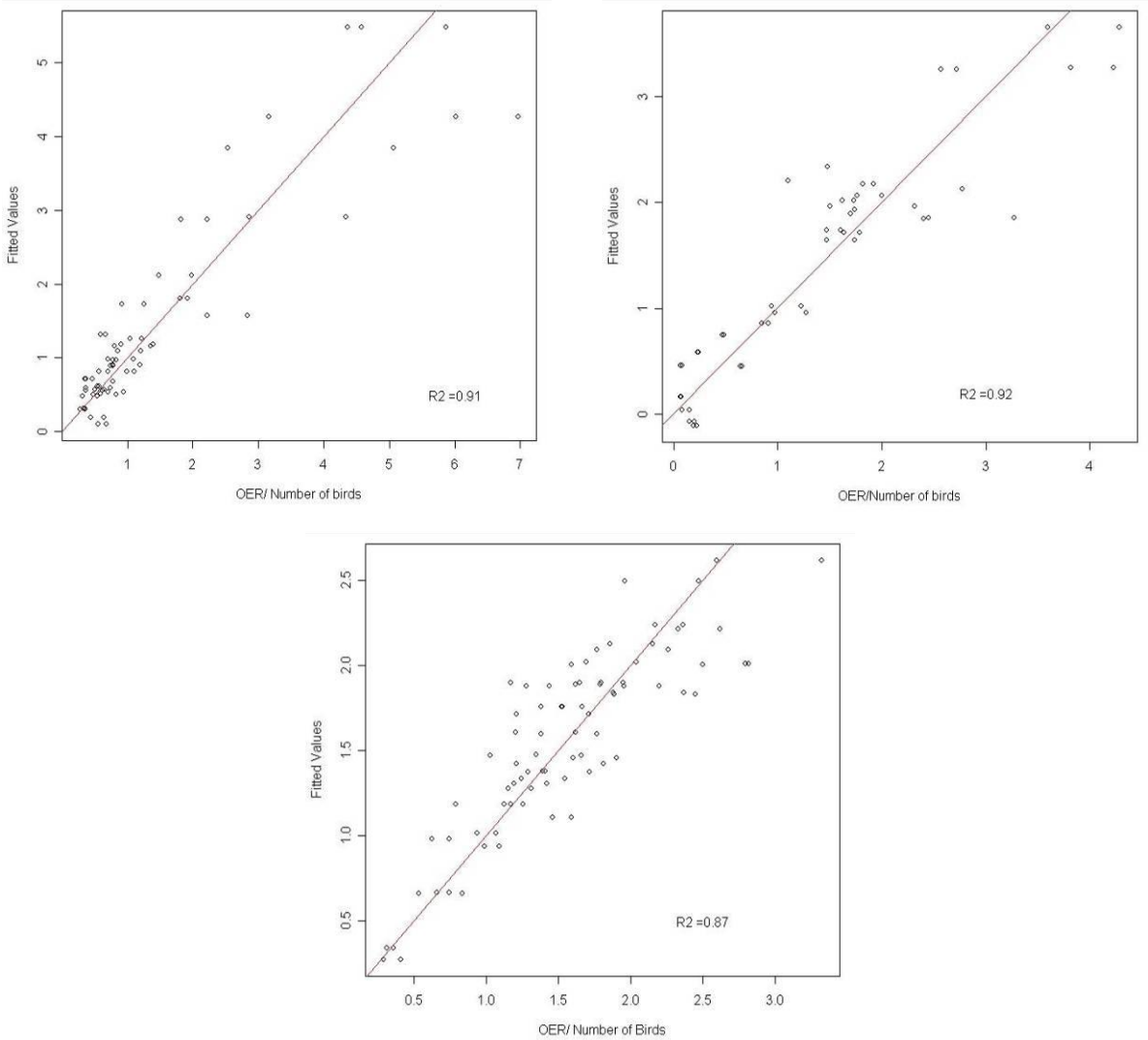
Figure 86: **Correlation between measured and model-generated log odour emission rate per 1000 birds placed (*top left* – Farm A, *top right* – Farm B and *bottom* Farm C)**

The models were compared to olfactometry and artificial olfaction system (AOS) data for Farm A (winter) and Farm C (batch 2—partially reused litter). For each of these batches, the model was applied using both 'season' values.

Figure 87 displays the result of the Farm A model when applied to the Farm A winter batch. It can be seen that the model performed poorly when compared to the AOS and olfactometry data. When the alternate season coefficient was used (bottom chart in Figure 87), OER prediction was even worse; highlighting the need for correct selection of this model factor. Necessity for selection of the correct 'season' value casts doubts on the use of this model using autumn or spring batches.
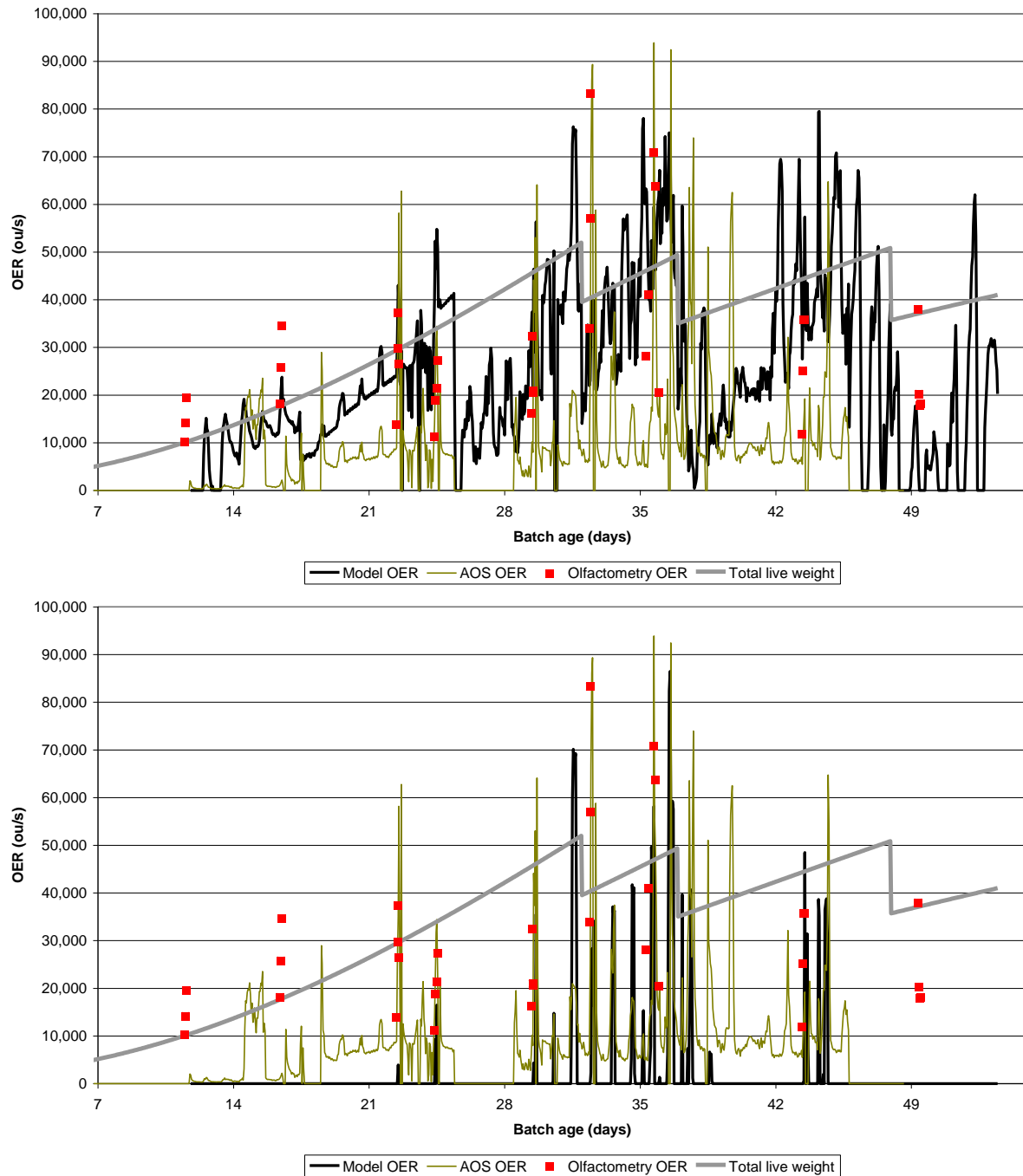
Figure 87: **Application of the model for Farm A to Farm A winter batch. (*top* – using the 'winter' coefficient (season = 1) and *bottom* – using the 'summer' coefficient (season = 0)**

Figure 88 displays the result of the Farm C model when applied to the Farm C partially reused litter batch (batch 2). It can be seen that the model performed poorly when compared to the AOS and olfactometry data by consistently over-predicting daily maximum OER and under-predicting daily minimum OER. When the alternate season coefficient was used (bottom chart in Figure 88), OER prediction was

particularly bad; highlighting the need for correct selection of this model factor. Necessity for selection of the correct 'season' raises questions about which value should be selected for any non-summer batch. Additionally, as shown in other parts of this report, the reuse of litter was found not to be a significant factor for increasing odour. Considering that the two batches were sequential and weather conditions were similar, questions could also be raised as to why the two batches were significantly different (by season).
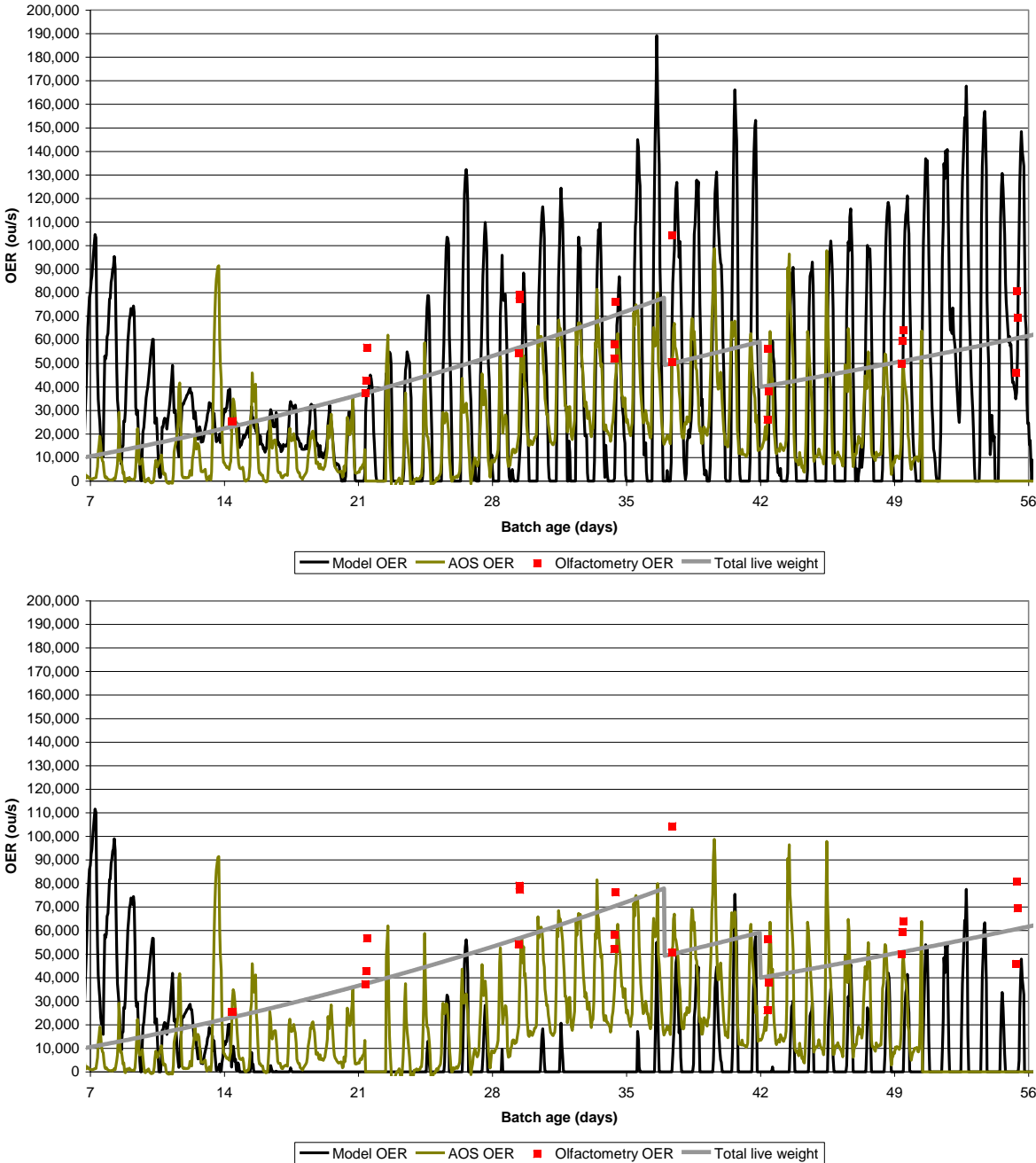
Figure 88: Application of the model for Farm C to Farm C partially reused litter batch. (*top* – using the 'not-summer coefficient (season = 0) and *bottom* – using the 'summer' coefficient (season = 1)

The time series charts in Figure 87 and Figure 88 demonstrate that the models provided relatively poor capability for predicting OER when compared to the olfactometry and AOS measurements, even using the data on which the models were based.

The method that was used to develop the models—stepwise linear regression—produced some counter-intuitive relationships between the factors and OER. The influence of the input parameters on predicted OER from Farms A, B and C are displayed in Figure 89. To interpret the figures, the x-axis corresponds

to the value of the parameters (for example ventilation rate or live weight density) and the y-axis corresponds to the relative change in OER (the middle of the y-axis, 0%, indicates no change). Low gradient of the slope (i.e. close to horizontal) means that changes in the input parameter will only have a small effect on OER. A negative slope (decreasing from right to left) indicates that the predicted OER would decrease with increasing values of the individual parameter.

For Farm A (*top* charts in Figure 89), the model predicted increasing OER with increasing ventilation rate, live weight density and litter moisture content, but decreasing OER with batch age and ambient temperature. While the contribution of each of these parameters was slightly different when using 'summer' and 'winter' coefficients for season, the trend for OER to increase or decrease with each of the parameters remained relatively consistent. For Farms B and C (*middle* and *bottom* charts in Figure 89); however, the effect of the parameters on the prediction of OER changed between the two seasons, and OER was seen to decrease with increasing values for ambient temperature, live weight density and litter moisture content in some of these charts.
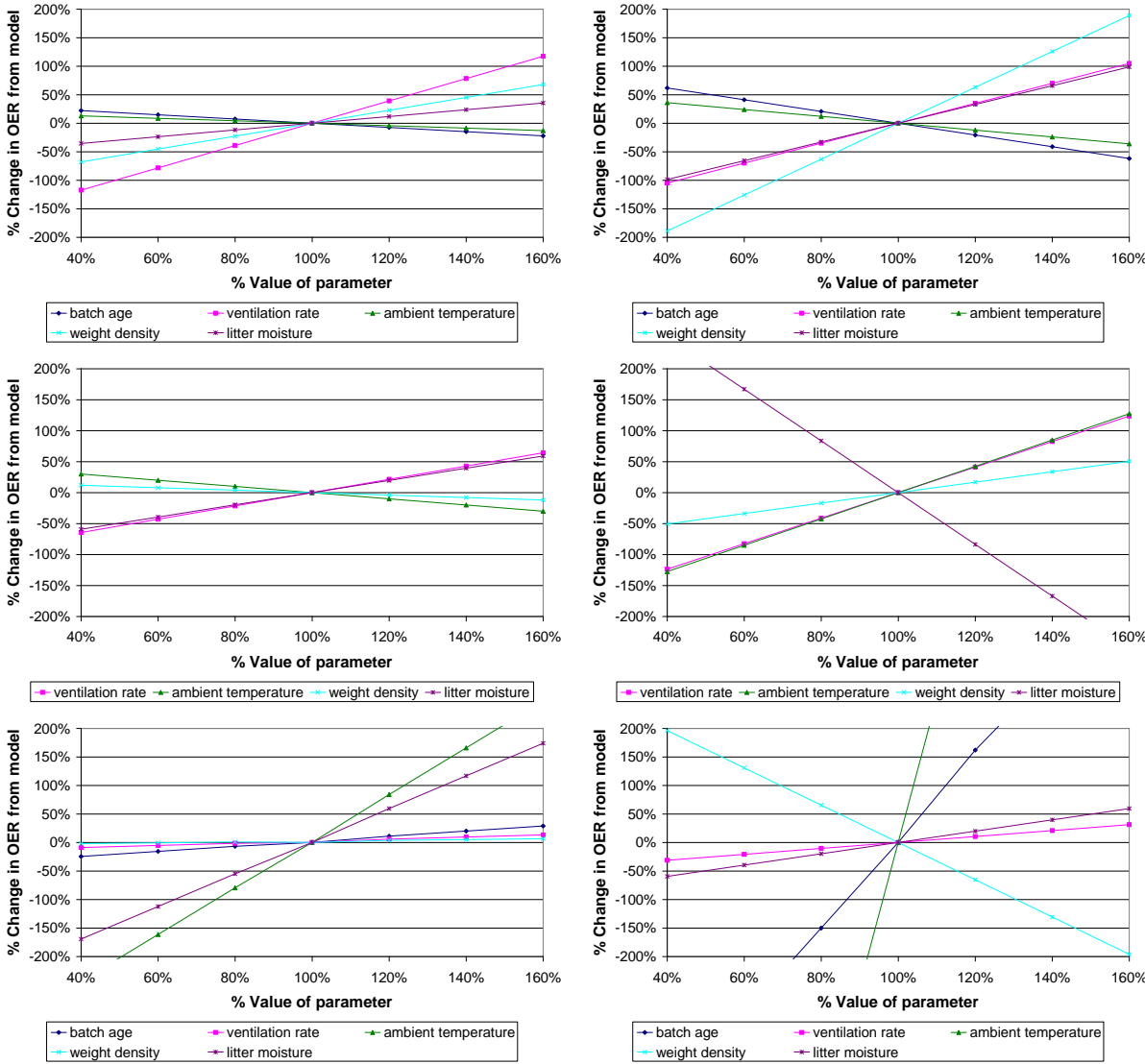
Figure 89: **Changes in predicted OER with changes in parameter values using the model developed from data collected at: Farm A, summer (*top left*) and winter (*top right*); Farm B, summer (*middle left*) and winter (*middle right*); and Farm C, summer (*bottom left*) and not-summer (*bottom right*).**

The inconsistency of the effect of the parameters on the prediction of OER between each farm and season demonstrates that these models are unlikely to be able to be applied to other farms, or at other times of the year.

Consequently, these models should not be used for predicting odour emission rates at broiler farms for planning purposes.

To improve the predictive ability of the models, more data will be required under a broader range of conditions, potentially requiring instrumental odour monitoring such as AOS. Additionally, the effect of the individual factors on OER need to be established and these effects need to be reflected in the model (for example, OER would be expected to increase with live weight density, litter moisture content and ventilation rate, which increases with temperature and batch age; therefore the model predicted OER should increase with these factors).

4.8.2 **Relationships between OER single factors**

The production and emission of odour from broiler sheds is a complicated and intertwined process, and is demonstrated through the complex interactions of the factors in the models (in the previous Section 4.8.1), where singular factors are inherently affected by many other factors (also see Figure 6 in Section 2.2.6.2).

The following sections expand on some of the single factor relationships:

- ventilation rate;
- litter moisture content;
- live weight density; and
- ambient temperature.

4.8.2.1 Effect of ventilation rate on odour emissions

The ventilation rate measured at the time of each odour sample collection was assessed in order to identify any possible relationships between odour and ventilation rate. The relationship between odour concentration and ventilation rate is shown in Figure 90. Odour concentration tends to decrease as ventilation rate increases.
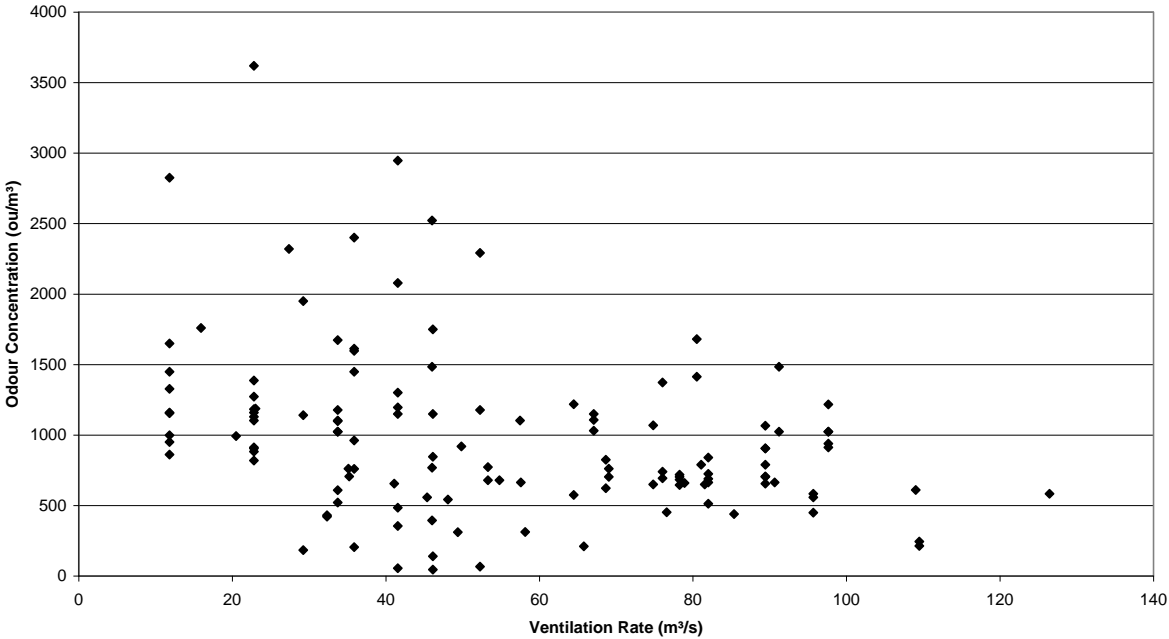
Figure 90: Odour concentration with increasing ventilation rate

The relationship between OER per 1000 birds placed and ventilation rate is shown in Figure 91. OER tends to increase as ventilation rate increases.
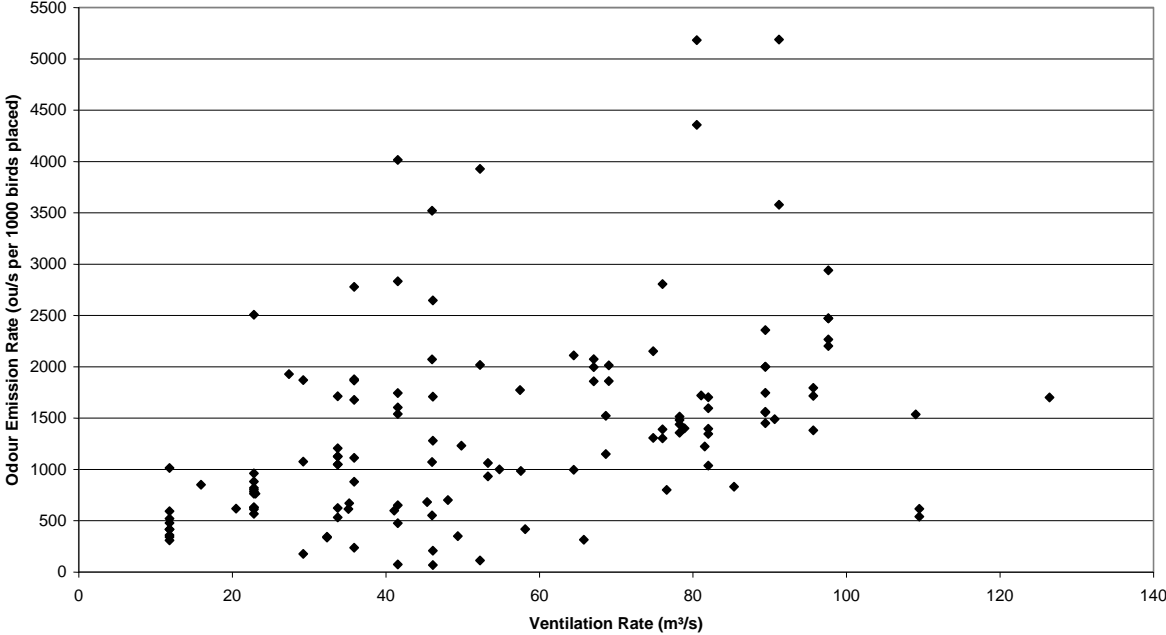
Figure 91: Odour emission rate per 1000 birds placed with increasing ventilation rate

The relationships observed with change in odour concentration and emission rate due to ventilation rate were also observed by Simons (2006). In fact, it is common to all emission rate processes (Hudson and Ayoko, 2009; Hudson *et al.*, 2009)

4.8.2.2 *Effect of litter moisture content on odour emissions*

Litter moisture content was measured on each day that air quality was measured. The vast range of litter conditions that can be experienced in a broiler shed make it difficult to accurately estimate litter moisture content throughout the shed. By collecting samples in a grid pattern, we attempted to collect litter from the whole spectrum of moisture ranges that were present in a shed on each day without bias. Contour plots of the litter moisture content measured on (or close to) each sampling day are presented in Appendix 13 to Appendix 16.

Figure 92 represents the relationship between odour concentration and shed-average litter moisture content while Figure 93 illustrates the relationship between odour emission rate (ou/s per 1000 birds placed) and shed-average litter moisture content. In this study, there did not appear to be a clear trend towards increased odour concentration or odour emission rate with increased shed-average litter moisture content. However, as explained in section 2.2.6.1, shed-average litter moisture may not be the most appropriate measure of litter moisture relating to odour emissions because small areas of very wet, anaerobic litter may generate strong odours.
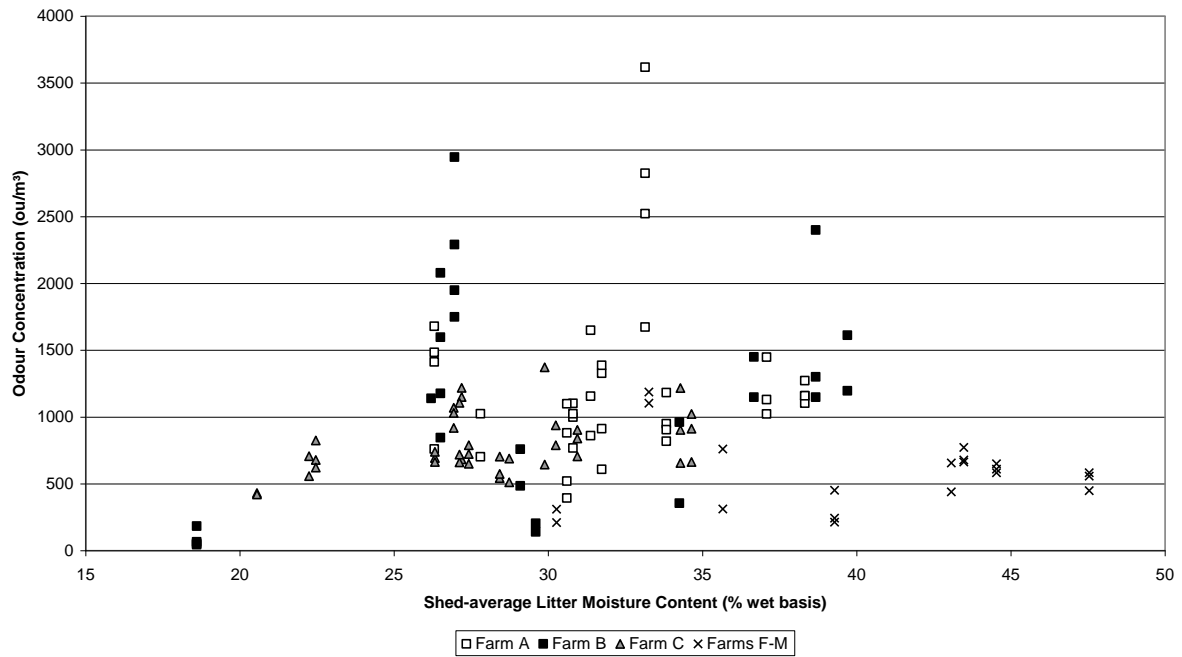
Figure 92: Odour concentration with increasing shed-average litter moisture content
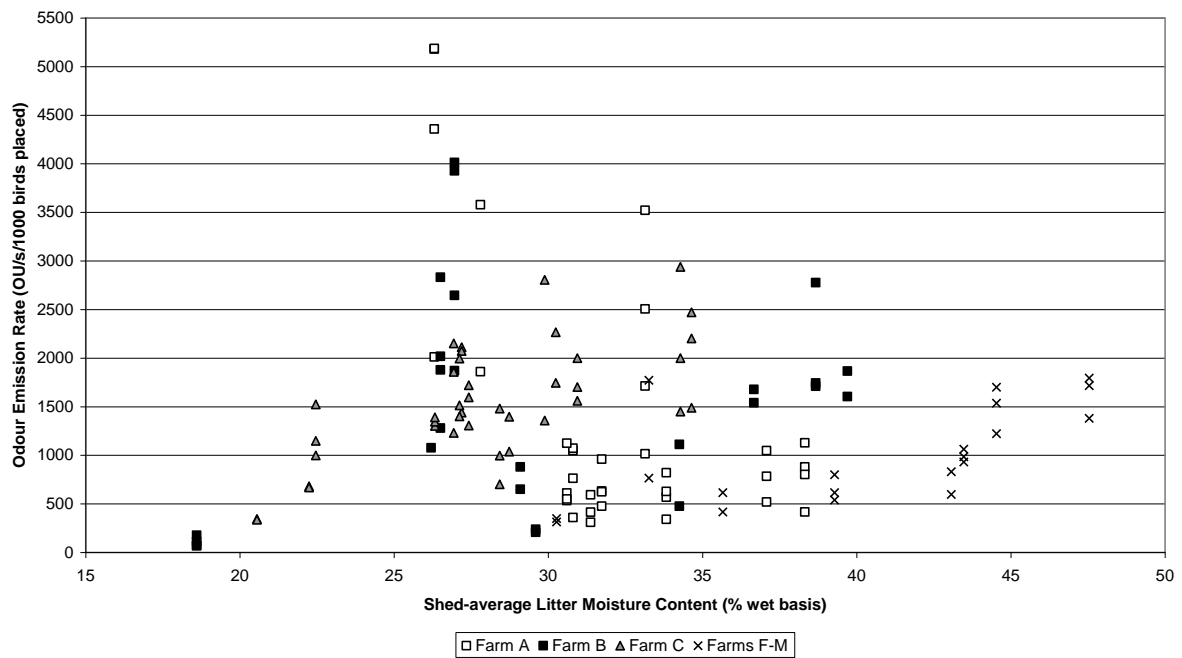
Figure 93: Odour emission rate (ou/s) with increasing shed-average litter moisture content

Small areas of wet litter may generate proportionally more odour than the rest of the floor area (as explained by Hudson *et al.* (2009) in reference to beef feedlot manure pad odour emissions). To explore this hypothesis further, using only the collected moisture content data, the results were broken down into ranges of moisture content. Figure 94 and Figure 95 (displaying odour concentration and odour emission rate respectively) illustrate the range of litter moisture measured on each measurement day when bird weight and density were greatest, i.e. before the first pickup. Using this method, we can see the frequency of individual samples collected in a shed that had dry (less than 20%), typical (21–39%), or wet (greater than 40%) moisture content.
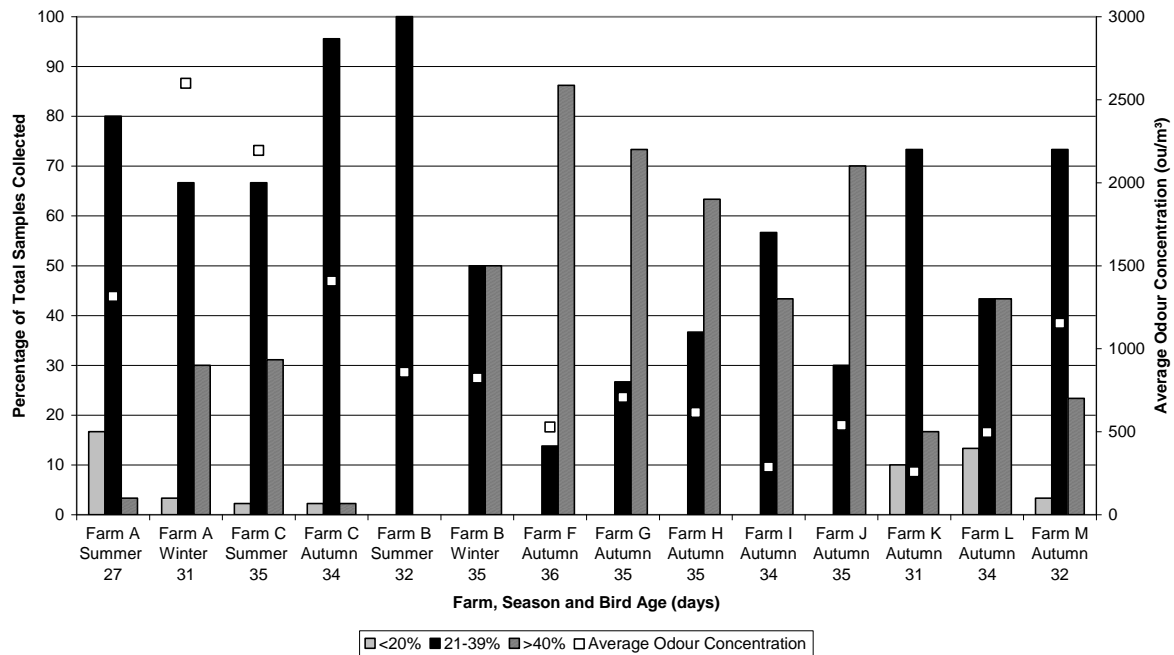
Figure 94: **Odour concentration versus litter moisture content for peak in-shed bird weight (day prior to first pickup)** (*note:* **the number under the x-axis categories indicates the batch age**)
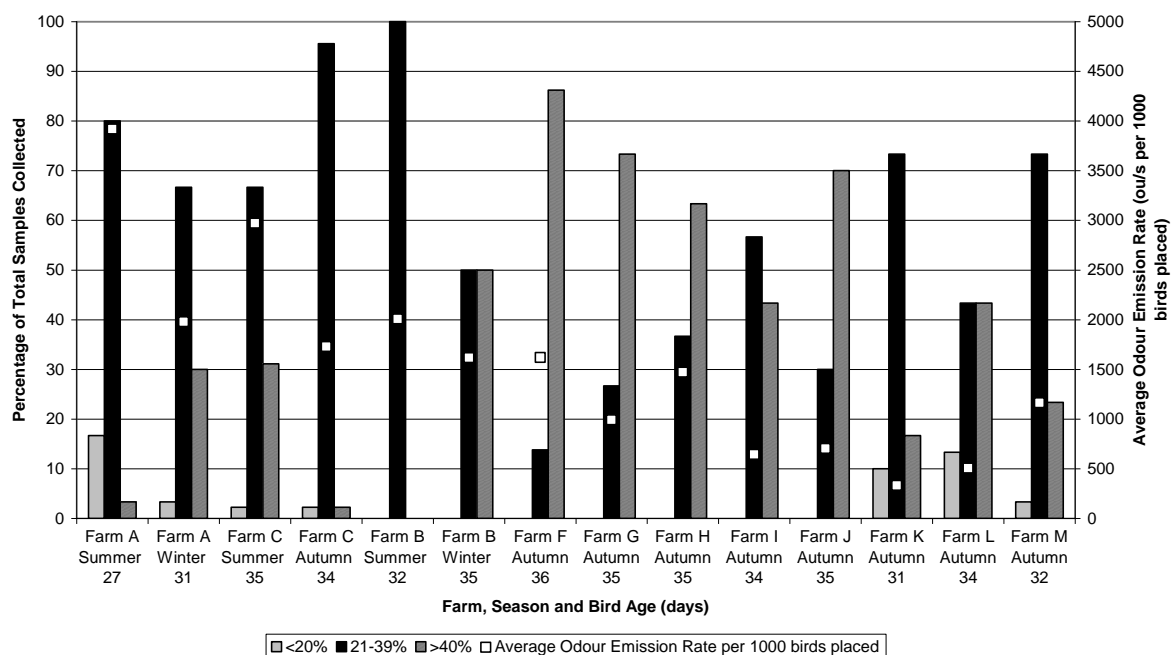
Figure 95: **Odour emission rate versus litter moisture content for peak in-shed bird weight (day prior to first pickup)** (*note:* **the number under the x-axis categories indicates the batch age**)

The litter moisture results shown in Figure 94 and Figure 95 indicate that the proportion of dry, typical and wet litter at the time of peak bird density can vary between farm and season. A conclusion that can be drawn from these results is that farms with wetter litter did not necessarily have higher odour concentrations or emission rates.

The data collected during this study contradict the previous observations made by Clarkson and Misselbrook (1991) and support the observations by Sneath and Robertson (2000) and Simons (2006) (discussed previously in Section 2.2.6.1).

4.8.2.3 Effect of live weight density on odour emission rates

The relationship between live weight density, described as average kilograms per square metre floor area, and odour concentration is shown in Figure 96—odour concentration did not generally increase with live weight density.
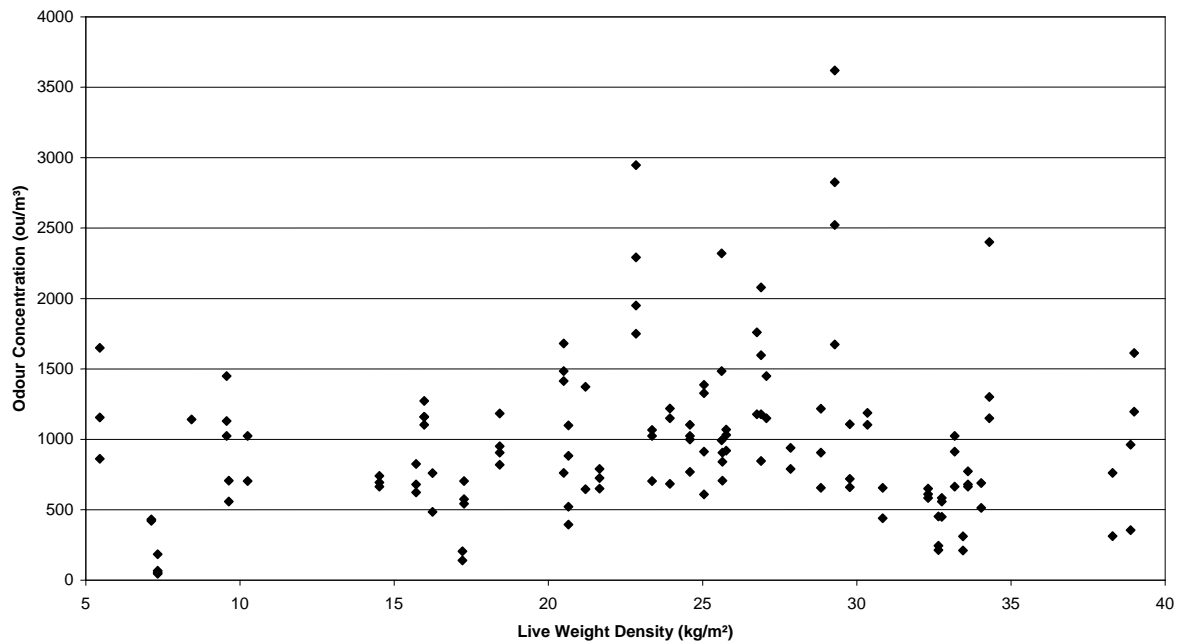
Figure 96:   Odour concentration with increasing live weight density

The relationship between odour emission rate per 1000 birds placed and live weight density is shown in Figure 97—odour emission rate per 1000 birds placed did not appear to increase with live weight density.
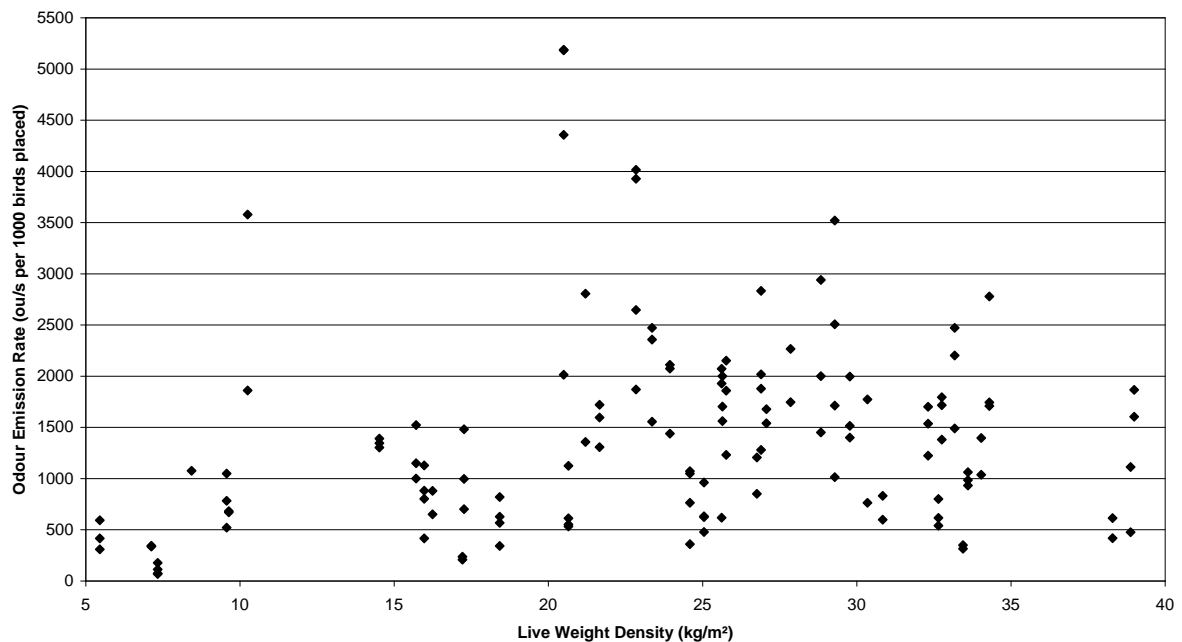
Figure 97:   Odour emission rate per 1000 birds placed with increasing live weight density

As shown in Table 16, live weight density was found to significantly influence odour emission rate during the regression analysis; however, Simons' (2006) data and the data presented in Figure 97 did not visibly demonstrate any clear relationship. One reason for this may be that live weight density changes along with other conditions/factors such as batch age, litter moisture content, ventilation rate, season—evidenced by the two way interactions in Table 16.

4.8.2.4 Effect of ambient temperature on odour emission rates

The relationship between ambient temperature (°C) and odour concentration is shown in Figure 98. There is a slight downward trend in odour concentration as ambient temperature increases.
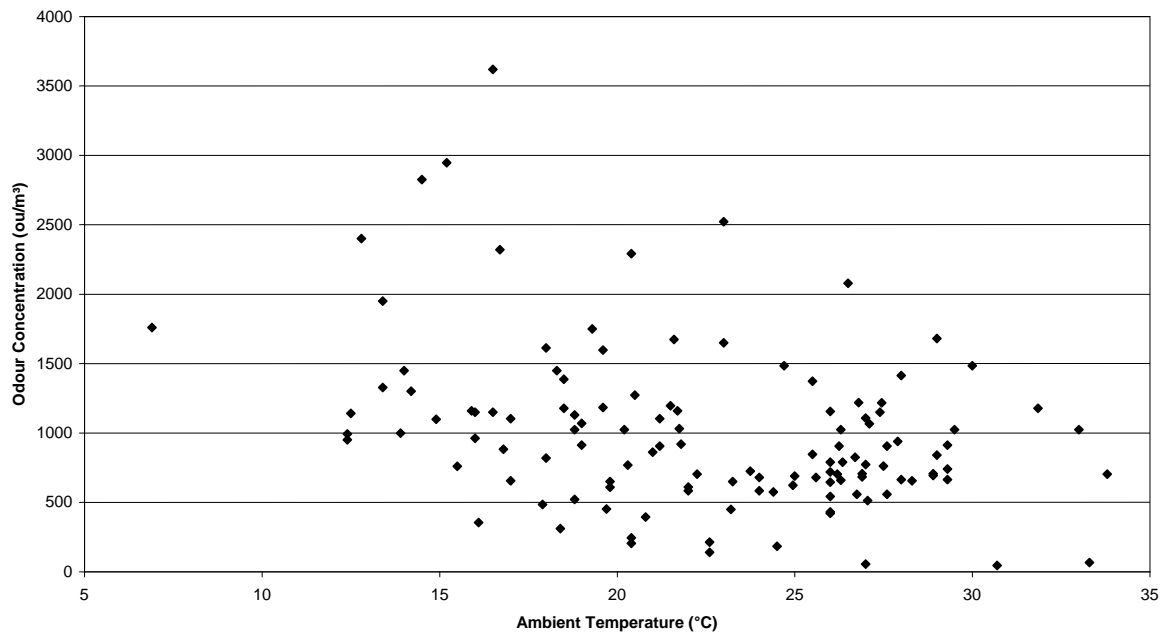
Figure 98:   Odour concentration with increasing ambient temperature (°C)

The relationship between ambient temperature (°C) and odour emission rate per 1000 birds placed is shown in Figure 99. Odour emission rate tended to increase with ambient temperature. This was expected to occur as ventilation rate generally increases with ambient temperature in order to maintain correct target temperature for optimal bird performance (see Figure 100). As a result, increasing ventilation rate usually results in increased odour emission rate.
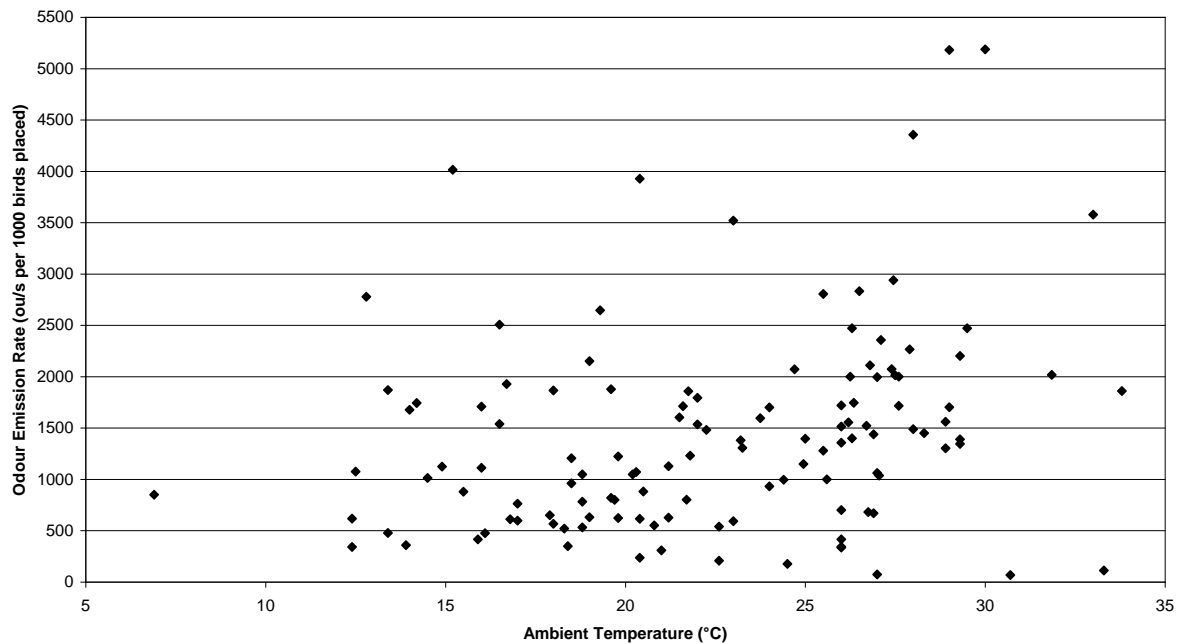
Figure 99:   Odour emission rate per 1000 birds placed with increasing ambient temperature (°C)

A relationship between OER and ambient temperature was also identified by Simons (2006), where measurements from a local Bureau of Meteorology weather station were recorded at 0900 for the minimum daily temperature.
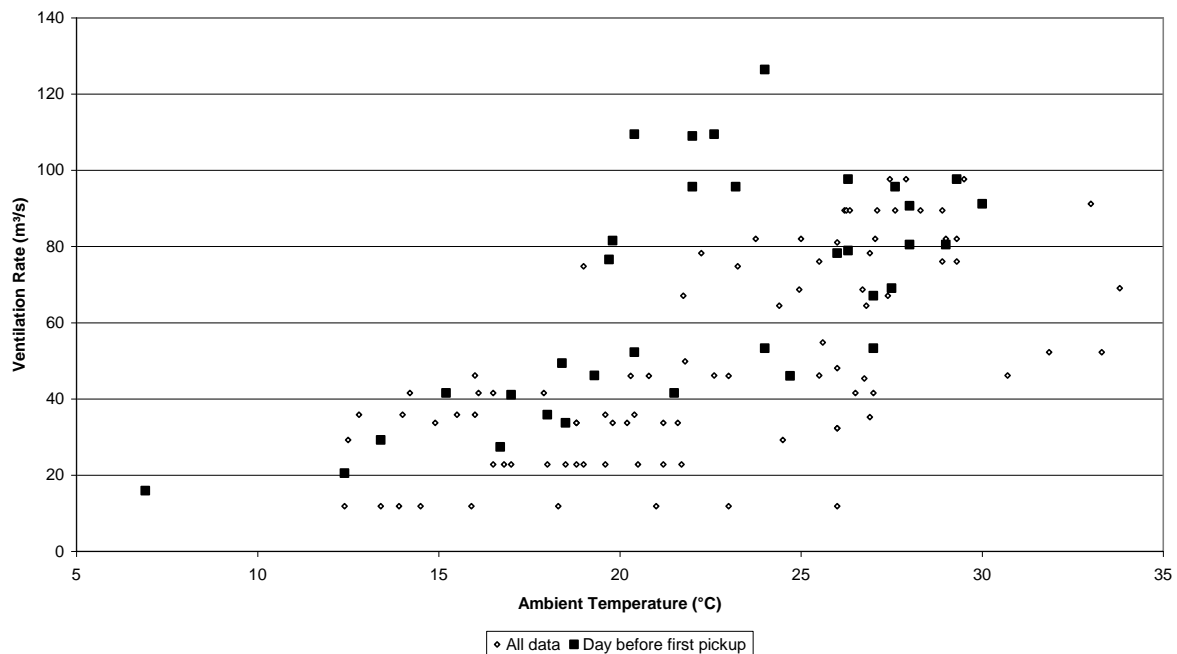
Figure 100: Broiler ventilation rate with increasing ambient temperature

4.9 **Summary of broiler odour emissions**

Odour emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight).

- From November 2005 to May 2008, 349 odour emission measurements were made at eleven broiler farms located in Queensland and Victoria.

- Odour emissions were measured throughout the production cycle.

- The majority of odour emission rates range from:
    - o   2000–105,000 ou/s
    - o   100–3000 ou/s per 1000 birds placed
    - o   100–5000 ou/s per 1000 birds (in the shed at the time of measurement)
    - o   0.25–2.5 ou/s per kg live weight (of birds in the shed at the time of measurement)

- Odour emission rates were observed to vary throughout the day (24 hour period); however the majority of samples were collected between 5:30 am and 2:00 pm, consequently the majority of the measured odour emission rates may not representative of the maximum daily spread of odour emission rates. Odour was rarely measured at night (due to logistical challenges) and therefore the measured emission rates are unlikely to be representative of daily minimum values and periods of time when atmospheric conditions lead to poor dispersion.

Continued over the page.

Summary of broiler odour results continued from previous page.

- Odour emission rates before bird placement (on fresh litter) and after litter removal were found to be lower than when birds were present in the shed. Odour emission rates decreased once birds were removed from the shed.

- Some of the measured odour emission rates were suspected of being unrealistic due to the ventilation rate being manually increased above 'normal' levels (given the ambient temperature and batch age) by the research team while attempting to measure the full range of possible odour emission rates. These data points have been identified in the data set and should be disregarded.

- Odour emission rates tended to be higher during summer, compared to winter, presumably due to greater ventilation requirements.

- Odour emission rates were similar for broiler farms located in Queensland and Victoria; however, this conclusion is based on a very limited number of farms that may not represent other farms in each of the respective states.

- Reusing litter in broiler sheds did not appear to increase odour emissions; however, weather, litter moisture content and stocking density were slightly different between the single use and partially reused batches, which confounded the analysis of the data.

- Odour emission rates measured at eight broiler farms in SE Queensland were different at each of the farms, even though shed design and management were similar. Weather may have been a contributing factor, but it is likely that odour emission rates will be variable between farms.

- Stepwise regression techniques were used to develop models to estimate odour emission rates from three different broiler farms using a selection of factors. Individual models were required to suit each farm and the relationship between odour emission rate and the factors (for example ventilation rate and live weight density) were inconsistent between the farms. **For these reasons, model development was not considered successful and the models should not be applied to other poultry farms, especially for predictive or planning purposes.**

- Relationships between odour emission and individual factors:
    - In-shed odour concentration generally tended to decrease with increasing ventilation rate, presumably because of dilution.
    - Odour emission rate generally tended to increase with ventilation rate.
    - There was no clear relationship between shed-average litter moisture content and odour emission rate. Maximum odour emission rates tended to occur when shed-average litter moisture content was 26–40%.
    - There was no clear relationship between odour emission rate and live weight density.
    - There were only weak relationships between odour emission rate and ambient temperature, even though ventilation rates tended to increase with ambient temperature.
    - It is unlikely that any of the aforementioned factors will influence odour emission rate in isolation with other factors. Consequently, variability in odour emission rate must be considered in conjunction with all contributing factors.

5 Dust emissions

5.1 Overview of dust results

Dust was measured at three broiler farms in two states during different seasons and stages of the production cycle. The dust-related variables recorded at each farm were particle mass concentration (for both PM_{10} and $PM_{2.5}$ size fractions), particle number concentration and count median diameter (mid-point of the size distribution). Concentration measurements were combined with ventilation rates to calculate particle number and mass emission rates (see section 3.3.2). All of the dust data collected as part of this project is provided in Appendix 5 to Appendix 23. The values in these appendices are themselves averages of hundreds of dust measurements taken over time intervals when ventilation rate was relatively constant (this interval varied from ~10 minutes up to a few hours).

The following section summarises the average dust data from broiler sheds in graphical form. As the graphs will show, there is considerable spread in the measured dust concentrations and emission rates. This is due to the complex interaction of a range of factors including ventilation rate, shed design, time of day and in-shed microenvironment. Care should be taken to consider all of these factors and more when interpreting the dust measurements.

5.1.1 PM_{10} concentration and emission rates for Farms A, B and C

Figure 101 displays the PM_{10} concentrations measured at Farms A, B and C against bird age. PM_{10} concentrations varied from 0.04–1.62 mg/m³. These values fall towards the lower end of broiler shed PM_{10} concentrations found in the literature (see Appendix 1). There is a lot of scatter observed in Figure 101, which was expected because of variation in the range of factors for each data point (ventilation rate, season, time of day, litter). Nevertheless there appears to be a general increase in PM_{10} concentration up to day 35 where a spike in concentration was observed. For most farms, day 35 was just prior to the first pickup. After the first pickup, concentrations appear to stabilise.
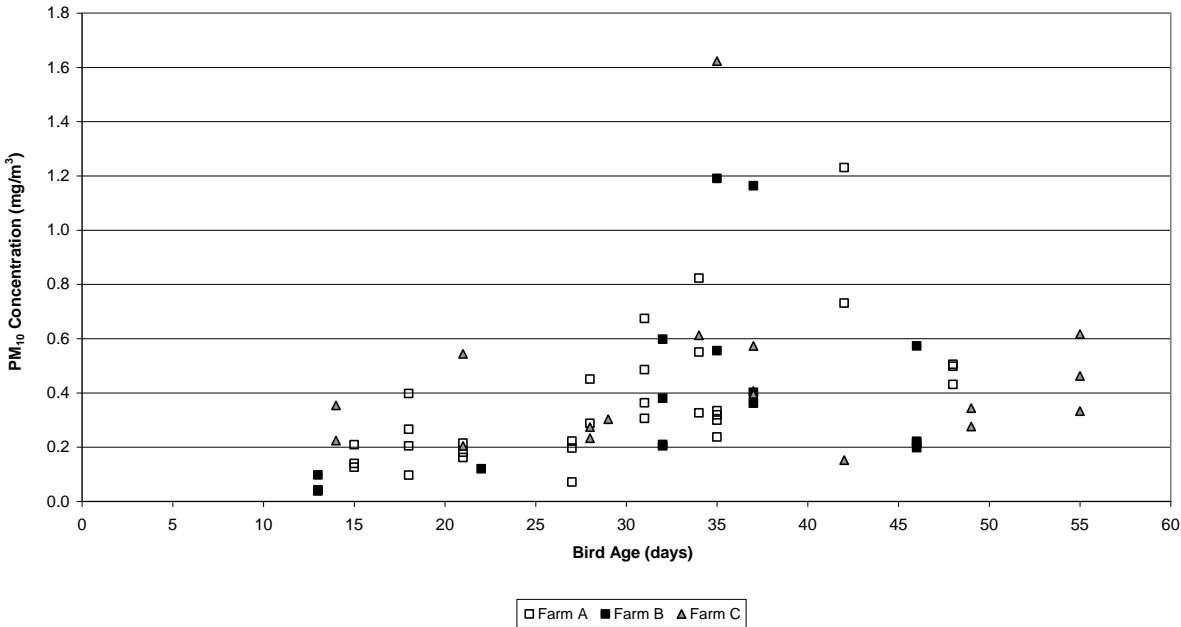
Figure 101: PM_{10} concentrations for Farms A, B and C

Figure 102 displays the PM_{10} emission rates measured at Farms A, B and C against bird age. The maximum PM_{10} emission rate measured was 158.5 mg/s (Farm C, single use litter batch). This was far higher than all other emission rates during the project and was the result of high PM_{10} concentrations during maximum ventilation. To improve the presentation of the remaining data in Figure 102, this maximum value was written above the graph instead of presenting it as a data point. All the other

emission rates measured at broiler farms during this project varied from 1.8–48.3 mg/s. These values are towards the lower end of PM_{10} emission rates from broiler farms found in the literature (see Appendix 1). Similarly to PM_{10} concentration, a spike in PM_{10} emission rate was observed around day 35 of the production cycle.
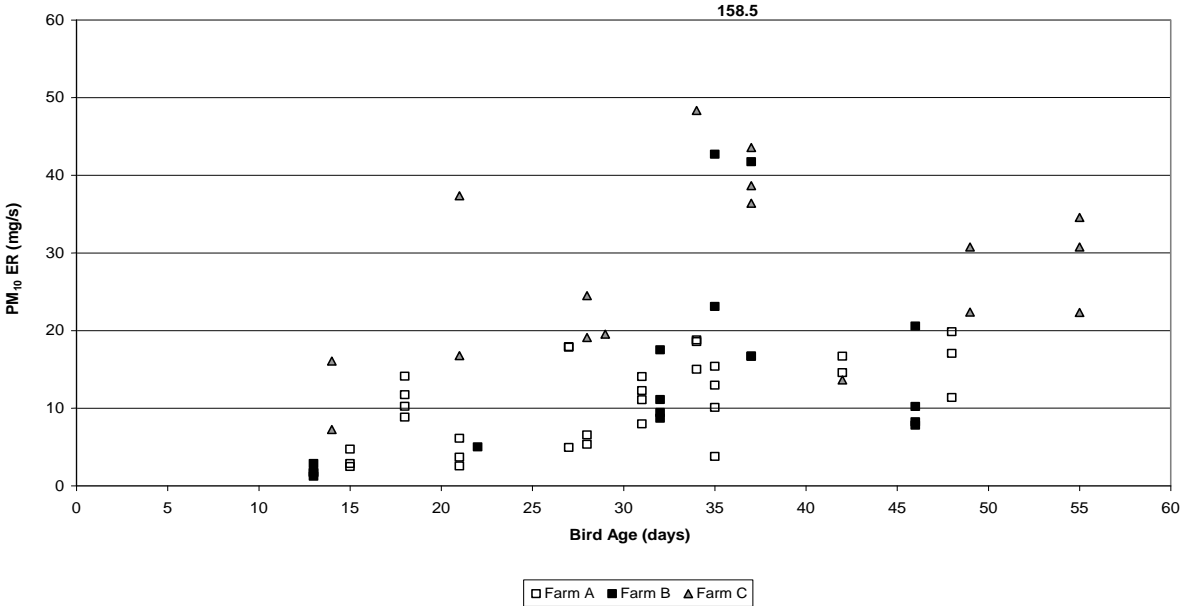
Figure 102: PM_{10} emission rates for Farms A, B and C. (The value 158.5 represents a single value recorded at Farm C on day 35 that was removed to improve presentation of the chart.)

Figure 103 displays the PM_{10} emission rates per 1000 birds placed at Farms A, B and C. PM_{10} emission rates per 1000 birds placed varied from 0.04–3.9 mg/s per 1000 birds placed, although the majority of values were smaller than 1.4 mg/s per 1000 birds placed. From comparison of Figure 102 and Figure 103 it can be seen that normalising the emission rate to the number of birds placed in a shed has little effect on the general trend observed across the whole emission rate dataset. In this report, emission rates will be expressed as 'per 1000 birds placed' when emissions from different sized sheds are being compared.
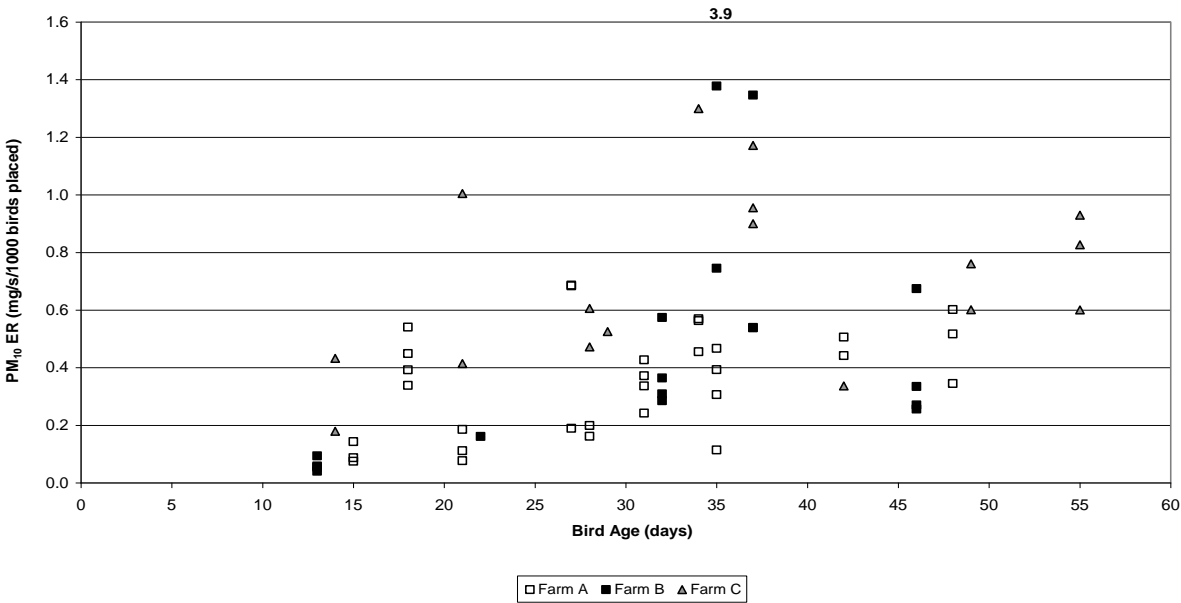
Figure 103: PM_{10} emission rates per 1000 birds placed for Farms A, B and C. (The value 3.9 represents a single value recorded at Farm C on day 35 that was removed to improve chart presentation.)

Figure 104 displays the PM_{10} emission rates per kg live weight at Farms A, B and C. PM_{10} emission rates per kg live weight varied from 0.08 x 10^{-3} to 2.05 x 10^{-3} mg/s per kg, although the majority of values were

smaller than 0.8 x 10^{-3} mg/s per kg. Normalising emission rate values to the live weight of birds in the sheds had a levelling effect on the dataset.
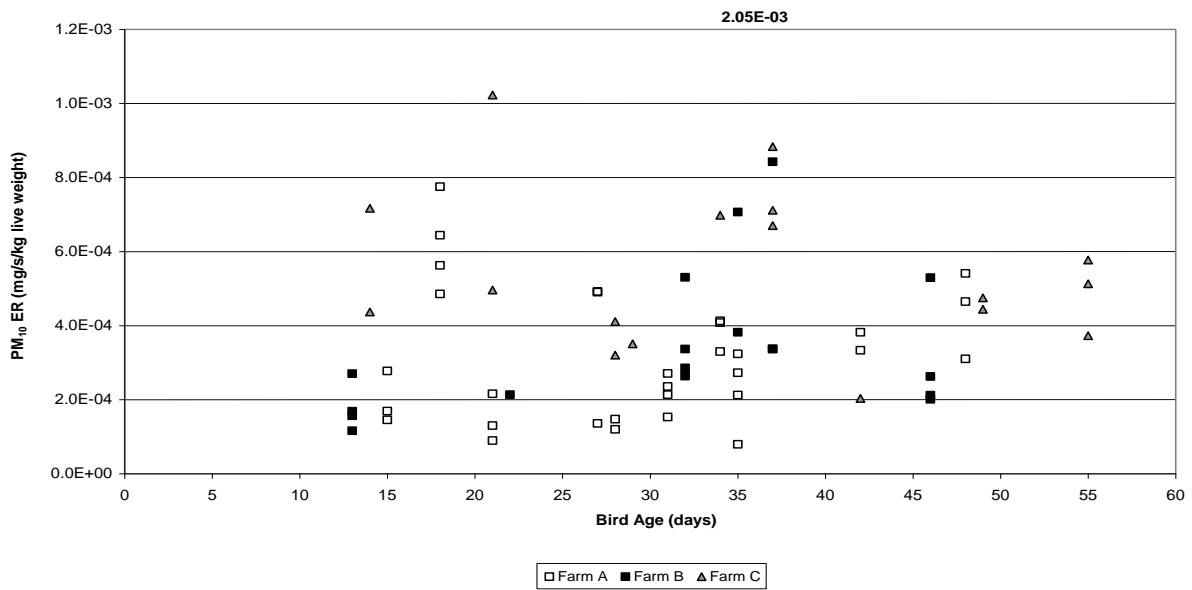
Figure 104: PM$_{10}$ emission rates per kg live weight for Farms A, B and C. (The value 2.05E-03 represents a single value recorded at Farm C on day 35 that was removed to improve chart presentation.)

5.1.2 PM$_{2.5}$ concentration and emission rates for Farms A, B and C

PM$_{2.5}$ was measured less frequently than PM$_{10}$ due to equipment availability. Figure 105 displays the PM$_{2.5}$ concentrations measured at Farms A, B and C. PM$_{2.5}$ concentration generally varied from 0.001–0.153 mg/m³. One relatively high measurement of 0.515 mg/m³ was also recorded (displayed as a label above Figure 105 instead of a data point). These values were similar to PM$_{2.5}$ values found in the literature for broiler farms (see Appendix 1). Similarly to PM$_{10}$ concentration (Figure 101), there is a general trend of increasing PM$_{2.5}$ concentration with bird age. However, PM$_{2.5}$ concentrations did not appear to spike at day 35 of the production cycle.
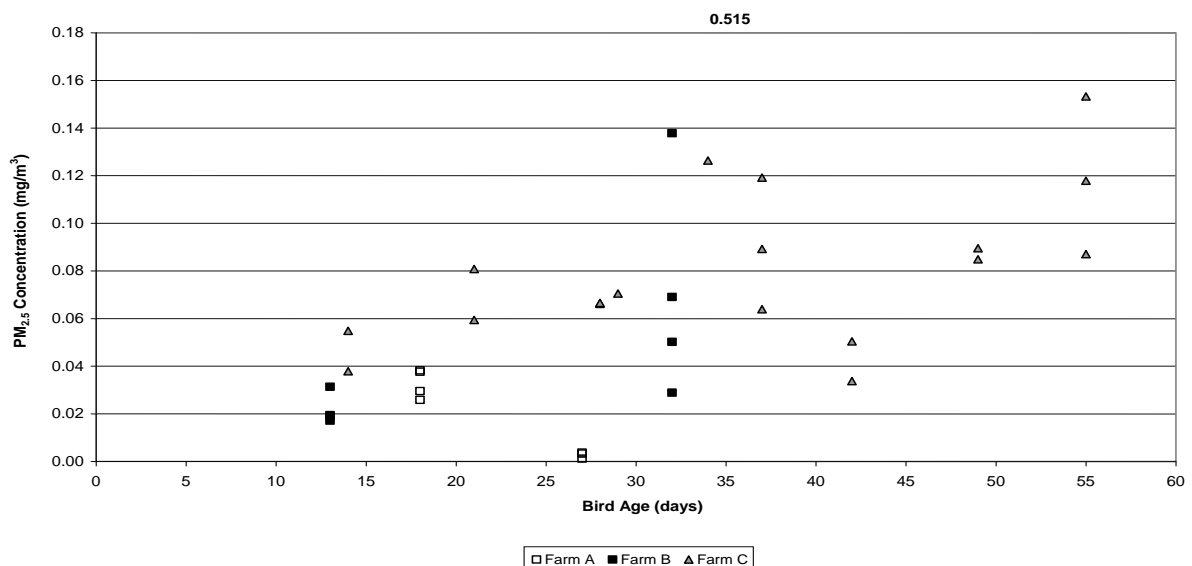
Figure 105: PM$_{2.5}$ concentrations for Farms A, B and C. (The value 0.515 represents a single value recorded at Farm C on day 35 that was removed to improve chart presentation.)

Figure 106 displays the PM$_{2.5}$ emission rates measured at Farms A, B and C. PM$_{2.5}$ emission rates generally varied from 0.08–9.97 mg/s. One relatively high measurement of 50.3 mg/s was also recorded. This was the result of an unusually high concentration measurement (0.515 mg/m³) taken at maximum

ventilation. In the literature there is only one measurement of PM$_{2.5}$ emission rate from a broiler shed (Roumeliotis and Van Heyst, 2007). An emission rate of 0.014 mg/s per kg live weight was measured during the aforementioned study, which converts to 2.03 mg/s for a hypothetical shed of 40,000 birds at an average weight of 1.8 kg. This value lies within the range of PM$_{2.5}$ emission rates that we have measured in this study.
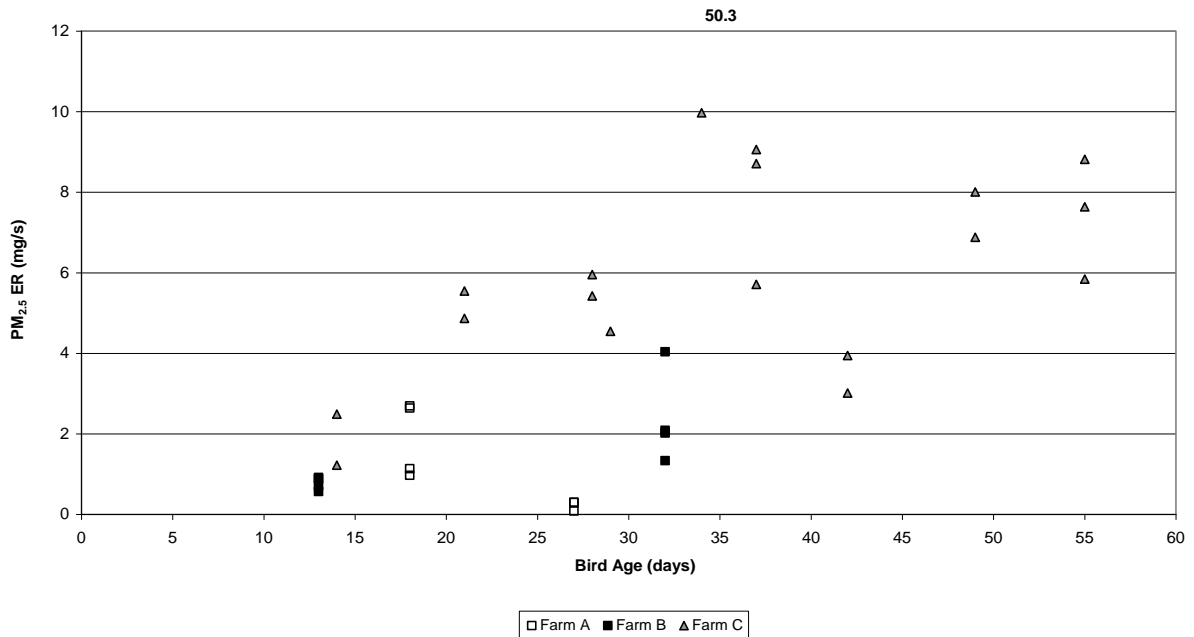
Figure 106: PM$_{2.5}$ emission rates for Farms A, B and C. (The value 50.3 represents a single value recorded at Farm C on day 35 that was removed to improve chart presentation.)

Figure 107 displays the PM$_{2.5}$ emission rates per 1000 birds placed at Farms A, B and C. PM$_{2.5}$ emission rates per 1000 birds placed generally varied from 0.003–0.27 mg/s per 1000 birds placed. However, one relatively high measurement of 1.24 mg/s per 1000 birds placed was also recorded.
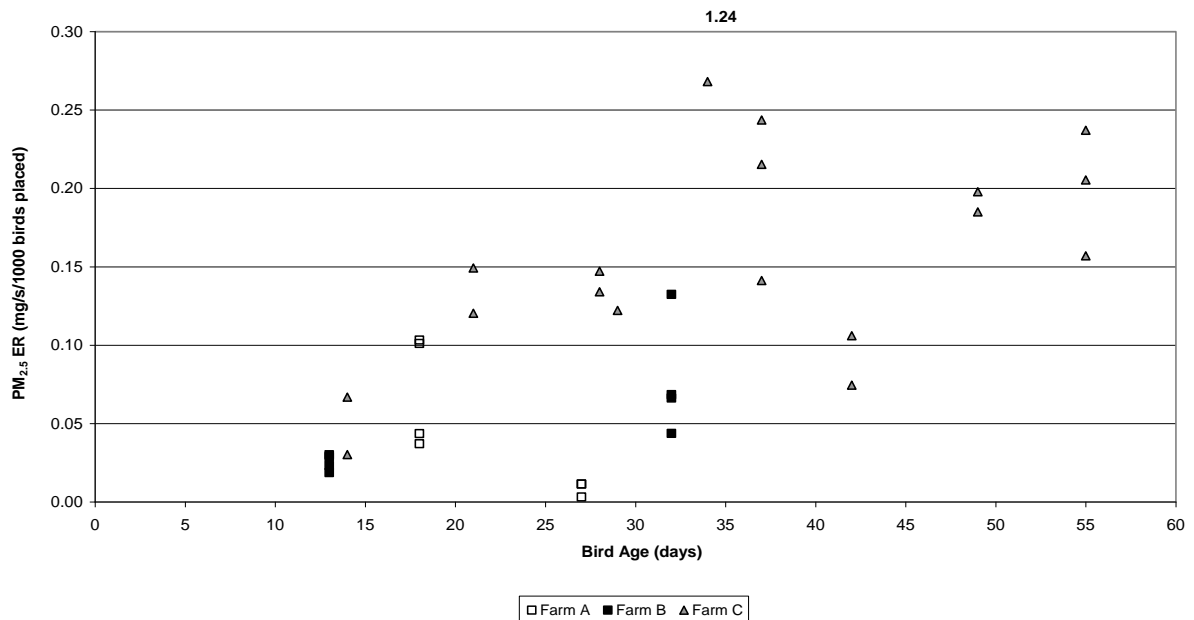
Figure 107: PM$_{2.5}$ emission rates per 1000 birds placed for Farms A, B and C. (The value 1.24 represents a single value recorded at Farm C on day 35 that was removed to improve chart presentation.)

5.1.3 Particle number (PN) concentration and emission rates for Farms A, B and C

Figure 108 displays the PN concentrations measured at Farms A, B and C. PN concentrations varied from 0.13×10^7 to 4.34×10^7 particles/m³. Unlike particle mass, particle number concentrations did not show a clear increasing trend with bird age. This is probably because average PN concentrations were easily influenced by random fluxes of small particles that would not have a significant effect on the total amount (mass) of emitted particulate matter.
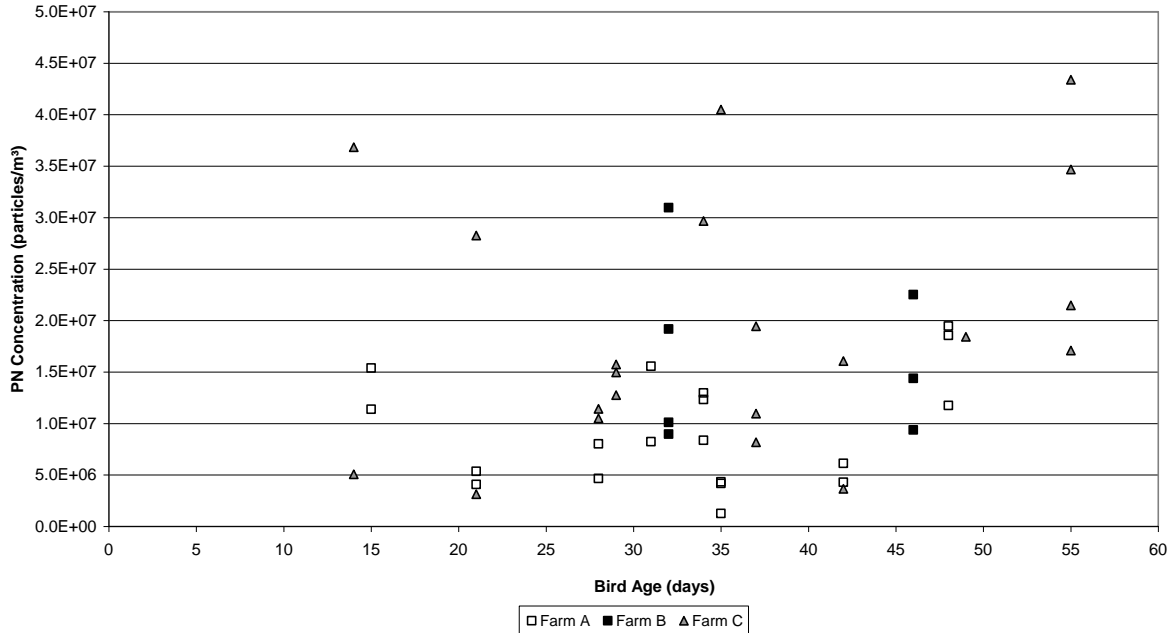
Figure 108: Particle Number (PN) concentrations for Farms A, B and C

Figure 109 displays the PN emission rates measured at Farms A, B and C. PN emission rates varied from 0.015×10^9 to 2.34×10^9 particles/s. The number emission of dust particles was noticeably greater at Farm C than Farms A and B.
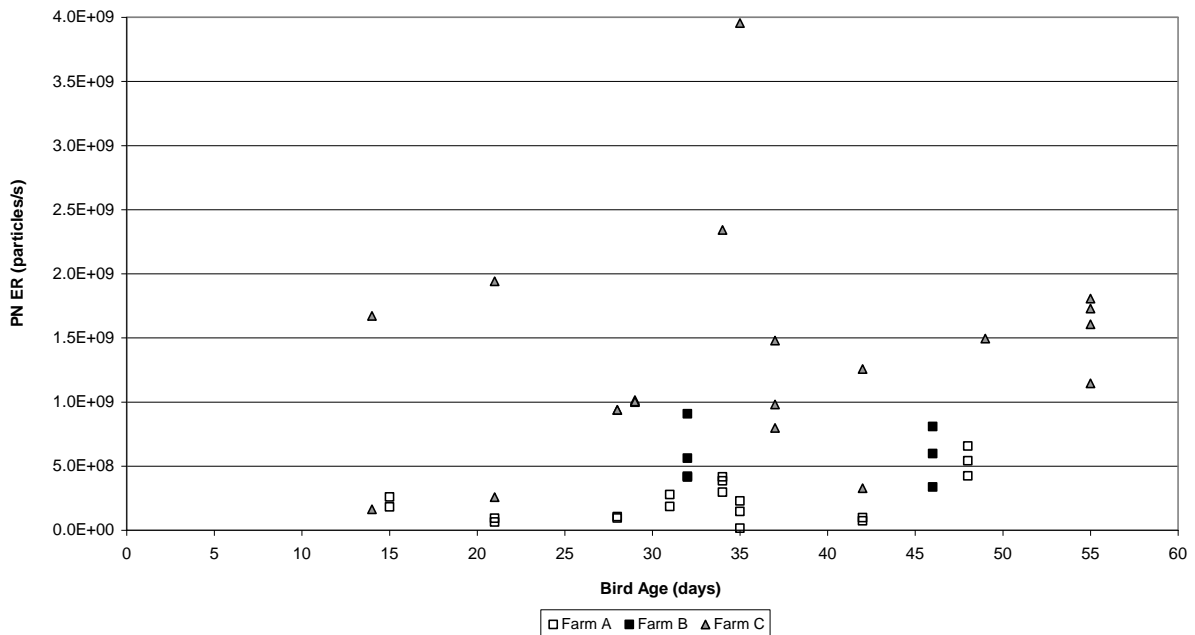
Figure 109: Particle Number (PN) emission rates for Farms A, B and C

Figure 110 displays the PN emission rates per 1000 birds placed measured at Farms A, B and C. PN emission rate per 1000 birds placed varied from 0.045 x 10^7 to 6.3 x 10^7 particles/s per 1000 birds placed.
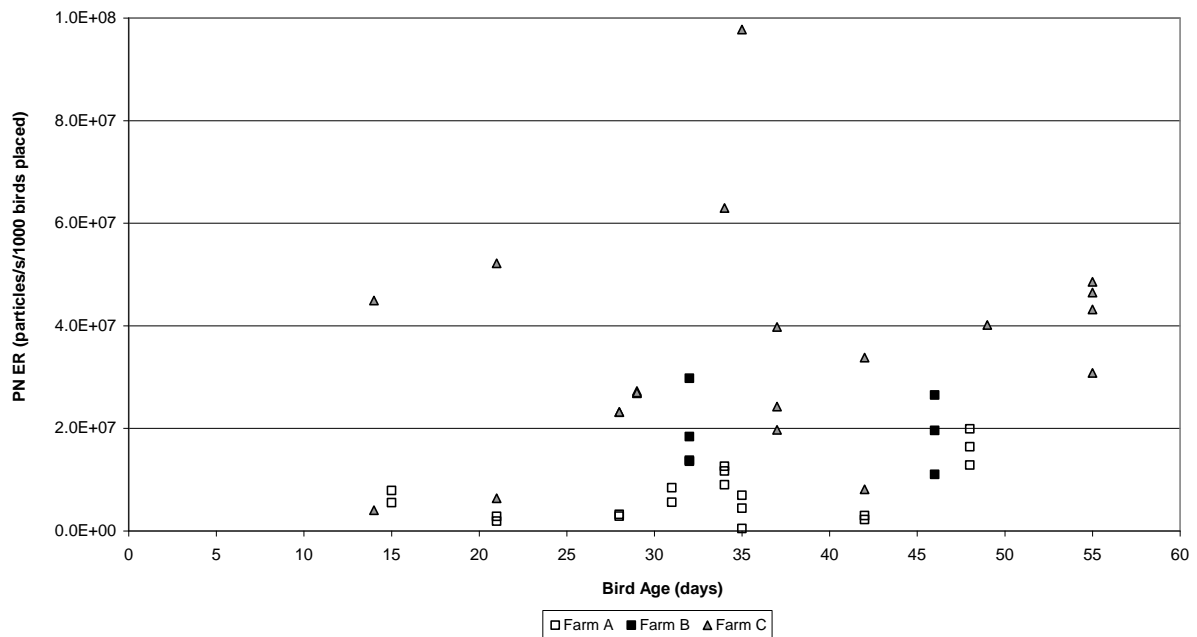
Figure 110: Particle Number (PN) emission rates per 1000 birds placed for Farms A, B and C

5.1.4 Count median diameter (CMD) for Farms A, B and C

Figure 111 displays the CMD values measured at Farms A and C. CMD was not calculated at Farm B. The spread in CMD values was much smaller than the spread in particle concentrations and emission rates at the broiler farms, suggesting that farm specific and environmental factors have a greater effect on the amount rather than the size distribution of dust particles emitted from broiler sheds. The average CMD value for Farms A and C was 1.96 μm. This means that, on average, 50% of the total number of particles emitted from a broiler shed will be smaller than 1.96 μm in diameter. This fraction of particles will have a large effect on particle number concentration, but much less effect on particle mass concentration.
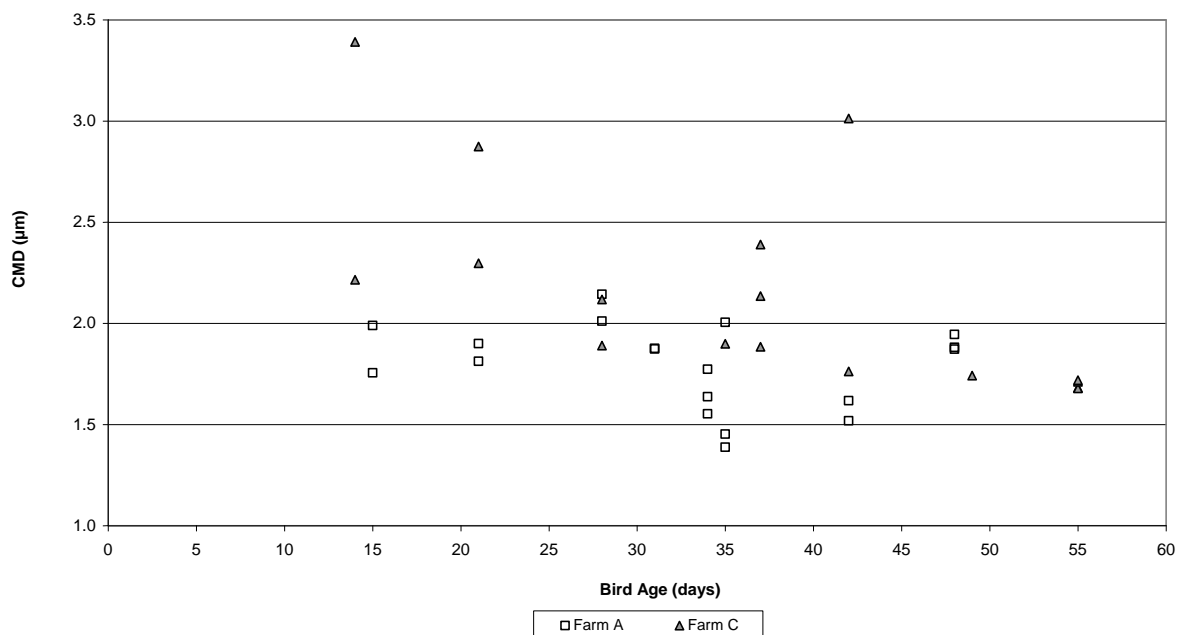
Figure 111: Count Median Diameter (CMD) for Farms A and C

5.1.5 The effect of ventilation rate on broiler dust concentrations and emissions

The variation seen in the data presented in Figure 101 to Figure 111 is due to a range of factors including shed design, ventilation rate, microenvironment, time of day, season and litter management practices. Of these factors, ventilation rate had the most noticeable impact on the broiler dust concentrations and emissions. Increased ventilation rate means there is increased dilution of the shed air with air drawn from upstream of the shed. If we assume that the dust concentration in the upstream air is relatively low compared to the shed air, then increased dilution will tend to decrease the dust concentration in the shed air. On the other hand, increased ventilation rate means that there is greater airspeed through a shed. One method of dust generation in a poultry shed is the entrainment of matter into the air due to animal activity or the movement of air, indicating that increased ventilation rates will increase the amount of dust entrainment. Therefore at a given ventilation rate, dust concentration will be influenced by a 'dilution effect' as well as a 'dust generation effect'.

To investigate this in more detail, we categorised the PM_{10} concentrations and emission rates (per 1000 birds placed) at Farms A, B and C according to ventilation rate (Figure 112). PM_{10} was chosen as the dust variable for this comparison because more PM_{10} data was collected than $PM_{2.5}$ or particle number data. The graph shows that higher concentrations of PM_{10} tended to occur during periods of low ventilation rate (less than 40 m³/s), while lower concentrations occurred at higher ventilation rates. On the other hand, PM_{10} emission rates tended to increase with increasing ventilation rate. The error bars in Figure 112 are one standard deviation of all the data collected for a particular ventilation rate category. They indicate that there is considerable spread in the data which is not surprising considering the range of farm specific factors, environmental factors and bird age between each measurement of PM_{10} concentration or emission rate.
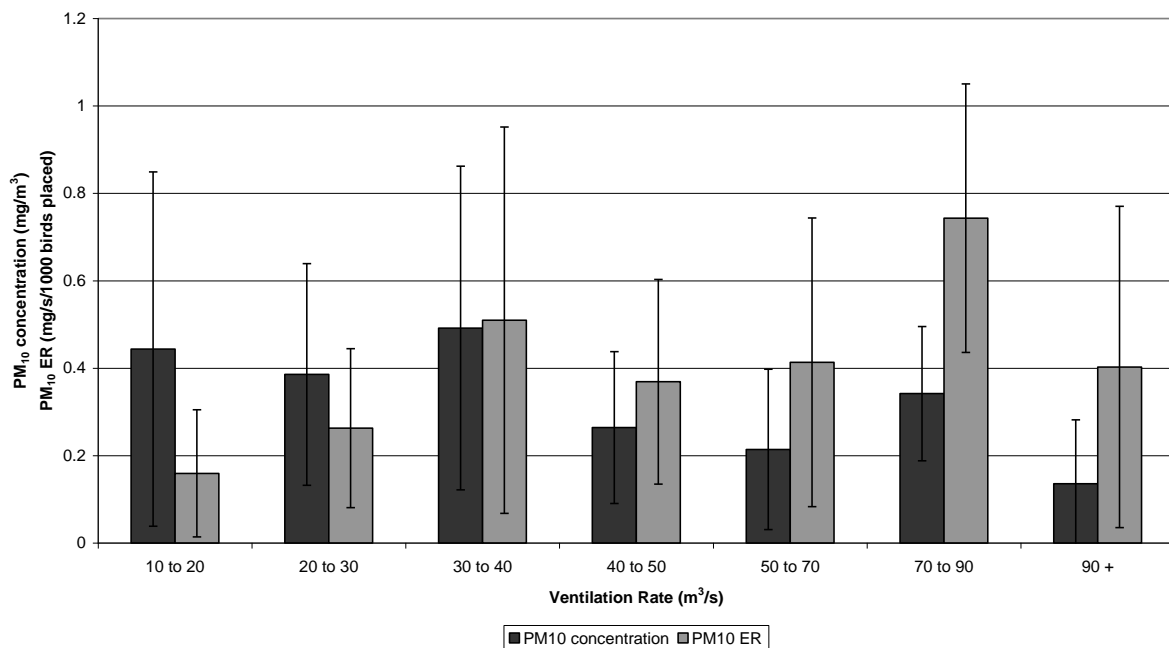
Figure 112: PM_{10} concentration and emission rate versus ventilation rate for Farms A, B and C

In an attempt to reduce the day-to-day variance in the data and further investigate the relationship between PM_{10} levels and ventilation rate, we normalised the PM_{10} measurements to the average PM_{10} values measured on that day. For example, on a given day, PM_{10} concentration and emission rate may have been measured at three different ventilation rates. To normalise these measurements, each one would be divided by the average of all three measurements. The aim of this process is to observe the relative changes in PM_{10} concentration and emission rate with ventilation rate. Normalised values greater than one indicate concentrations or emission rates greater than the average measured value, while

normalised values less than one indicate concentrations or emission rates less than the average. The normalisation process was performed for each sampling day and the results are presented in Figure 113.
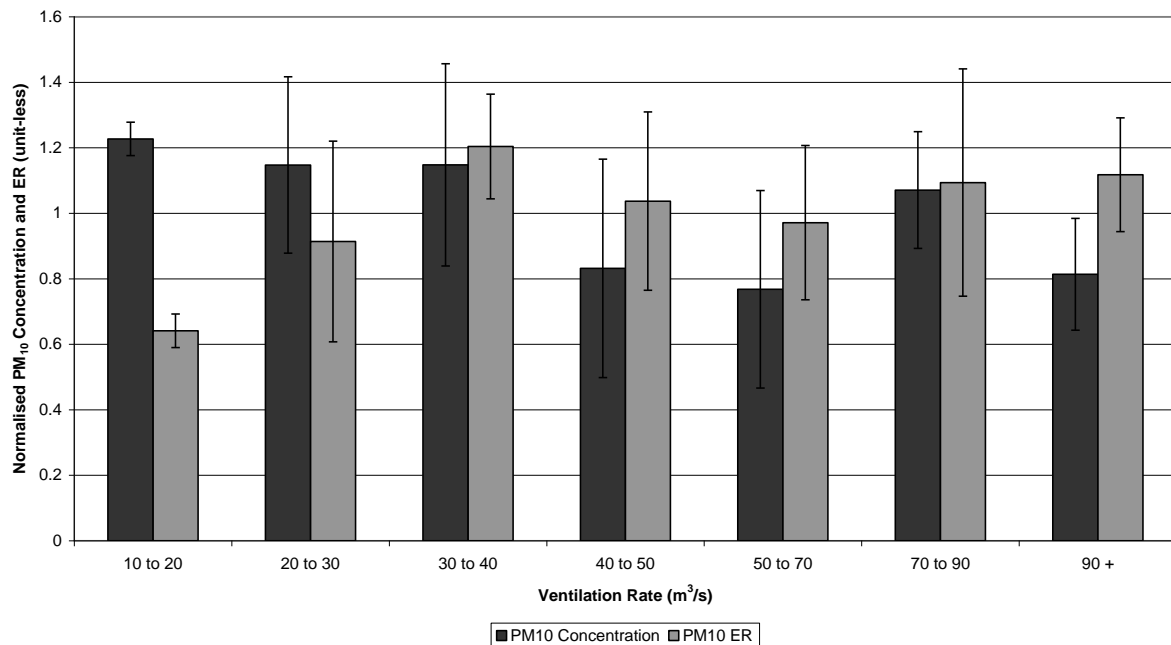
Figure 113: Normalised PM$_{10}$ concentration and emission rate versus ventilation rate for Farms A, B and C

The error bars in Figure 113 indicate that the normalisation process significantly reduced the standard deviation in the PM$_{10}$ datasets. The trends that were barely evident in Figure 112 were confirmed in Figure 113. Initially, normalised PM$_{10}$ concentration decreased with ventilation rate. At the same time, PM$_{10}$ emission rate increased sharply. This pattern indicates that both the 'dilution effect' and 'dust generation effect' were in play. As the ventilation rate increased, the shed air became more diluted and the mass of dust per unit volume of air (concentration) decreased. However, even though the concentration was less, there was greater volume of air moving through the shed and the total mass of dust emitted from the sheds per second (emission rate) was greater. This observation indicated that the greater movement of air generated more dust. At ventilation rates above 30–40 m³/s the relative changes in dust concentrations and emission rates stabilised.

5.2 Diurnal variation in broiler dust emissions

As described previously in Section 4.2 for odour emissions, diurnal variability of dust emissions from a broiler shed was measured at Farm A in June 2007. Emissions were assessed over a 20 hour time frame commencing in the afternoon and finishing at midday the following day (no measurements were made in the remaining 4 hours).

PM$_{10}$ particle mass concentrations and emission rates are shown in Figure 114. PM$_{10}$ concentration and emission rate increased in the evening as ventilation rate decreased from 50 m³/s to 25 m³/s. Concentrations were then relatively stable throughout the night, except for a sharp unexplained decrease at around 21:15. The next morning, concentrations and emission rates were significantly lower than the night-time values. This complements the diurnal odour data which suggested that there was no significant 'purge' of built-up emissions during the night. However, in contrast to the diurnal odour data, no increase in PM$_{10}$ concentration or emission rate was observed as ventilation rate increased throughout mid-morning.
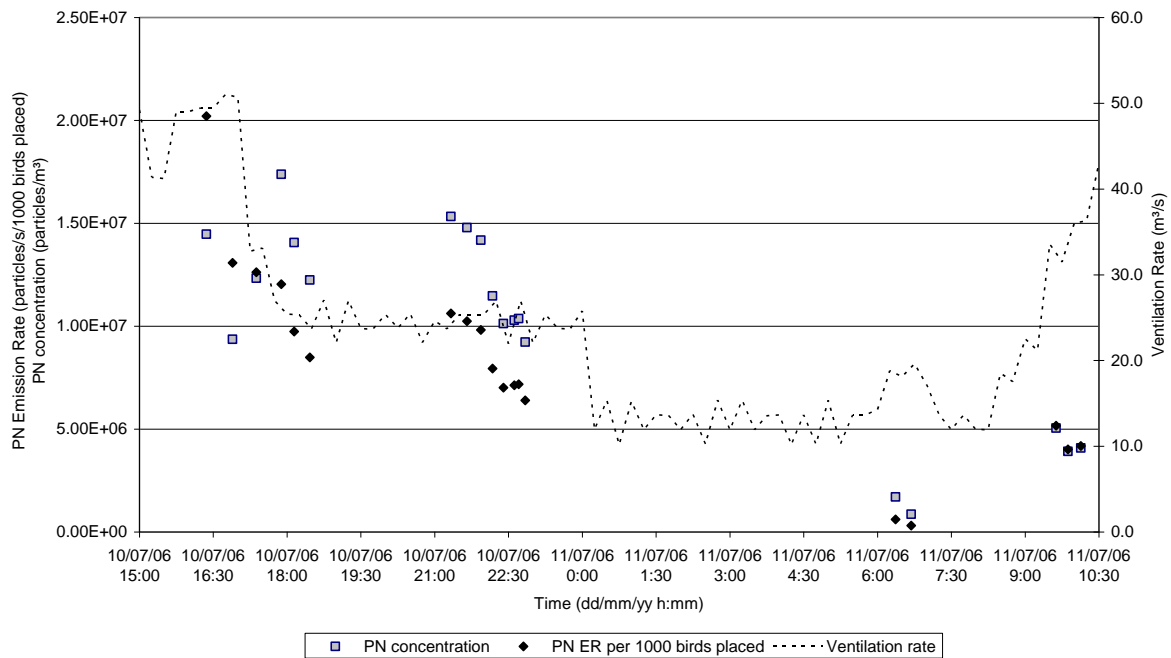
Figure 114: PM$_{10}$ concentration and emission rates over a 20 hour period (Farm A, July 2006)

Particle number (PN) concentrations and emission rates are shown in Figure 115. The night-day differences for both of these variables are similar to the respective differences for PM$_{10}$. However there are notable differences between the particle mass and number measurements. Firstly PN concentration stayed relatively constant during the evening when ventilation rate fell from 50 m³/s to 25 m³/s as opposed to the increase seen in PM$_{10}$ concentration. Secondly, PN concentration increased slightly with the mid-morning increase in ventilation rate, while PM$_{10}$ concentration stayed relatively constant. Again, no significant purge of the night's dust accumulation was observed in this dataset.
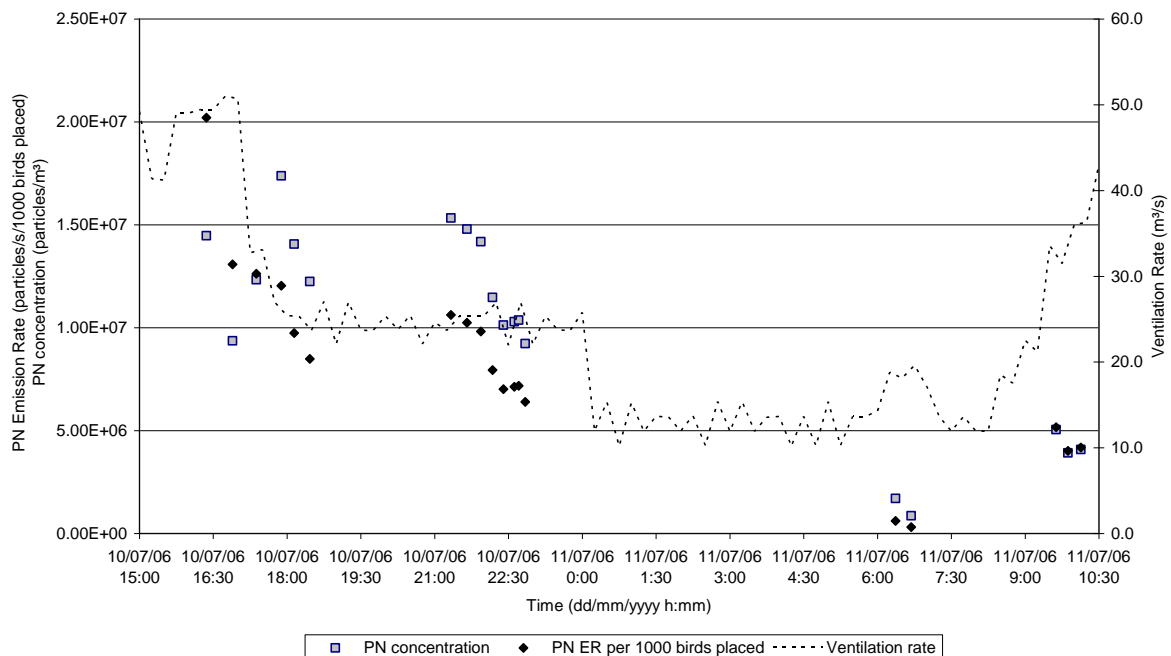
Figure 115: Particle number concentration and emission rate over a 20 hour period (Farm A, July 2006)

5.2.1 **Summary of diurnal variability of dust emissions**

Similar trends were observed with dust concentrations as were seen with odour emissions. Dust concentration and emission rates were highest in the afternoon and decreased during the evening. In the morning, emission rates again began to increase as ventilation rate increased.

Afternoon emissions of PM_{10} were noticeably lower than the night time emissions; however, PN concentration and emission rate in the afternoon were similar to the night time. For both PM_{10} and PN emissions, measurements taken in the early morning were considerably lower than those taken during the afternoon and evening.

5.3 **Broiler single litter use seasonal variability**

5.3.1 **Farm A**

PM_{10} concentrations measured at Farm A during summer and winter are displayed against batch age in Figure 116. For a given batch age, different columns represent concentrations when a particular number of fans were in operation. The average concentrations over entire sampling days are also included as line graphs. Both summer and winter graphs are displayed on an equal sized y-axis to enable easy comparison.

Firstly, for a given batch age PM_{10} concentration generally, but not always, decreased with increasing number of fans operating (ventilation rate). This was because dilution of the shed air increased with increasing ventilation rate (see Section 5.1.5). Also, a dependence of PM_{10} concentration on batch age was clearly evident for the winter data, which showed a general trend of increasing concentration with bird age. PM_{10} concentration appeared to decrease with increasing bird age in the summer data. However, this observation was only based on two data points (18 days and 27 days), and there were more fans in operation on day 27 than day 18 resulting in a greater dilution effect. From the summer data it is also clear that PM_{10} concentrations were far lower when there were no birds present in the shed with fresh litter or no litter (range 0.007–0.023 mg/m³), although significant concentrations of approximately 0.11 mg/m³ were still observed when there were no birds in the shed with used litter present.

In regards to the seasonal comparison, winter PM_{10} concentrations were higher than summer concentrations. For example at a batch age of 28 days the average daily PM_{10} concentration during winter was 0.369 mg/m³. The corresponding value during summer was only 0.163 mg/m³. Higher ventilation rate in summer is the most likely explanation for this summer-winter difference (because of greater dilution). During winter there were generally only 1–4 fans in operation; while during the summer, 2–8 fans were usually in operation.
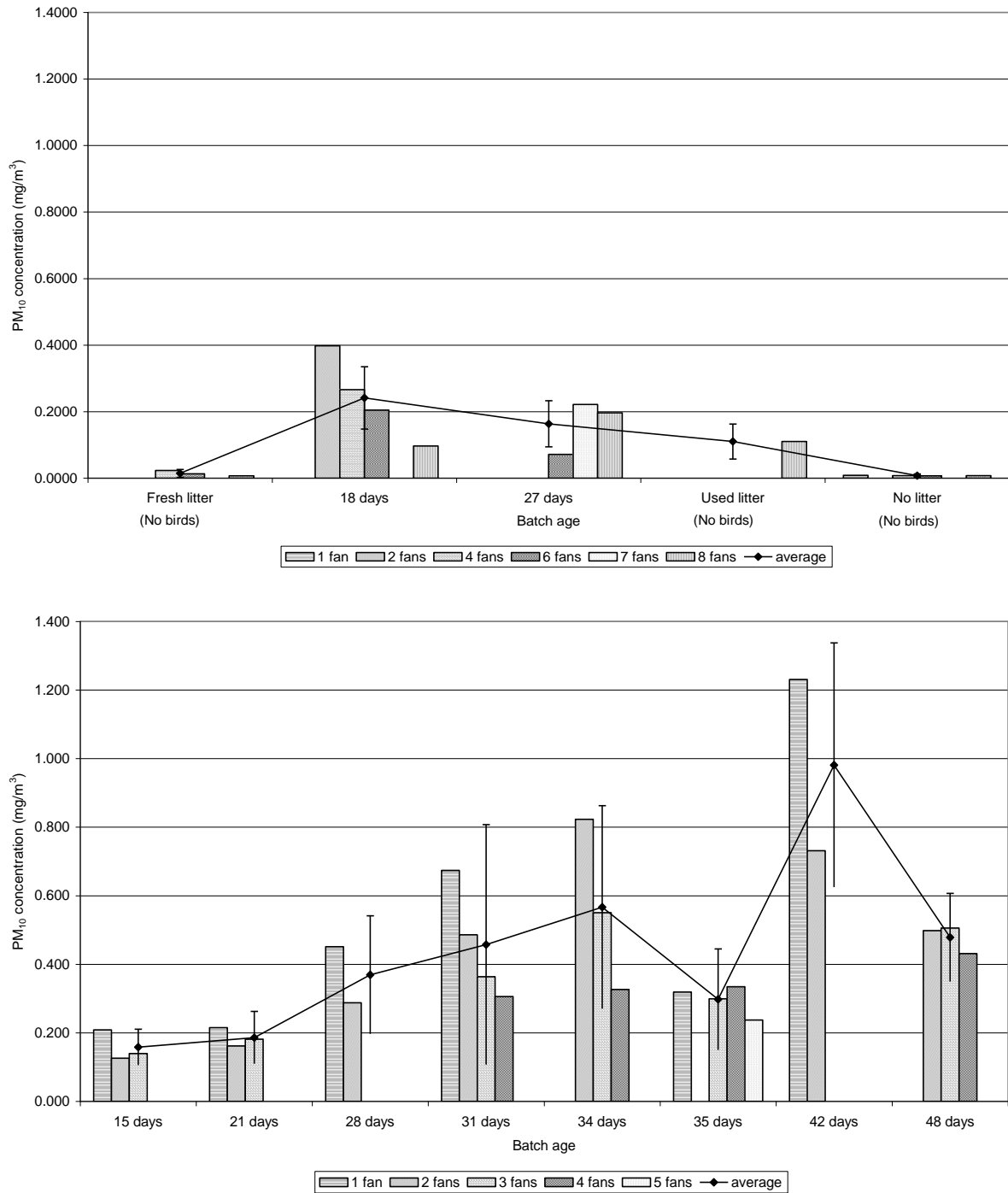
Figure 116: PM$_{10}$ concentrations versus batch age during summer (top) and winter (bottom) at Farm A.

PM$_{10}$ emission rates per 1000 birds placed measured at Farm A during summer and winter are displayed against batch age in Figure 117. For a given batch age, different columns represent emission rates when a particular number of fans were in operation. The average emission rates over entire sampling days are also included as line graphs. Both summer and winter graphs are displayed on an equal sized y-axis to enable easy comparison.

PM$_{10}$ emission rates generally increased with increasing number of fans (see Section 5.1.5). Emission rate increased with batch age in both the summer and winter data, although the winter emission rate plateaued at 34 days. It is interesting to compare the summer PM$_{10}$ concentrations and emission rates at 18 and 27

days. Although the PM_{10} concentration at 27 days was lower, the emission rate is actually higher because ventilation rate was higher on this day.

In regards to the seasonal comparison, summer PM_{10} emission rates were noticeably higher than winter emissions. For example, at a batch age of 27 days, the average daily PM_{10} emission rate during summer was 0.54 mg/s per 1000 birds placed. The corresponding value during winter was only 0.18 mg/s per 1000 birds placed. This observation is a little surprising considering winter PM_{10} concentrations were far higher than summer concentrations (see Figure 116). This difference may be due to higher ventilation rates and therefore more dilution during summer. When ventilation rate is taken into account, the emission rates show that at the same point in the production cycle far more dust is generated during summer than winter. This could be because of meteorological-related factors such as higher temperatures and lower litter moisture content. Average temperature during summer sampling was 29.1 °C and average litter moisture content was 22.4%. The corresponding values for winter sampling were 18.4 °C and 33.3%. In addition, greater dust generation in summer may have been due to the fact that higher ventilation rates caused greater entrainment of dust into the air.
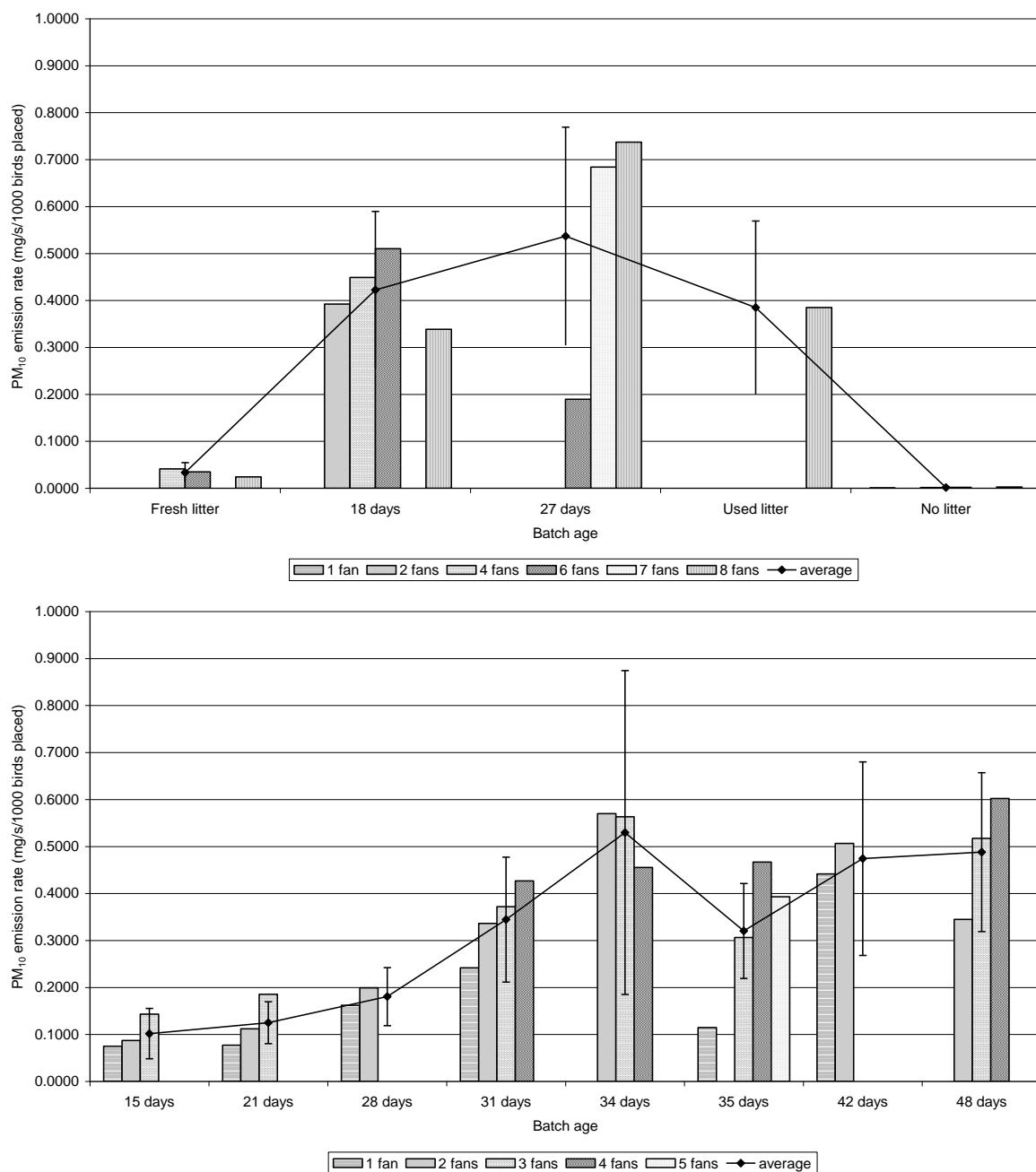
Figure 117: PM_{10} emission rates versus batch age during summer (top) and winter (bottom) at Farm A

5.3.2 **Farm B**

PM_{10} concentrations measured at Farm B during summer and winter are displayed against bird age in Figure 118. For a given bird age, different columns represent concentrations when a particular number of fans were in operation. The average concentrations over entire sampling days are also included as line graphs. Both summer and winter graphs are displayed on an equal sized y-axis to enable easy comparison. Both datasets show a decrease in PM_{10} concentration with increasing ventilation rate (see section 5.1.5). Also the relationship between PM_{10} concentration and bird age was similar to what is seen for the entire broiler PM_{10} concentration dataset (see Section 5.1.1).

In regards to the seasonal comparison, winter PM_{10} concentrations were noticeably higher than summer concentrations. For example, at a batch age of 35 days, the average daily PM_{10} concentration during winter was 0.87 mg/m³. The corresponding value during summer was only 0.35 mg/m³ (at 32 days). Ventilation rate is unable to explain this summer-winter difference because ventilation rates were relatively similar between both seasons.
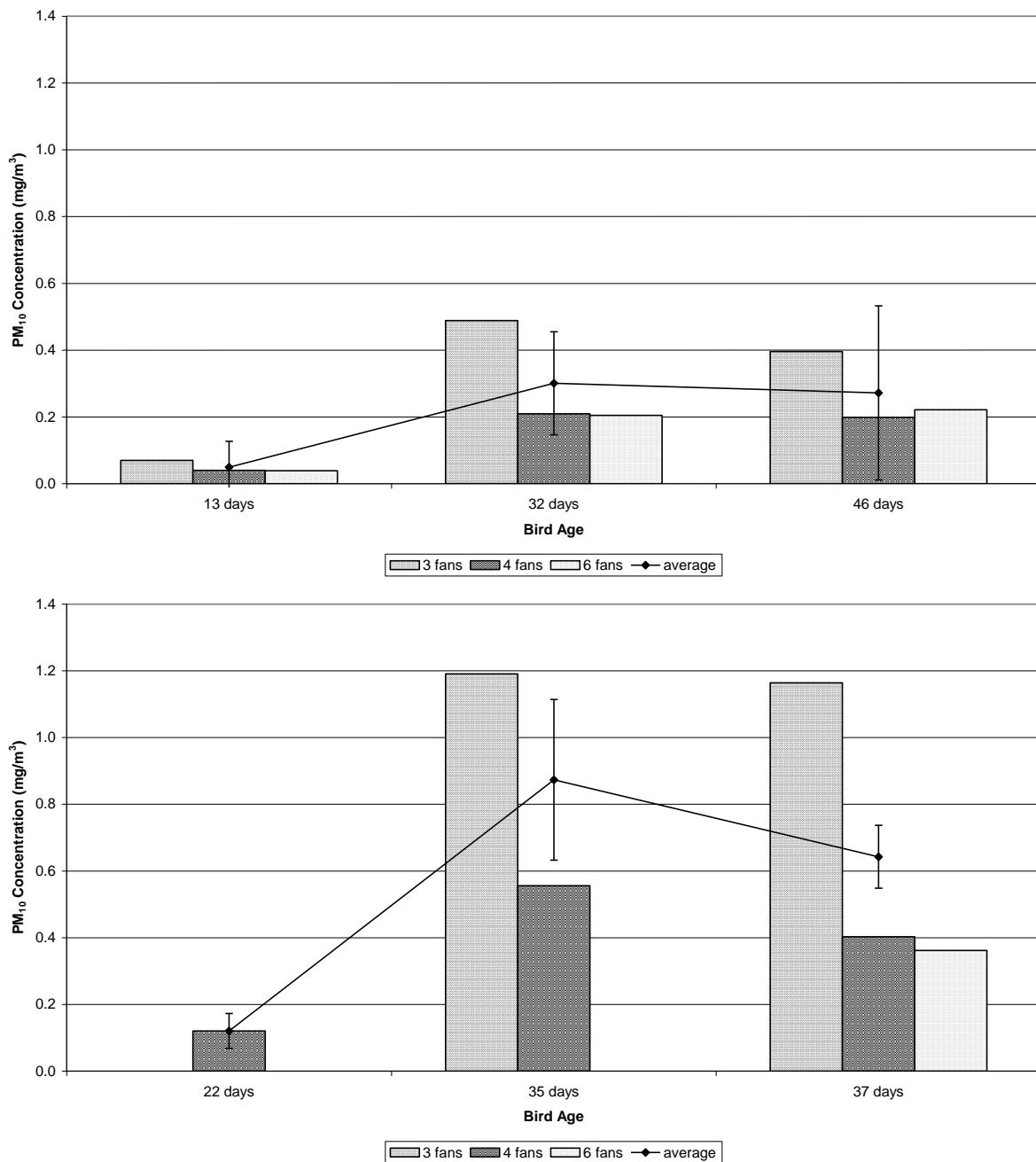
Figure 118: PM$_{10}$ concentrations during summer (top) and winter (bottom) at Farm B

PM_{10} emission rates per 1000 birds placed measured at Farm B during summer and winter are displayed against bird age in Figure 119. For a given bird age, different columns represent emission rates when a particular number of fans were in operation. The average emission rates over entire sampling days are also included as line graphs. Both summer and winter graphs are displayed on an equal sized y-axis to enable easy comparison.

The increase in PM_{10} emission rates with increasing ventilation rate observed at other broiler farms (see section 5.1.5), is not apparent in the Farm B dataset. This is probably because measurements were conducted over a narrower range of ventilation rates, especially during winter. Emission rate was observed to initially increase before levelling out at 32–35 days in both the summer and winter data.

In regards to the seasonal comparison, winter PM_{10} emission rates were noticeably higher than summer emissions. For example, at a batch age of 35 days, the average daily PM_{10} emission rate during winter was 1.06 mg/s per 1000 birds placed. The corresponding value during summer was only 0.28 mg/s per 1000 birds placed (at 32 days). This observation was to be expected because for similar ventilation rates because PM_{10} concentrations during winter were higher than in summer. The reason PM_{10} concentrations and emission rates at this farm were so much higher during winter than summer is unclear. During winter the litter moisture content was generally quite high: the average value was 37.42% compared to 33.86% during summer. Also, live weight was higher during winter (49,000 kg) than summer (40,000 kg) due to placement of more birds in the winter batch. Only a limited amount of data was collected during the winter sampling period, and caution drawing conclusions is required due to the small dataset.
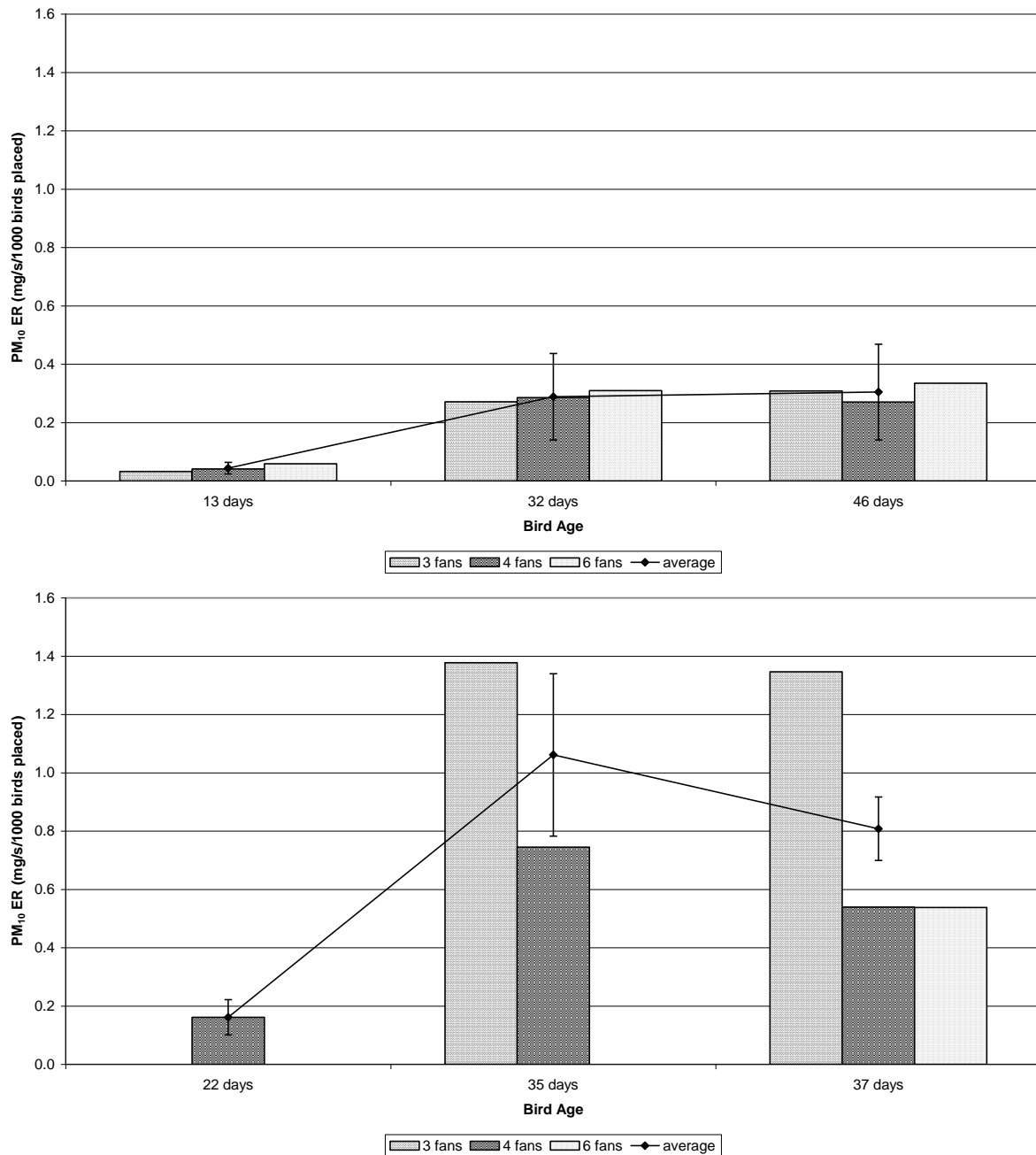
Figure 119: PM$_{10}$ emission rates per 1000 birds placed during summer (top) and winter (bottom) at Farm B

5.3.3 Summary and conclusions from the seasonal studies

For both Farm A and Farm B, dust concentrations were noticeably higher in winter than summer. At Farm A, higher winter dust concentrations could be explained by low ventilation rates.

Emission rate data from Farm A showed that individual emission rates taken at similar points in the production cycle were higher in summer than winter (comparing emission rates at 27 days in summer with rates at 28 days in winter in Figure 117). On the other hand, dust emission rates at Farm B during winter were higher than the emission rates during summer (see Figure 119). Ventilation rates cannot explain the winter-summer dust concentration difference seen at Farm B. Possible factors that could explain the observed difference are litter moisture content, live weight, litter material—wood chips used in summer and rice hulls used in winter—or may be artefacts due to small sample size.

5.4 Comparison of emissions from single use litter and partial litter reuse

Comparing average dust concentrations over entire sampling periods should generally be avoided because measurements were usually taken on different days during the production cycle at different times, ventilation rates and so on. However, the litter reuse study is an exception to this rule. For this study we will simply compare the averages of all dust concentration and emission rate measurements taken during each sampling period. This is permissible for this study because dust concentrations did not vary a great deal with bird age (see Appendix 9, Appendix 10, Appendix 22 and Appendix 23) and measurements were taken at similar bird ages during each sampling period. Nevertheless, the variation in factors such as ventilation rate, microenvironment, litter moisture content and live weight between individual data points should be kept in mind when considering the average values graphed in this section.

High dust concentrations were detected during sampling on day 35 of the production cycle with single use litter (6 March 2007). This day registered the highest PM_{10} (1.62 mg/m³, see Figure 101) and $PM_{2.5}$ (0.515 mg/m³, see Figure 105) concentrations and the second highest PN concentration (4.05 x 10^7 particles/m³, see Figure 108) of all measurements taken as part of this project. These concentrations occurred at maximum ventilation rate so the corresponding emission rates are also well above those measured on any other day (see values on top of Figure 102, Figure 106, and Figure 109). Examination of all the parameters recorded during sampling suggests only one possible reason why dust concentrations were so high on this particular day. Air velocity in the polyethylene sampling duct was only ~2 m/s despite the fact that the shed was operating at maximum ventilation. This duct velocity was one of the lowest measured during the project, indicating that the ventilation rate through the sampling duct was unusually low (even if the ventilation rate through the entire shed was high). The reduced movement of air through the duct may have allowed dust concentrations to build up to artificially high levels at the measurement point in the sampling duct. In any case, in the following analysis the high concentration values measured on this day were considered outliers and excluded from the calculation of averages.

Figure 120 and Figure 121 display the average of all PM_{10}, $PM_{2.5}$ and PN concentration measurements taken at Farm C with single use and partially reused litter. It is clear that all three dust concentrations were higher when partially reused litter was present in the shed. In particular, the average PN concentration with partially reused litter was 3.14 times greater than the average concentration with single use litter. This might be because the average temperature was 2–3 °C lower during the partially reused litter sampling period which meant ventilation rates were generally lower and there was less dilution (see section 5.1.5). In addition, the average shed litter moisture content was less during partial litter reuse (26.7%) than single use litter (29.7%) which may have led to more dust generation with partially reused litter. Finally, the difference might be related to the particle size of the single use and partially reused litter.
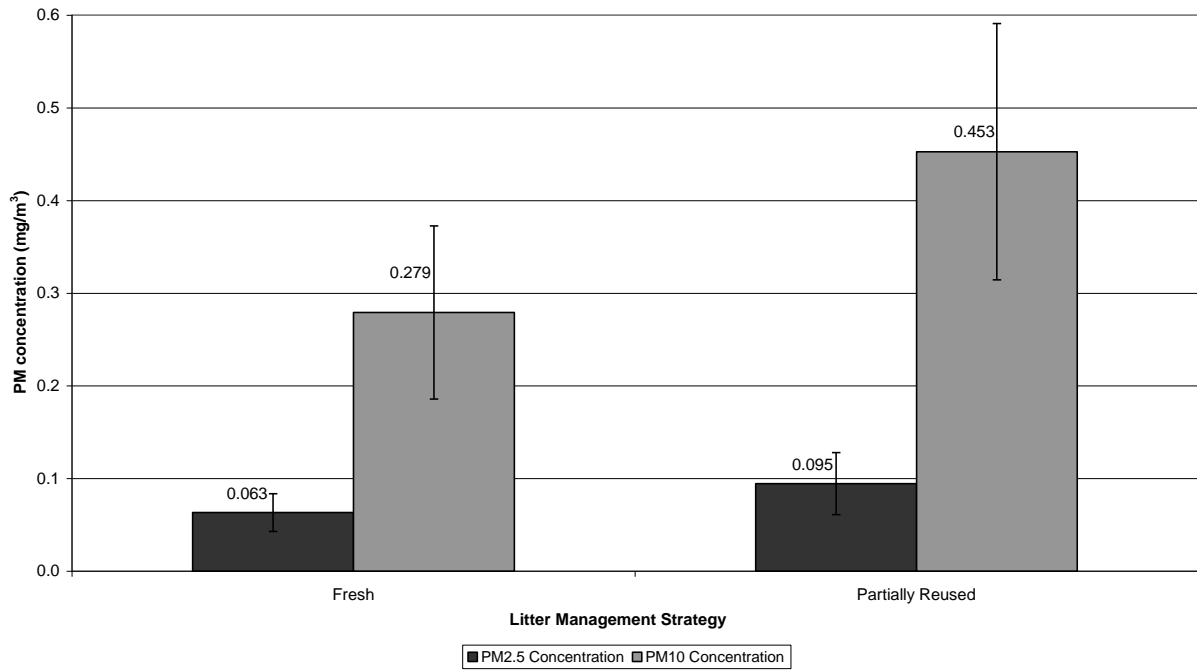
Figure 120: Average PM$_{10}$ and PM$_{2.5}$ concentrations at Farm C with single use and partially reused litter
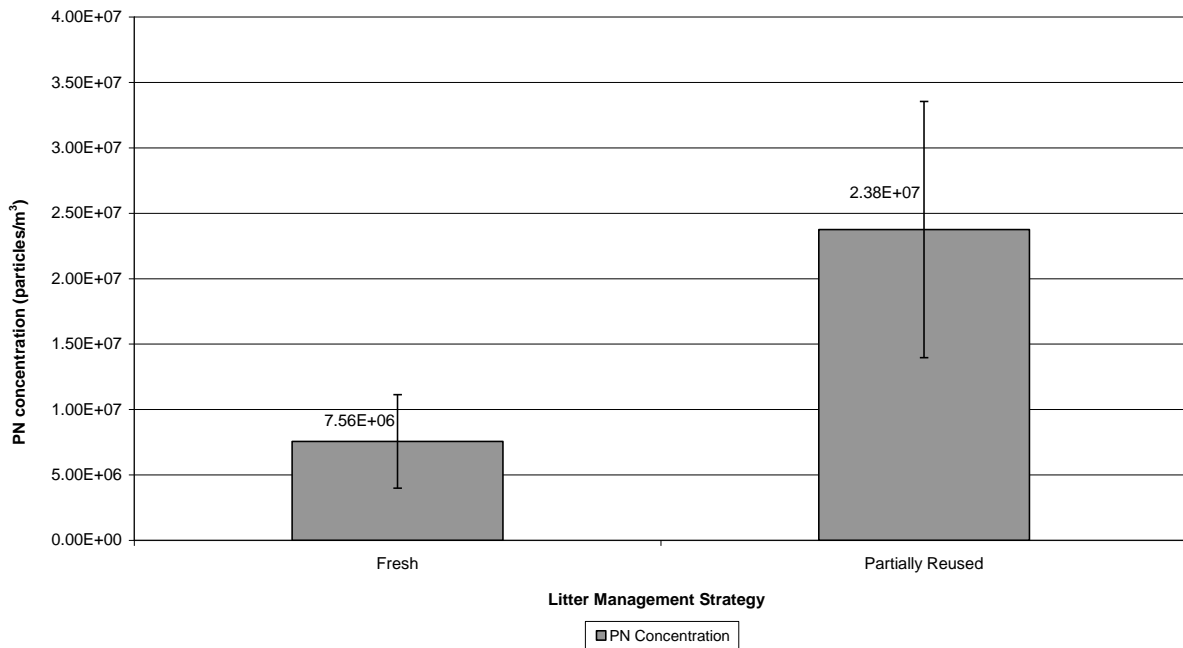
Figure 121: Average PN concentrations at Farm C with single use and partially reused litter

Wood shavings were employed as the litter material in this shed. This means the single use litter pieces are quite large (~cm). However, during a production cycle bird movement grinds these wood shavings into finer pieces. This means the partially reused litter would contain a greater number of smaller, fine pieces of litter than the single use litter. These smaller litter pieces would be more easily entrained into the shed air due to animal activity or the movement of air. Therefore we might expect that a greater number of smaller dust particles might be generated from the finer partially reused litter. To investigate this we calculated the average of all count median diameters measured at Farm C with single use and partially reused litter (Figure 122). Count mean diameter (CMD) decreased when partially reused litter was present in the shed, which means a greater numbers of smaller dust particles (< 1.85 μm) were in fact generated from the partially reused litter. These small, light particles would have a greater effect on

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particle number concentration than mass concentration, which is consistent with the relatively greater increase in PN concentrations (Figure 121) than PM_{10} or $PM_{2.5}$ concentrations (Figure 120).
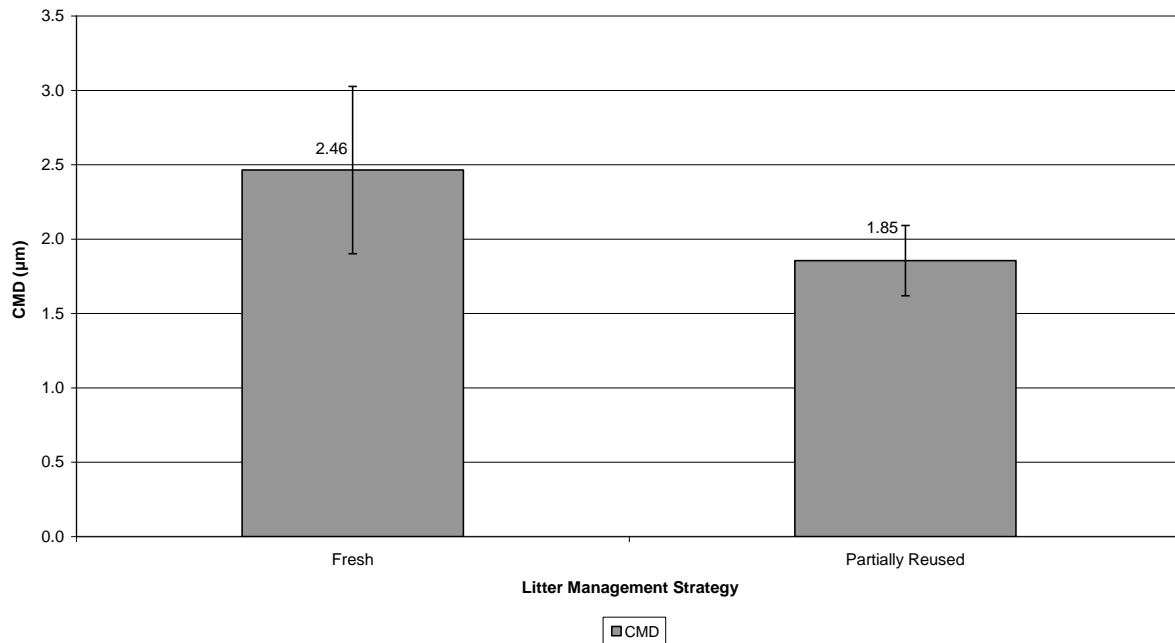
Figure 122: Average CMD values at Farm C with single use and partially reused litter

Figure 123 and Figure 124 display the average of all PM_{10}, $PM_{2.5}$ and PN emission rate per 1000 birds placed measurements taken at Farm C with single use and partially reused litter. Again, there was an increase in all three measurements of dust emission when partially reused litter was present in the shed. By definition, dust emission rates take into account shed ventilation rate. Therefore if lower average ventilation rates were the reason that dust concentrations were higher for partially reused litter than single use litter, we would expect that the dust emission rates for the two litter types would be relatively similar. Figure 123 and Figure 124 indicate that this is not the case. It is likely that lower litter moisture content and the fineness of litter are the two main reasons why dust concentrations and emissions increased when litter was used for more than one batch of birds in this shed.

It's worth remembering at this point that litter moisture content is managed by the farmer to prevent excessive dust and odour emissions that may result from dry or wet litter respectively. It was observed in this shed that dust emissions were higher, with finer particles, when litter was reused. However, it cannot be clearly concluded that the increased dust emissions were due solely to the litter being reused because the litter was drier throughout the reused litter batch (see Figure 82) and this may have confounded the results.
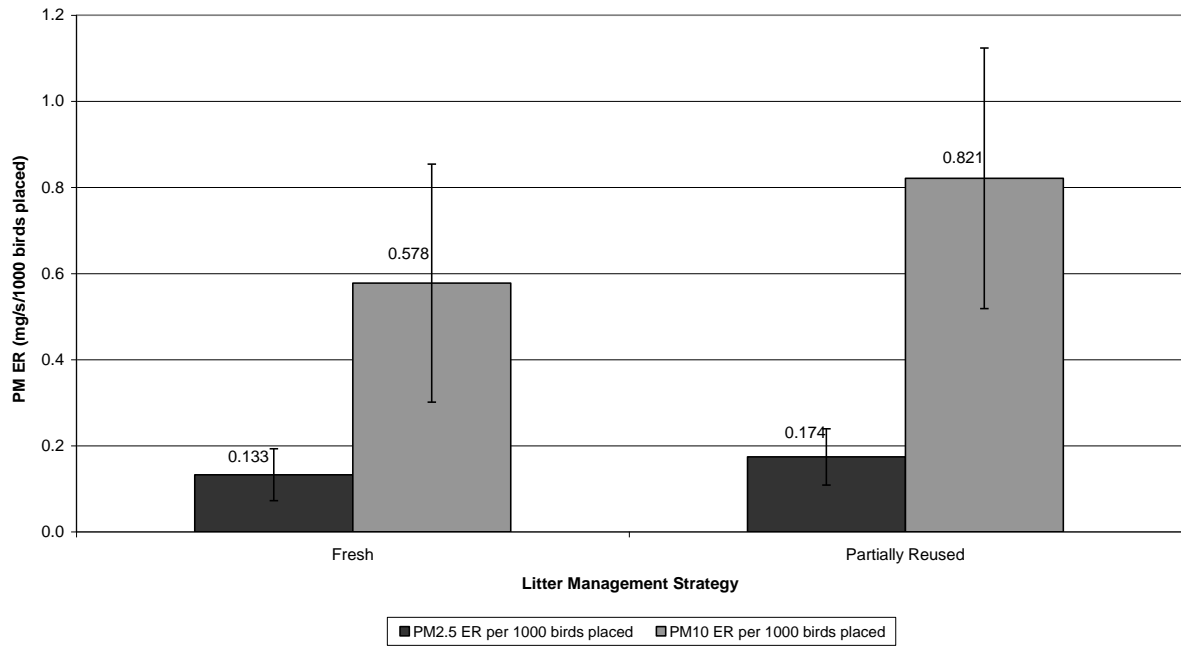
Figure 123: Average PM$_{10}$ and PM$_{2.5}$ emission rates per 1000 birds placed at Farm C with single use and partially reused litter
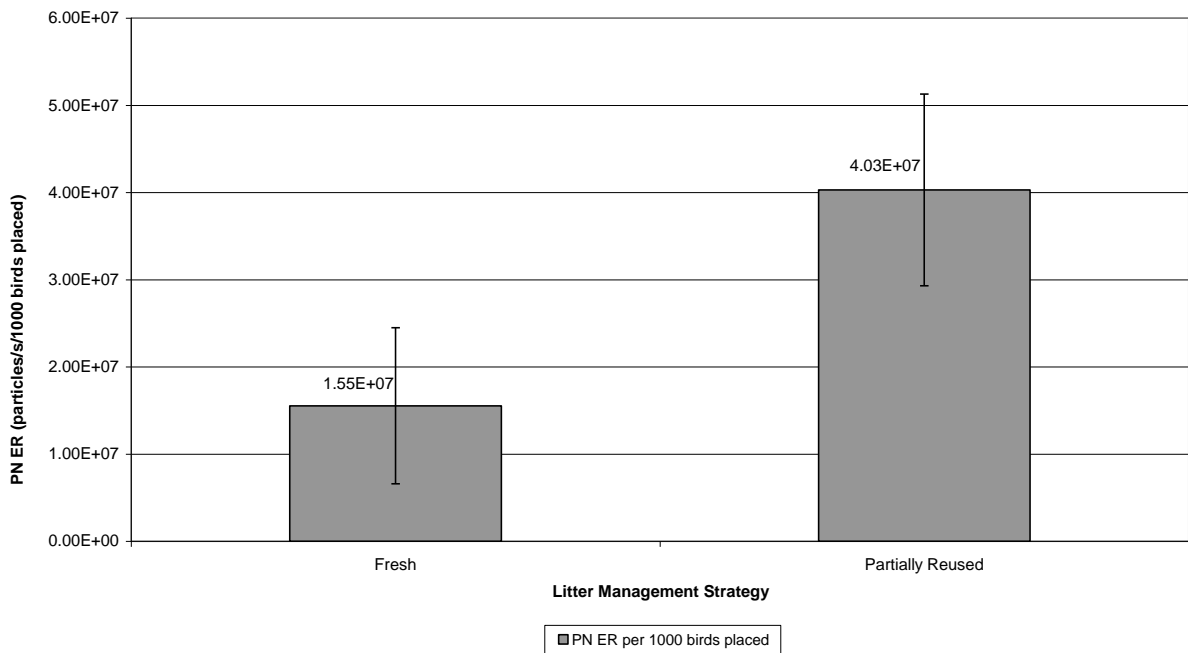
Figure 124: Average PN emission rate per 1000 birds placed at Farm C with single use and partially reused litter

5.5 **Summary of broiler shed dust concentrations and emissions**

Dust emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight).

- From November 2005 to June 2007, dust measurements were taken at three broiler farms – two in Queensland and one in Victoria

- PM_{10} and $PM_{2.5}$ concentrations and emission rates, particle number concentration, and count median diameter (Queensland only) measurements were recorded.

- Dust emissions were measured throughout the production cycle.

- The majority of broiler dust emission rates per 1000 birds placed ranged from:
    - 0.1–1 mg/s per 1000 birds placed for PM_{10}
    - 0.025–0.25 mg/s per 1000 birds placed for $PM_{2.5}$
    - (0.1–4) x 10^7 particles/s per 1000 birds placed for particle number

- The count median diameter for the majority of measurements ranged from 1.5–2.5 µm.

- The concentration of dust in the air exiting the broiler sheds was highly variable. Consequently, dust emission rates from the sheds also varied widely. Dust emissions varied by ventilation rate, farm, bird age, season, microenvironment, litter management practice and possibly due to other factors.

- PM_{10} and $PM_{2.5}$ emission rates peaked on the measurement day prior to the first pickup.

- Emission rates varied throughout the batch, and throughout each day.

- For Queensland, PM_{10} emission rates were higher in summer compared to winter; conversely for Victoria, the opposite was true.

- PM_{10} concentrations for both Queensland and Victoria were noticeably higher in winter compared to summer.

- Partially reusing litter in broiler sheds appeared to cause changes to dust emissions and composition. Average PM_{10}, $PM_{2.5}$ and particle number concentrations were higher for the partially reused batch as compared to the single use batch. Average count median diameter was lower for the partially reused batch. The differences may be due to the breakdown of the litter; however, weather, litter moisture content and stocking density were slightly different between the batches and may have confounded the results.

6 Volatile organic compound emissions from broiler farms

6.1 Introduction

The chemical characterisation of the non-methane volatile organic compounds (NMVOCs) from poultry facilities entailed extensive field sampling during the project. Sites representative of a temperate and tropical climate were selected and sampled during both summer and winter to gather information pertaining to the chemical composition of the gas phase emissions. The chemical speciation and odorant identification was performed with gas chromatography with simultaneous mass spectrometry and olfactory stimulus detection.

The chemical assessment and odorant profiling consisted of three stages: the first stage was the identification (qualitative assessment) of the NMVOCs; the second stage was the determination of odorant species; and the third stage was the quantification of the NMVOCs.

6.2 Results Part A—Identification of non-methane volatile organic compounds at broiler Farms A and B

The following sections outline the progressive changes to the composition of the air, with relation to NMVOCs, at different stages throughout the batch. NMVOC samples were collected from the polyethylene duct attached to the duty fan of the broiler sheds, with the exception of the diffusive samples as indicated. As the laboratory methods were refined during the progression of this project, each spectral figure is unique to that sample and can not be empirically compared to another unless otherwise specified.

6.2.1 Fresh bedding present, prior to bird placement

NMVOCs that were present at Farm A and Farm B prior to bird placement—following shed cleaning and with clean bedding material laid in the shed—were dominated by compounds that were characteristic of the bedding material. Consequently, NMVOC matrices from sheds using different bedding material were distinctly different.

The two total ion chromatograms shown in Figure 125 and Figure 126 illustrate the representative variety of chemical species obtained from the analysis of the sorbent tubes for a broiler shed in Queensland and Victoria, respectively. The two spectra were both obtained from chromatographic separation on a non-polar column.
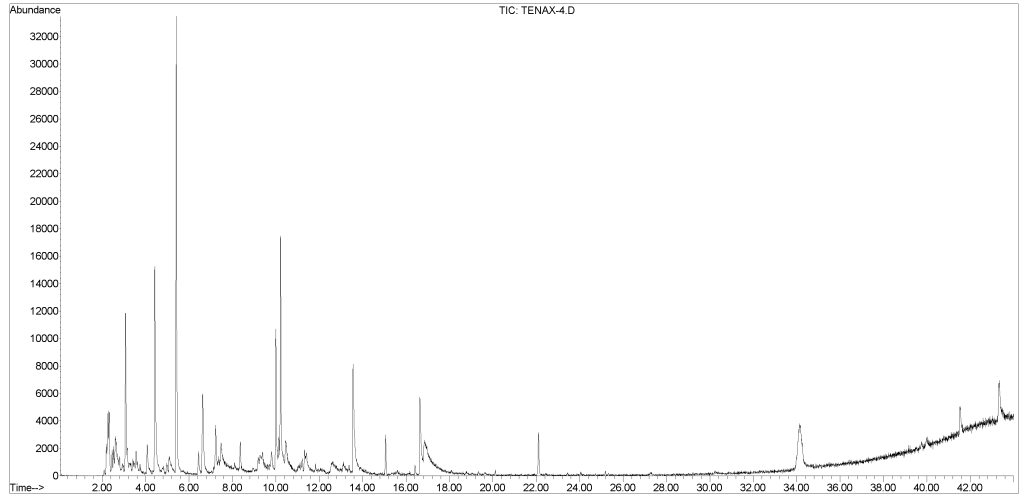
Figure 125: Total ion chromatogram from Farm A prior to bird placement, where pine shavings were used as bedding material. The chemical species present are in low abundances reflecting low concentrations
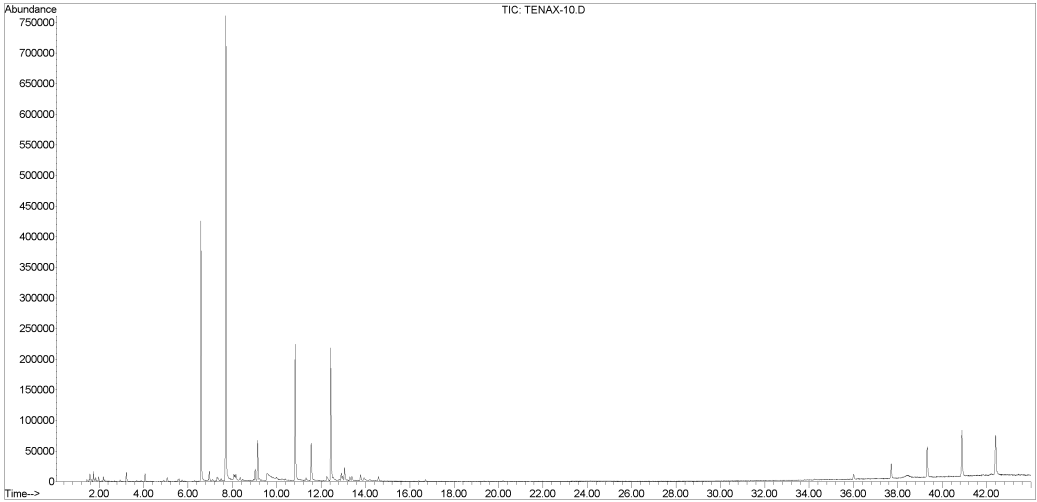
Figure 126: Total ion chromatogram from Farm B prior to bird placement, where pine wood chips were used as bedding material. The chemical species present are in low abundances reflecting low concentrations

Compounds identified from the mass spectral database are listed in Table 17, these compounds were predominantly aromatic compounds and terpines.

Table 17: **Chemical species identified at Farm A and Farm B prior to bird placement, containing only fresh bedding material**

	Farm A	Farm B
Season	Summer	Summer
Bird Age (days)	Prior to Placement (-2)	Prior to Placement (-2)
Compounds Present	Decanal	Toluene
	Nonanal	o-xylene
		p-xylene
	Benzene	Styrene
	Toluene	
	Ethylbenzene	α-pinene
	p-xylene	β-pinene
	o-xylene	3-Carene
	Trimethylbenzene	Camphene
		Limonene
	α-pinene	Camphor
		Fenchone
	Dimethyl Disulphide	Exo-Fenchol
		Dimethyl Disulphide

6.2.2 Batch age ~2 weeks

As the birds began to grow and deposit manure on the bedding, changes with the number and abundance of chemical species collected in the sorbent tubes was observed. Figure 127 to Figure 130 represent the total ion chromatograms obtained from the GC-MS analysis of the sorbent tubes collected during sampling when the sheds contained 24,000–32,000 birds 13–18 days old.

The chemical compounds that were identified within the matrices included a variety of aldehydes that were not present within the samples from the initial sampling of the empty poultry shed. There were also several sulphur species detected including dimethyl sulphide, dimethyl disulphide and dimethyl trisulphide. The four spectra shown (Figure 127 to Figure 130) were obtained using different GC-MS analysis methods and therefore the spectra can not be directly compared.
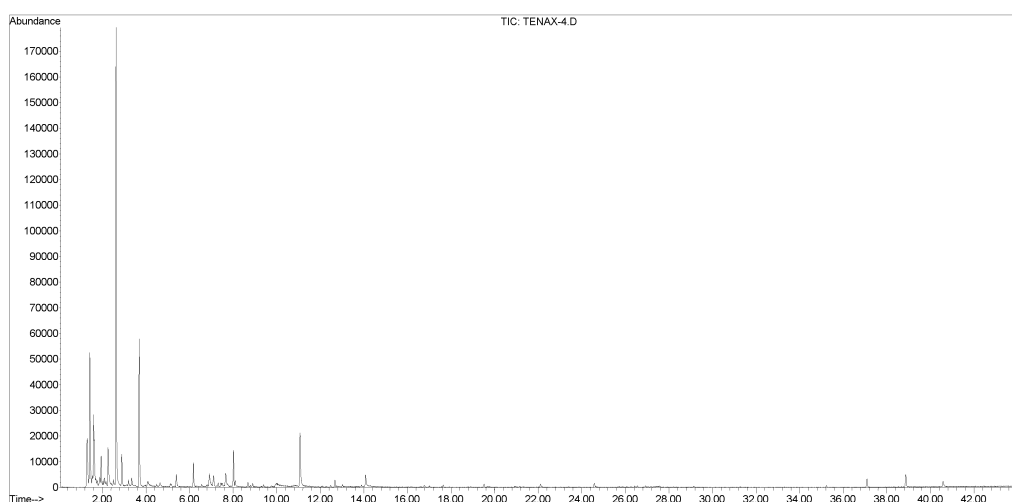
Figure 127: Total ion chromatogram from Farm A during summer—26,000 birds @ 18 days old—GC performed using non-polar column
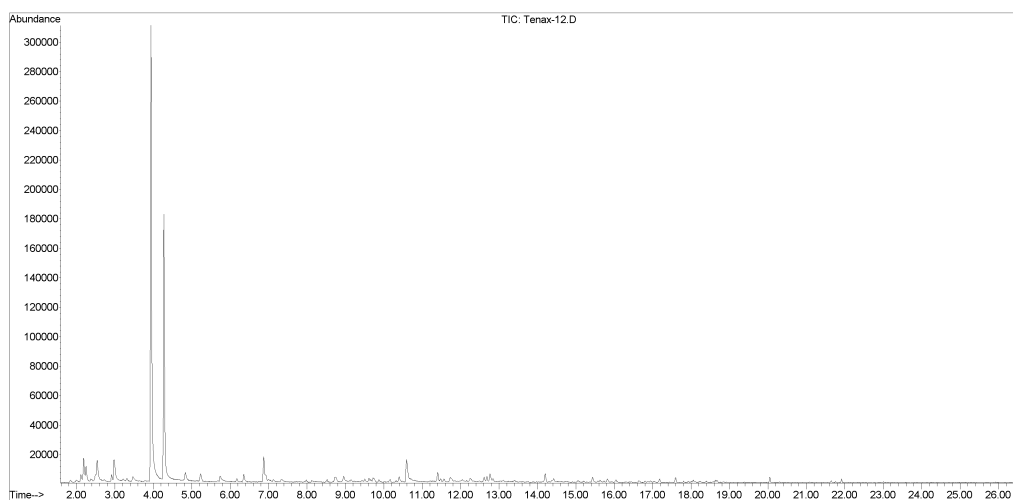
Figure 128: Total ion chromatogram from Farm A during winter—32,282 birds @ 15 days old—GC performed using non-polar column
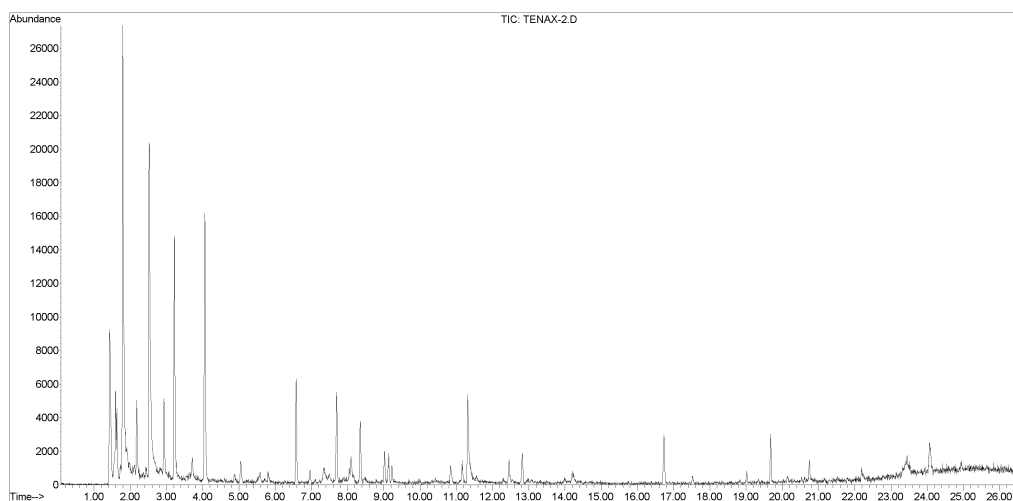
Figure 129: Total ion chromatogram from Farm B during summer—24,000 birds @ 13 days old—GC performed using non-polar column
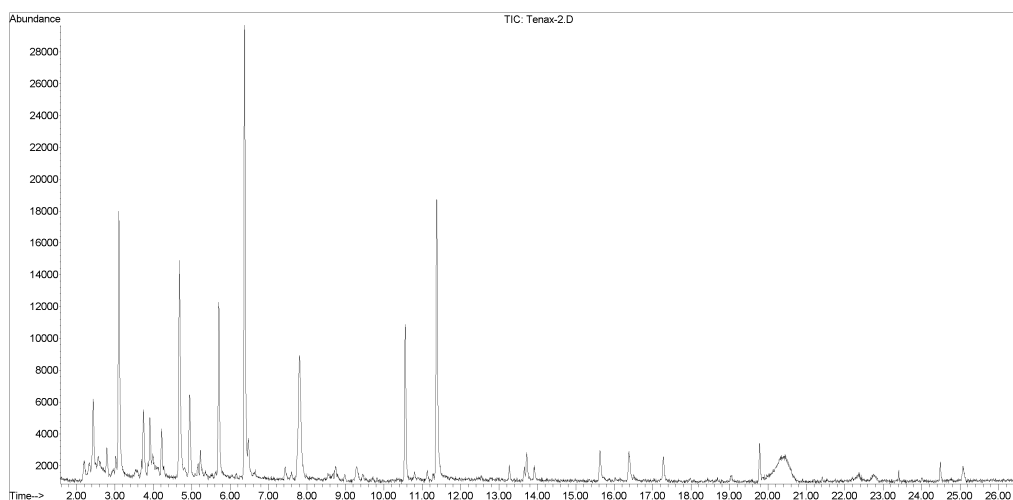
Figure 130: The above spectra from Farm B during winter— 30,215 birds @ 14 days old—GC performed using polar column

The spectra showed a large increase in the number of chemical compounds present within the samples when compared with the empty broiler sheds. Table 18 lists the chemical compounds that were identified from mass spectral databases.

Table 18: Chemical species identified at Farm A and B containing 24,000–32,000 birds at approximately 2 weeks old

Season	Farm A		Farm B	
	Summer	Winter	Summer	Winter
Bird Age (days)	18	15	13	14
Compounds Present	3-methyl-butanal Hexanal Heptanal Octanal Nonanal Decanal Toluene Ethylbenzene Benzaladehyde Acetophenone o-xylene p-xylene Styrene α-pinene Limonene Dimethyl disulphide Dimethyl trisulphide	Acetone 1-butanol 3-methyl-butanal 1,3-butanediol 2-ethyl-1-hexanol Hexanal Nonanal Benzene Toluene Benzaladehyde Acetophenone o-xylene p-xylene Styrene Ethanethiol Dimethyl sulphide Dimethyl disulphide Dimethyl trisulphide	3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Hexanal Nonanal Benzene Toluene Benzaldehyde α-pinene β-pinene Limonene Dimethyl disulphide	Acetone 1-butanol 2-butanone 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione 2-ethyl-1-hexanol Acetic Acid Benzene Toluene Acetophenone Styrene

6.2.3 Batch age ~3 weeks

Figure 131 and Figure 132 show the total ion chromatograms obtained from the GC-MS analysis of the sorbent tubes collected during winter at Farm A and Farm B respectively when the sheds housed 30,000–32,000 birds 22–23 days of age. The chemical compounds that were identified within the matrices included a variety of aldehydes and aromatic compounds. These two chromatograms were obtained using different GC-MS analysis methods and therefore can not be directly compared.
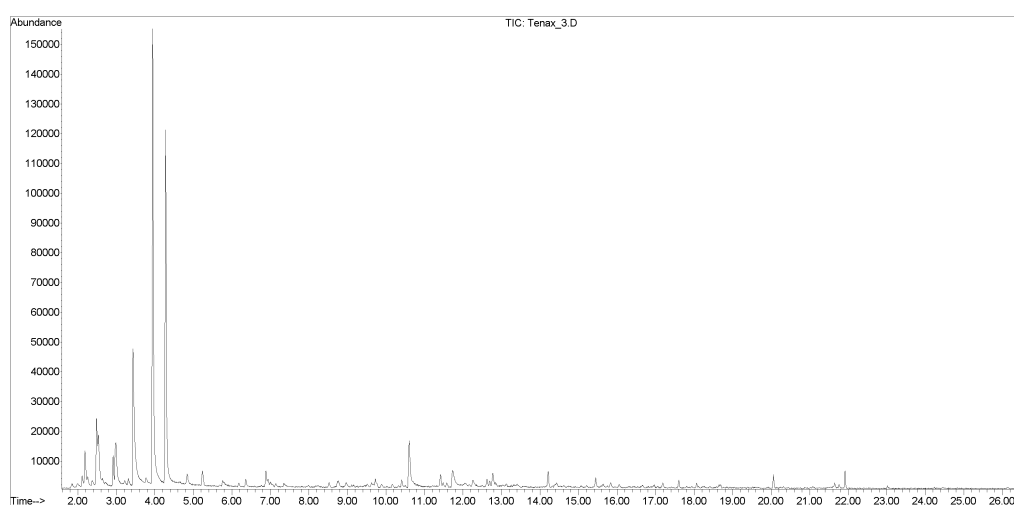
Figure 131: Total ion chromatogram from Farm A during winter—32,015 birds @ 23 days old—GC performed on non-polar column
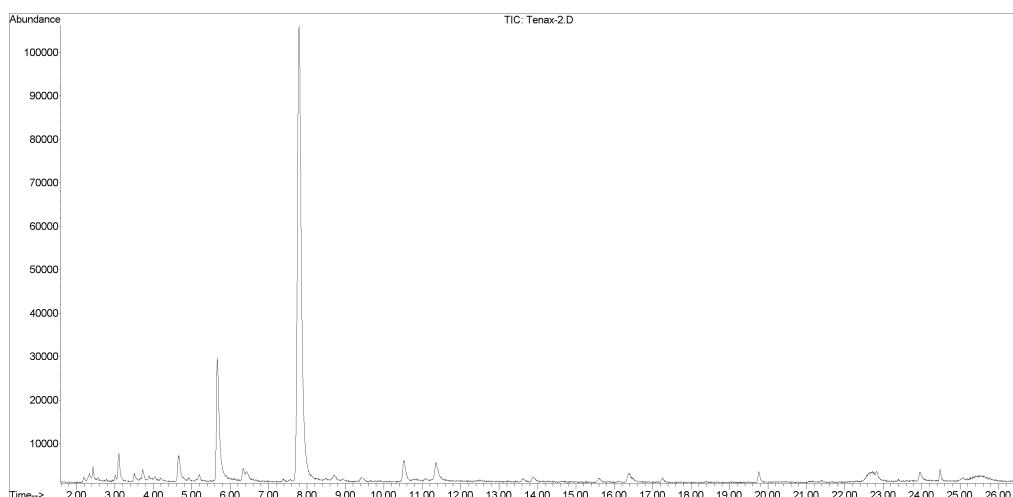
Figure 132: Total ion chromatogram from Farm B during winter—30,013 birds @ 22 days old—GC performed on polar column

The spectra obtained and chemical species identified show slight variation from the previous (~2 weeks old) sampling, however there is still a substantial difference from the chemicals identified from the emissions from an empty broiler shed. Table 19 lists the chemical species identified within the samples from the mass spectral databases.

Table 19: Chemical compounds identified at Farm A and B containing 30,000–32,000 birds at approximately 3 weeks old

	Farm A	Farm B
Season	Winter	Winter
Bird Age (days)	23	22
Compounds Present	Acetone Ethanol 1-butanol 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione 2-ethyl-1-hexanol Acetic acid Hexanal Nonanal Benzene Toluene Acetophenone o-xylene p-xylene Styrene Ethanethiol Dimethyl disulphide	Acetone 1-butanol 2-butanone Butanal 2,3-butanedione 2-ethyl-1-hexanol Toluene Phenol Acetophenone Styrene Dimethyl disulphide

6.2.4 Batch age ~4 weeks

The NMVOC field sampling of the broiler sheds continued as the birds grew; Figure 133 to Figure 136 are the total ion chromatograms obtained from the GC-MS analysis of the sorbent tubes collected during sampling when the sheds contained 22,000–32,000 birds approximately 30 days old. The chemical compounds that were identified within the matrices included a variety of aldehydes, ketones, aromatic compounds and also sulphur compounds (see Table 20). The spectra shown were obtained using different GC-MS analysis methods, and therefore the spectra can not be directly compared.
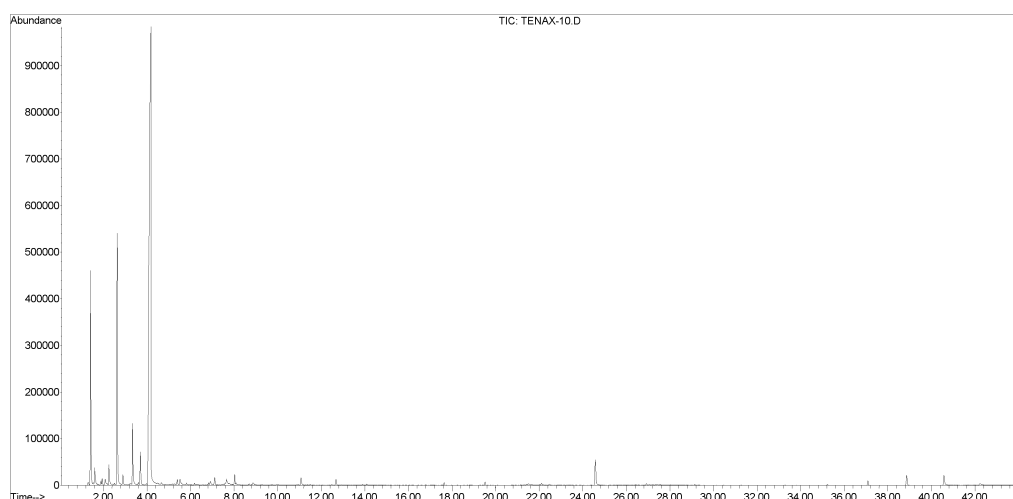
Figure 133: Total ion chromatogram from Farm A during summer—26,000 birds @ 27 days old—GC performed on non-polar column
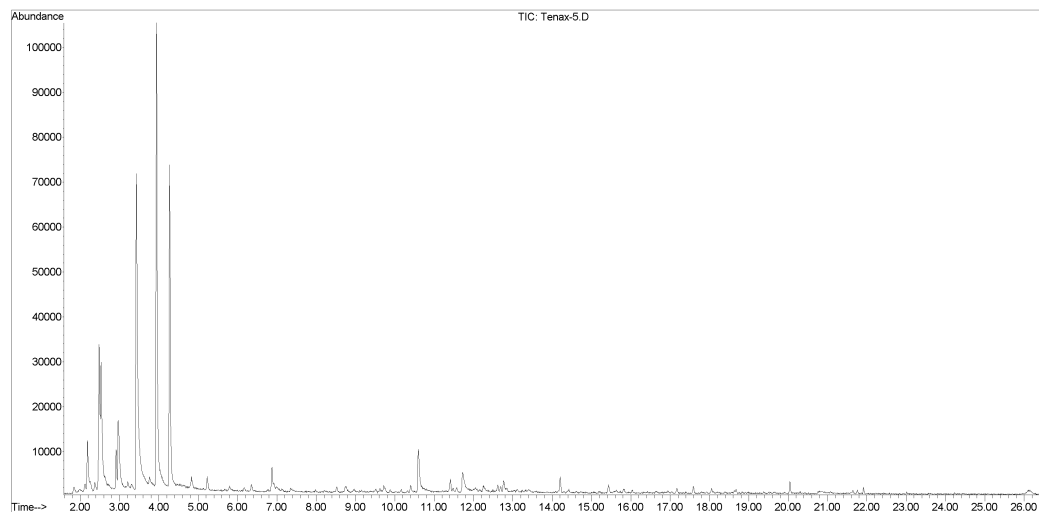
Figure 134: Total ion chromatogram from Farm A during winter—31,913 birds @ 28 days—GC performed on non-polar column
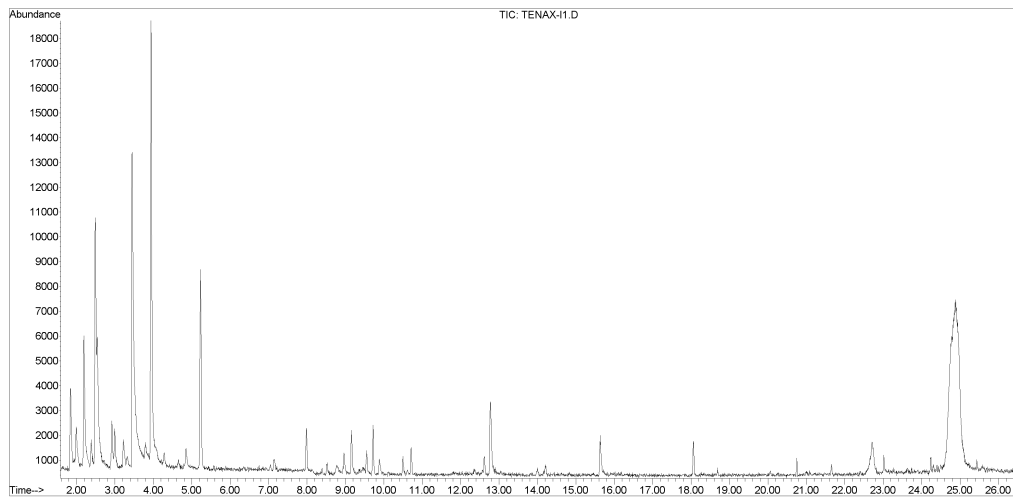
Figure 135: Total ion chromatogram from Farm B during summer—22,000 birds @ 32 days old—GC performed on non-polar column
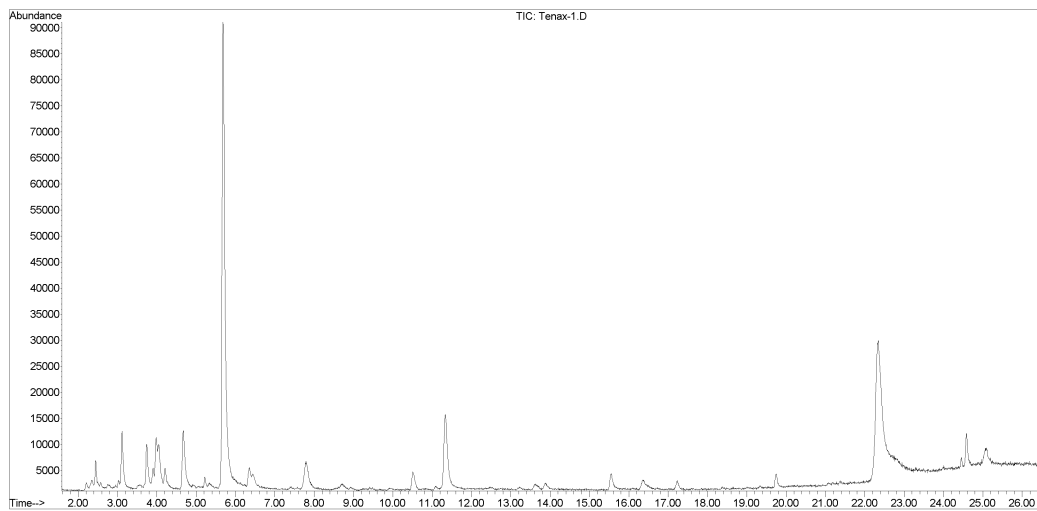
Figure 136: Total ion chromatogram from Farm B during winter—29,876 birds @ 29 days old—GC performed on polar column

Table 20:   Chemical compounds identified at Farm A and B containing 22,000–32,000 birds at approximately 4 weeks old

State	Queensland		Victoria	
Season	Summer	Winter	Summer	Winter
Bird Age (days)	27	28	32	29
Compounds Present	3-methyl-butanal Heptanal Octanal Nonanal Decanal 2-butoxy-ethanol 2-ethyl-1-hexanol Benzene Toluene Phenol Benzaldehyde Acetophenone α-pinene Eucolyptol Dimethyl disulphide Dimethyl trisulphide	Acetone 1-butanol 2-butanone 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Nonanal 2-ethyl-1-hexanol Benzene Toluene Acetophenone Styrene Dimethyl sulphide Dimethyl disulphide	Acetone 2-butanone 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Nonanal Decanal α-pinene β-pinene Limonene Dimethyl disulphide	Acetone 1-butanol 2-butanone Butanal 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione 2-ethyl-1-hexanol Acetic Acid Benzene Toluene Benzaldehyde Acetophenone Styrene Dimethyl disulphide Diethyltoluamide

6.2.4.1   *Diffusive sampling at batch age ~4 weeks*

During the winter broiler shed sampling at both Farm A and Farm B, a limited number of diffusive samples were collected to observe the compounds that were dominant within the air inside the poultry shed. The sorbent tubes were placed within the shed and left to passively collect any NMVOCs present. Figure 137 and Figure 138 are the spectra obtained from the analysis of the sorbent tubes that were collected passively over approximately one week.

Figure 137 shows the total ion chromatogram from the GC-MS analysis of a sorbent tube collected from Farm A during winter commencing when the birds were 23 days old, concluding 8 days later. The spectra shows only a limited number of compounds that were dominant within the composition of the air inside the poultry shed. These passive samples support the presence of the identified compounds within the actively sampled sorbent tubes from the sampling point within the duct.
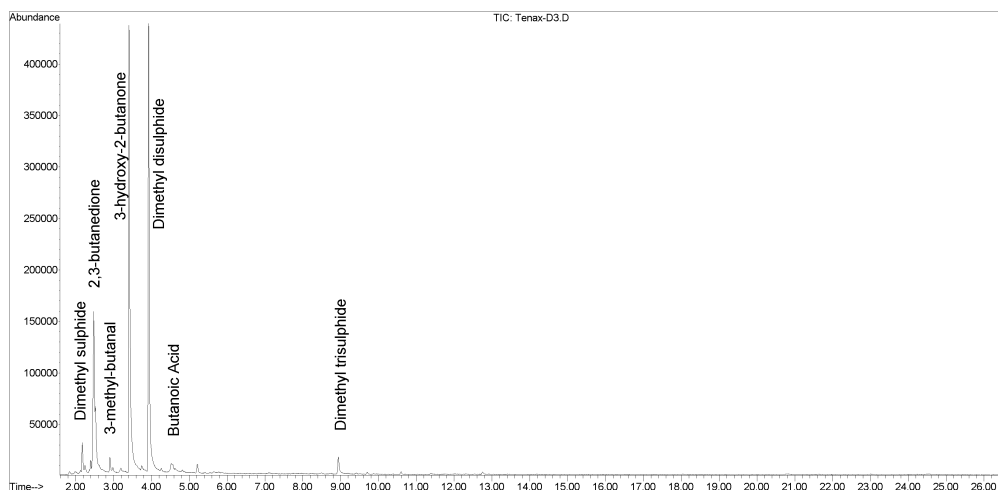
Figure 137: Spectra from Farm A during winter containing ~32,000 birds commencing at day 23 for 8 days duration—GC analysis performed on non-polar column

Figure 138 shows the spectra from the analysis of a sorbent tube collected from a broiler shed at Farm B during winter commencing when the birds were 22 days old and concluding 7 days later. In similarity to the passive sample from an analogous period at Farm A; the Farm B sample shows fewer peaks in the total ion chromatogram than the actively collected samples.
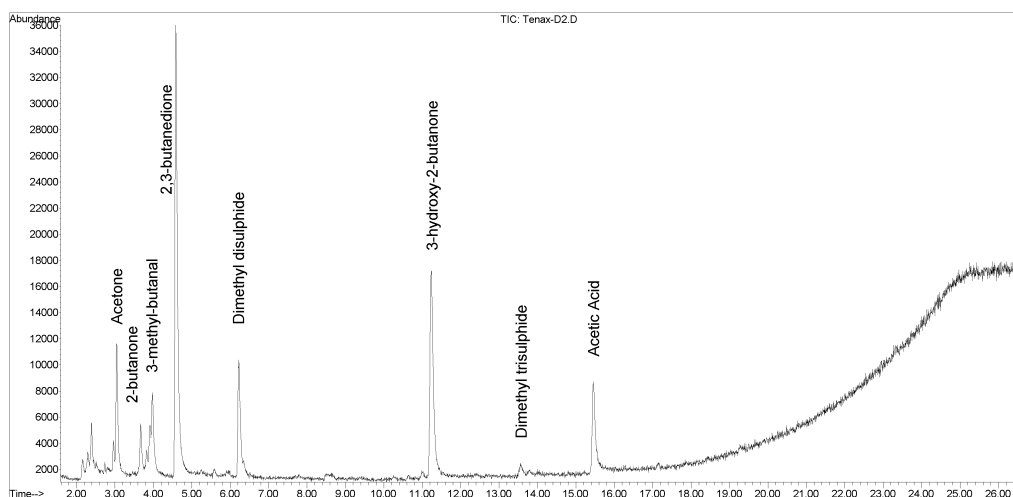
Figure 138: Spectra from Farm B during winter containing ~30,000 birds commencing at day 22 for 7 days duration—GC analysis performed on a polar column

Table 21:   Chemical compounds identified from the passively collected sorbent tubes

	Farm A	Farm B
Season	Winter	Winter
Bird Age (days)	23-31	22-29
Compounds Present	3-methyl-2-butanal 3-hydroxy-2-butanone 2,3-butanedione Butanoic Acid Dimethyl sulphide Dimethyl disulphide Dimethyl trisulphide	Acetone 2-butanone 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Acetic Acid Dimethyl disulphide Dimethyl trisulphide

6.2.5 Batch age ~6 weeks

Figure 139 and Figure 140 are the total ion chromatograms obtained from the GC-MS analysis of the sorbent tubes collected at Farm A and Farm B respectively during winter—the sheds containing 17,000–20,000 birds. The chemical compounds that were identified within the matrices included a variety of aldehydes, ketones and aromatic compounds. The two spectra shown were obtained using different GC-MS analysis methods, and therefore the spectra can not be directly compared.
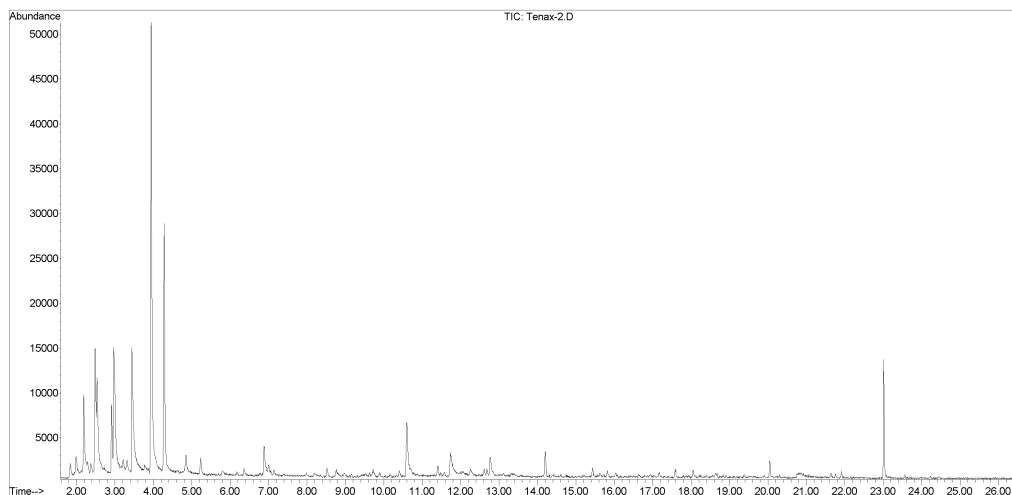
Figure 139: Total ion chromatogram from Farm A during winter—17,067 birds @ 43 days old—GC performed on non-polar column
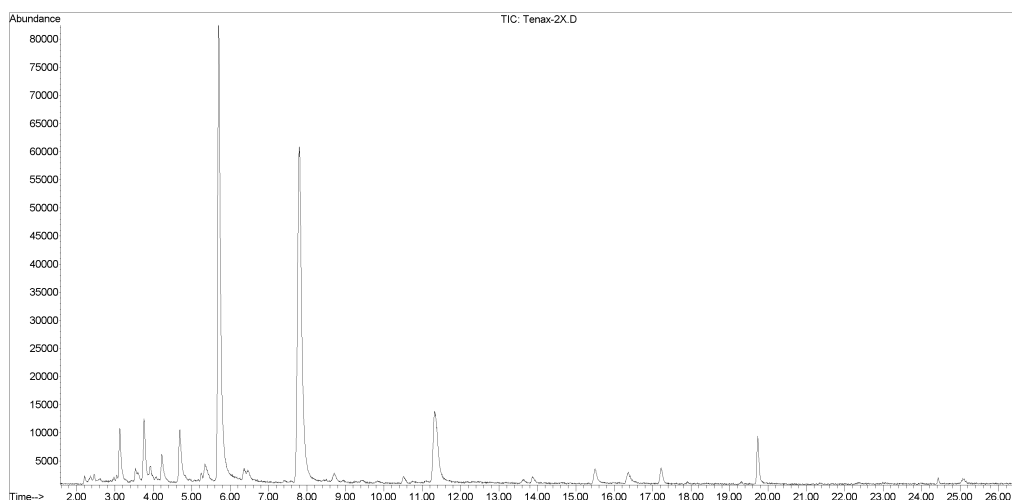
Figure 140: Total ion chromatogram from Farm B during winter—19,504 birds @ 43 days old—GC performed on polar column

The analytes identified from the GC-MS analysis of the broiler shed samples from Farm A and B during winter with approximately 20,000 birds, 43 days old, are listed in Table 22.

Table 22:   Chemical compounds identified at Farm A and B containing ~20,000 birds at approximately 6 weeks old

State	Queensland	Victoria
Season	Winter	Winter
Bird Age (days)	43	43
Compounds Present	Acetone 1-butanol 2-butanone 3-hydroxy-2-butanone 2,3-butanedione 3-methyl-butanal Hexanal 2-ethyl-1-hexanol Toluene Acetophenone p-xylene Styrene Dimethyl sulphide Dimethyl disulphide	Acetone 1-butanol 2-butanol Butanal 2-butanone 3-methyl-butanal 2,3-butanedione 2-ethyl-1-hexanol Acetic Acid Benzene Toluene Benzaldehyde Acetophenone Dimethyl disulphide

6.2.5.1 Diffusive Sampling at batch age ~5–7 weeks

To coincide with the pumped sorbent tube samples a second group of passive sorbent tubes were collected as the birds reached full maturity. The results of the GC-MS analysis are shown in Figure 141 and Figure 142. These sorbent tubes were collected passively over approximately one week from sheds at Farm A and B.

Figure 141 was the results of the analysis of a sorbent tube collected from Farm A during winter commencing when the birds were 32 days old and concluding 11 days later. In relation to the previous passive samples, there were fewer peaks than seen in the pumped sorbent tube samples; however, the predominant peaks are unchanged from the previous passive samples.
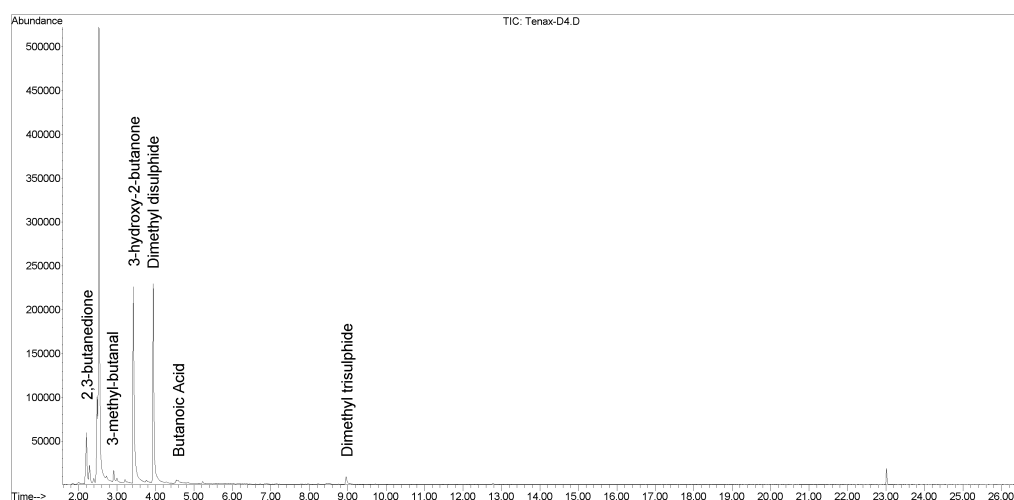
Figure 141: The spectra obtained from Farm A during winter—commencing on day 32 for a duration of 11 days

Figure 142 was the results of the analysis of a sorbent tube collected from Farm B during winter commencing when the birds were 35 days old and concluding 8 days later.
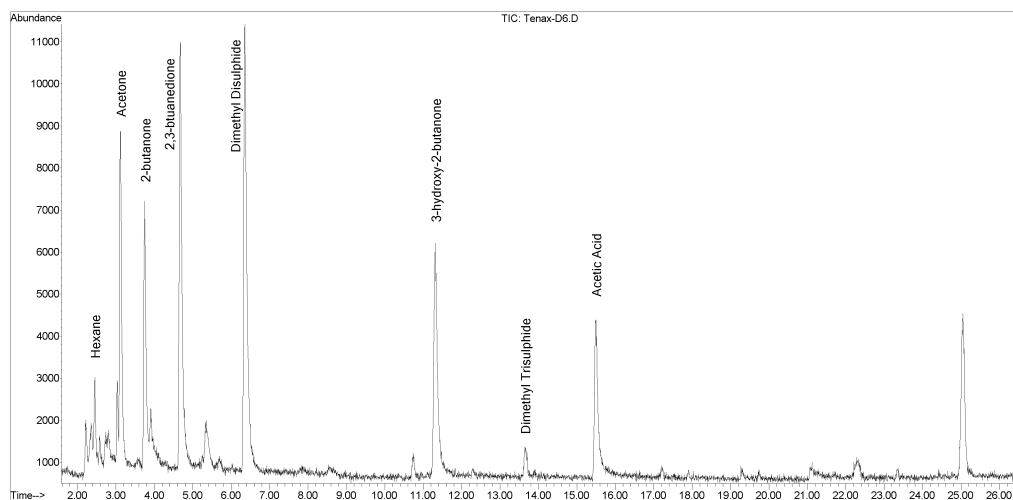
Figure 142: The spectra obtained from Farm B during winter—commencing on day 35 for 8 days duration

The analytes that were identified from the passive samples are listed in Table 23; although there were fewer than was collected in the actively sample sorbent tubes, they are no less significant.

Table 23:   Chemical compounds identified at Farm A and B during winter

	Farm A	Farm B
Season	Winter	Winter
Bird Age (days)	32 - 43	35 - 43
Compounds Present	3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Butanoic Acid Dimethyl disulphide Dimethyl trisulphide	Acetone 2-butanone 3-hydroxy-2-butanone 2,3-butanedione Acetic Acid Dimethyl disulphide Dimethyl trisulphide

6.2.6 **Batch age ~7 weeks**

The final day of field sampling at the broiler facilities with birds present occurred when the remaining birds were approximately 7 weeks of age. Although a number of the birds had already been removed during previous pickups, the NMVOCs that were identified from the GC-MS analysis of the sorbent tubes were more diverse in variety and of greater abundances. The total ion chromatograms shown in Figure 143 to Figure 146 illustrate the large abundance and variety of chemicals emitted from the sheds containing 8,000–14,000 birds 46–49 day old.

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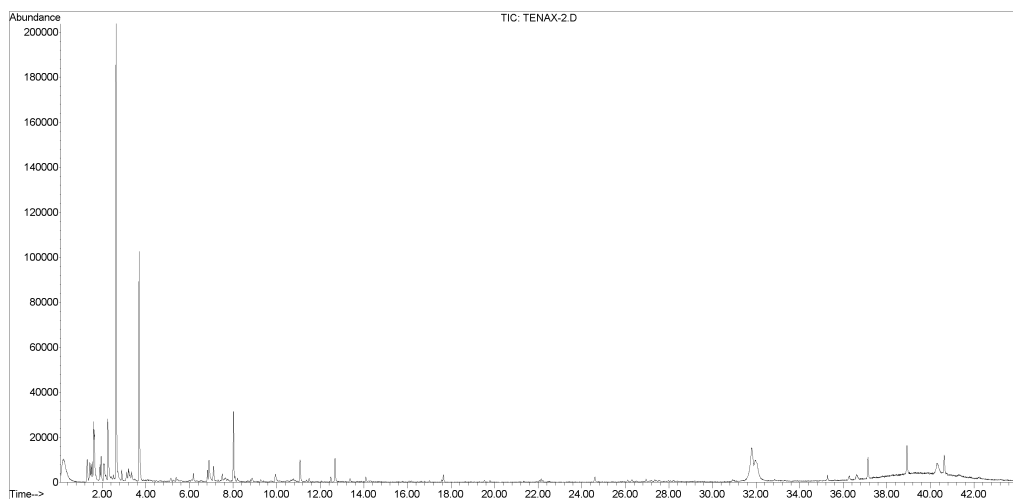
Figure 143: Total ion chromatogram from Farm A during summer—9,965 birds @ 47 days old—GC performed on non-polar column
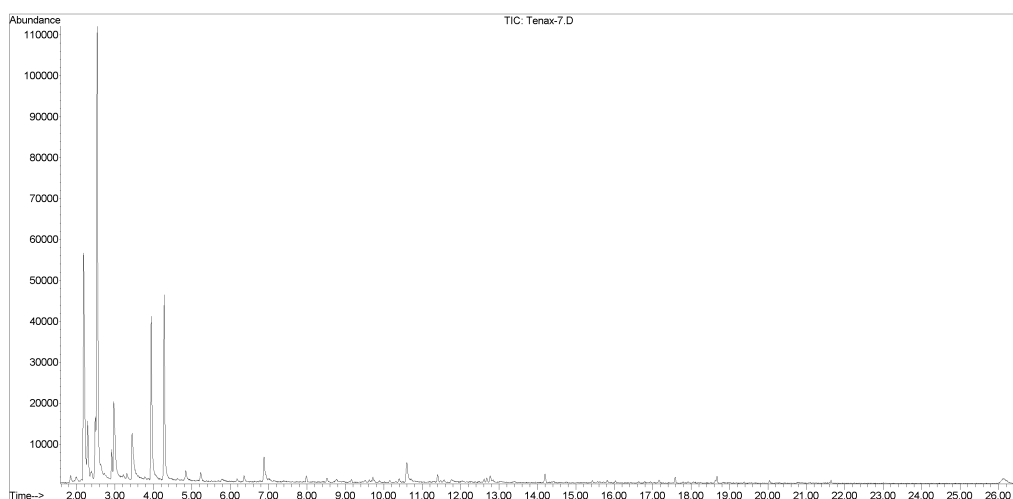
Figure 144: Total ion chromatogram from Farm A during winter—12,018 birds @ 49 days old—GC performed on non-polar column
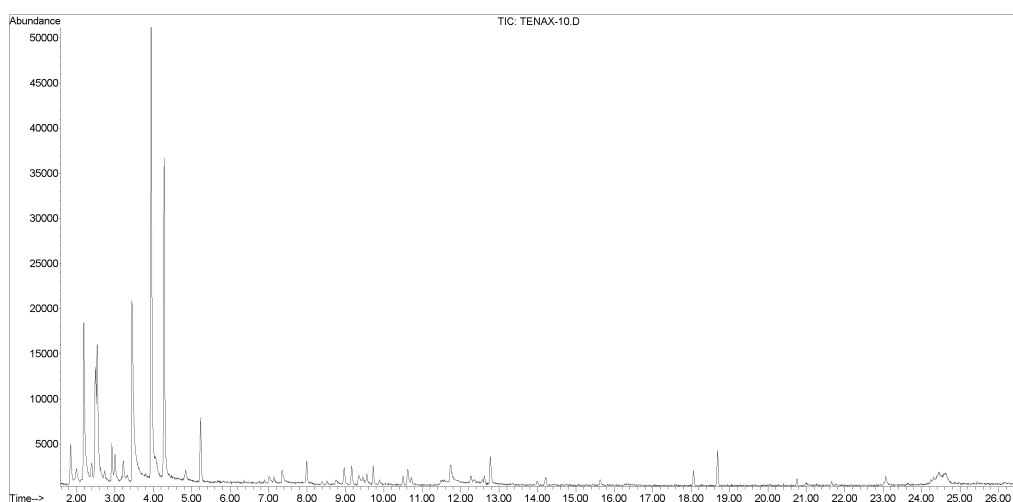
Figure 145: Total ion chromatogram from Farm B during summer—13,636 birds @ 46 days old—GC performed on non-polar column
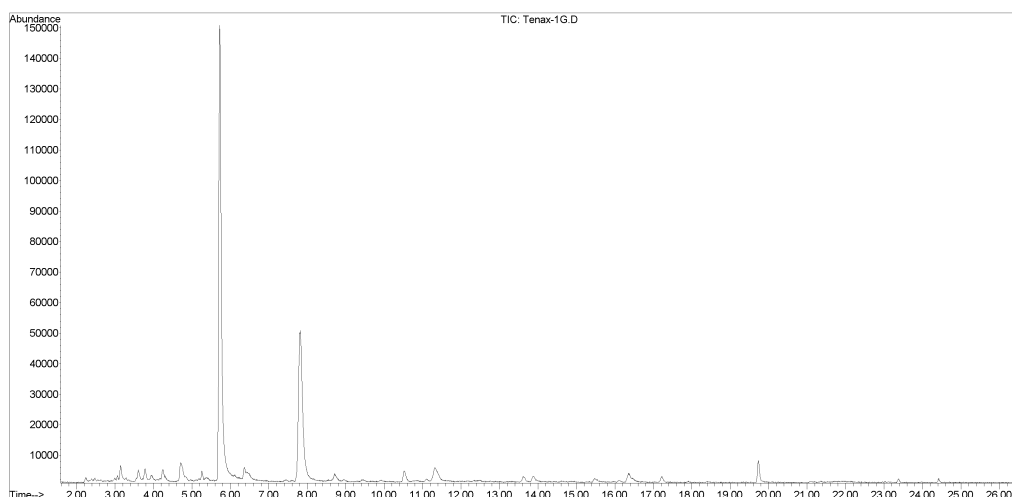
Figure 146: Total ion chromatogram from Farm B during winter—7,773 birds @ 49 days old—GC performed on polar column

The chemical compounds that were identified from the sorbent tube analysis are listed in Table 24. These spectra show the greatest diversity in chemical species and abundance. The dominance of the aldehydes and ketones is of particular interest in subsequent odorant speciation.

Table 24: Chemical compounds identified at Farm A and B containing mature birds approximately 7 weeks old

	Farm A		Farm B	
Season	**Summer**	**Winter**	**Summer**	**Winter**
Bird Age (days)	**47**	**49**	**46**	**49**
Compounds Present	3-methyl-butanal 3-hydroxy-2-butanone Hexanal Heptanal 2-heptanone Octanal Nonanal Decanal 2-ethyl-1-hexanol Benzene Toluene Benzaldehyde Acetophenone o-xylene β-pinene 3-carene Dimethyl disulphide Dimethyl Trisulphide	Acetone 1-butanol 2-butanone 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Hexanal 2-ethyl-1-hexanol Acetic Acid Toluene Phenol Benzaldehyde Styrene Dimethyl sulphide	Acetone 2-butanone 3-methyl-butanal 3-hydroxy-2-butanone 2,3-butanedione Nonanal Toluene Acetophenone α-pinene β-pinene Dimethyl disulphide Dimethyl trisulphide	Acetone 1-butanol 2-butanone 3-methyl-butanal 2,3-butanedione Heptanal Benzene Toluene Phenol Benzaldehyde Acetophenone Styrene Dimethyl disulphide

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6.2.7 **Post bird removal, spent litter present**

At the completion of the grow-out cycle, the birds were removed from the sheds; however, the litter remained for a few extra days—as is common practice. At this stage, the litter is mixture of bedding that is enriched with approximately eight weeks of bird manure, and continues to emit NMVOCs. These were collected into sorbent tubes and the results of the GC-MS analysis are shown in Figure 147 to Figure 150—the total ion chromatograms show definite peaks despite the absence of birds.

As explained previously in section 4.3 for odour emissions from sheds without birds, this exercise was primarily academic because emissions of NMVOCs from sheds between batches are minimal due to minimal shed ventilation. Artificial conditions, including elevated ventilation rates, were created by the research team to allow sample collection and emission rate calculation.
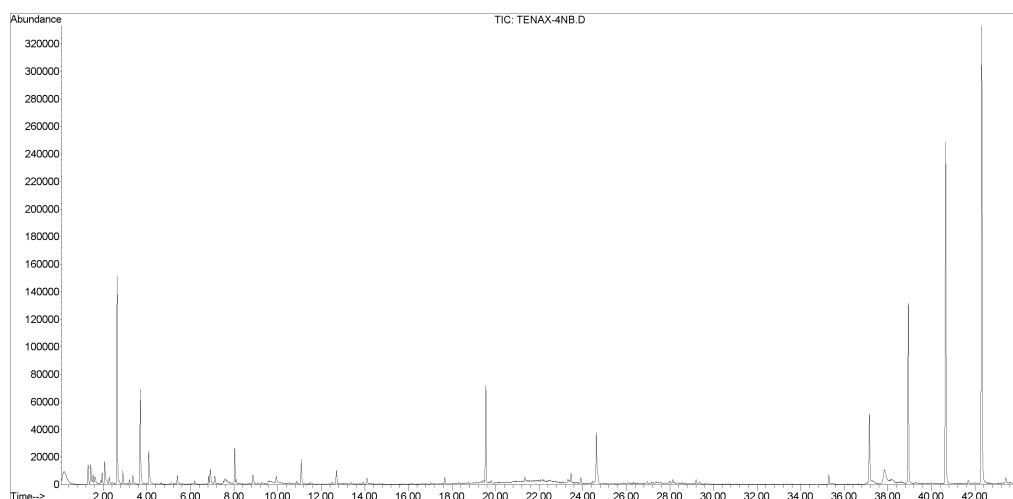
Figure 147: Total ion chromatogram obtained from Farm A during summer—containing only spent litter
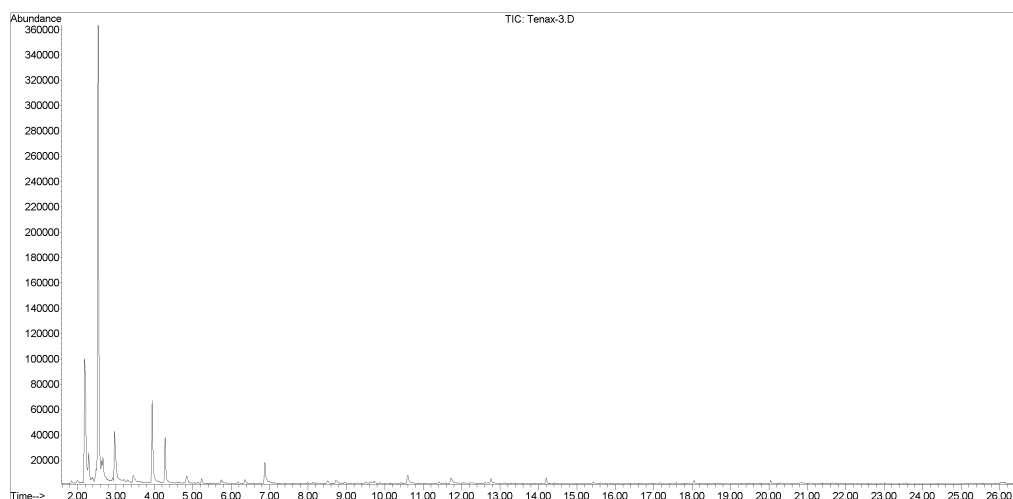
Figure 148: Total ion chromatogram obtained from Farm A during winter—containing only spent litter

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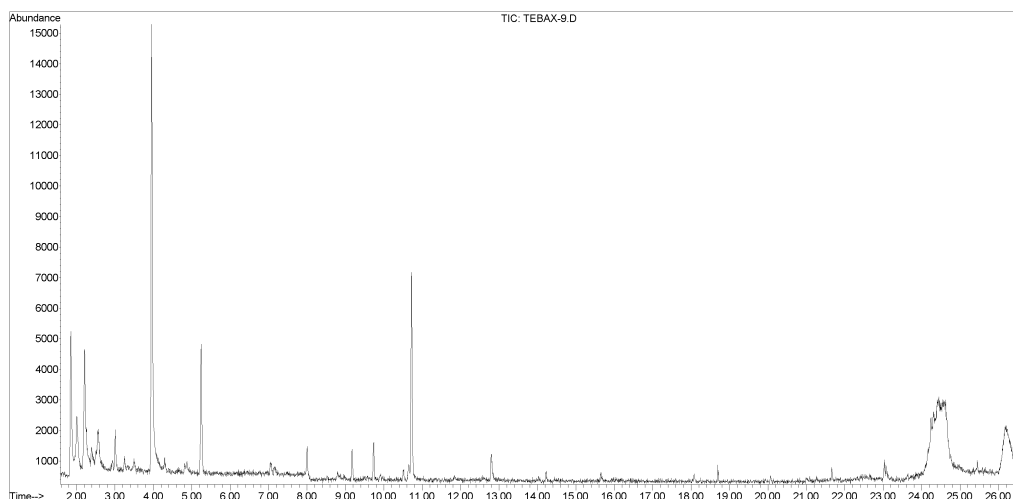
Figure 149: Total ion chromatogram obtained from Farm B during summer—containing only spent litter
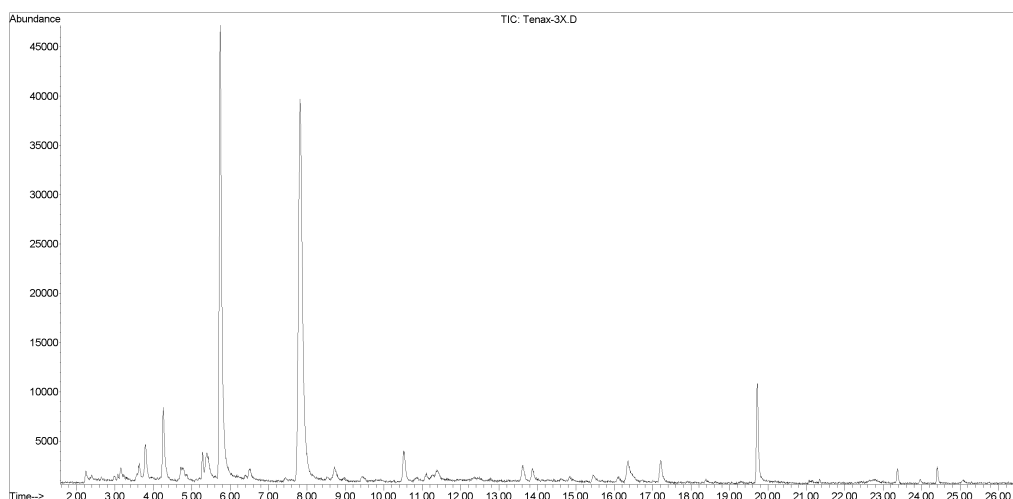
Figure 150: Total ion chromatogram obtained from Farm B during winter—containing only spent litter

Whilst the broilers were no longer present, the spent litter remaining in the broiler sheds continued to be a source for NMVOCs. The results of the NMVOC speciation identified a large number of chemical compounds within the samples collected from the sheds illustrating that it is not just the presence of the birds that produces a NMVOC emission. Table 25 lists the chemical species identified from the GC-MS analysis of the sorbent tubes collected from the broiler sheds post bird removal but prior to litter removal and shed cleaning.

Table 25: Chemical compounds identified at Farm A and B containing only spent litter, no birds

	Queensland		Victoria	
Season	**Summer**	**Winter**	**Summer**	**Winter**
Bird Age (days)	N/A (No Birds Present, spent litter)			
Compounds Present	3-methyl-2-butanal Hexanal Heptanal Octanal Nonanal Decanal 2-ethyl-1-hexanol Benzene Toluene Phenol Benzaldehyde Acetophenone α-pinene Dimethyl disulphide Dimethyl trisulphide	Acetone 1-butanol 2-butanol 2-butanone 2,3-butanedione Hexanal 2-ethyl-1-hexanol Toluene Phenol Ethylbenzene Benzaldehyde Acetophenone p-xylene Styrene Dimethyl disulphide	Eucolyptol Dimethyl disulphide	1-butanol 2-butanol 2-butanone 2-ethyl-1-hexanol Benzene Toluene Phenol Ethylbenzene Benzaldehyde Acetophenone p-xylene o-xylene Styrene Dimethyl disulphide

6.2.8 Post shed cleaning and fumigation

Once the birds were removed and the spent litter cleaned out, the sheds were cleaned and fumigated in preparation for the next batch of birds. The results of the GC-MS analysis of sorbent tubes collected after shed cleaning and fumigation are shown in Figure 151 and Figure 152.
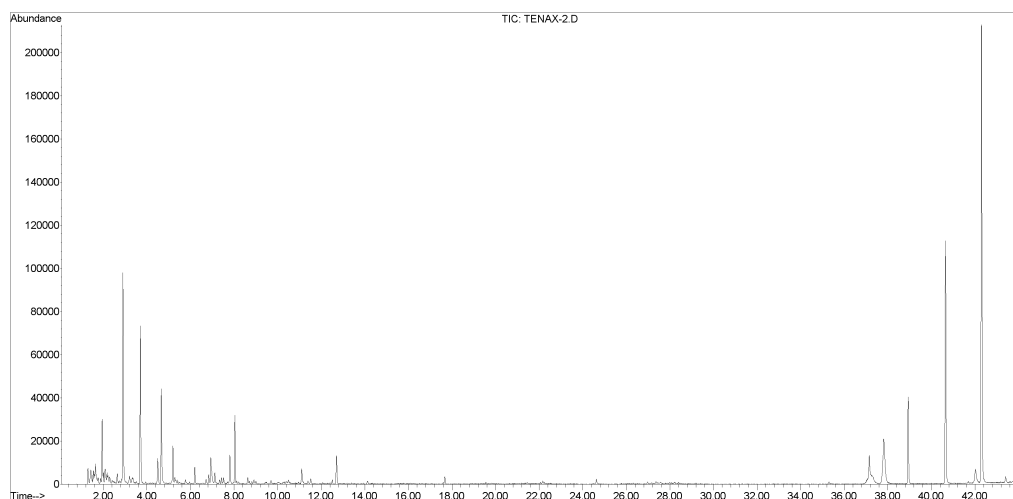
Figure 151: Total ion chromatogram obtained from Farm A during summer—shed cleaned and fumigated
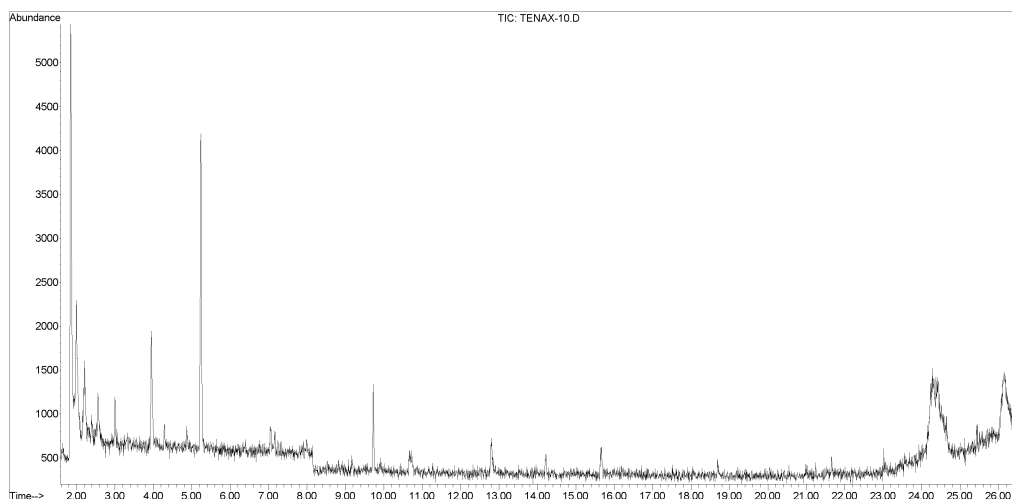
Figure 152: Total ion chromatogram obtained from Farm B during summer—shed cleaned and fumigated

The chemical species that were identified from the sorbent tubes collected at the broiler sheds after being cleaned and fumigated are listed in Table 26. The total ion chromatogram from Farm B had no peaks detectable above the baseline noise. Although it is plausible that various odorous and non-odorous chemicals were present in the shed emissions post clean out, they were in abundances that fell below the detection limits of the methodology engaged.

Table 26: Chemical compounds identified from Farm A after sheds were cleaned and fumigated

	Farm A
Season	**Summer**
Bird Age (days)	**N/A (Post shed cleaning and fumigation, no birds or litter present)**
Compounds Present	Hexanal
	Nonanal
	Decanal
	Benzene
	Toluene
	Ethylbenzene
	Benzaldehyde
	p-xylene
	Trimethylbenzene
	α-pinene
	β-pinene

6.2.9 Summary of non-methane volatile organic compounds identified at Farms A and B

Collection and analysis of thermal desorption tubes using gas chromatography-mass spectrometry provided insight into the NMVOC emissions from the broiler sheds during the grow-out cycle.

The GC-MS analysis of the broiler shed emissions provided a substantial list of NMVOCs (see Table 27) including aldehydes and ketones (hexanal, heptanal, octanal, 2-butanone, 2,3-butanedione, 3-hydroxy-2-butanone) alkanoic acids (ethanoic acid, propanoic acid, butanoic acid) with numerous other species including terpines. Whilst beyond the classification of NMVOC, the broiler shed results also included large abundances of sulphides (dimethyl sulphide, dimethyl disulphide, dimethyl trisulphide) which were

consistently identified from the vast majority of samples.

Summary table of the NMVOCs predominantly identified from GC-MS analysis of sorbent tubes collected at Farms A and B

Season	Farm A		Farm B	
	Summer	Winter	Summer	Winter
Alcohols	1-butanol 2-ethyl-1-hexanol 2-butoxy-ethanol	Ethanol 1-butanol 2-butanol 2-ethyl-1-hexanol		1-butanol 2-butanol 2-ethyl-1-hexanol
Aldehydes	3-methyl-butanal Hexanal Heptanal Octanal Nonanal Decanal	3-methyl-butanal Hexanal Nonanal	3-methyl-butanal Hexanal Nonanal Decanal	Butanal 3-methyl-butanal Heptanal
Ketones	2-butanone 3-hydroxy-2-butanaone 2,3-butanedione 2-heptanone	Acetone 2-butanone 3-hydroxy-2-butanone 2,3-butanedione	Acetone 2-butanone 3-hydroxy-2-butanone 2,3-butanedione	Acetone 2-butanone 3-hydroxy-2-butanone 2,3-butanedione
Carboxylic Acids		Acetic Acid Butanoic Acid		Acetic Acid
Aromatics	Benzene Toluene Ethylbenzene Phenol Trimethylbenzene Benzaldehyde Acetophenone o-xylene p-xylene Styrene	Benzene Toluene Ethylbenzene Phenol Benzaldehyde Acetophenone o-xylene p-xylene Styrene	Benzene Toluene Benzaldehyde Acetophenone	Benzene Toluene Ethylbenzene Phenol Benzaldehyde Acetophenone o-xylene p-xylene Styrene
Terpines	α-pinene β-pinene 3-carene Eucolyptol Limonene		α-pinene β-pinene 3-carene Eucolyptol Limonene	
Sulphur	Dimethyl disulphide Dimethyl trisulphide	Ethanethiol Dimethyl Sulphide Dimethyl disulphide Dimethyl trisulphide	Dimethyl disulphide Dimethyl trisulphide	Dimethyl disulphide Dimethyl trisulphide

One of the most significant results from the assessment of the NMVOCs from the broiler shed emissions was the change in the chemical profile as the birds matured; from a matrix dominated by terpines from the bedding material when the birds were young, through to a matrix dominated by aldehydes, ketones and sulphide as the birds matured and the litter became soiled with manure.

6.3 Results Part B—Identification of odorant species within the NMVOCs

The non-methane volatile organic compound (NMVOC) speciation detailed in the preceding section (Section 6.2) allows for the identification of the chemical species being emitted from the poultry houses; however, chemical speciation does little to elucidate the odorant profile. The addition of the olfactometry detection port (ODP) and the corresponding splitting of the gas chromatograph (GC) effluent between the two detectors (mass selective detector (MSD) and (ODP)) provide both chemical speciation and odorant identification. This section describes the odorants detected from the broiler sheds throughout the batch.

It should be noted that the identification of the odorants within a sample is often considered subjective owing to the subjective nature of the human sense of smell. Different chemicals will often have differing detection thresholds for different people; also different chemical species exhibit different levels of olfactory stimulus. This means that while individual odorants will contribute to the strength and character pleasantness of the 'whole' odour, there is presently no way to quantify this contribution (i.e. it is possible that a whole air sample may contain a mixture of pleasant and unpleasant odorants and still have a pleasant or neutral character and low strength or intensity).

The odorant chromatograms that appear in the proceeding text seek to be an average representation of the multiple samples collected from a given site at a particular time. Whilst the method of analysis was constant (i.e. gas chromatography with mass spectrometry and olfactory detection), refinement of the method during the project means that a given chromatogram pair is unique and can not empirically be compared to another.

6.3.1 Clean broiler house, no birds, fresh litter

As observed from the chemical speciation of NMVOCs; a broiler shed void of birds can potentially emit NMVOCs. Litter material that is placed within the poultry shed for bedding may acts as an emission source of NMVOCs; however, ventilation rates are minimal when birds are absent so emission rates will also be minimal. Figure 153 shows both the total ion chromatogram and the corresponding odour chromatogram obtained from a sorbent tube sample collected from Farm B during the summer prior to the bird placement, with fresh bedding material laid in the shed. The chemical speciation was performed using the mass spectral data, whilst the odorant identification was performed using a combination of the descriptor as recorded by the operator and the retention time (RI).
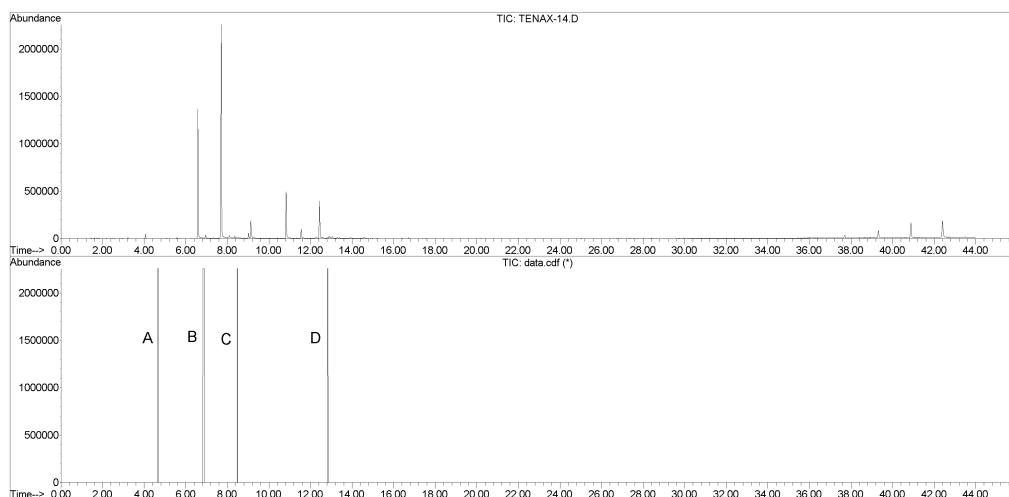
Figure 153: Total ion chromatogram (top) and the olfactory chromatogram (bottom) from Farm B - fresh litter, no birds

The mass spectral data identified numerous chemical species; however the dominant chemicals were terpines; including α-pinene, β-pinene, camphor, camphene and limonene. The odorants identified from the olfactory stimulus data were dominated by pine scents, with characteristic odour descriptors of pine featuring prominently. Table 28 lists the ODP peaks as seen in the odour spectra and their respective

descriptor, and the chemical responsible for the odour. Odorant species within this sample included α-pinene and β-pinene.

Table 28:   Odorants identified from Farm B with no birds, only fresh bedding material

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	4.66	Pungent	Unknown (no MSD peak)
B	6.86	Pine	α-pinene
C	8.48	Pine	β-pinene
D	12.84	Mildly Unpleasant	camphor

[##] *refers to peaks in Figure 153*

In similarity to the NMVOC analysis of the fresh bedding with no birds in the broiler shed, the odorant emissions are characterised by terpines with natural wood and pine scents, which although effect an olfactory response are not generally unpleasant in hedonic tone.

6.3.2 **Batch age ~2 weeks**

After the bird placement, the litter material that is within the shed begins to become soiled with the manure of the birds. As the litter material becomes soiled, the NMVOCs that are being identified within the emissions from the poultry shed changes, and so to does the odorant profile.

6.3.2.1 *Broiler sheds in Queensland (Farms A and C)*

Figure 154 and Figure 155 show the total ion chromatograms and odorant chromatograms from two different samples representative of the respective broiler sheds in summer and winter in Queensland. Sheds at Farm C and Farm A contained 39,913 and 32,282 birds aged 14 and 15 days respectively. Table 29 and Table 30 lists the odorants identified from the chemical and olfactory analysis.
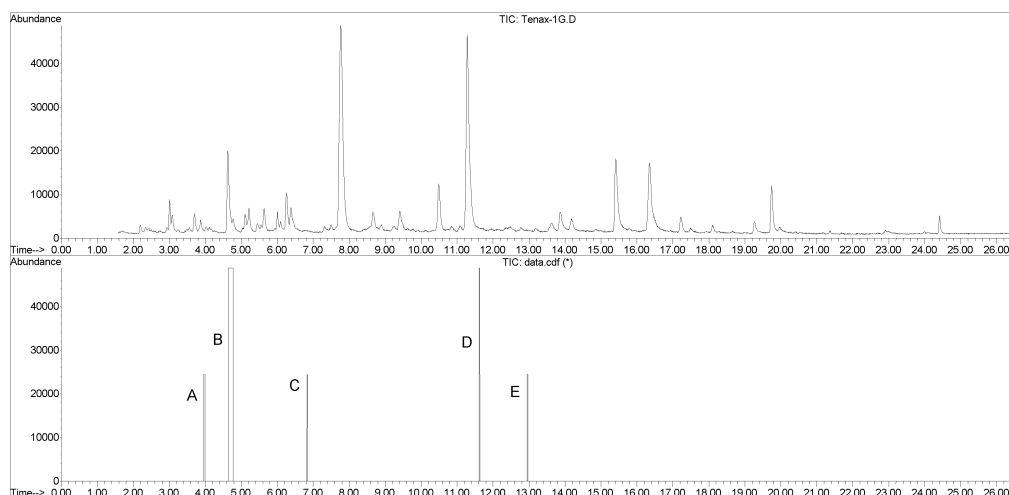
Figure 154: Total ion chromatogram and odorant chromatogram from Farm C during summer containing 39,913 birds 14 days old

The chemical compounds labelled in Figure 154 (A,B,C,D & E) that have been identified as the odorants are listed in Table 29. It should be noted that the presence of an olfactory stimulus peak does not always correspond to a peak in the total ion chromatogram. When a chemical is asterisked (*), it is a speculation based upon the retention time and the odorant descriptor if available.

Table 29: Odorants identified from samples (see Figure 154) collected during summer at Farm C, containing 39,913 birds at 14 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	3.97	Unpleasant, malt	3-methyl-butanal
B	4.73	Rancid, butter	2,3-butanedione
C	6.84	Unpleasant	Dimethyl disulphide
D	11.62	Butter	3-hydroxy-2-butanone
E	12.96	Pungent Sulphur	Dimethyl trisulphide*

[##] *refers to peaks in Figure 154*

The odorant characteristics have shifted from the pine scents observed in the samples prior to bird placement to a more unpleasant, rancid and sulphur-esque odours as listed in Table 29 attributed to chemical species including 3-methyl-butanal with an unpleasant malt odour, 2,3-butanedione with a rancid butter odour and dimethyl trisulphide with a pungent sulphur odour.
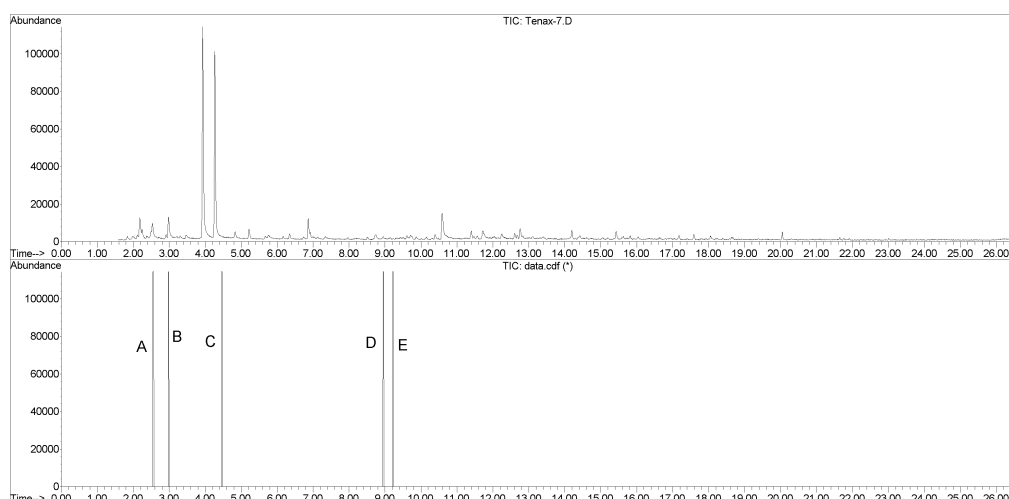
Figure 155: Total ion chromatogram and odorant chromatogram from a sample collected during winter at Farm A, containing 32,282 birds at 15 day old

The chemical compounds labelled in Figure 155 (A,B,C,D & E) that have been identified as the odorants from a broiler facility sampled during winter in Queensland are listed in Table 30.

Table 30: Odorants identified from the sample collected during winter at Farm A, containing 32,282 birds at 15 day old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	2.56	Rancid, butter	2,3-butanedione
B	3.00	Sweet	Benzene
C	4.47	Solvent	Toluene
D	8.94	Pungent, sulphur	Dimethyl trisulphide*
E	9.22	Earthy/mushroom	β -pinene*

[##] *refers to peaks in Figure 155*

The odorant characteristics have shifted from the pine scents observed in the samples prior to bird placement to more solvent, rancid and sulphur-esque odours as listed in Table 30 attributed to chemical species including 2,3-butanedione with a rancid butter odour and dimethyl trisulphide with a pungent sulphur odour.

6.3.2.2 Broiler sheds in Victoria (Farm B)

Figure 156 and Figure 157 show the total ion chromatograms and odorant chromatograms from two different samples representative of the respective broiler sheds in summer and winter in Victoria; with the sheds containing 24,000 and 30,215 birds aged 13 and 14 days respectively. Table 31 and Table 32 list the odorants identified from the chemical and olfactory analysis.
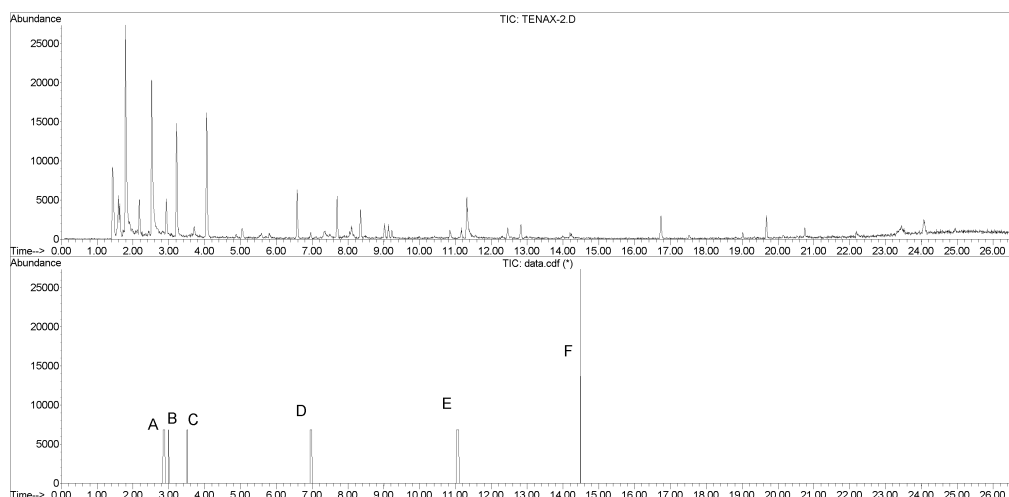
Figure 156: Total ion chromatogram and odorant chromatogram from a sample collected during summer at Farm B, containing 24,000 birds at 13 days old

The chemical compounds labelled in Figure 156 (A,B,C,D, E & F) that have been identified as the odorants from a broiler facility sampled during summer in Victoria are listed in Table 31.

Table 31:   Chemical species identified as odorants from the NMVOC suite from Farm B, containing 24,000 birds at 13 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A & B	2.86 & 3.00	Sweet/organic/Fruit	3-methyl-isovaline
C	3.52	Smoke	Toluene
D	6.94	Pine	α -pinene
E	11.05	Unpleasant, burning	L-Fenchone*(terpine)
F	14.48	Unpleasant/Earthy	Camphor*

[##] *refers to peaks in Figure 156*

The odorant characteristics changed to include unpleasant, earthy scents additional to the pine scents observed in the samples prior to bird placement. These odorants and their descriptors are listed in Table 31 and attributed to chemical species including 3-methyl-isovaline and a sweet organic odour, toluene, with a smoke-like odour and α –pinene with a pine scent.
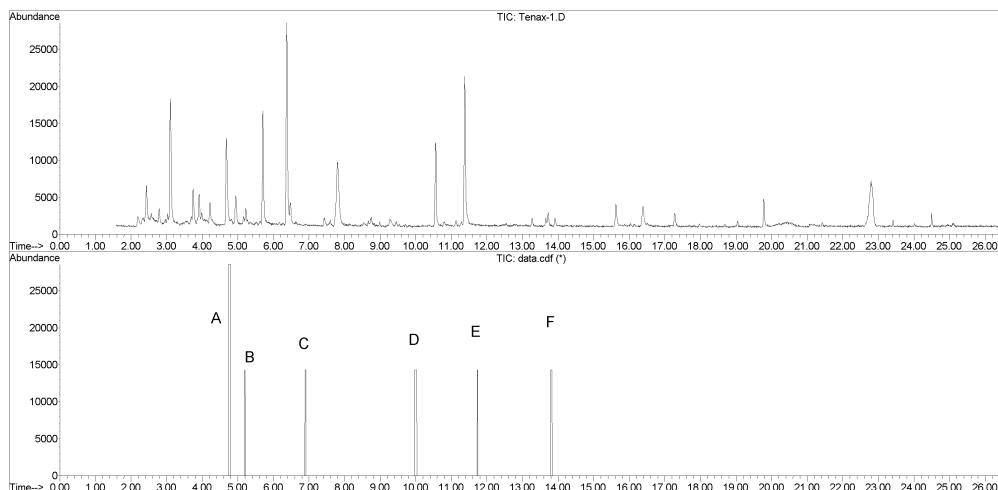
Figure 157: Total ion chromatogram and the odorant chromatogram from winter at Farm B, containing 30,215 birds at 14 day old

The chemical compounds labelled in Figure 157 (A,B,C,D, E & F) that have been identified as the odorants from a broiler facility sampled during winter in Victoria are listed in Table 32.

Table 32:   Odorants identified from the chemical and olfactory stimulus analysis from Farm B during winter with 30,215 birds at 14 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	4.77	Rancid, butter	2,3-butanedione
B	5.20	Faint solvent	2-propenenitrile*
C	6.90	Solvent/burning	Dimethyl Disulphide*
D	10.00	Unpleasant/Solvent	Unknown (no MSD peak)
E	11.74	Earth, mushroom	3-hydroxy-2-butanone
F	13.82	Metallic/Pungent	Dimethyl trisulphide

[##] *refers to peaks in Figure 157*

The odorant characteristics have again shifted from the pine scents observed in the samples prior to bird placement to more unpleasant, rancid and sulphur-esque odours as listed in Table 32 attributed to chemical species including 2,3-butanedione with a rancid butter odour, 3-hydroxy-2-butanone with an earthy mushroom scent and dimethyl trisulphide with a pungent sulphur odour.

In comparison to the odorants identified from the initial samples collected from a broiler shed void of birds (only containing bedding), the observed odorants at 13-15 days show that the chemical species are different and most likely reflect the impact promoted by the presence of the birds. The identification of sulphides and butyl species at 13-15 days is consistent with a change from a pleasant pine or woody scent observed from the empty poultry shed to more of a 'poultry' odour as the bedding material becomes soiled with bird manure.

The chemical species responsible for the olfactory stimulus within the shed at two weeks are primarily 2,3-butanedione with a rancid butter odour, 3-methyl-butanal with an unpleasant malt odour and dimethyl trisulphide with a pungent sulphur odour. These chemical species are known to be nuisance odorants (Schiffman *et al.*, 2001).

6.3.3 **Batch age ~4 weeks**

With the birds now approaching four weeks of age there was an observed change in the number and abundance of the NMVOCs identified from the chemical analysis, which was comparable with an increase in the number of odorants identified within the NMVOC suite. Figure 158 to Figure 161 show the total ion chromatograms and the odorant chromatograms for the respective samples collected in Queensland and Victoria during summer and winter. Table 33 to Table 36 list the odorants identified from the simultaneous mass selective detection and olfactory stimulus detection.

6.3.3.1 Broiler sheds in Queensland (Farm A and Farm C)
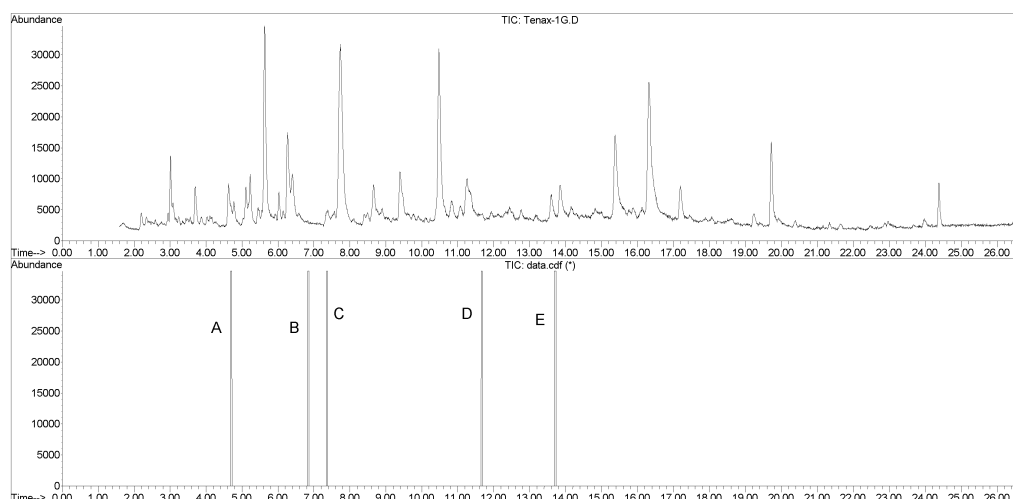
Figure 158: Total ion chromatogram and the odorant chromatogram from a sample collected during summer at Farm C, containing 39,747 birds at 28 days old

The chemical compounds labelled in Figure 158 (A,B,C,D & E) that have been identified as the odorants from a broiler shed sampled during summer in Queensland are listed in Table 33.

Table 33:   Odorants identified from the olfactory detection port from a sample collected during summer at Farm C containing 39,747 birds at 28 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	4.77	Butter	2,3-butanedione
B	6.90	Solvent/burning	Dimethyl Disulphide*
C	7.36	Faint Earthy	Unknown (no MSD Peak)
D	11.65	Faint Earthy	3-hydroxy-2-butanone
E	13.70	Metallic/Pungent	Dimethyl trisulphide

[##] *refers to peaks in Figure 158*
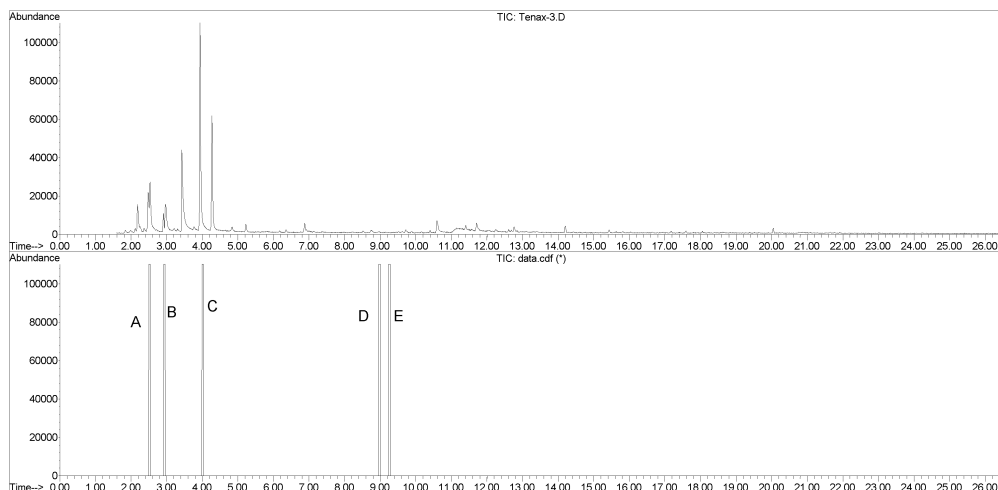
Figure 159: Total ion chromatogram and odorant chromatogram from a sample collected during winter at Farm A, containing 31,913 birds at 28 days old

The chemical compounds labelled in Figure 159 (A,B,C,D & E) that have been identified as the odorants from a broiler shed sampled during winter in Queensland are listed in Table 34.

Table 34: **Odorants identified from a sample collected during winter in Queensland from Farm A, containing 31,913 birds at 28 days old**

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	2.52	Butter, rancid	2,3-butanedione
B	2.94	Malt, unpleasant	3-methyl-butanal
C	4.02	Smoke, burning	Dimethyl disulphide
D	8.96	Pungent, metallic	Dimethyl trisulphide*
E	9.26	Earthy, mushroom	β-pinene*

[##] *refers to peaks in Figure 159*

6.3.3.2 Broiler sheds in Victoria (Farm B)
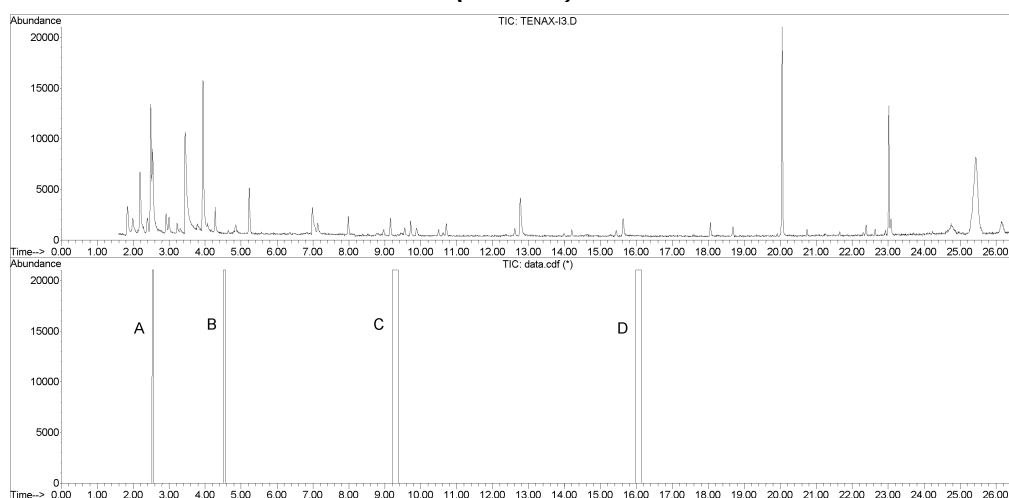
Figure 160: Total ion chromatogram and odorant chromatogram from a sample collected during summer at Farm B containing 22,000 birds at 32 days old

The chemical compounds labelled in Figure 160 (A,B,C & D) that have been identified as the odorants from a broiler shed sampled during summer in Victoria are listed in Table 35.

Table 35:   Odorants identified from a sample collected during summer at Farm B containing 22,000 birds at 32 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	2.55	Cheese, unpleasant	2,3-butanedione
B	4.55	Smoke, burning	Dimethyl disulphide
C	9.30	Pungent, metallic	Dimethyl trisulphide
D	16.05	Rancid, citrus	Heptanal

[##] *refers to peaks in Figure 160*
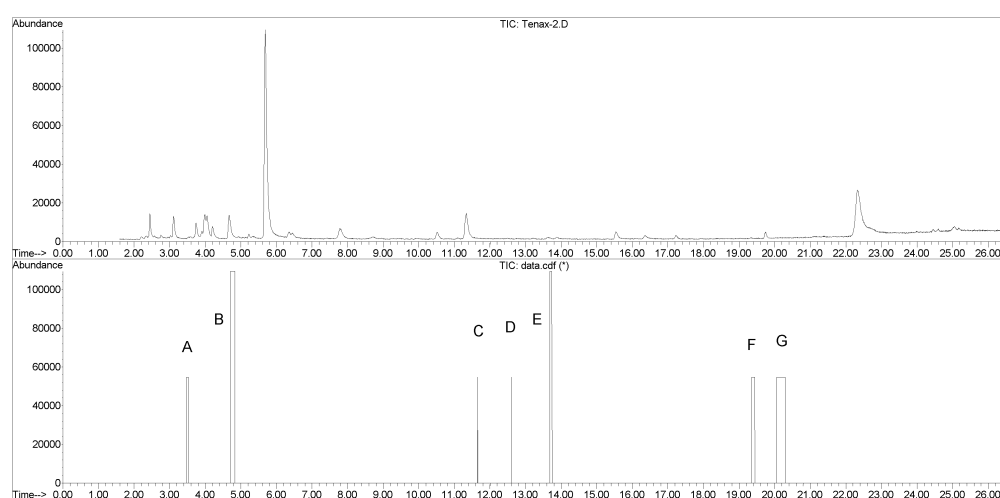
Figure 161: Total ion chromatogram and the odorant chromatogram from a sample collected during winter at Farm B containing 29,876 birds at 29 days old

The chemical compounds labelled in Figure 161 (A,B,C,D, E, F & G) that have been identified as the odorants from a broiler shed sampled during winter in Victoria are listed in Table 36.

Table 36:   Odorants identified from a sample collected during winter at Farm B containing 29,876 birds at 29 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	3.50	Sweet, solvent	Acetone*
B	4.75	Butter, rancid	2,3-butanedione
C	11.65	Non-descript	3-hydroxy-2-butanone
D	12.61	Non-descript	Unknown (no MSD peak)
E	13.68	Non-descript	Dimethyl trisulphide
F	19.35	Non-descript	Unknown (no MSD peak)
G	20.16	Non-descript	Unknown (no MSD peak)

[##] *refers to peaks in Figure 161*

Note: Occasionally the microphone used to record the odorant descriptor was unable to effectively record the voice comment of the operator and thus the descriptor was listed as non-descript.

A suite of odorant species have been identified with characteristics consistent with a trend towards an unpleasant hedonic tone. Chemical species identified from the simultaneous mass spectral and olfactory stimulus detection have included 2,3-butanedione with a rancid butter odour, dimethyl trisulphide with a pungent sulphur odour, 3-hydroxy-2-butanone with an earthy mushroom odour and dimethyl disulphide with a smoky, burning odour. These have been previously reported as nuisance odorants (Schiffman *et al.*, 2001), but they were found in the exhaust air, their contribution to the character of the whole odour was not quantified.

6.3.4 Batch age ~7 weeks

Figure 162 to Figure 165 show the total ion chromatograms and the odorant chromatograms from Farms A, B and C during summer and winter, with each broiler shed containing 7,000~21,000 birds of approximately 7 weeks of age. Table 37 to Table 40 list the odorants identified from the chemical and odorant analysis.
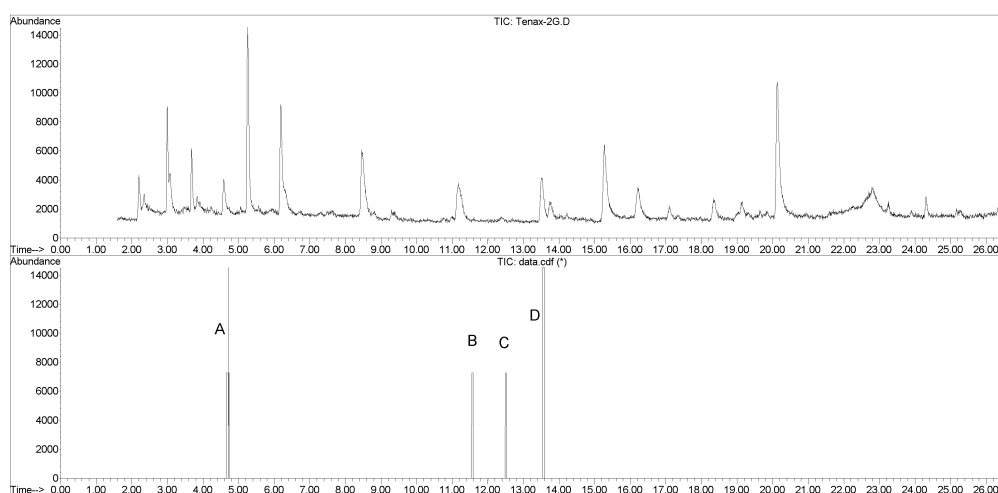
Figure 162: Total ion chromatogram and odorant chromatogram from a sample collected during summer at Farm C containing 21,083 birds of 49 days old

The chemical compounds labelled in Figure 162 (A,B,C & D) that have been identified as the odorants from a broiler shed sampled during summer in Queensland are listed in Table 37.

Table 37:   Odorants identified from a sample collected during summer at Farm C, containing 21,083 birds at 49 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	4.68	Rancid	3-methyl-butanal
B	11.56	Mushroom, earth	3-hydroxy-2-butanone
C	12.50	Meat	Unknown (no MSD Peak)
D	13.56	Pungent Metallic	Dimethyl trisulphide

[##] *refers to peaks in Figure 162*

184
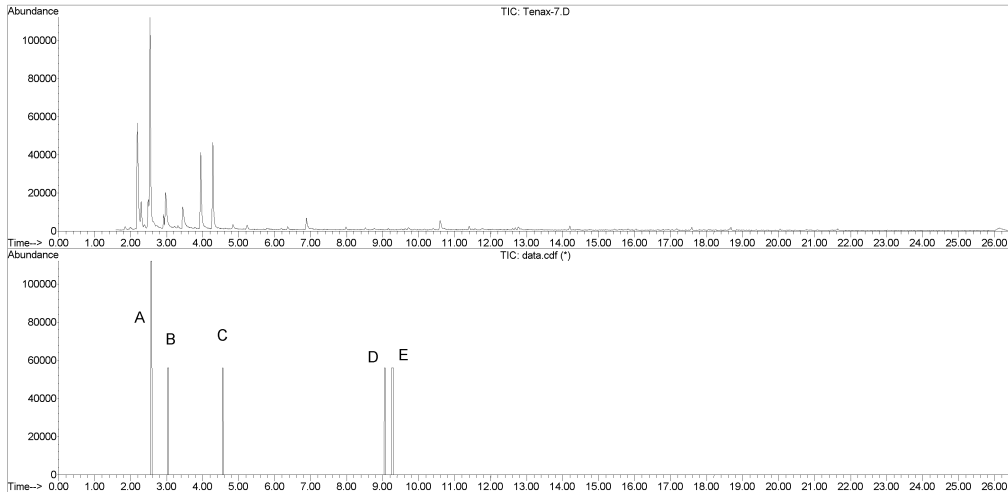
Figure 163: Total ion chromatogram from a sample collected during winter in Queensland from Farm A containing 12,018 birds at 48 days old

The chemical compounds labelled in Figure 163 (A,B,C,D & E) that have been identified as the odorants from a broiler shed sampled during winter in Queensland are listed in Table 38.

Table 38:   Odorants identified from a sample collected during winter at Farm A, containing 12,018 birds at 48 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	2.58	Butter, rancid	2,3-butanedione
B	3.04	Solvent	1-butanol
C	4.56	Solvent	Toluene
D	9.06	Pungent, metallic	Dimethyl trisulphide*
E	9.28	Earth	β-pinene*

[##] *refers to peaks in Figure 163*
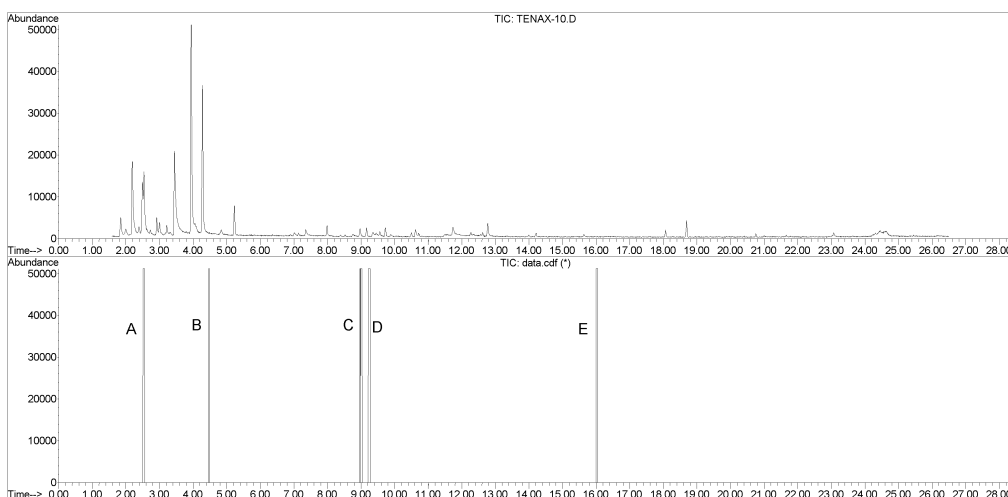
Figure 164: Total ion chromatogram and odorant chromatogram from a sample collected during summer at Farm B containing 13,636 birds at 46 days old

The chemical compounds labelled in Figure 164 (A,B,C,D & E) that have been identified as the odorants from a broiler shed sampled during summer in Victoria are listed in Table 39.

Table 39: Odorants identified from a sample collected during summer from Farm B, containing 13,636 birds at 46 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	2.54	Butter, rancid	2,3-butanedione
B	4.47	Burning, rubber	Dimethyl disulphide
C	9.00	Pungent, metallic	Dimethyl trisulphide
D	9.25	Earth, mushroom	β-pinene
E	16.02	Gas, earth	Unknown (no MSD peak)

[##] *refers to peaks in Figure 164*
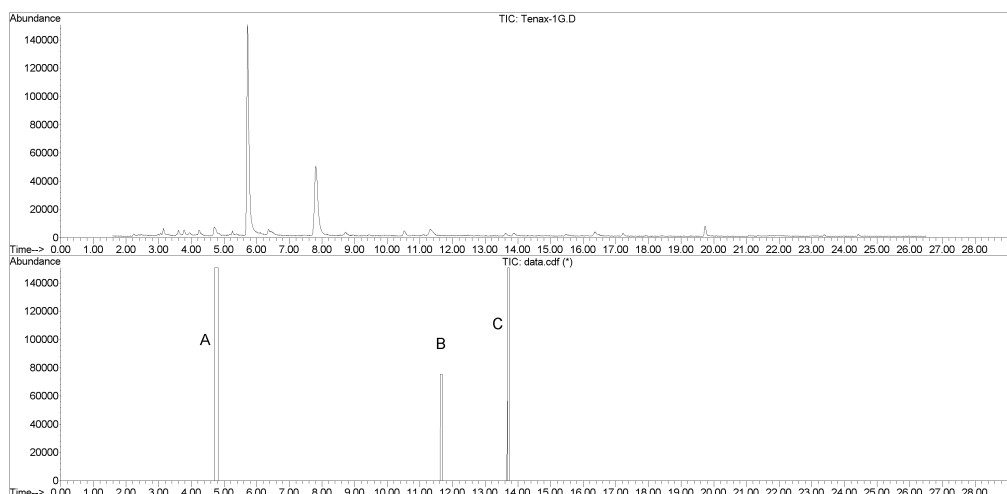
Figure 165: Total ion chromatogram and the odorant chromatogram from a sample collected during winter at Farm B containing 7,773 birds at 49 days old

The chemical compounds labelled in Figure 165 (A,B & C) that have been identified as the odorants from a broiler shed sampled during winter in Victoria are listed in Table 40.

Table 40: Odorants identified from a sample collected during winter from Farm B containing 7,773 birds at 49 days old

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	4.76	Rancid, fat	2,3-butandione
B	11.66	Mushroom	3-hydroxy-2-butanone
C	13.70	Metallic	Dimethyl trisulphide

[##] *refers to peaks in Figure 165*

The chemical and odorant analysis of the samples collected at the different farms toward the end of each batch showed a presence of 2,3-butanedione and 3-methyl-butanal. There was also a consistent dominance of dimethyl trisulphide within the odorant profiles, characterised by a pungent sulphur odour, although frequently having little to almost negligible response from the mass selective detector. While

odorants described as unpleasant were found in the exhaust air, their contribution to the character of the whole odour was not quantified.

6.3.5 Post bird removal

The presence of the spent litter within the broiler shed once the grow-out cycle of the birds has concluded represents a potential emission source for odour emissions. Samples were collected during summer in Victoria once the birds were removed from the shed before the spent litter had been removed. Figure 166 illustrates the total ion chromatogram and odorant chromatogram from a sample collected, whilst the abundances of the chemical species was lower than when the birds were present, there were still discernable odorant peaks. Table 41 lists the odorants identified from the chemical and odorant analysis.
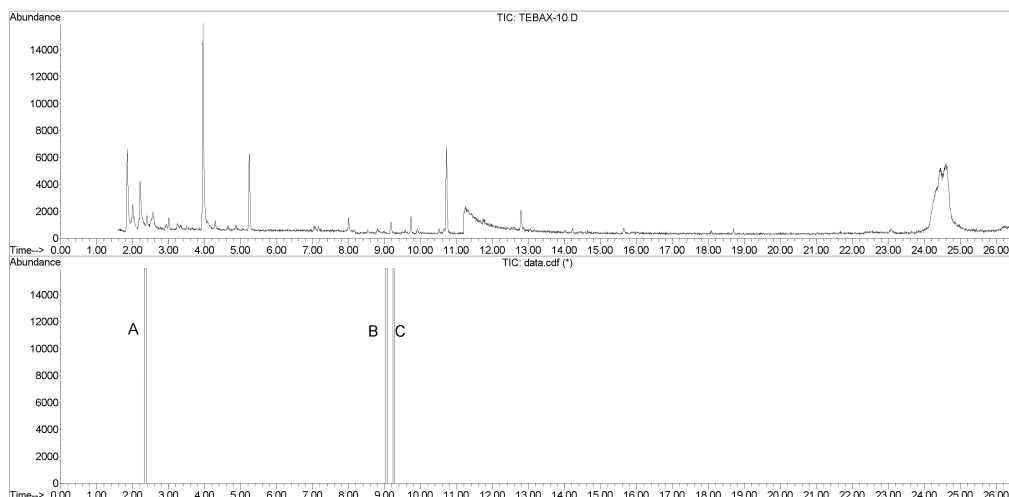
Figure 166: Total ion chromatogram and odorant chromatogram from a sample collected during summer from Farm B with only the spent litter present

The chemical compounds labelled in Figure 166 (A,B & C) that have been identified as the odorants from a broiler shed sampled post bird removal in Victoria during summer are listed in Table 41.

Table 41:   Odorants identified from a sample collected during summer from Farm B with only the spent litter present

Odour Peak		Descriptor	Chemical
Label[##]	RI (min.)		
A	2.35	Faint solvent	Acetone
B	9.06	Pungent, sulphur	Dimethyl trisulphide*
C	9.25	Earth, mushroom	β-pinene

[##] *refers to peaks in Figure 166*

The presence of odorants with descriptors pungent, sulphur and earthy mushroom detected in the broiler shed post bird removal demonstrates that the spent litter is a source of unpleasant smelling odorants.

6.3.6 Queensland broiler shed comparison (Farms I to M)

During the initial broiler shed sampling during 2005–2006, the results of the dilution olfactometry testing and NMVOC analysis revealed that odour and NMVOC emissions peaked when the birds were approximately five weeks of age (35 days). For this reason, a series of broiler sheds in Queensland were selected to determine any similarities between sites when the birds were approximately 35 days.

Field sampling of sorbent tubes was undertaken at different broiler sheds with birds ranging from 31 to 36 day of age, with bird numbers ranging from 29,680–42910, the following total ion chromatograms are illustrated with two odour stimulus chromatograms. Each pair of olfactory stimulus chromatograms (OSC) represents a highly sensitive (upper OSC) receptor and a normal receptor (lower OSC) as determined by the Australian Standard (AS/NZS 4323.3:2001) *n*-butanol test for assessing panellist suitability for dilution olfactometry. By engaging multiple operators to undertake the olfactory detection an understanding can be gained as to the subjective nature of the odours and how different odorants will potentially impact on different receptors. A series of replicates were collected and analysed by two experienced operators; the first being highly sensitive and the second considered to fall within the normal (20–80 ppb) range for *n*-butanol sensitivity.

(Note: NMVOC samples were also collected at Farms F, G and H, but analysis of the sorbent tubes was unable to be completed due to an equipment malfunction.)

6.3.6.1 Farm I

The first broiler shed for the comparison contained 42,463 broilers at 34 days of age. Figure 167 illustrates the total ion chromatogram and the olfactory stimulus chromatogram from this broiler shed, whilst Table 42 lists the odorants detected by the two operators and the characteristic of these odorants as interpreted by each operator respectively.
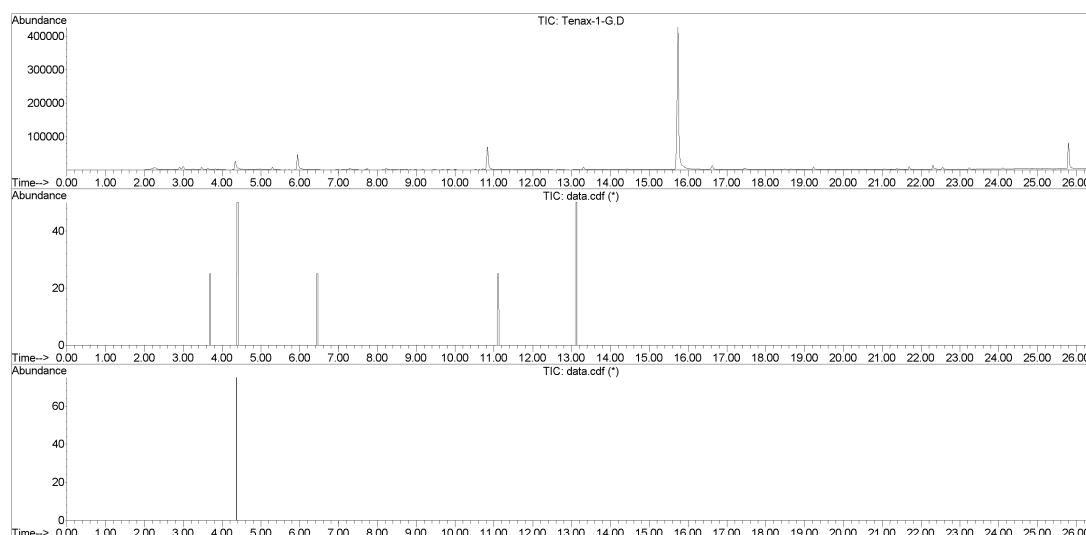
Figure 167: Total ion chromatogram and olfactory stimulus chromatograms from Farm I, containing 42,463 birds aged 34 days

The chemical compounds that have been identified as the odorants and their respective descriptors as characterised by the two operators from Farm I containing 42,463 birds aged 34 days are listed in Table 42.

Table 42: Odorants and the descriptors given by each operator identified from samples collected during autumn from Farm I containing 42,463 birds aged 34 days

Odour Peak RI (min)	Descriptor		Chemical
	Operator 1	Operator 2	
3.68	Acrid, solvent		3-methyl-butanal
4.40	Butter, rancid	Solvent smell	2,3-butanedione
6.45	Burning, solvent		hexanal
11.08	Earthy, mushroom	Solvent smell	3-hydroxy-2-butanone
13.12	Pungent, metallic		Dimethyl trisulphide

6.3.6.2 Farm J

The second broiler shed for the comparison contained 42,910 broilers at 35 days of age. Figure 168 illustrates the total ion chromatogram and the olfactory stimulus chromatogram from this broiler shed, whilst Table 43 lists the odorants and their descriptors as identified by the two operators.
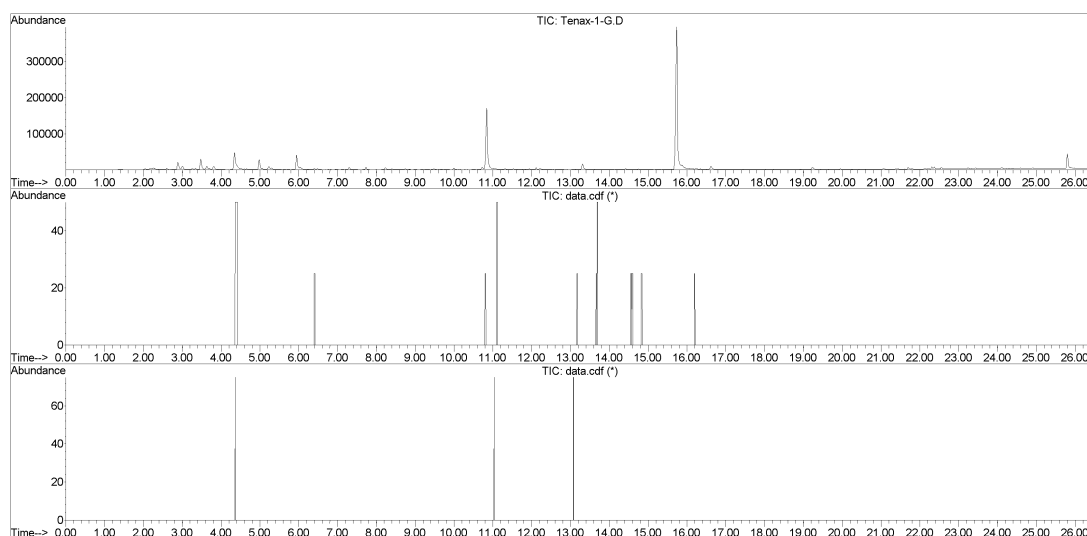
Figure 168: Total ion chromatogram and olfactory stimulus chromatograms from Farm J, containing 42,910 birds aged 35 days

The chemical compounds that have been identified as the odorants and their respective descriptors as characterised by the two operators from Farm J containing 42,910 birds aged 35 days are listed in Table 43.

Table 43:   Odorants and the descriptors given by each operator identified from samples collected during autumn from Farm J containing 42,910 birds aged 35 days

Odour Peak	Descriptor		Chemical
RI (min)	Operator 1	Operator 2	
4.40	Rancid, butter		2,3-butanedione
6.40	Smoke, burning	Solvent smell	hexanal
10.80	Green, citrus		Octanal
11.10	Earth, mushroom	Solvent smell	3-hydroxy-2-butanone
13.16	Pungent, sulphur	Sulphur compound	dimethyl trisulphide
13.66	Sweet, ether		2-butoxy-ethanol*
14.57	Plastic, solvent		unknown
14.84	Plastic, solvent		unknown
16.20	Solvent, plastic		2-ethyl-1-hexanol

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6.3.6.3 Farm K

The third broiler shed for the comparison contained 43,000 broilers at 31 days of age. Figure 169 illustrates the total ion chromatogram and the olfactory stimulus chromatogram from this broiler shed, whilst Table 44 lists the odorants and their descriptors as characterised by the two operators.
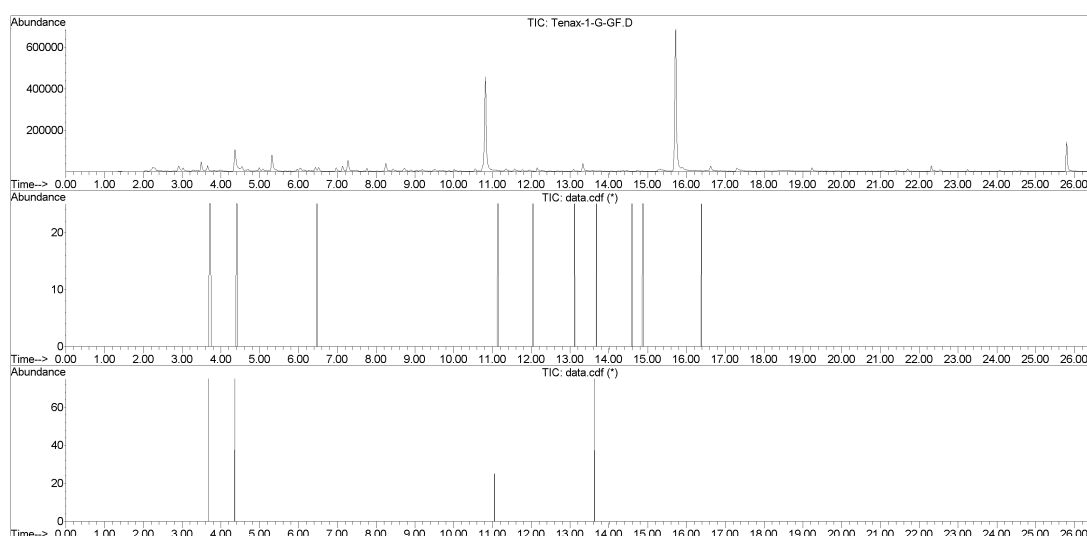
Figure 169: Total ion chromatogram and olfactory stimulus chromatograms from Farm K containing 43,000 birds aged 31 days

The chemical compounds that have been identified as the odorants and their respective descriptors as characterised by the two operators from Farm K containing 43,000 birds aged 31 days are listed in Table 44.

Table 44:   Odorants and the descriptors given by each operator identified from samples collected during autumn from Farm K containing 43,000 birds aged 31 days

Odour Peak RI (min)	Descriptor		Chemical
	Operator 1	Operator 2	
3.76	Ethereal	Butanol	3-methyl-butanal
4.40	Rancid, butter	Solvent	2,3-butanedione
6.40	Smoke, burning		hexanal
11.10	Earth, mushroom	Solvent	3-hydroxy-2-butanone
12.05	Meat, cooking		unknown
13.10	Pungent, sulphur		dimethyl trisulphide
13.68	Earthy, mushroom	Solvent	2-butoxy-ethanol*
14.60	Plastic, solvent		unknown
14.88	Plastic		unknown
16.38	Solvent, plastic		2-ethyl-1-hexanol

6.3.6.4 Farm L

The fourth broiler shed for the comparison contained 42,675 broilers at 34 days of age. Figure 170 illustrates the total ion chromatogram and the olfactory stimulus chromatogram from this broiler shed, whilst Table 45 lists the odorants identified from the chemical and odorant analysis.
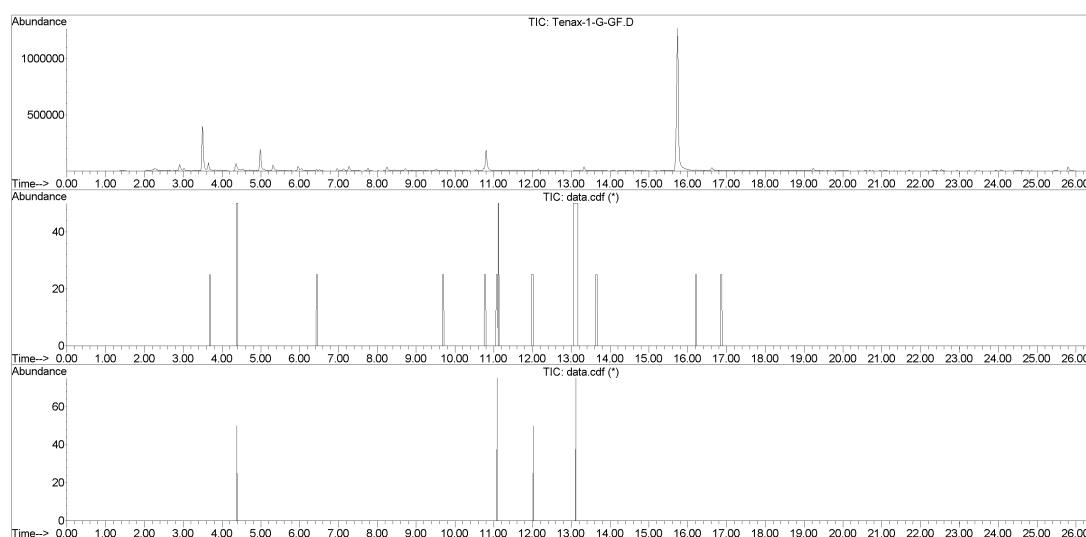
Figure 170: Total ion chromatogram and olfactory stimulus chromatograms from Farm L containing 42,675 birds aged 34 days

The chemical compounds that have been identified as the odorants and their respective descriptors as characterised by the two operators from Farm L containing 42,675 birds aged 34 days are listed in Table 45.

Table 45:   Odorants and the descriptors given by each operator identified from samples collected during autumn from Farm L containing 42,675 birds aged 34 days

Odour Peak RI (min)	Descriptor		Chemical
	Operator 1	Operator 2	
3.70	Pungent		3-methyl-butanal
4.40	Rancid, butter	Solvent	2,3-butanedione
6.40	Smoke, solvent		hexanal*
9.70	Rancid		unknown
10.78	Detergent, citrus		octanal
11.10	Earth, mushroom	Solvent	3-hydroxy-2-butanone
12.00	Popcorn, butter	Roasted nut	N,N-dimethyl-formamide
13.10	Pungent, sulphur	Sulphur compound	dimethyl trisulphide
13.65	Solvent		2-butoxy-ethanol*
16.22	Solvent		2-ethyl-1-hexanol
16.86	Solvent		Benzaldehyde

6.3.6.5 Farm M

The fifth broiler shed for the comparison contained 33,684 broilers at 32 days of age. Figure 171 illustrates the total ion chromatogram and the olfactory stimulus chromatogram from this broiler shed.
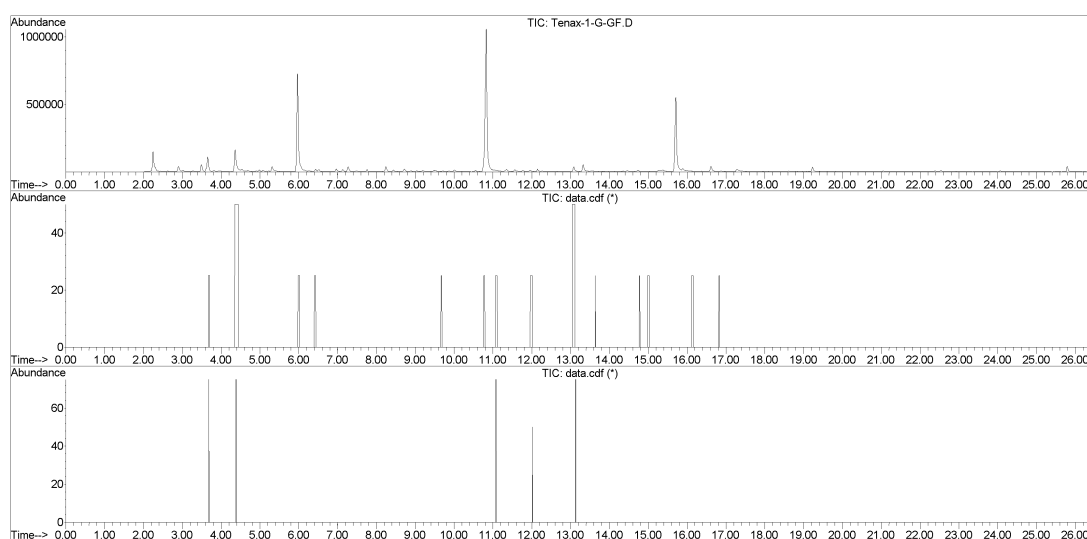
Figure 171: Total ion chromatogram and olfactory stimulus chromatograms from Farm M, containing 33,684 birds aged 32 days

The chemical compounds that have been identified as the odorants and their respective descriptors as characterised by the two operators from Farm M containing 33,684 birds aged 34 days are listed in Table 46.

Table 46: Odorants and the descriptors given by each operator identified from samples collected during autumn in Queensland from a broiler house containing 33,684 birds aged 32 days

Odour Peak RI (min)	Descriptor		Chemical
	Operator 1	Operator 2	
3.70	Pungent	Butanol	3-methyl-butanal
4.40	Rancid, butter	Solvent	2,3-butanedione
6.00	Pungent, sulphur		dimethyl disulphide
6.40	Smoke, solvent		hexanal*
9.68	Smoke, burning		unknown
10.78	Detergent, citrus		octanal
11.10	Earth, mushroom	Solvent	3-hydroxy-2-butanone
12.00	Cooking, oil	Roasted nut	N,N-dimethyl-formamide
13.10	Pungent, sulphur	Sulphur compound	dimethyl trisulphide
13.65	Mushroom		2-butoxy-ethanol*
16.14	Plastic, solvent		2-ethyl-1-hexanol
16.84	Solvent		Benzaldehyde

6.3.6.6 *Broiler farm comparison summary*

The results from the comparison of the broiler sheds containing birds aged approximately 5 weeks revealed that there were similarities in the chemical species present and the odorants being detected by the two operators. One of these operators was hypersensitive to odour according to the n-butanol test and consequently recorded higher levels of odorant stimulus compared to the other operator, who had 'normal' sensitivity to n-butanol.

The chemical species identified and characterised by the operators as odorants that were consistently detected within the majority of the samples included a predominance of aldehydes and ketones, with sulphide species also present. These odorants were characterised by general unpleasant descriptors including 2,3-butanedione with a rancid butter odour, 3-methyl-butanal with a pungent odour, burning/solvent odour of hexanal, the citrus/detergent odour of octanal, with the additional pungent and sulphur odours of dimethyl disulphide and dimethyl trisulphide.

6.3.7 Summary of broiler shed odorant identification

The chemical speciation of the NMVOCs that were identified from the different broiler sheds provided insight into the chemical composition of the emissions. The identification and characterisation of the odorants within the NMVOC suite improves understanding of the contribution of these chemicals to the strength and character of what is recognised as 'poultry odour'. It must be remembered that the presence of individual odorants will not necessarily dominate the overall character or strength of the whole odour.

The odorants identified from the broiler shed prior to bird placement were dominated by woody, pine scents of various terpines including α-pinene, β-pinene and limonene. Once the birds were placed and the bedding material within the broiler sheds became increasingly soiled, the character of the odorants being detected shifted towards descriptors of an unpleasant nature. These odorants were predominantly characterised by aldehydes and ketones with unpleasant descriptors including rancid butter of 2,3-butanedione, unpleasant malt of 3-methyl-butanal, rancid citrus of heptanal and burning solvent of hexanal. The presence of sulphur compounds was significant as they are odorants with very low odour detection thresholds, and are characterised by the pungent sulphur of dimethyl trisulphide and burning sulphur of dimethyl disulphide. Table 47 lists the odorants and their descriptors identified in the majority of samples from the sampling at broiler sheds.

Table 47:   Odorants and their respective descriptors identified from broiler shed emissions

Descriptor	Chemical
Solvent, sweet	Acetone
Butter, rancid, fat	2,3-butanedione
Mushroom, earth	3-hydroxy-2-butanone
Smoke, burning, rubber	Dimethyl disulphide
Solvent	1-butanol
Malt, rancid	3-methyl-butanal
Rancid, citrus	Heptanal
Green, citrus	Octanal
Sweet, solvent	Benzene
Sweet, solvent	Toluene
Metallic, sulphur, pungent	dimethyl trisulphide
Pine	α-pinene
Earth, mushroom	β-pinene

6.4 Quantification of NMVOC odorants

The non-methane volatile organic compound (NMVOC) and odorant emissions from poultry houses contain numerous chemical species including aldehydes, ketones, terpines and sulphides. Following on from chemical speciation and odorant identification, the a selection of chemicals identified as the key odorants within the NMVOC emissions were quantified—including 2,3-butanedione, 3-methyl-butanal 3-hydroxy-2-butanone and toluene; additionally dimethyl disulphide was quantified as it was observed to be an odorant in the majority of samples. Quantification of some compounds was not possible for all samples collected—a chemical species may have elicited an olfactory response yet been absent in a mass spectral response, or it may have been of inadequate abundance to be considered above the level of quantification.

6.4.1 Details of NMVOC quantification — refinement of methods

Throughout the initial stages of the project, the laboratory analysis method was refined to improve data acquisition and maximize the interpretation of the data collected from each sample. These methodological improvements must be considered when comparing spectra from different sampling campaigns to ensure that the correct conclusions are drawn.

Improved GC column selection

Initial gas chromatographic analysis was performed using a non-polar column (HP-5ms, (5%-Phenyl)-methylpolysiloxane) but it was soon realised that this would not be the most appropriate option for low molecular weight moderately polar molecules (aldehydes and ketones). A comparative experiment was conducted using a series of duplicate samples to evaluate the relative performance of a polar column (HP-INNOWax, polyethylene glycol). It was found that the polar column provided increased compound separation over the same run time without the co-elution of the non-polar column allowing for more accurate peak integration and hence quantification.

Compounds present but not quantifiable

The analysis procedure could not be targeted to ideally suit the quantification of each compound of interest because each sample had a diverse range and abundance of NMVOCs. Consequently, there were instances when a compound was found to be present but was below the level of quantification. To further explain this, it is commonly accepted with chemical analysis that the signal from a detector will have a baseline value (considered to be unavoidable noise) above which will be the actual detector response. The limit of detection for a chemical is considered to be at a detector response signal three times the baseline (level of detection; $LOD = 3$ x the baseline). The limit of quantification is considered to be at a detector response signal ten times higher than the baseline (limit of quantification; $LOQ = 10$ x baseline). Therefore, the abundance of a chemical in each sample needed to be ten times greater than the baseline value otherwise it wouldn't be quantifiable.

Calibration compounds

To enable quantification of compounds detected in each sorbent tube, specific compounds of known concentration are used to calibrate or scale the response from the GC-MS. The compounds selected for the calibration were either compounds that frequently appeared in field samples or closely related species to provide a method of relative quantification. To afford coverage of a large range of compounds, nine diverse compounds were selected: these were 2-butanone, 3-methyl-2-butanone, benzene, 2,3-butanedione, toluene, dimethyl disulphide, 1-butanol, 3-hydroxy-2-butanone and acetic acid. Of the extensive list of compounds that have been identified within the VOC suite from the poultry house emissions, only a few have been identified as odorants, therefore quantification has focussed on these odorants. The rationale for the selection of these compounds is both their frequency of identification in different samples, and their dominance within the olfactory stimulus chromatograms.

6.4.2 Abundance of NMVOC odorants present in broiler sheds

One of the NMVOCs consistently identified as an odorant using gas chromatography-mass spectrometry/olfactometry (GC-MS/O) was 2,3-butanedione. It was chosen for detailed quantification throughout the sampling campaigns of the broiler houses. Dimethyl disulphide was also selected for quantification despite not being an NMVOC, as it was recognised to be a frequently occurring odorant in the broiler sheds.

Abundance results have been expressed per bird to simplify comparison between batches and farms. To approximate the total emission rate of the compound, the abundance value needs to be multiplied by the number of birds in the shed and the ventilation rate.

It can be seen in the following sections that certain odorants increase in abundance in the shed throughout the batch. This increase in odorant abundance compares well with the increase in odour emissions (determined using dilution olfactometry) throughout the batch and may help to explain the observed changes.

6.4.2.1 2,3-butanedione from Farms A, B and C

Emission of 2,3-butanedione was able to be quantified at Farms A during winter (except samples collected on 21/06/2006), Farm B during winter and Farm C during summer (see Figure 172, Figure 173 and Figure 174 respectively). These figures illustrate the variation of 2,3-butanedione with the growth cycle of the birds. Sampling conditions on each date can be derived from the tables provided in the appendices.

It was observed that the abundance of 2,3-butanedione generally tended to increase throughout each batch (with the exception of Farm C, due to an unexplainable high abundance recorded on the first sampling day). With ventilation rate also expected to generally increase throughout the batch, it would be expected that the emission of this compound would also increase throughout each batch.

The unrefined gas-chromatographic method used for analysing samples from Farm A and Farm B during summer yielded inadequate retention time separation between 2,3-butanedione and 2-butanone, consequently there was not possible to quantify NMVOCs for these batches.
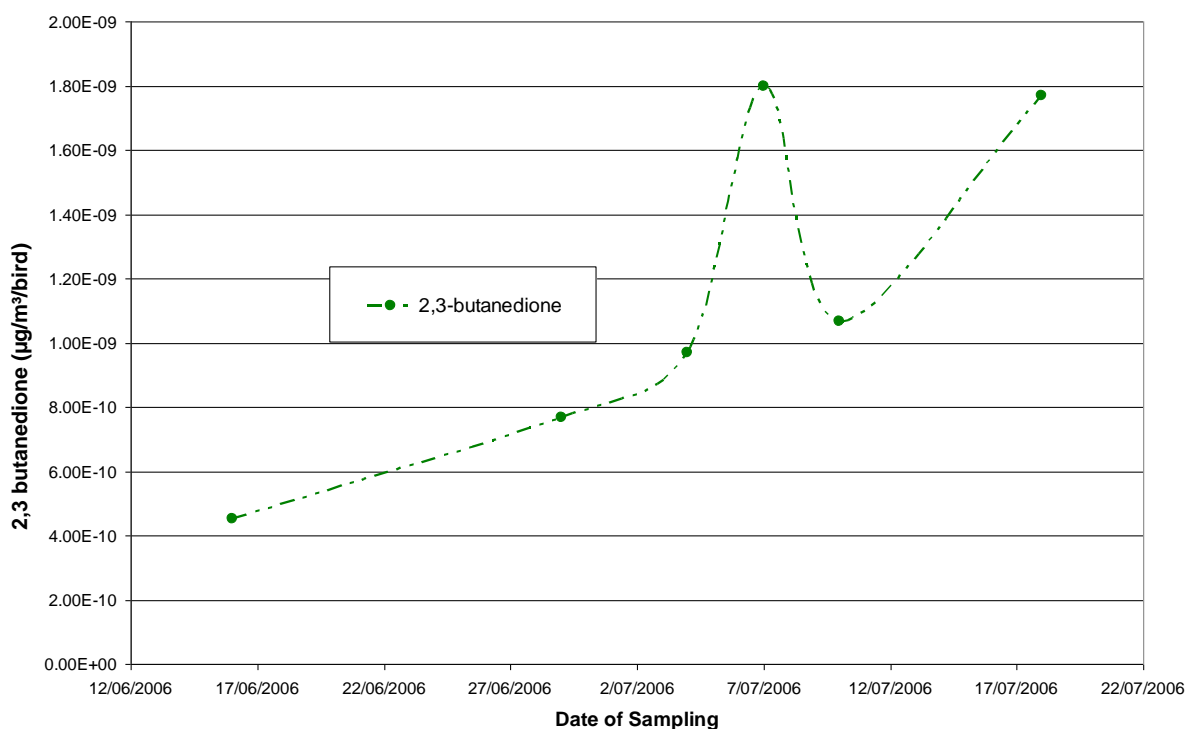
Figure 172: 2,3-butanedione from Farm A during winter
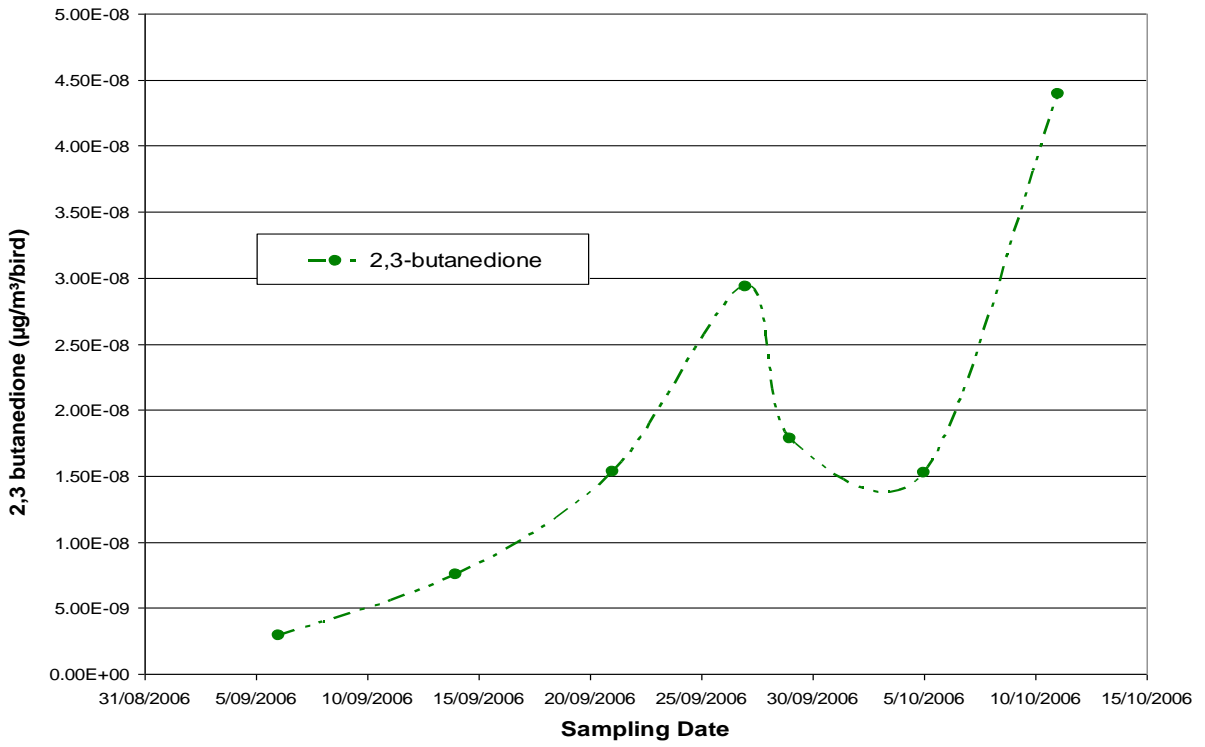
Figure 173: 2,3-butanedione from Farm B during winter
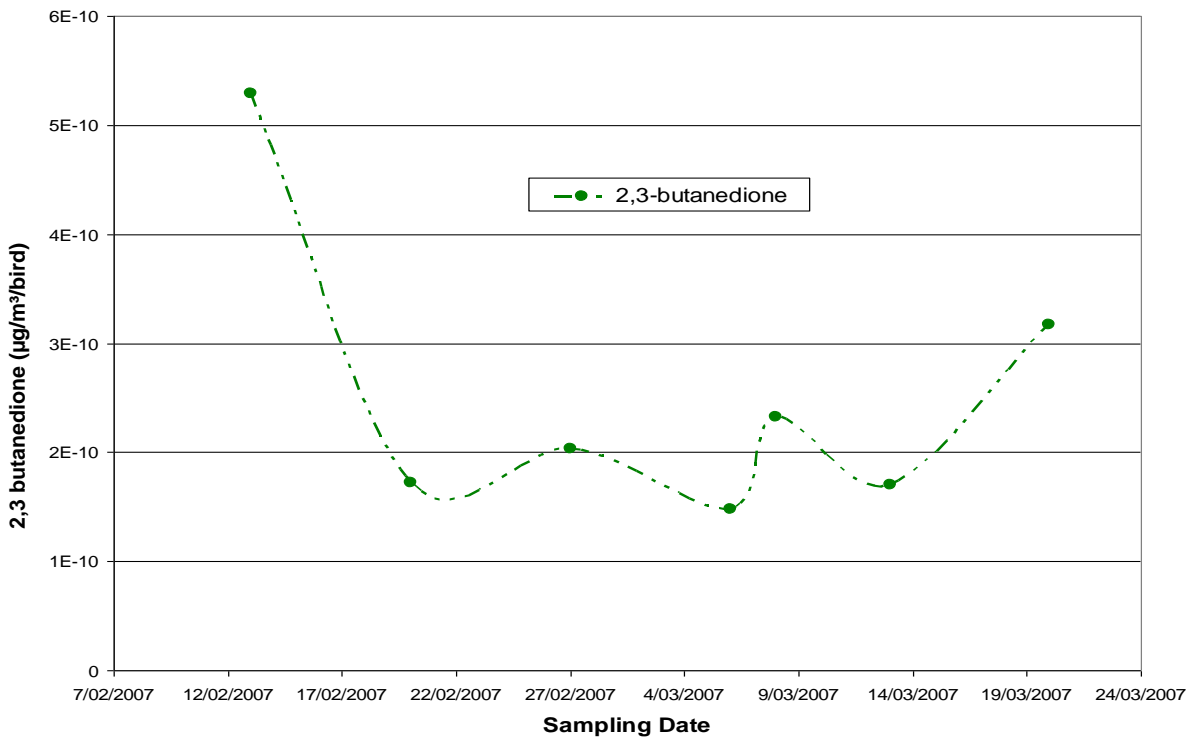
Figure 174: 2,3-butanedione from Farm C during summer

6.4.2.2 Dimethyl disulphide from Farms A, B and C

Although not a NMVOC, the significance of the presence of dimethyl disulphide should not be disregarded. It is *per se* an odorant and it also indicates towards a strong probability that methyl mercaptan (a considerably more potent odorant) may be present in the shed.

Abundance of dimethyl disulphide was able to be quantified for samples collected at Farm A during winter, Farm B during summer and Farm C during summer (see Figure 175, Figure 176 and Figure 177 respectively). These figures illustrate the variation of the dimethyl disulphide with the growth cycle of the birds. Note that there are more sample points for Farm C because of the revised sampling program.

As observed with 2,3-butanedione, there was a tendency for the abundance of dimethyl disulphide to increase throughout the batch. With the expectation of increasing ventilation rate through the batch, it would be expected that the emission rate of this compound would also be increasing.
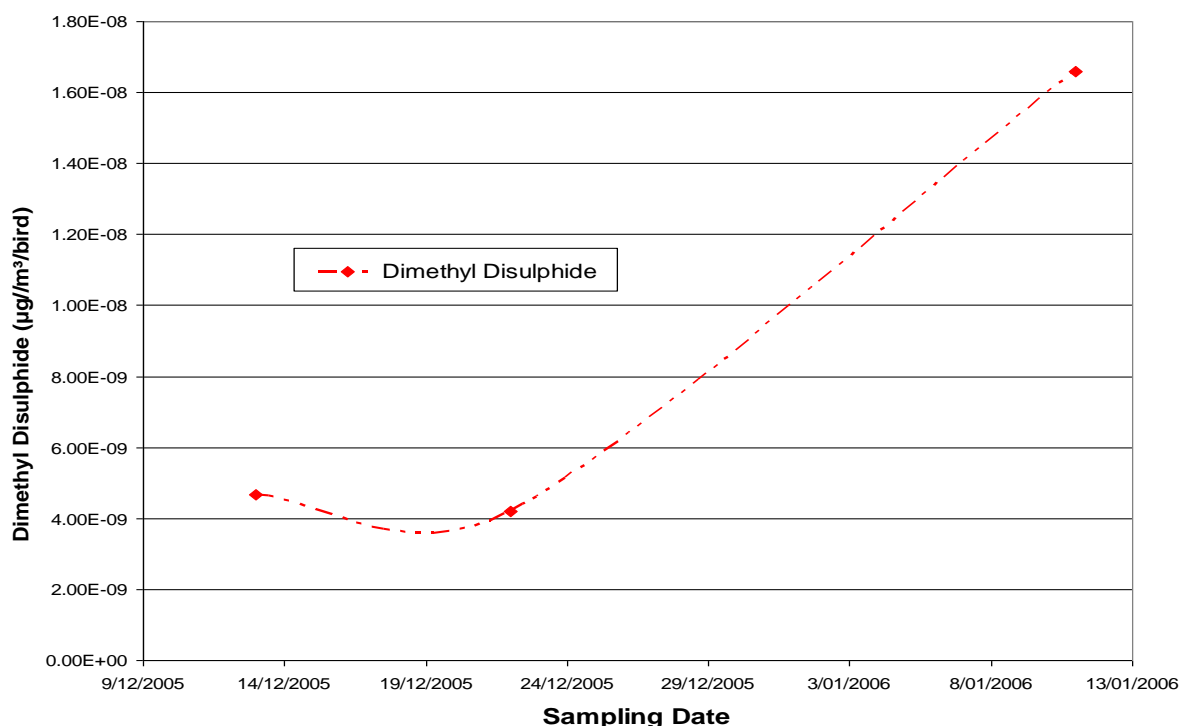
Figure 175: Dimethyl disulphide measured from Farm A during summer
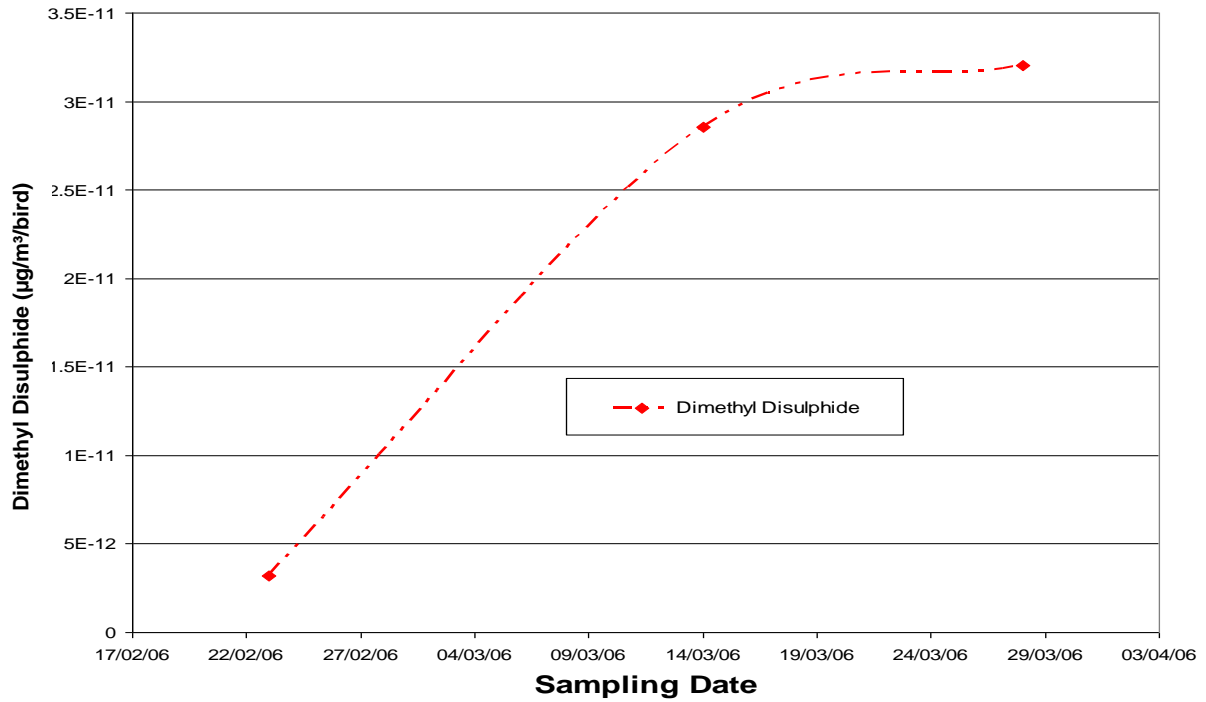
Figure 176: Dimethyl disulphide from Farm B during summer
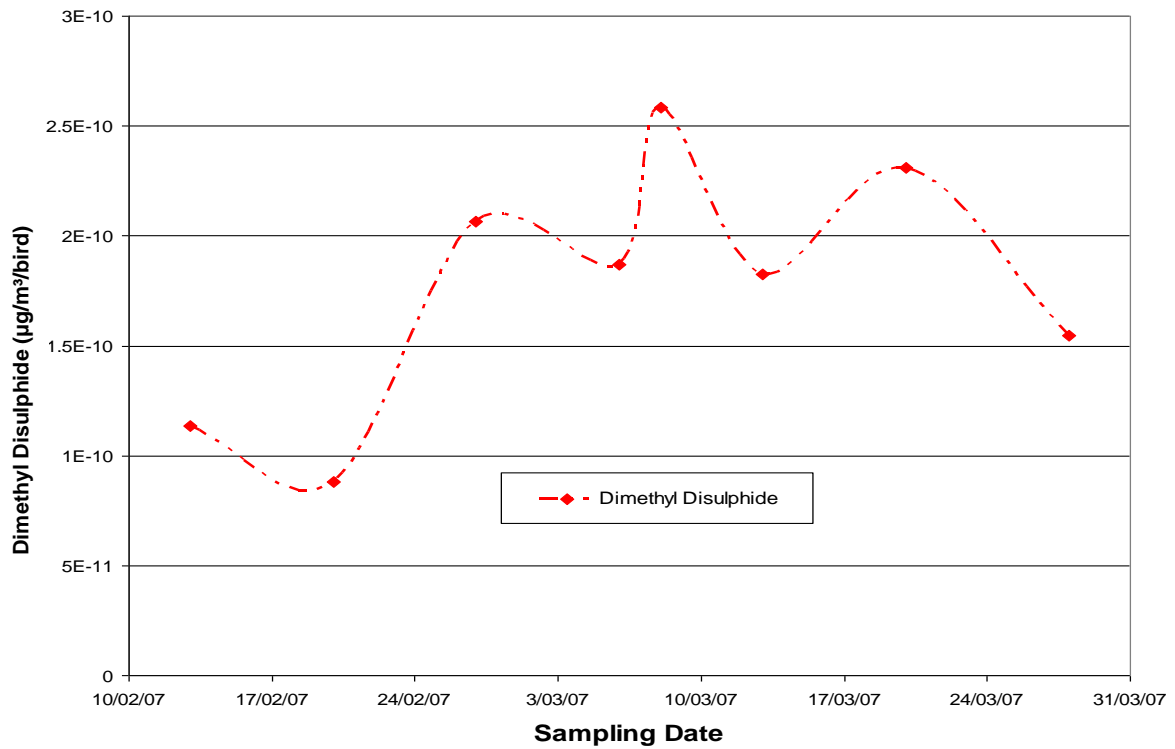
Figure 177: Dimethyl disulphide from Farm C during summer

6.4.2.3 NMVOC diversity and abundance - comparison at Farms H to M

NMVOCs were quantified at broiler sheds H to M around 31 – 35 days of bird age to assess inter-farm variability. It was intended that Farms F and G would also be included in this comparison but the data is not available due to an equipment malfunction during the quantification analysis. Figure 178 illustrates the variability in the chemical composition of five broiler houses when standardised to the number of the birds in each shed. It can be seen that the composition of the air was different at each of the five broiler sheds.

In general, there was a lower overall abundance of odorants at Farm I and a higher abundance of odorants at Farm M. Farm M also featured a higher abundance of Dimethyl Disulphide than the other farms. If the combined abundance of these selected odorants are compared with the odour concentrations results (measured using dilution olfactometry, see Appendix 10), it can be seen that they are generally comparable—Farm M had the highest odour concentration of these six farms and the remaining five farms had similar but lower odour concentrations. The odour concentration and odorant abundance values are not automatically transferable to emission rates because ventilation rates were quite different at each of these farms.
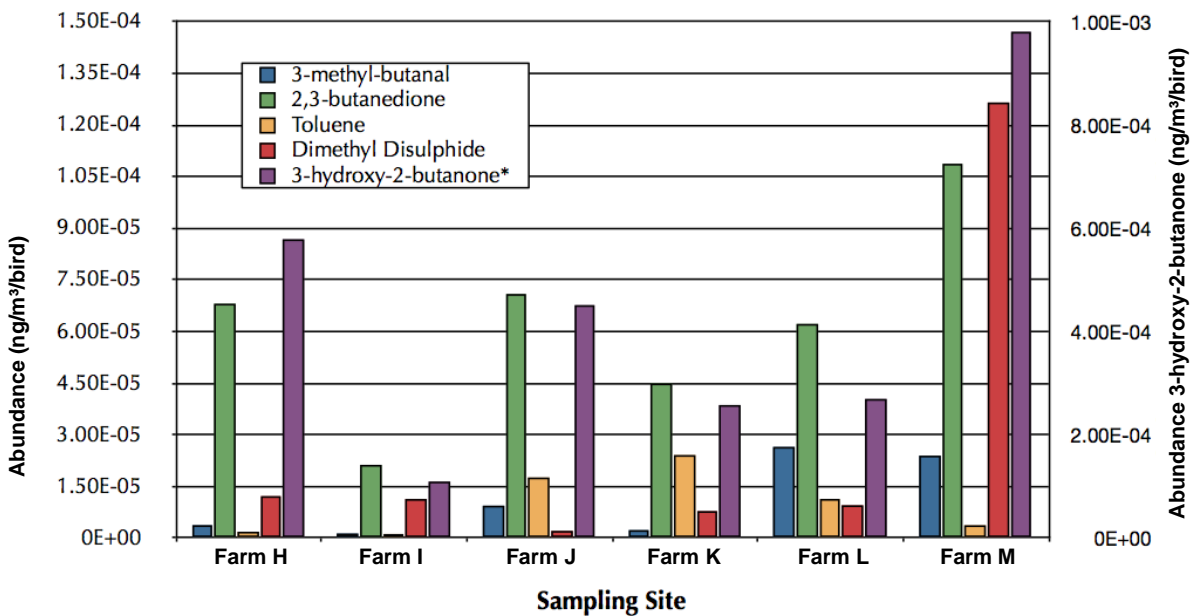
Figure 178: Results of NMVOC quantification from five broiler houses—variation in chemical abundance
 *note the different scale for 3-hydroxy-2-butanone

6.4.2.4 *Quantification of diurnal variation*

A series of samples were collected over a 20 hour period during the winter sampling at Farm A to observe any diurnal influence on the emissions. Figure 179 shows the trends in abundance of dimethyl disulphide (DMDS) and diacetyl over the 20 hour monitoring period. The observed variation of the chemical abundances was loosely reflected by the variation in the measured odour concentrations (reported previously in Section 4.2) with the exception of the low abundance of NMVOCS at 06:00 when slightly higher odour concentrations were measured.
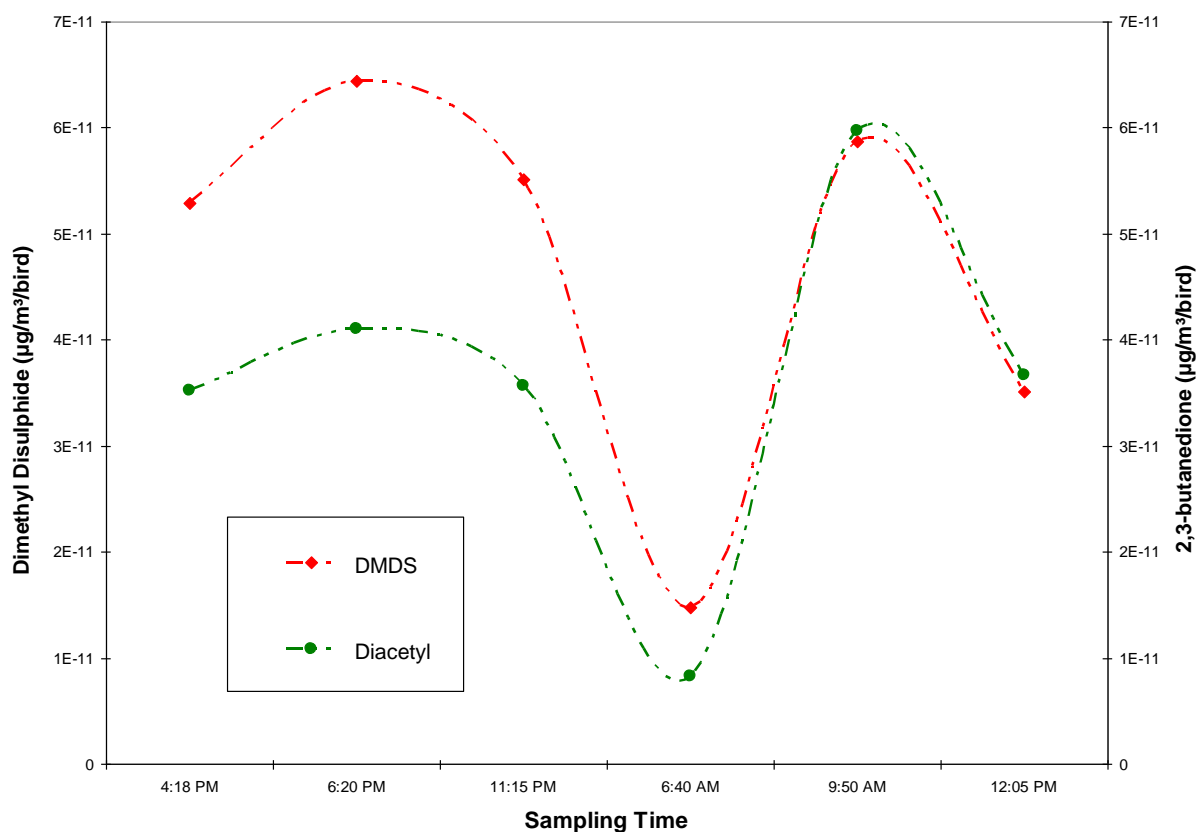
Figure 179: Diurnal variation of dimethyl disulphide and 2,3-butanedione from Farm A.

6.4.3 **NMVOC quantification summary**

The quantification of the NMVOCs within the emissions from the broiler facilities illustrated that there exists significant variation across the growth cycle of the broilers and also between different sampling sites. With a particular emphasis upon the key odorants such as 2,3-butanedione and dimethyl disulphide, it was observed that the concentrations of these compounds vary between 2.0×10^{-5} ng/m³ per bird and 1.2×10^{-4} ng/m³ per bird during the 31–35 day old at Farms H to M.

The similarity between the measured odour concentration as determined with dilution olfactometry and the abundances of 2,3-butanedione and dimethyl disulphide detected within the thermal desorption analysis indicate that these should be given a high priority within the suite of odorant compounds.

6.5 Summary of broiler VOC results

NMVOC emission need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight)

- NMVOC data was collected between November 2005 and May 2008.

- The abundance and type of chemicals changed throughout the life of the batch.

- The type and composition of the bedding material influence the NMVOC emissions from the broiler houses in the initial growth stages.

- Initial odorant emissions were dominated by terpine (β-pinene and α-pinene).

- As the birds mature the odorant profile becomes dominated by aldehydes, ketones and aromatics including; 2-butanone, 3-hydroxy-2-butanone, 2,3-butanedione, 3-methyl-butanal, hexanal, octanal, toluene, benzene, acetophenone, benzaldehyde and styrene.

- Although beyond the definition of NMVOC, the sulphides were important from an odorant perspective. Sulphides identified as odorants within the broiler house emissions included dimethyl sulphide, dimethyl disulphide and dimethyl trisulphide.

- There were observed variations from different sites sampled during the round robin sampling campaign at 31–35 days of age.

- Variations in the abundance of odorants were observed during the diurnal sampling during winter at Farm A.

- Abundance of key odorants 2,3-butanedione and dimethyl disulphide were observed to follow a similar trend to odour concentration.

- There was no observed seasonal behaviours in the emission of the NMVOCs from the broiler houses studied.

7 Selection of a suitable ventilation measurement method for poultry sheds

There are several methods that may be used to measure ventilation rate in tunnel ventilated broiler sheds (described in section 3.2.9), which are based on standard methods for measuring airspeed in stacks or ducts (described in AS 4323.1:1995 (Standards Australia, 1995a)). An alternate method is to use fan performance data, supplied by the manufacturer or independent laboratories, obtained through an assessment of a new fan under standardised laboratory conditions.

Multiple methods were used to measure ventilation rate throughout this project, with the view that one method would be chosen for the calculation of emission rates. This section discusses the benefits and disadvantages of each of the ventilation rate measurement techniques used, and ultimately, the reasons behind the selection of the fan performance method (as described in section 3.2.9.3).

7.1 Comparison of ventilation rate measurement methods

The use of a hot wire anemometer to measure airspeed, either at the fan face or inside the shed, provides measurements that are directly related to the specific conditions experienced at the farm. Specific variability in static pressure and fan performance (due to age, wear or cleanliness) are accounted for. However, there are inherent inaccuracies and difficulties with the measurement of airspeed from within a poultry shed or at the fan face.

Measurement of airspeed at the fan face has the following shortcomings:

- inaccurate measurement by the hot wire anemometer due to pulsating flow from the fan;
- non-conformance with the Australian Standard 4323.1 (1995a) due to close proximity to source of flow; and
- vulnerability to external sources of flow such as cross-winds.

Measurement of airspeed inside the shed also has shortcomings:

- inability to account for flow from side wall fans or fans located at the opposite end to the tunnel ventilation fans;
- inability to account for flow from mini-vents when the shed is not in tunnel ventilation mode because air flow through the shed is not laminar, or moving along the length of the shed (as designed, mini-vent ventilation does not generate much airspeed);
- at low ventilation rates, airspeed is very low, increasing the contribution of instrumentation errors on the airspeed measurement; and
- shed structures (including posts and rafters) and the birds will change the effective cross-sectional shed area and interfere with air flow (and the exact contribution of these are difficult to account for).

A comparison between airspeed measured inside the shed and at the fan face during this investigation is shown in Figure 180. Even though the measurement of airspeed at the fan face does not comply with the Australian Standard, the difference in the ventilation rate compared to those measured inside the shed is minimal (r^2=0.90).
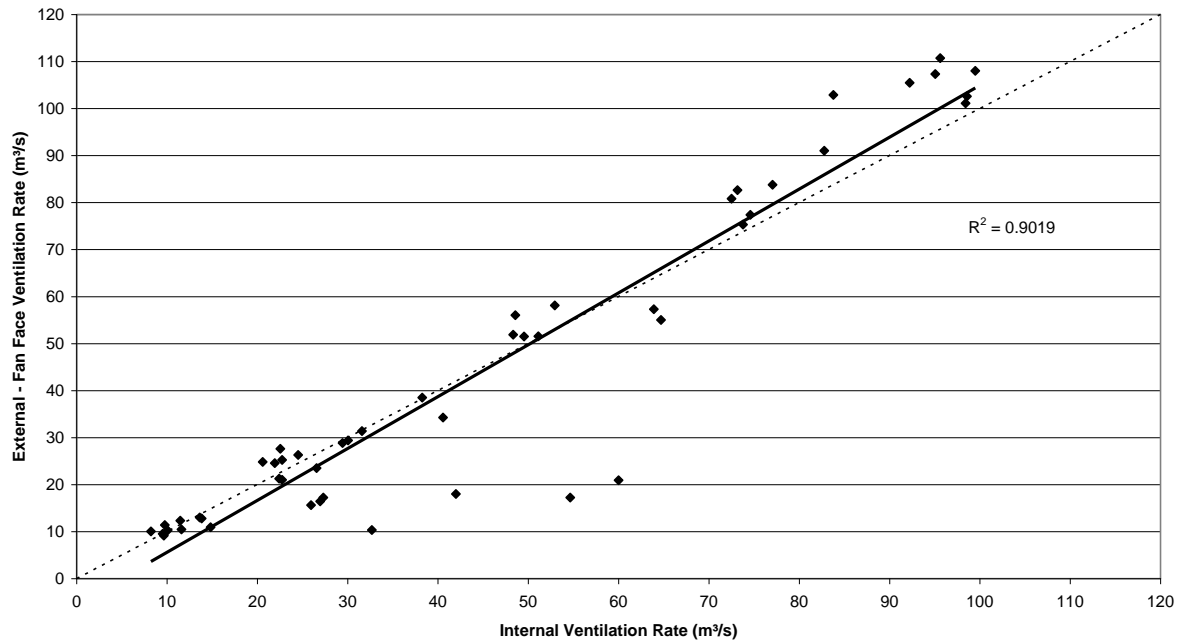
Figure 180: Comparison between ventilation rate measured from fan face and inside the shed

In terms of calculating ventilation rate using fan performance curves (corrected for shed static pressure), the inability to account for wear or poor maintenance on fans, which would negatively impact performance, is the main weakness. Even though this can cause inaccuracies in calculating ventilation rate using fan performance curves, the relationship shown in Figure 181 shows that the differences between flow measured using a hot wire anemometer and those calculated using fan curves is minimal ($r^2=0.93$). The variance from the 1:1 line shown at low ventilation rates is presumably due to reduced accuracy of the hot wire anemometer method during minimum ventilation conditions—primarily due to reduced precision when measuring very low airspeeds and no accounting for side wall duty fans. On the other hand, the fan curve method ensured that flow from all fans was included in the ventilation rate estimations and removed instrument precision errors.
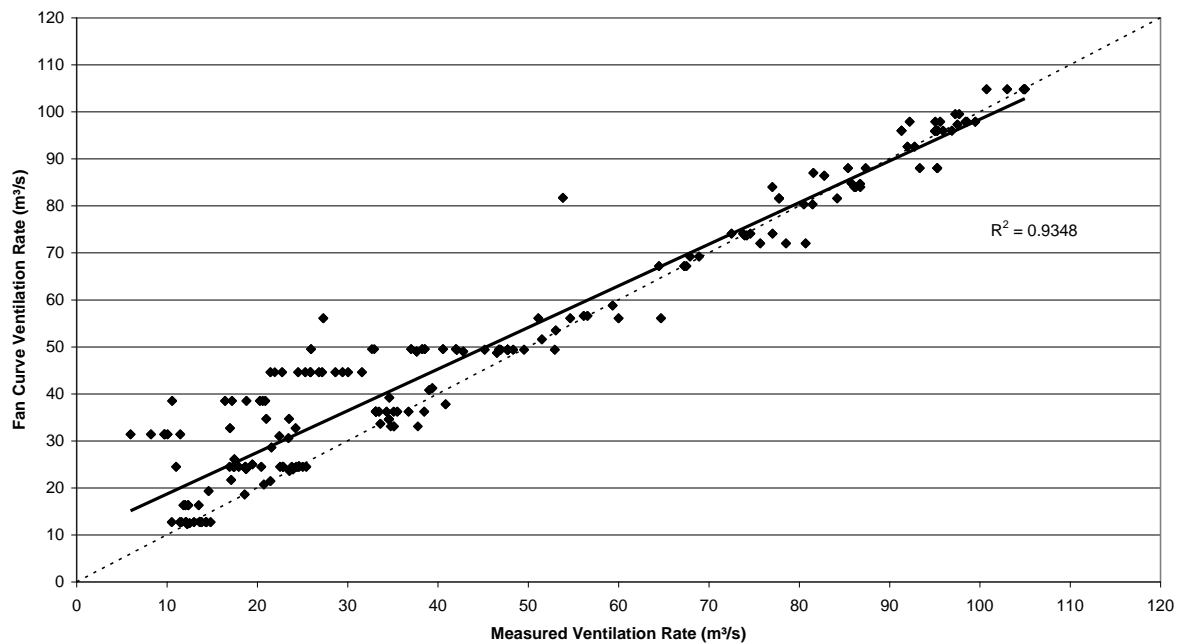
Figure 181: Comparison between ventilation rate measured using fan performance curves and inside the shed

7.2 Application of Australian Standard methods to tunnel ventilated sheds

Australian Standard AS 4323.1:1995 (Standards Australia, 1995a) specifies a number of conditions that must be met at the sampling plane, summarised in the following points:

- gas flow is basically in the same direction at all points along each sampling traverse;
- gas velocity at all points is greater than 3 m/s (assumes use of vane anemometer or pitot tubes);
- gas flow profile must be steady, evenly distributed and not cyclonic in nature;
- the ratio between the highest to lowest velocities must not exceed 3:1.

In addition, the sampling plane must be located 2–3 D upstream of a disturbance and 6–8 D downstream from a disturbance (where D is the diameter of a circular duct, or the hydraulic diameter of a non–circular duct, calculated as four times the duct internal area divided by the duct perimeter). For typical tunnel ventilated broiler sheds, hydraulic diameter is of the order of 4.1–4.6 m, if working on the dimensions underneath a baffle, or 5.4–6.0 m if working on the total internal shed cross-sectional area including the roof line. This requires the sampling plane to be positioned a minimum of 12.5–18.0 m upstream of the fans (depending on exact shed dimensions).

For internal shed measurement, the minimum required number of sampling points is 24 for a typical shed. For measurement at the fan face, the number of sampling points is at least 12 per fan (using 2 transects with 6 sampling locations per transect). These numbers need to be increased when the position of the sampling plane cannot meet the required minimum distance from the disturbance (i.e. the fan, louvers or grill).

7.2.1 Internal shed measurement

In response to the required sampling conditions (listed in dot points above), it would be reasonable to assume that air flow inside will be in roughly the same direction when the shed is in tunnel ventilation, but unlikely to be in the one direction during mini-vent ventilation because of the way that air enters the shed. Air velocity is unlikely to be greater than 3 m/s; however, it could be argued that the use of a hot-wire anemometer instead of pitot-tubes or vane anemometers may make this condition less critical. The air flow across the sampling plane is unlikely to be evenly distributed unless all fans are active. When a proportion of fans are active, shed air flow will be higher in front of these fans and lower in front of inactive fans.

7.2.2 External shed measurement

In response to the required sampling conditions (listed in dot points above), air flow from the fan will be greater than 3 m/s; however, the air flow profile across the face of an axial fan is not uniform. Air flow at the centre of the fan may actually be zero or in the opposite direction (drawing air back into the fan). Air flow will be cyclonic and turbulent, adversely affecting the measurements.

In addition, the minimum number of sampling points—12 per fan—is arduous when the shed approaches full ventilation—96 samples for 8 fans and 144 samples for 12 fans.

7.2.3 Summary of applying the Australian Standards to measure ventilation in tunnel ventilated poultry sheds

Measurement of ventilation rate by measuring airspeed across the internal cross section of the shed, or by measuring the airspeed through ventilation fans, is not ideal for the many reasons identified in sections 7.1 and 7.2. However, measurement of ventilation rate is required to determine emission rates so compromises need to be made in the absence of a perfect method. In effect, measurements cannot be made in strict accordance with AS 4323.1:1995, but useful results may still be possible to obtain. It is recommended that far more sampling points be used than the minimum numbers recommended in the

Standard. This will help to overcome non-uniformity of air flow across the sampling plane. When the shed is in mini-vent ventilation mode, internal shed airspeed measurements are not recommended.

7.3 Recommended ventilation measurement technique

It is recommended that fan performance curves be used to estimate ventilation rate in mechanically ventilated poultry sheds comparing to in-shed and fan face measurement with a hot wire anemometer. However, accurate records of fan specifications and shed static pressure must be taken, and the fans must be clean and well maintained. It is also recommended that additional hot wire anemometer measurements be made as a cross-check for the calculated curve ventilation rates to ensure that maintenance or other issues are not adversely affecting the estimation of ventilation rates. This can be done either inside the shed (during tunnel ventilation only) or at the fan face (not to Australian Standard).

Consistent estimation of ventilation rates in different sheds and under different conditions (tunnel and mini-vent ventilation; calm weather and windy, rainy weather; and where fans are properly maintained in terms of cleanliness, belt tensioning and wear) can be achieved by calculating ventilation rate based on fan performance data (when fans are tested according to recognised standards) and adjusted for shed static pressure (and temperature and barometric pressure when values for standard temperature and pressure, STP, are required). It is, however, imperative that the correct fan performance curve is selected. Details of fan dimensions, fan manufacturer, fan model, blade pitch (where adjustable), motor manufacturer and motor size will be required to ensure the correct fan curve is selected.

The direct measurement of airspeed in poultry sheds (in the shed or at the fan face) may be used to provide estimates of ventilation rate at the time of sample collection (accounting for fan activity, specific fan performance and operating conditions), but when sheds are ventilating in mini-vent mode, i.e. not in tunnel ventilation, the measurement of airspeed within the shed is inaccurate due to the swirling action of the air rather than laminar flow down the length of the shed. It also doesn't account for the activity of duty fans. One way to overcome this problem is to measure the flow directly from the fan face; however, this method does not comply with the Australian Standard, is affected by interferences from the fan and cross winds, and is time consuming. Measurements must be conducted in a manner that exceeds the minimum requirements of the Australian Standard (number of samples and position of sampling plane). This is necessary because the fundamental requirements of AS4323.1:1995 cannot be met. In addition, ventilation rate needs to be measured at each fan, or inside the shed, every time that ventilation conditions changes in the shed, which can be an arduous task. Ventilation rate may change mid-measurement, preventing complete and accurate measurement of airspeed.

8 Investigation of appropriate storage time for odour samples

Odour samples are known to be unstable and change with time due to interactions of the numerous odorous constituents with themselves and sample storage materials. Previous studies have shown that odour can change over time when stored in sample bags (Pollock and Friebel, 2002a; Trabue *et al.*, 2006; van Harreveld, 2003) and the Australian Standard AS/NZS 4323.3:2001 provides recommendations for sample storage times to minimise changes within the sample and ensure that sample integrity is maintained until olfactometry analysis can be completed. The Standard recommends that samples be analysed as soon as possible after sampling (ideally 4–5 hours) and that the interval between sampling and measurement shall not exceed 30 hours. While the Standard provides these arbitrary recommendations, the behaviour of poultry odours in odour sample drums (in particular the sample bags material used during this project) is not clearly understood. To address this issue, three odour decay investigations were undertaken to assess how poultry odour samples change over time, and to provide recommendations on how long poultry odour samples should be stored prior to analysis.

8.1 Methods

Odour samples were collected on three days at three different broiler farms, and analysed using dynamic olfactometry at specified times from 1.5 to 28 hours after collection.

Nine drums were filled simultaneously (arranged in three groups of triplicates) from within the shed (see Figure 182). An assumption was made that samples collected in each drum were identical.

Figure 182: Collection of odour samples for odour decay study

One drum from each triplicate groups was randomly selected to be analysed at staggered times post collection. Storage time varied slightly for each of these pre-designated times due to allowances for travel and olfactometry analysis time (approximately 45 minutes per sample). Unique drum descriptors and sample storage time for each of the three farms is detailed in Table 48.

Each set of triplicates was allocated a descriptor (A, B or C), with each drum within a triplicate randomly allocated a number (1, 2 or 3). For the first decay study, each triplicate was analysed in order, with repeated analyses on triplicates 1 and 2 for sessions 4 and 5 respectively (see Table 48). For the second and third decay studies, one drum from each triplicate was randomly chosen for each session.

Table 48: **Sample code and time (hours:minutes) between collection and analysis for each decay study**

Analysis group	12/05/2005			21/07/2005			12/07/2006		
1	1A 2:57	1B 3:31	1C 3:55	3B 2:29	1A 3:05	2C 3:24	3B 1:23	1A 1:37	2C 2:30
2	2A 6:43	2B 7:28	2C 8:00	3C 5:11	2A 5:35	1B 6:56	3C 4:10	2A 4:29	1B 5:09
3	3A 11:02	3B 11:49	3C 12:42	2B 8:55	1C 10:08	3A 10:47	2B 7:52	1C 8:24	3A 9:30
4	1A 21:16	1B 21:54	1C 22:46	2B 21:05	3C 22:18	1A 22:54	2B 19:47	3C 20:50	1A 21:09
5	2A 26:21	2B 26:57	2C 27:50	3B 25:26	2A 25:49	1C 27:00	3B 24:09	2A 24:47	1C 25:09

8.2 **Results**

The odour decay results for each of the three tests showed that decay of poultry odour was not consistent. All results for the three tests are shown in Figure 183 (all data is provided in Appendix 4). Results were averaged for each designated analysis group (each a different storage period, see Figure 184). For the first test, on 12 May 2005, odour concentration slowly increased up to 22.5 hours post collection, then rose sharply at 27 hours. For both the second and third tests on 21 July 2005 and 12 July 2006 respectively, odour concentration decreased slightly, with the third test increasing sharply at 24 hours post collection.
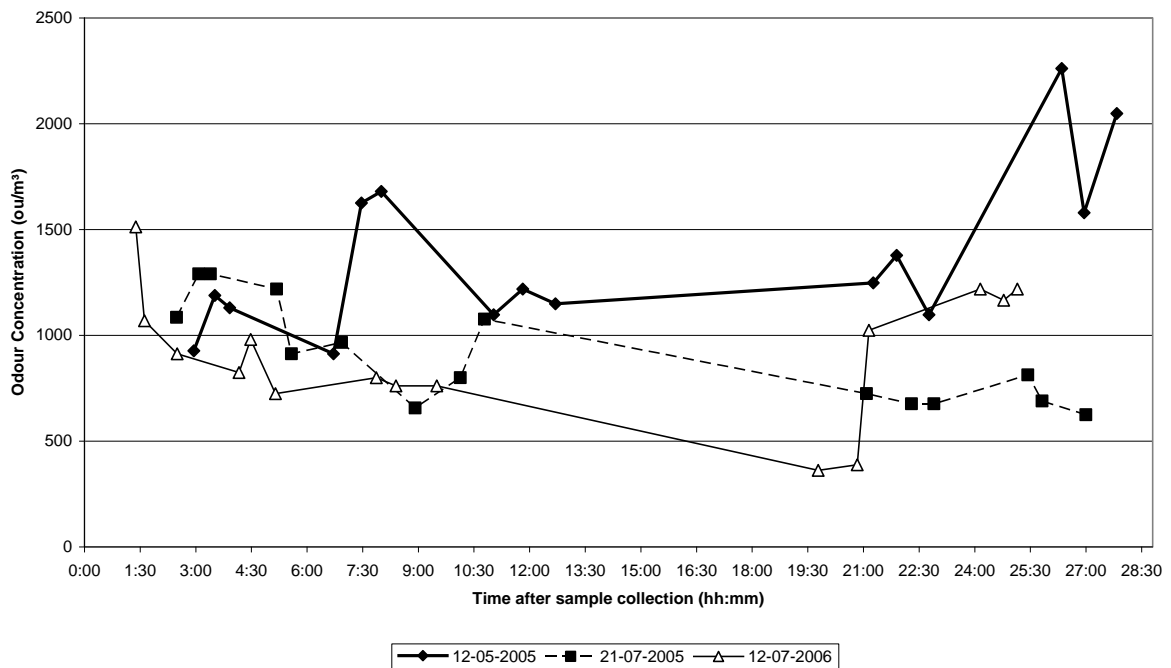
Figure 183: Change in odour concentration over time (individual sample results)
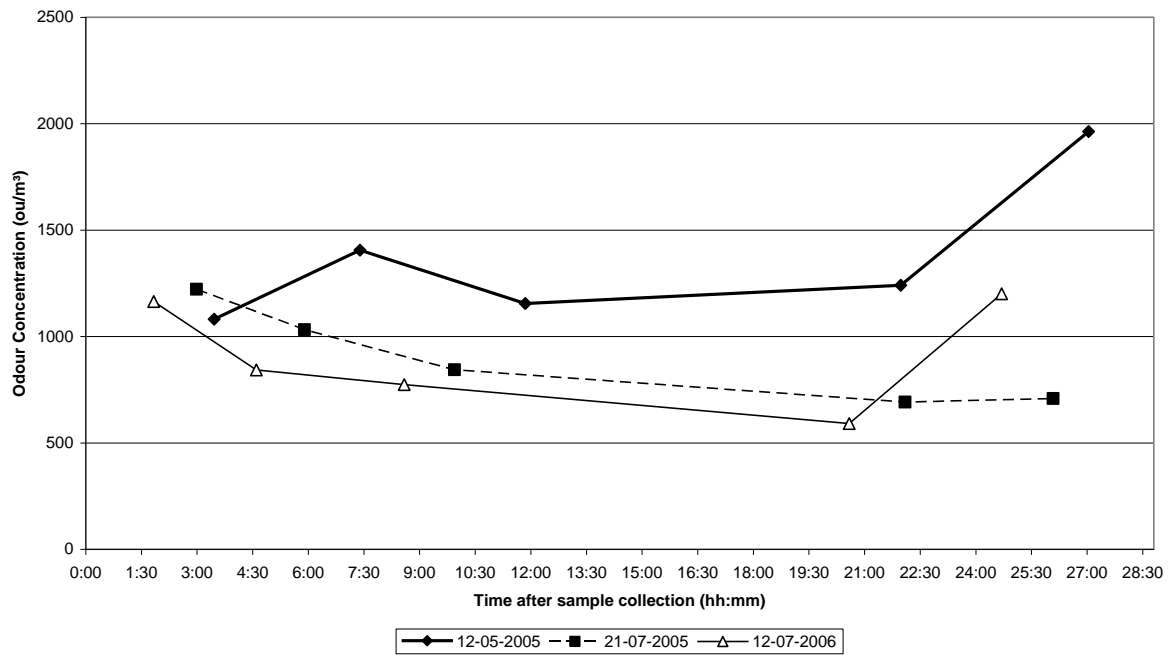
Figure 184: Change in average odour concentration over time (results averaged at each time interval)

When the data is presented in a format which shows percentage gain or loss compared to the initial olfactometry analysis (see Figure 185 and Figure 186), it can be seen that test 1 on 12 May 2005 increased by approximately 12.5% of the initial odour concentration up to 22.5 hours post collection, then at 27 hours post collection increased by approximately 75%. For test 2 on 21 July 2005, the odour steadily reduced concentration compared to the initial olfactometry analysis, to end at approximately 65% of the initial concentration. For test 3 on 12 July 2006, odour concentration decreased to 50% of the initial concentration, but then increased to the initial analysis concentration at 25 hours post collection.
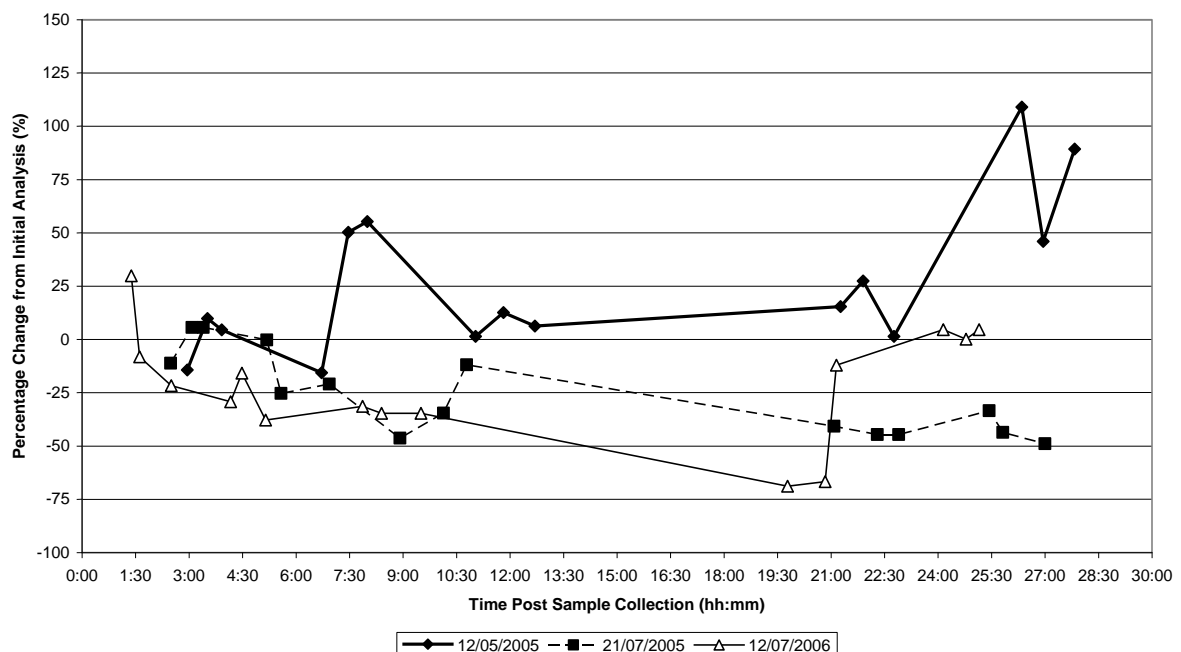
Figure 185: Percentage change in odour over time compared to initial analysis—average of samples in the first analysis group (individual sample results)
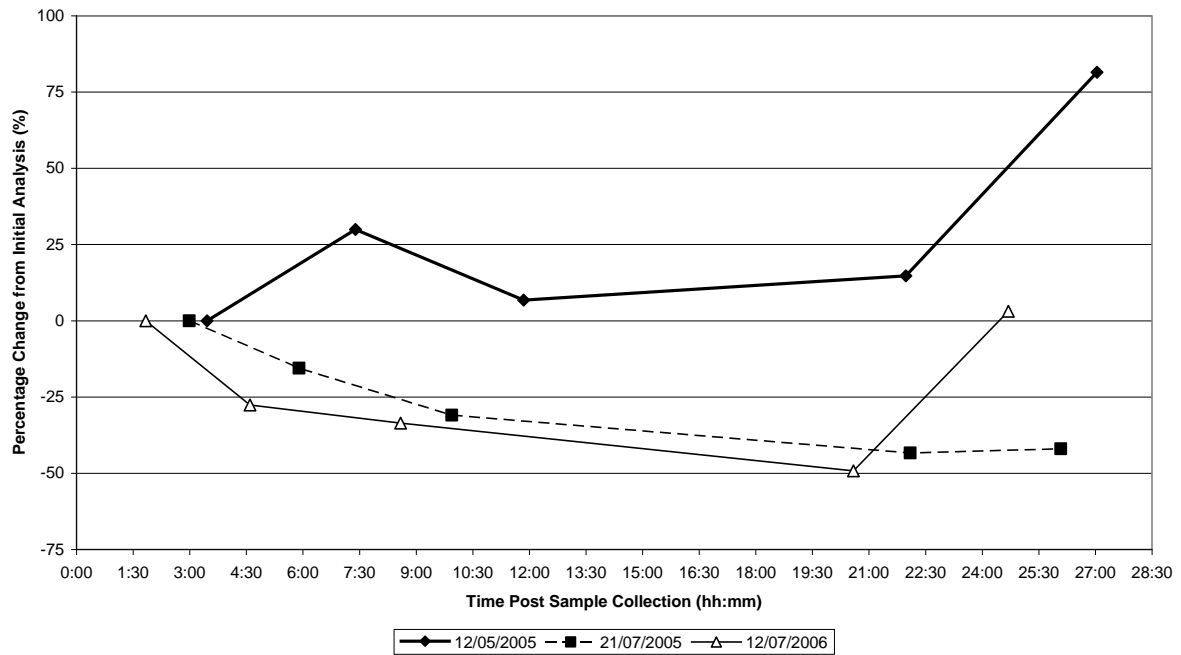
Figure 186: Average percentage change in odour over time compared to initial analysis (results averaged for each time interval)

Changes in odour over time were different for the three tests. Figure 187 displays the log transformed data that was used to normalise the measured odour concentrations. An ANOVA (analysis of variance) test was used to calculate any significant differences between sample age and test. The analysis showed that the mean odour concentration measured 21.5 hours after sample collection was significantly different to the mean odour concentration measured at 2.75 hours after sample collection. Also, the mean odour concentration measured 21.5 hours after sample collection at tests 2 and 3 were significantly different from test 1. However, as shown in Figure 187, divergence from the initial measured odour concentration began at 6 hours post sample collection.
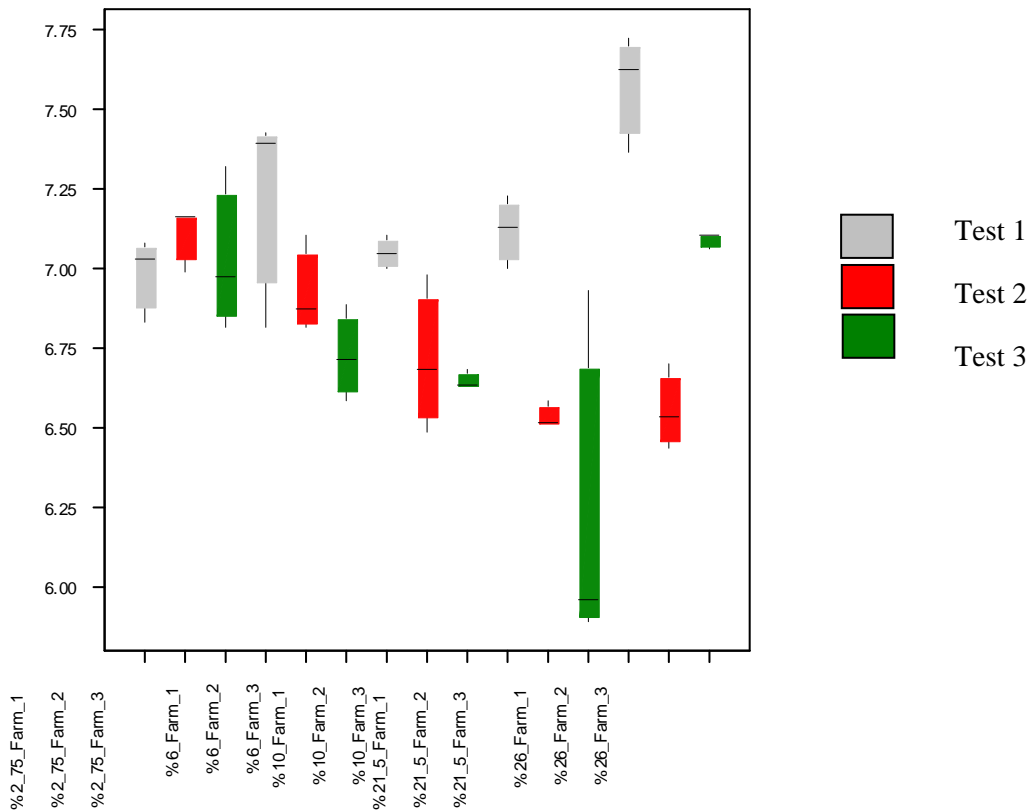
Figure 187: Log change in odour concentration over time (*note - % sign in the x-axis caption is an artefact of the graphical program and the numbers indicate the length of storage time in hours—e.g. 2.75 hours)

There is no simple explanation as to what caused the increase in odour concentration for the first test, or decrease in odour concentration for the second and third tests. There were possibly differences in temperature and humidity (during collection, transport and storage) on the three sampling days; or different combinations of odorants and subsequent reactivity within the samples.

8.3 **Summary and recommendations to minimise sample changes during storage**

The measured odour concentration for poultry odour began to diverge from the original measurement at 6 hours post collection. Divergence from the original odour measurement became significant 21.5 hours post collection. It is recommended that poultry odour samples are analysed within 6 hours of collection, however samples may be analysed up to a maximum of 21.5 hours post collection.

The recommendation from the analysis of poultry air samples over time is that broiler exhaust air samples should be analysed as soon as possible post sample collection (preferably before 6 hours, definitely before 21.5 hours post sample collection). The best ways to achieve this are to:

- choose an olfactometry laboratory in close proximity to the test site;

- transport the samples to the olfactometry laboratory as soon as possible;

- pre-arrange delivery and analysis time to ensure the samples are analysed as soon as possible after delivery; and

- samples should be transported and stored using the recommendations provided in AS/NZS 4323.3:2001 (clause 10.3.3, Standards Australia (2001))—kept at a temperature less than 25 °C but above dew point to avoid condensation.

9 Odour and dust interactions

9.1 Importance of dust in odour concentration

It has long been hypothesised that dust particles can carry odorous compounds—this may affect the way that odours are perceived in the areas surrounding poultry farms and may affect the analysis of odours using olfactometry. In an attempt to quantify the significance of the adherence and transport of poultry odour to on particulate matter, three separate methods were trialled. Initially, an inline HEPA filter was used to filter one odour sample in a series of duplicates in order to quantify the difference between unfiltered and filtered poultry air. Secondly, odour samples were filtered using glass fibre filters. The filters were subsequently heated in order to release odorants from the particulates captured on the filter and re-capture them into another sample using high-purity nitrogen. Thirdly, in-line filters used during the collection of VOC samples were analysed using a GC–MS/O in order to identify compounds that adhered to the particulate matter on the filters.

9.2 Filtration of odour samples

9.2.1 In-line HEPA and glass fibre filtration

The first test aimed to remove all the particulate matter from poultry air samples in order to assess the impact on odour concentration. On the four occasions that odour samples were filtered, the first two used HEPA capsule filters (Gelman Sciences, product number 12144), and the final two used glass fibre filters (nominal pore size 1.2 μm). Duplicate odour samples were collected, with one drum fitted with a filter. The samples were analysed consecutively through the DEEDI olfactometer.

Where HEPA filters were used, samples were collected from within the shed as shown in Figure 188. The HEPA filter was attached to the inlet fittings of the sample drum. A short length of PTFE tubing was attached to the inlet of the unfiltered sample drum so that the air collected in each drum was drawn from approximately the same height from the shed floor.
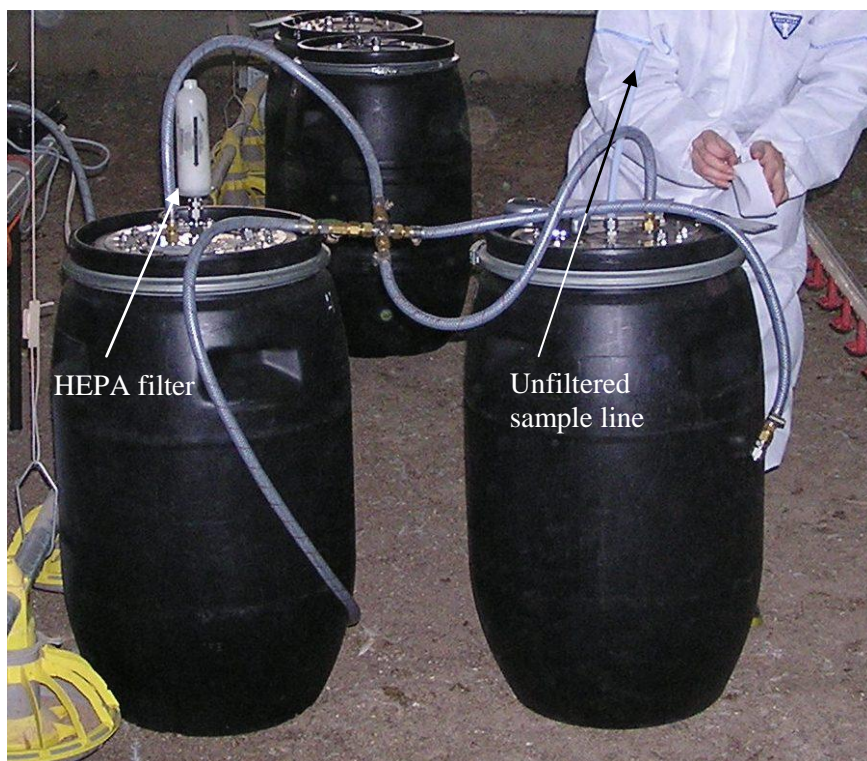
Figure 188: Simultaneous collection of HEPA filtered sample and unfiltered sample

Where glass fibre filters were used, samples were drawn from within a polyethylene duct as described previously in Section 3.2.4, except that one of the paired samples was filtered while the other was not.

The results for all four sample collection days are shown in Figure 189. There is no clear indication that filtration of poultry odour samples will reduce measured odour concentrations when analysed using olfactometry. In fact, on many occasions, the filtered odour concentrations were higher than the unfiltered concentrations.
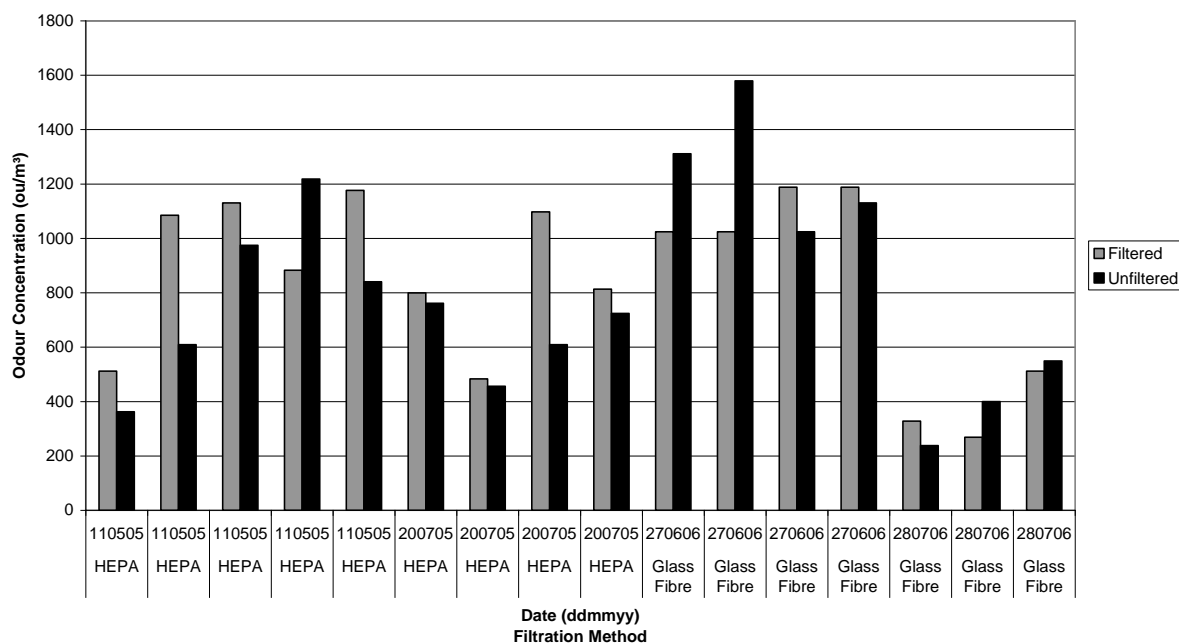
Figure 189: Comparison of filtered and unfiltered odour samples

One possible reason for the limited difference in odour concentration is the electrostatic charge on the surface of the odour sample bags and the olfactometry system. When sample air was drawn from within the unfiltered sample bag through a laser particle analyser (TSI Incorporated DustTrak™ Model 8520), it was found that little if any particles were suspended inside the sample bag. The particles appear to adhere to the sample bag material where they remain trapped. The olfactometry system may act in a similar fashion in which the particulate matter adheres to the PTFE tubing.

As this method for measuring the importance of particulate matter on odour concentration produced inconclusive results, a new method was developed whereby odour samples were generated directly from the odorants on captured particulate matter. This test is discussed in 9.2.2.

9.2.2 Glass fibre filtration and regeneration of odour from particulate matter

The second test focussed on the odorous nature of the particulate matter. The aim of the test was to capture the particulate matter in the poultry air and conduct olfactometry testing on the odorants present on the particulate matter. This was achieved by filtering the poultry air then passing warmed nitrogen over the filter to release and re-capture odorants into a new odour sample bag.

Duplicate odour samples were collected from within a broiler shed. One duplicate set was collected without filtration in order to measure the entire poultry air sample. The remaining two duplicate sets were collected with in-line glass fibre filters (nominal pore size of 1.2 µm, see Figure 190). The filters were then used to regenerate odour samples using heated nitrogen gas. Figure 191 shows the particulate matter used to regenerate the odour samples as captured on a glass fibre filter. Volatile material was recovered from the particulate material trapped on the filter using the customised equipment provided by QUT. Individual filters were placed in stainless steel holders with thermocouples before and after the filters. A stream of high purity nitrogen (5 L per min) was preheated to achieve an effective temperature of either

60 °C or 100 °C at the filter. The air stream from the filter was captured in a Melinex® sample bag stored in a sample drum. Air was recovered for 20 minutes to ensure that each drum contained 100 L of sample.

Figure 190: Filters attached to inlet of sample drum

Figure 191: Glass fibre filter post sample collection (air volume 120 L)

The following samples shown in Table 49 were analysed using DEEDI's olfactometer.

Table 49: Description of samples used for filter odorant regeneration study

Sample Number	Sample Description	Regeneration Temperature
1	Unfiltered	N/A
2	Unfiltered	N/A
3	Filter 1	N/A
4	Filter 2	N/A
5	Filter 3	N/A
6	Filter 4	N/A
7	Regenerated from filter 1	Nitrogen Gas at 60 °C
8	Regenerated from filter 2	Nitrogen Gas at 100 °C
9	Regenerated from filter 3	Nitrogen Gas at 60 °C
10	Regenerated from filter 4	Nitrogen Gas at 100 °C
11	Control clean filter (blank)	Nitrogen Gas at 100 °C

Odour concentration results are shown in Figure 192. The comparison of the average unfiltered odour concentration and the four separate filtered odour samples indicate that filtration of poultry air does not consistently reduce the measured odour concentration. In terms of regeneration of odour samples using particulate matter captured on the inline filters, there is no apparent trend in the amount of odour regenerated from the filters. Unfortunately, problems were experienced with the regenerated samples from Filter 1, and no odour concentration was recorded. For Filter 2 and Filter 4 which were heated at 100 °C (35% and 8% of original respectively), the regeneration rate was lower than Filter 3 which was heated at 60 °C (75% of original). Interestingly, the odour concentration of the blank filter was higher than that of the regenerated sample from Filter 4.
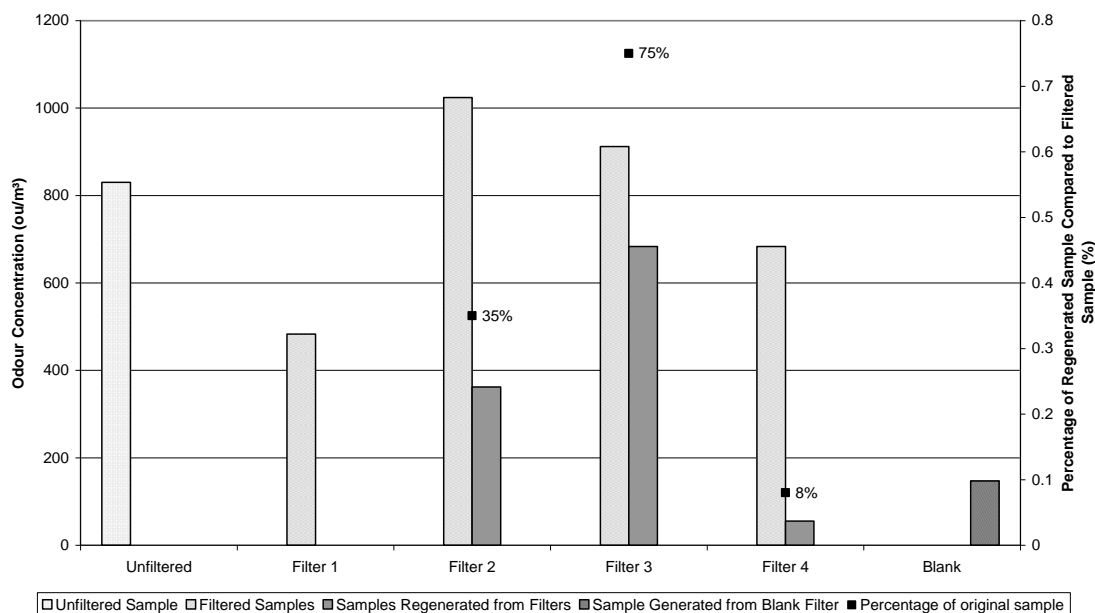
Figure 192: Odour concentration results from regeneration of odour using glass fibre filters

9.3 Particle losses in sampling bags

The static nature of the Melinex® odour bags was raised as a possible contributor to the lack of difference in odour results between filtered and unfiltered samples. Air inside Melinex® bags was assessed for the presence of particles. After collection of odour samples, the number and size of particles was measured over time.

Losses were measured both for laboratory generated particles and poultry dust. The tests conducted on the poultry dust covered particles less than 20 μm. We found that the particle concentration inside the bags dropped by 1–2 orders of magnitude in the first 2–3 hours after filling of the Melinex® bags (see Figure 193). This indicates that by the time the odour sampling bags are brought from the field to the olfactometer, the majority of particles will be lost from the airstream and attached to the plastic bag due to wall deposition.
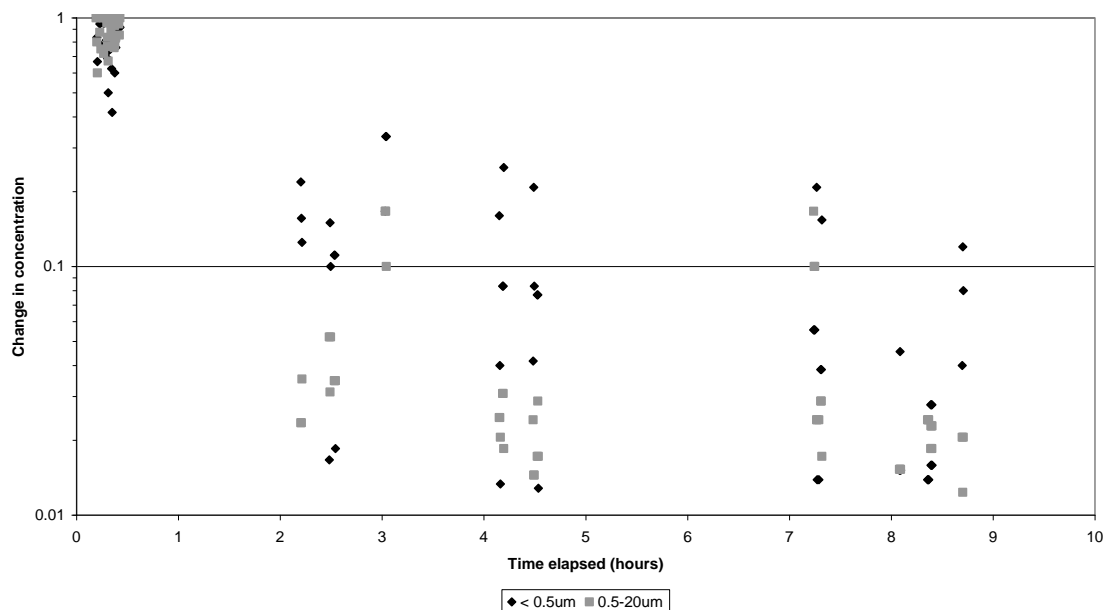
Figure 193: Relative change in particle number concentration inside a Melinex® bag as a function of time for data collected during field measurements

Measurements conducted on laboratory generated aerosol particles in Melinex® bags indicated that even after a short period of time (20 minutes) the particle concentration dropped by a factor of 5 (see Figure 194).
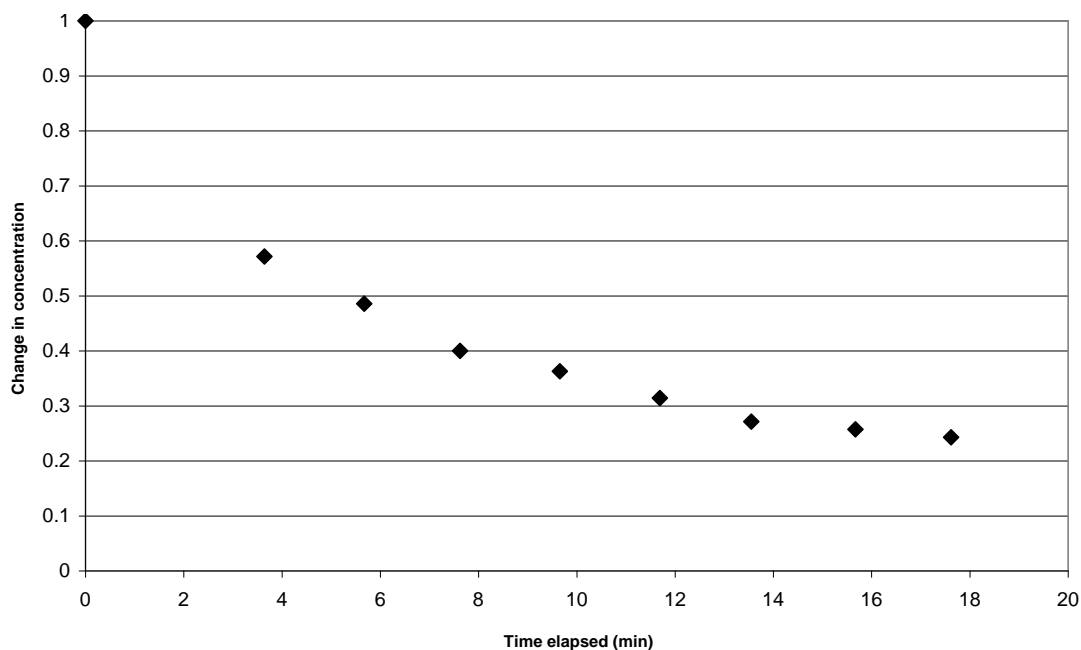
Figure 194: Short term relative changes of submicron particles inside a Melinex® bag. The data was collected for laboratory generated particles

Additional tests were conducted on bags made of conductive material (3M™ conductive bags) to assess whether the Melinex® material was the cause of particle loss. Although losses in these bags were smaller than the losses on Melinex® bags, the particle concentration after 2 hours was still significantly smaller than the initial concentration (see Figure 195). This indicates that even the use of conductive bags for olfactometry analysis is not a suitable method for investigating odour carried by particulates.
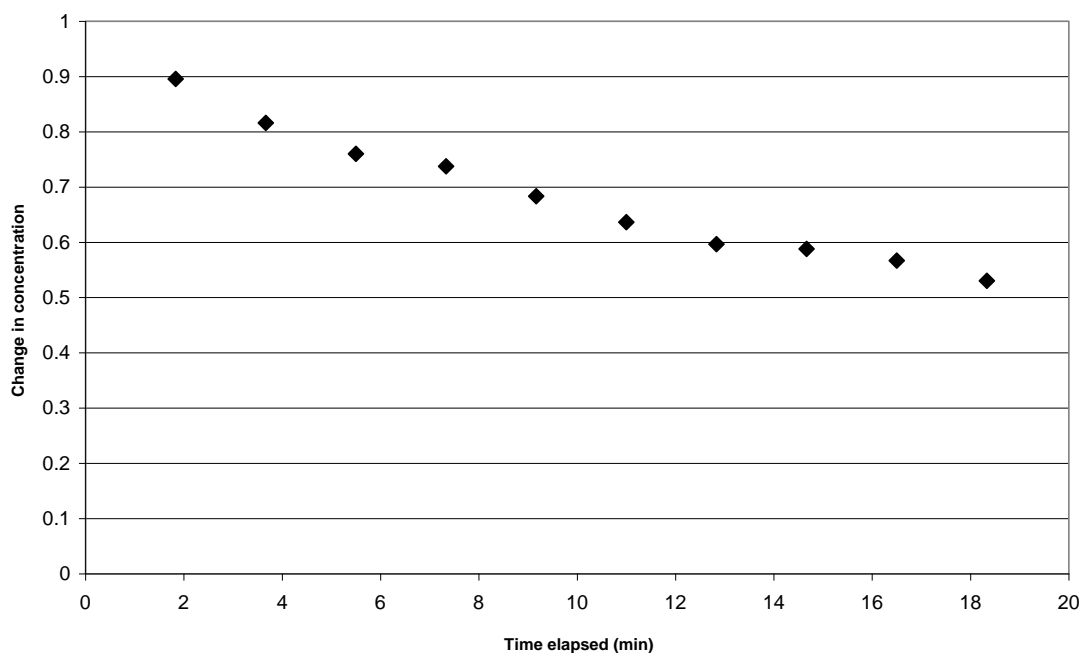
Figure 195: Short term relative changes of submicron particles inside a conductive bag. The data was collected for laboratory generated particles.

The relationship between dust and odour has not been adequately resolved or clarified adequately using the procedures applied to date. The methods that include any kind of bag sampling are prone to

significant particle losses; therefore by the time the poultry air samples are analysed by an olfactometer the majority of particles will be lost. No benefit will be gained from repeating these procedures again. More resources will be required to clarify this issue than was originally anticipated. It is anticipated that the GC-MS procedures will be very useful in identifying the relationship between dust and odour.

9.4 **Recommendations for further odour/dust assessment**

Olfactometry was not successful for determining the effectiveness of removal of particulate matter on odour concentration. The static nature of the Melinex® bags attract all particulate matter to the bag walls, causing all samples analysed through an olfactometer to be 'filtered'. This problem was also experienced by Williams (1989), where Tedlar® sample bags were used in an attempt to quantify the effect of particulate matter on odour concentration. The ability to discriminate between glass fibre filtered and unfiltered samples was made more difficult because no duplication of filtered samples occurred. It was not possible to determine which purge air temperature was more appropriate due to the failure of one filter and minimal experimental duplication.

The methods used during this project were not able to determine the effect of dust on perceived odour concentration. Where unfiltered and filtered (HEPA or glass fibre) odour samples were compared, no difference in odour concentration was measured. Measurement of particle concentration inside odour sampling bags found that particle concentration rapidly decreased post collection.

9.5 **Relationships between odour and dust emissions**

The results from Sections 4 and 5 indicate that odour and dust emissions appear to follow similar paths throughout each day of sample collection, and over time throughout batches of broilers. Investigations were undertaken to assess whether there was any statistically significant interaction between emission of dust and odour from broiler sheds. Emission of odour, number of particles, PM_{10} and $PM_{2.5}$ were assessed for any relationship in the magnitude of these variables.

All data in which concurrent odour, PM_{10}, $PM_{2.5}$ and PN measurements were collected was used to assess statistically significant interactions. A log transform was performed on all measurements.

The relationships involving odour emission rate per 1000 birds placed, PM_{10}, $PM_{2.5}$ and PN can be seen in Figure 196. A pairs plot was used to compare variables in a matrix format. For example, Row 1 and Column 1 depict the relationship between batch age and all other variables. Row 2 and Column 2 depict the relationship between log Number Emission Rate and all other variables. PM_{10}, $PM_{2.5}$ and PN appear to have a linear relationship with odour emission rate per 1000 birds placed (which can be seen by the section of the plot enclosed by the dashed area).
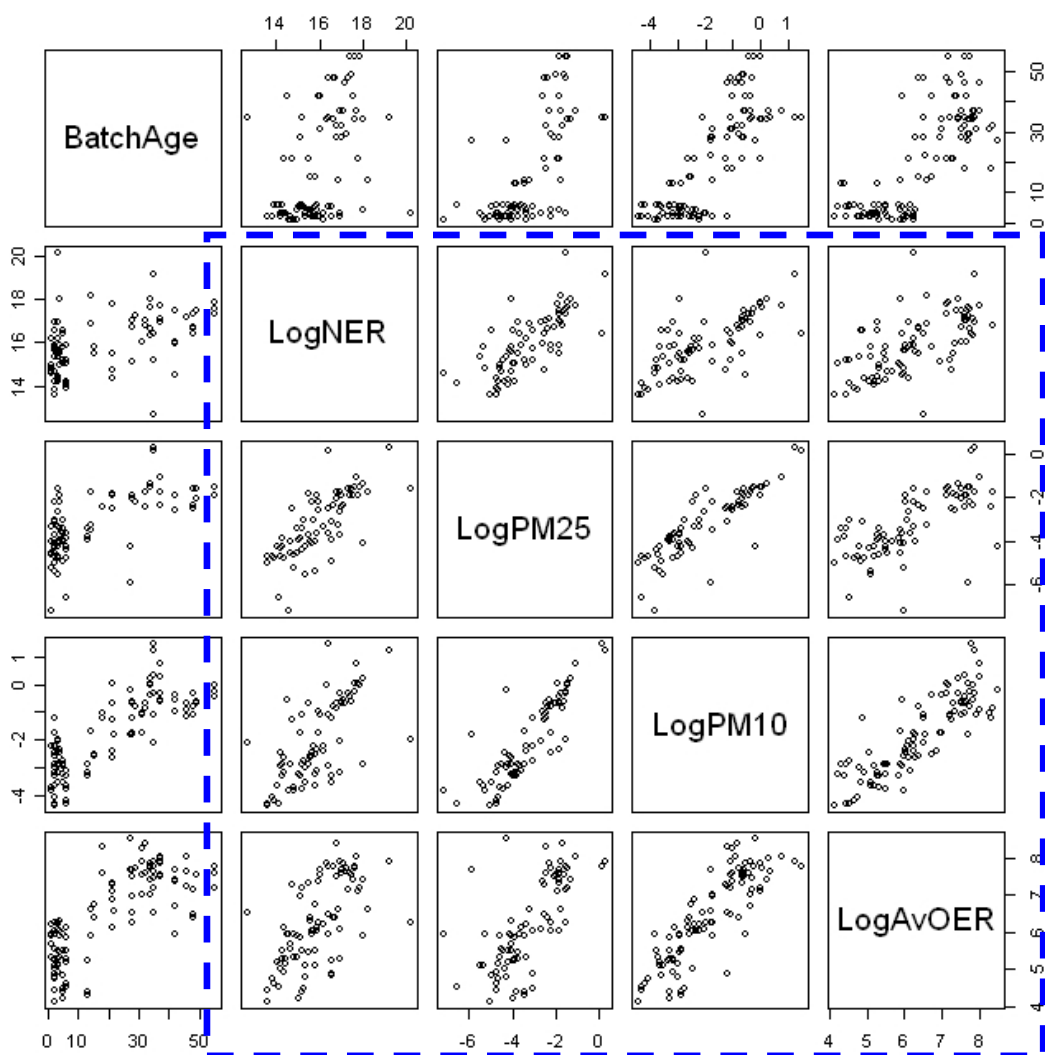
Figure 196: Pairs plot for emission of odour per 1000 birds placed, PM$_{10}$, PM$_{2.5}$ and PN

Since all dust fractions appear to be related to the magnitude of odour emission, a statistical investigation was undertaken to assess whether it was possible to accurately predict odour emission by measuring dust emission. A linear mixed effects model was used to determine which variables were needed to model the relationship of odour and dust. The model used was:

$$\log(OER) \sim \log(NER) + \log(PM_{10}) + \log(PM_{2.5}) + \text{batch age} + \text{property/management/season}$$

Property is a random effect in which management and season are nested within. Of these, property and season had significant effects; however management (i.e. litter reuse status) was not influential.

In this model the fixed effects indicate that $\log(PM_{10})$ is the only significant variable in the model ($p=0.0420$).

By using this technique, we have found that (for the occasions when all variables were collected concurrently), PM$_{10}$ and odour emissions were statistically related. However, the relationship between odour emission and dust emission was different at different farms and in different seasons. This means that the relationship between odour and dust emissions was not consistent or straight forward.

9.6 Summary of the interactions between odour and dust

- Poultry air samples were filtered using HEPA and glass fibre filters, and compared against unfiltered samples through olfactometry analysis.

- The methods used during this project were not able to determine the effect of dust on perceived odour concentration.

  - Olfactometry could not be used to assess the contribution of particulate matter on odour concentration due to the static nature of the odour sample bag material.

  - Odour could not be reliably regenerated using particulate matter captured on filters.

- The relationship between odour emission and dust emission was different at different farms and in different seasons. This means that the relationship between odour and dust emissions was not consistent or straight forward.

10 Continuous monitoring in-shed of air quality using sensor networks

10.1 Introduction

A variety of environmental and air quality monitoring sensors, connected using a wireless network, were installed into broiler sheds at Farms A, B and C over the full duration of a production cycle during the following periods:

- Farm A
    - Summer - Dec 05 – Jan 06
    - Winter - Jun 06 – July 06
- Farm B
    - Summer - Feb 06 – Apr 06
    - Winter - Aug 06 – Oct 06
- Farm C
    - Single use litter - Feb 07 – Mar 07
    - Partial re-use of litter - Apr 07 – Jun 07

A substantial quantity of data was recorded by the sensor networks.

The sensor networks were assessed in terms of:

- durability of the sensors within the broiler shed environment;
- reliability of the wireless network; and
- comparability with conventional measurements of odour and dust (using conventional olfactometry and dust measurement methods).

10.2 Reliability of the wireless network

The reliability of the network was assessed by comparing the proportion of sensor readings collected against the number of expected sensor readings. Table 50 shows that the reliability ranged between 21% and 93%. Poor reliability for the 'Farm A summer' study was primarily due to a prolonged outage at the start of that study; once rectified, the reliability of the rest of the study was 76%.

Table 50: Proportional reliability of sensors from all sensor stations for broiler studies

	Temp	*Humidity*	*Air Flow*	*NH₃*	*Dust*	*VOC*	*Combined average of all sensors*
Farm A summer	40%	28%	36%	38%	38%	-	36%
Farm B summer	89%	81%	69%	62%	76%	54%	72%
Farm A winter	82%	82%	78%	78%	57%	-	75%
Farm B winter	93%	93%	93%	86%	21%	93%	80%
Farm C	83%	82%	70%	55%	63%	78%	72%

Loss of readings occurred due to a variety of reasons:

- power interruptions;
- hardware failures;
- cable failures;
- radio connection failures; and
- temporary decommissioning during pickups.

Power interruptions were one of the major reasons for loss of data. During the early trials, when the sensor stations were battery powered, regular replacement and recharging of the batteries was required (at approximately weekly intervals). During later trials, when the addition of extra sensors necessitated the use of mains power (240 V), there was a noticeable increase in power interruptions, which temporarily prevented data recording. Options to minimise future power supply problems may include using sensors

with lower power requirements thus enabling battery power to be used; or to include an uninterruptible power supply (UPS) on mains powered stations to overcome short power outages.

Hardware failures were principally related to the sensors. Humidity sensors failed on two occasions, and the refurbishment and recalibration of the ammonia sensors caused interruptions to data collection.

On a number of occasions the wireless mesh network took a considerable time to establish connections. This was never fully diagnosed although it was suspected that it may have been due to the wireless system being sensitive to multi-path reflections inside the poultry buildings. More advanced mesh network software currently available for this hardware is reported to be less prone to this problem.

Detecting failures initially relied on site visits, but later studies included remote monitoring capability using a dial-up modem and remote access software. Remote access relied on sufficient mobile phone network coverage, and whilst this was good for Farm B, and fair for Farm A, connections could only rarely be made at Farm C. Remote access capability decreased the time taken to detect and rectify equipment failures.

While the reliability of the sensor network was not satisfactory during these studies, recent developments in several aspects of the technology and procedures may improve reliability.

10.3 Durability of the sensors within the broiler shed environment

Direct sensor failures due to mechanical and electrical breakdowns were uncommon; however, three issues that were encountered included:

1. fouling of the dust sensor optics (especially at Farm B);
2. requirement to change the sensitivity range for the VOC sensor; and
3. saturation or contamination of the sensors (especially ammonia sensors).

The combination of these issues resulted in periods of data where sensor readings were unrepresentative of actual conditions and therefore unusable.

The following sections present examples of the data collected by each sensor; describe the reliability of each sensor; and provide recommendations for future application of the sensors.

10.3.1 Temperature and humidity

Most temperature and humidity readings were taken with a custom built sensor incorporating modern, low cost micro-sensors. Retail cost of the sensors and components was approximately $100. Apart from one humidity chip failure, these sensors were robust and reliable.

Temperatures within the sheds were well controlled and while a slight gradient of 1–5 °C degrees was noted from the door end to the fan end of the sheds, daily oscillations were less than 10 °C (see Figure 197 for the first five weeks at Farm B, summer).
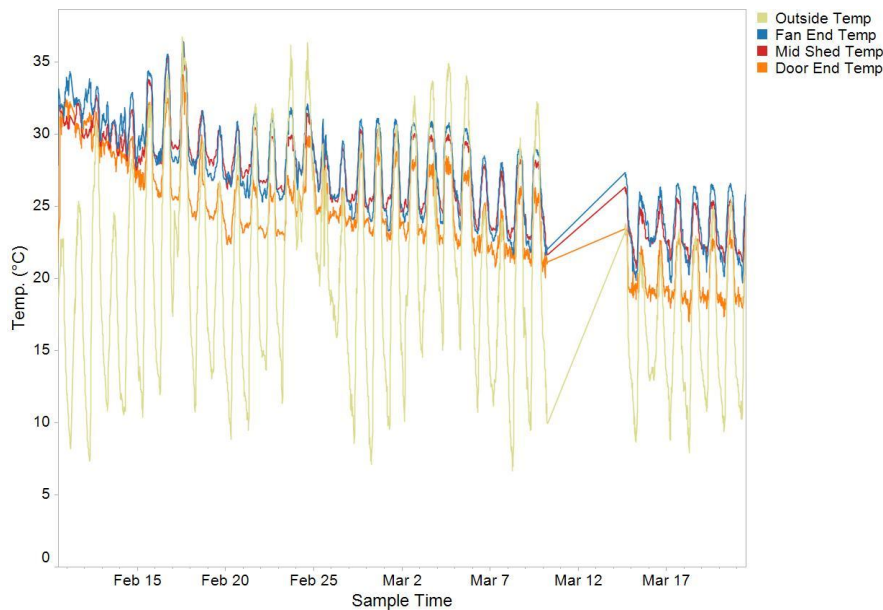
Figure 197: Temperature profiles for the first five weeks of Farm B monitoring

10.3.2 **Airspeed**

Airspeed was measured using commercially available three cup anemometers. In-shed airspeed fluctuated daily as seen in Figure 198 (as expected). While the placement of the anemometers provided a general indication of air flow, it was not sufficient for measurements of ventilation rates, principally due to:

- the turbulent and stratified nature of tunnel air flow;
- the influence of side fans and inlets; and
- lack of a relationship between airspeed and ventilation rate whenever the shed was not operating in tunnel ventilation mode.

In practical settings where continuous monitoring of ventilation rates was required, integrating the number of tunnel fans operating may give a superior measurement.
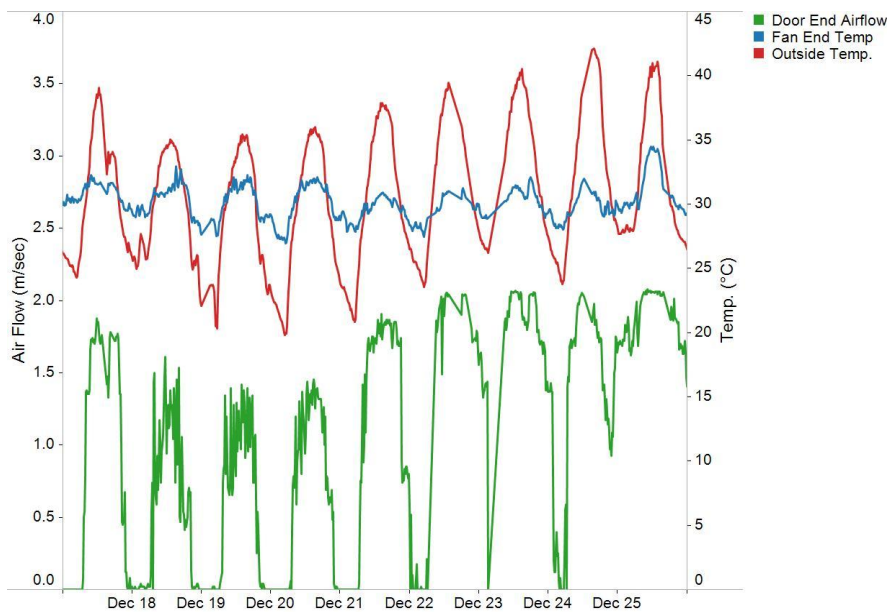
Figure 198: Changes in air flow due to increased ventilation rates in response to increasing ambient temperature (Farm A, summer)

10.3.3 **Ammonia**

The electrochemical reaction with ammonia that produces the sensor response consumed the electrolytes, and this consumption increased with ammonia concentration. For this reason, sensors were refurbished and recalibrated after each study. Not only was this costly, but also introduced dependencies on service companies that eventually led to poor reliability in the last series of studies due to mishandling of the recalibration.

Ammonia can alternatively be measured using metal oxide sensors (MOS) (similar to the VOC sensors used in this study), which are cheaper and longer-lasting; however, sensitivity is lower, and power consumption is higher.

Ammonia measurements (see Figure 199) showed the expected inverse relationship with airspeed (as a measure of ventilation rate). There was also a consistent gradient in concentration along the length of the shed, with higher levels towards the fan end, which was more obvious during ventilation. Ammonia levels also tended to increase over time, although this was influenced by changes in bird number and overall ventilation rate as related to the external temperature.
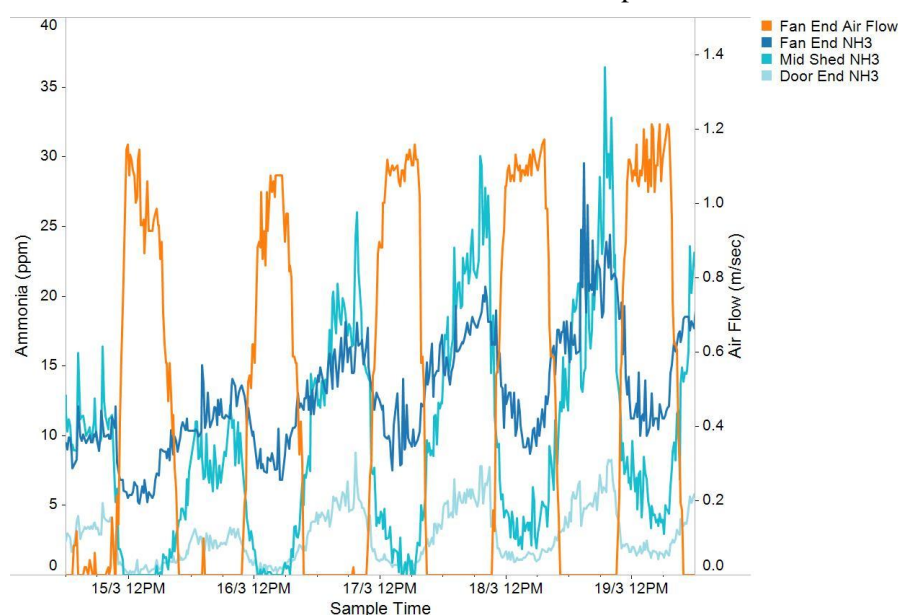
Figure 199: Changes in ammonia concentration over latter stages of production cycle at three positions as related to ventilation rate indicated by air flow at the fan end of the shed

One drawback with this type of electrochemical ammonia sensor is the high cost of refurbishing and recalibration. Furthermore, it is difficult with this type of senor to monitor electrolyte consumption, which is affected by the level of ammonia the sensor has been exposed to, and determine when the sensor is reaching the end of its life due to exhaustion of the electrolyte. These sensors are expensive and high maintenance, which reduces their suitability for continuous ammonia measurement on commercial broiler farms.

10.3.4 **Volatile organic compounds**

The metal oxide VOC sensors used in this study were sensitive to a wide range of compounds and enabled VOC concentrations to be monitored in the broiler sheds. However, because of the wide range of specificity it was not possible to calibrate the sensors in a meaningful way with relation to odour concentration.

One drawback of the metal oxide sensors (MOS) used in this investigation was their high power usage, requiring mains power connection rather than battery power. Recent developments in VOC sensor technology have reduced the power requirements for MOS sensors. For example, the sensor used in this

project used 400 mW of power whereas more recent research has described micro-machined MOS that consume less than 10 mW (Elmi *et al.*, 2008).

Initial studies showed an inverse response to ventilation (see Figure 200) and indicated that VOC concentrations generally increased throughout the batch, presumably due to bird growth and increasing biological activity in the shed (see Figure 201). Values were highest during the night, and declined as the shed was ventilated during the day.
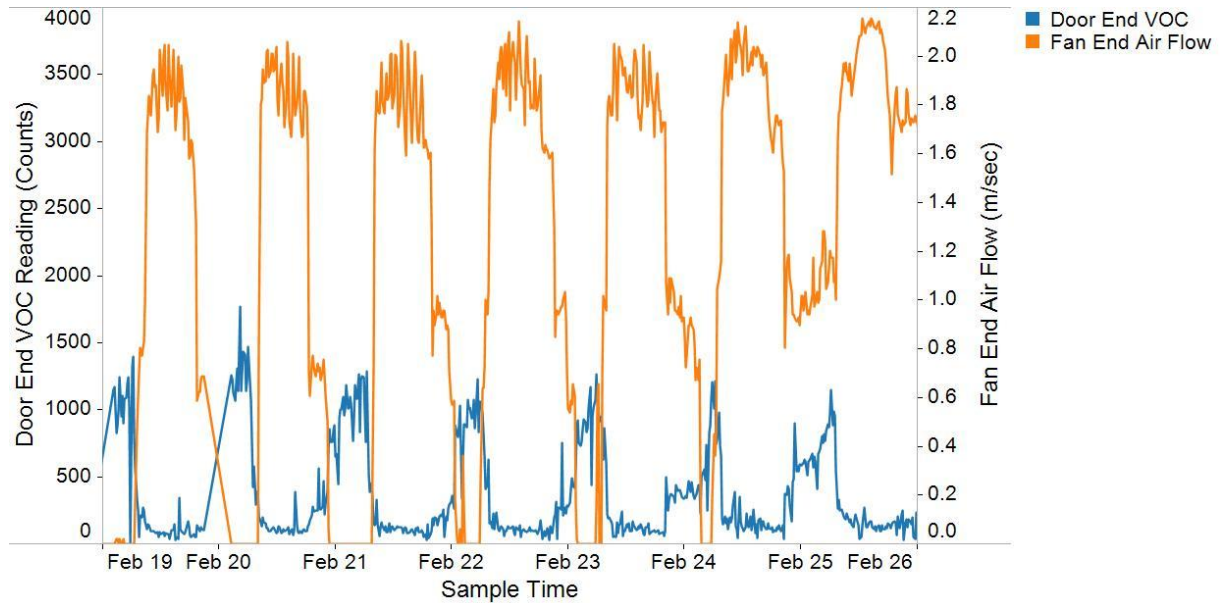
Figure 200: Response of VOC sensors to ventilation at Farm C
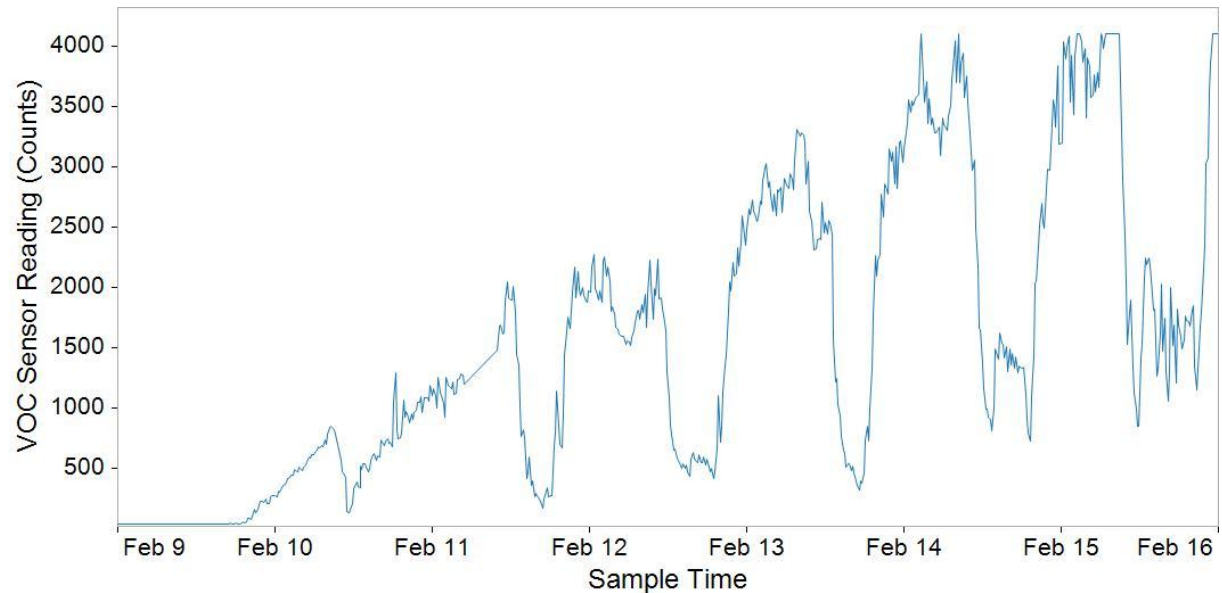
Figure 201: VOC sensor measurements during the first week of the batch (Farm B, summer)

10.3.5 Dust

The challenge for measuring dust for the sensor network was to provide a device that was of moderate cost, low maintenance, low power and able to measure either continuously or frequently. Low cost particle sensors are available for use in indoor air quality measurements, and we selected a model (PPD20V) designed for continuous monitoring utilising a simple heating element to draw the air sample by convection.

In situ calibrations were conducted during a summer study by co-deploying a DustTrak™ along with a sensor station. Both sensors recorded variable dust concentrations throughout the monitoring period (see Figure 202).
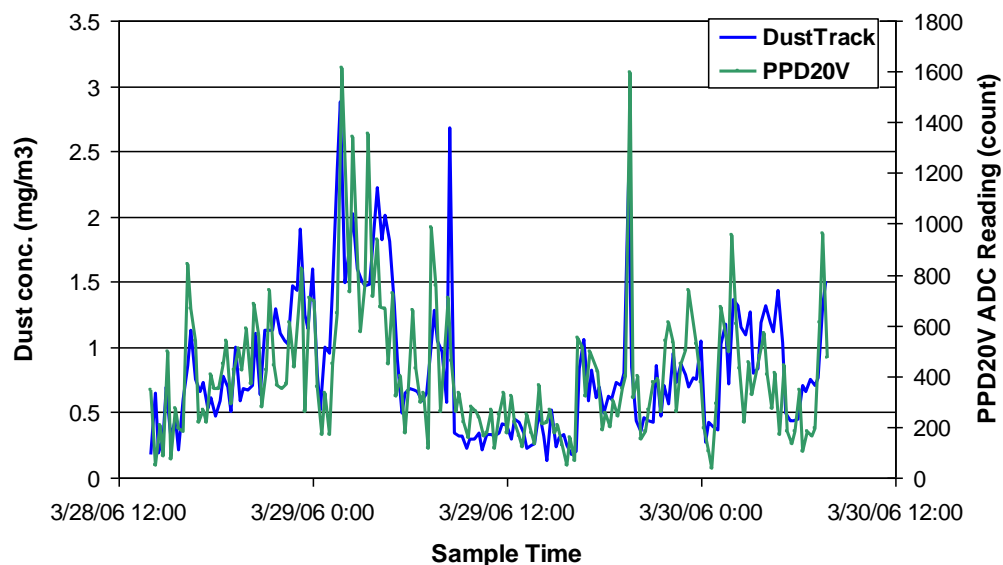
Figure 202: Plot of raw readings of dust measurements from DustTrak and PPD20V sensor

Correlation of the dust measurements by the DustTrak™ and PPD20V sensor were found to be significant ($P < 0.0001$) (see Figure 203).
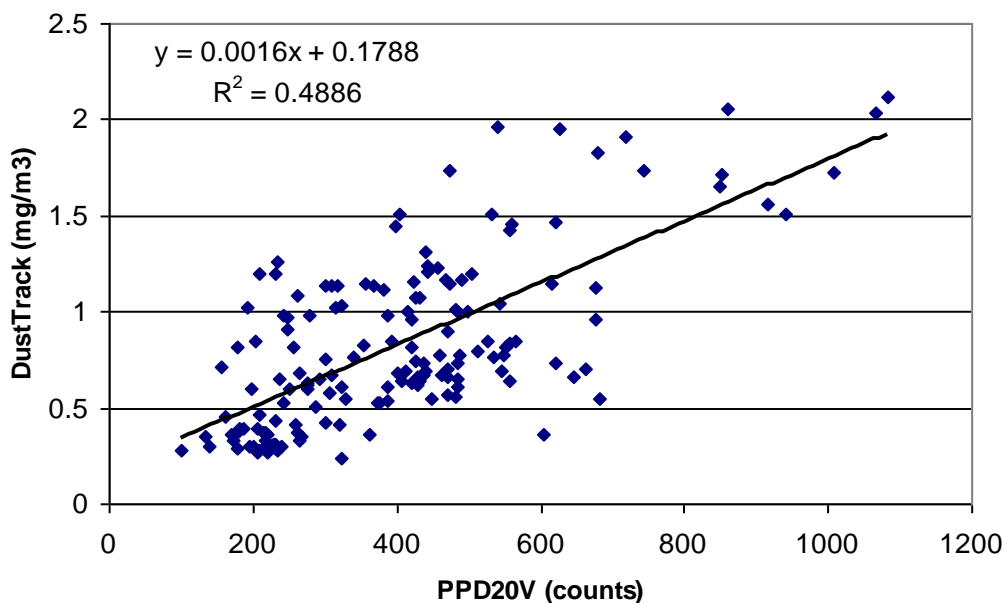
Figure 203: Correlation of dust measurements by DustTrak and PPD sensor

The sensors consistently showed an inverse relationship to air flow, with high concentration during low flow, and low concentration when during higher air flow (see Figure 204). This is in agreement with the dust concentration measurements using conventional techniques (reported in Chapter 5).
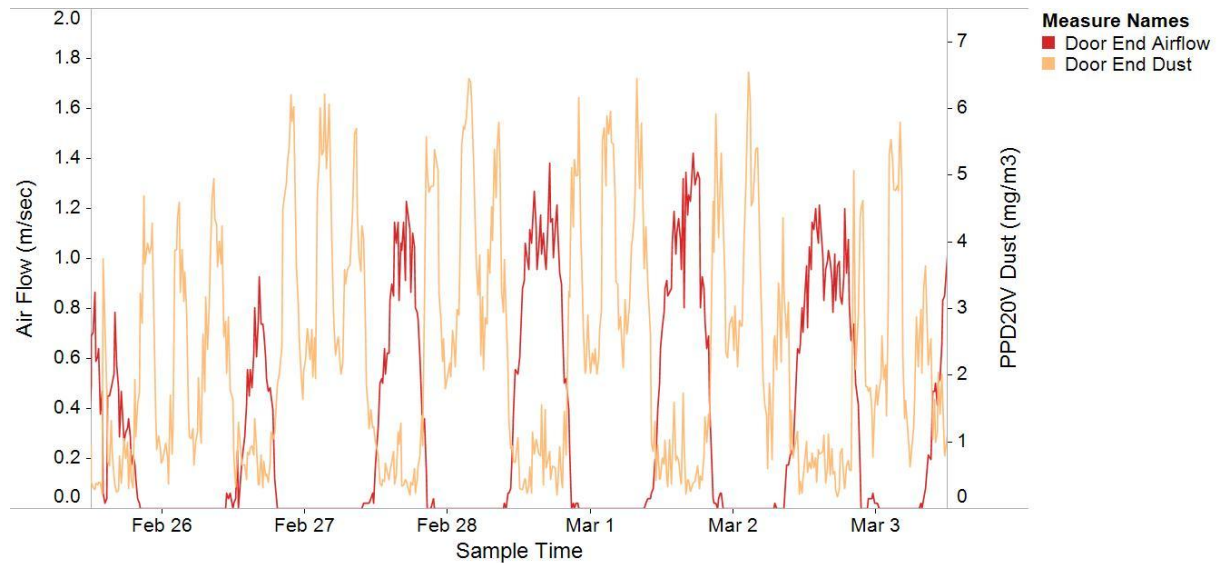
Figure 204: Relationship between dust measurement and air flow

Maintenance requirements for the sensor were found to vary depending on bedding/litter material used in the shed. During the first three studies at farms using wood shavings, the sensor lenses were cleaned according to manufacturer's recommendations at between two and four weekly intervals. At these times, particulate matter was observed on the lenses and removed with an alcohol swab. Comparing sensor response before and after cleaning indicated there was no evidence that cleaning had any consistent effect on the measurements recorded by the sensor.

A problem with the sensors emerged at Farm B when rice hulls were used as bedding. Subjectively, the initial level of dust was high, but decreased substantially over the first weeks of the study. This was apparently reflected in the outputs of the sensors. Due to the previous lack of effect of maintenance on the PPD sensor performance, the dust sensors were operated without cleaning. During the comparative dust studies (described previously in 3.2.5 and Chapter 5), it was noted that dust levels determined by conventional measures were still relatively high, although the PPD sensors were indicating very low ambient dust levels. Upon examination, the PPD sensor optics were found to be coated with a layer of dust. Upon removal, the sensor response increased noticeably (see Figure 205). Clearly, the nature of the dust from rice hulls was quite different from previous materials in the degree to which it adhered to the glass optics.
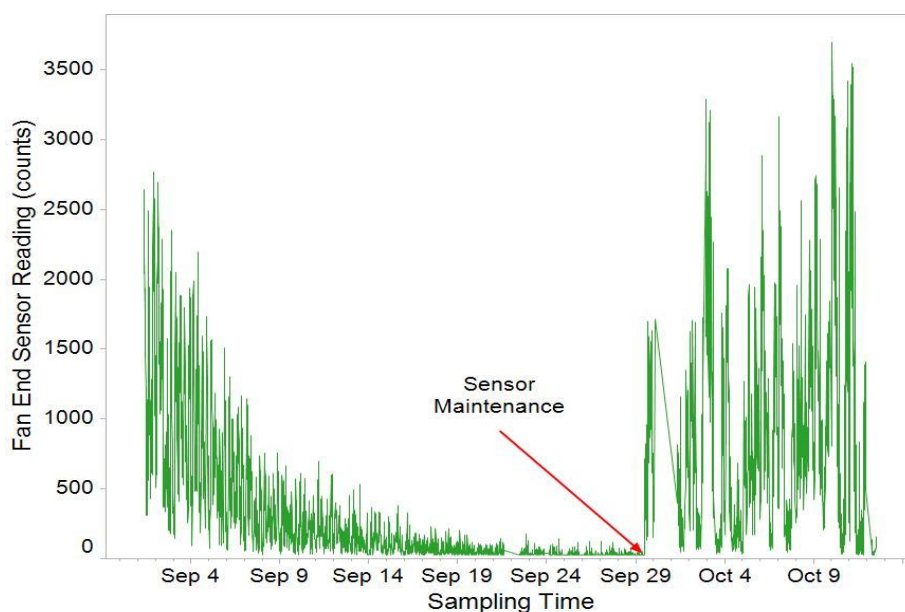
Figure 205: Measurement of dust on PPD20V sensor and effect of maintenance

The combination of un-calibrated sensor response and susceptibility to fouling effectively render the PPD sensor, as supplied, unsuitable for reliable dust measurement in broiler sheds. These sensors would require regular testing and calibration for each type of litter material. They would also require frequent maintenance and cleaning either by farm staff to undertake the fairly delicate task of wiping the optics without damaging the sensor, or some form of automatic cleaning.

10.4 Comparability with conventional measurements of odour and dust

The outputs from the sensor network were compared to:
- odour concentrations measured by dynamic olfactometry;
- ventilation rate monitoring results;
- dust concentration results; and
- continuous odour concentration results calculated from an artificial olfaction system developed by DEEDI.

The data sets from VDPI and DEEDI were merged into a data base through alignment of data points using date and time index for the development of odour and dust calibration models.

Four data mining techniques were applied to the combined data base. They were: (1) data pre-processing; (2) conventional statistical analysis (i.e., correlation analysis, linear and non-linear regressions); (3) chemometric methods (i.e., partial least squares regression); and (4) artificial neural network using back-propagation algorithms.

The results of data mining indicated that:
- *relationships could not be found between the sensor outputs and conventional odour and dust measurements* – The task to relate the two data sets was especially difficult because each of the measures were different in nature (i.e. the response from a non-specific VOC sensor was used as an indicative measure of odour concentration and a non-specific dust sensor was compared with PM_{10} measurements) and air quality was being measured in different locations (odour and dust were measured at the tunnel ventilation fans while the sensor motes were positioned at 25%, 50% and 75% along the length of the shed);
- *the chosen sensors used for monitoring air quality were not stable and were a limiting factor to the overall performance of the sensor network;* and

- *the sensors were unreliable and the network occasionally malfunctioned, resulting in extended periods where no data was collected.*

Due to these issues, it was not possible to develop reliable and repeatable odour and dust calibration models from the data produced by the sensor networks.

10.5 Discussion

The prospect of using multiple measurements from low cost sensors to provide equivalent measures to high quality odour and dust measurements appears difficult to achieve. The analysis was difficult to conduct effectively because of the limitations in the amount and quality of the sensor data. However, the very different nature of the types of measurements; indoor vs outdoor; sensor vs human panel; and divergent particle size coupled with the high variability between facilities makes it difficult to imagine that a single relationship could be developed even under optimum conditions. The possibility that some sensors could be used as indicators of odour based on conditions inside the shed is reasonable, given improvements in technology. The challenge would be to show the value of these measures in the routine management of broiler facilities.

Low cost sensors are available for a range of the factors that may be useful in monitoring the environment within broiler sheds.

Air flow inside sheds can be measured automatically, but the value of single point measures (i.e. the sensor station) is questionable where the flow inside the shed is complex and turbulent. For most purposes, air flow estimates based on fan operation probably provide sufficient accuracy where indoor airflow and emissions need to be quantified.

The dust sensor described in this report appeared capable of measuring dust within the shed, at modest cost and modest power usage; however, before this sensor could be used for continuous monitoring, some form of automated cleaning system would be required.

Odour is clearly an important management issue for poultry facilities but accurate measurement of odour is difficult and very costly — with limited likelihood of accurate, low cost sensors being available in the foreseeable future. As such, low cost monitoring would have to rely on surrogates such as specific gasses (ammonia, hydrogen sulphide) or general mixtures with some odorous components such as VOCs.

Two principal limitations in implementing sensor based air quality monitoring systems exist at present. First, the provision of a convenient power source. As indicated earlier, technologies are improving in this area, and there are good prospects that low power metal oxide-type sensors will be available, suited to limited power systems. The second limitation is the calibration, processing and presentation of the data that would allow odour and dust 'risks' to be identified in a meaningful way and in real time. Early development of such a system to deliver on-line odour warnings is being conducted by Pan *et al.* (2007) in Ontario, Canada for the monitoring of emissions from livestock farms. Full development of such a system would require some significant work in validating the sensing systems and models used to process the data that is collected. It also requires that some meaningful management options be developed, if possible, to mitigate short and long term risks from high level emissions. This is not a trivial point because, at present, 'turn-key' mitigation techniques for from broiler shed odour and dust emissions do not exist.

10.6 Conclusions

- Wireless sensor networks were found to be useful from an academic perspective for continuously monitoring the in-shed environment (in a largely qualitative sense); however they suffered from poor reliability.

- The low-cost VOC and dust sensors were found to be useful for measuring relative 'odour' and dust concentrations but were not robust enough for continuous monitoring in broiler sheds.

- The results of data mining indicated that:
  - relationships could not be found between the sensor outputs and conventional odour and dust measurements;
  - the chosen sensors used for monitoring air quality were not stable and were a limiting factor to the overall performance of the sensor network; and
  - the sensors were unreliable and the network occasionally malfunctioned, resulting in extended periods where no data was collected.

- Due to these issues, it was not possible to develop reliable and repeatable odour and dust calibration models from the data produced by the sensor networks.

- Sensor networks are not ready for deployment into poultry sheds, other than for research purposes

10.7 Recommendations and other considerations

Application of sensing stations in poultry sheds

- Using sensors to monitor in-shed air quality will not influence shed management or reduce emissions into the surrounding environment. We therefore do not recommend that air quality sensors be installed into broiler sheds except for research purposes.

- Representative sampling locations need to be determined to enable meaningful and useful measurement of air quality and in-shed environmental conditions. Such sampling locations need to be applicable during both tunnel and mini-vent modes of ventilation.

- The position of sensors, and required mobility, need to be determined to enable selection of power supply (battery or mains power)—can the sensor station be built into the shed (e.g. suspended from the ceiling) or does it need to be mobile?

- Sensor measurements need to be integrated with ventilation rate (e.g. using fan activity) to enable the estimation of emissions.

- Whilst sensor based measurements could not be correlated against conventional measures of dust and odour concentration, they did provide relative measures of dust, ammonia, VOC (surrogate for odour) and air flow (surrogate for ventilation rate) within the shed.

- Potential users of sensing stations need to identify what *really* needs to be monitored in order to reduce the number of sensors, which will improve power usage, mobility, price and size of a sensor system.

Sensor and network selection

- Select sensors that are robust and suited to the environment within poultry sheds, especially in terms of dust accumulation, high humidity, variable air flow and cleaning requirements.

- Sensor networks should be evaluated for suitability of operation in enclosed spaces, and intermittent interruption in operation to ensure robust transmission of data, and prompt recovery from interruptions.

- Calibrate the 'gain' setting on VOC and other sensors so that the sensor response equals the highest VOC concentrations within the shed. Whilst lower VOC concentrations may not elicit a sensor response, these lower levels would be of less interest.

- Utilise 'off-the-shelf' sensors (in un-modified form) to simplify construction and replacement of faulty/exhausted sensors.

11 Measuring odour emissions using an artificial olfaction system

The AOS system was used to continuously measure odour concentration at Farm A and Farm C to complement the discrete odour measurements obtained using olfactometry. At Farm A, the AOS monitored in-shed odour concentration over two successive batches during winter. Olfactometry measurements were also performed during the first batch. At Farm C, the AOS monitored in-shed odour concentration for both batches (single use litter and partially reused litter).

11.1 Development of a calibration formula to train the artificial olfaction system

The artificial olfaction system (AOS) was trained to measure odour concentration at Farms A and C. A calibration formula was developed using the method described in section 3.6.1. The relationships between odour concentrations measured by olfactometry and the AOS had a strong correlation and are presented in Figure 206. The r^2 values for Farms A and C were 0.73 and 0.77, respectively.
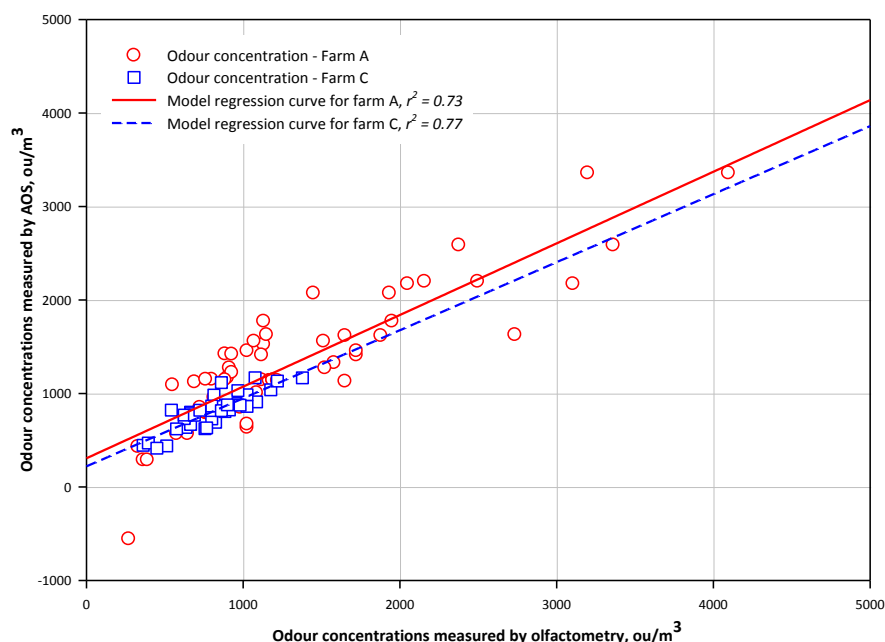
Figure 206: Comparison scatter plot of odour concentrations measured using olfactometry and AOS at Farm A and Farm C

The root-mean-square error of cross-validation (RMSECV) method was used to evaluate the performance of the models. RMSECV values for Farms A and C were 377.30 and 187.54, respectively. These values indicated that the odour concentrations measured by the AOS are expected to have maximum error range of ± 377.30 ou for Farm A and ± 187.54 ou for Farm C. The reason why the maximum error range at Farm A is higher than that of Farm C is due to the greater range of measured odour concentrations (200–4200 ou at Farm A and 200–1400 ou at Farm C).

The strong correlation to olfactometry results and relatively small error ranges support the use of this AOS for measuring broiler shed odour. The accuracy of AOS measurement may be enhanced by improving model generalisation capabilities to minimise 'over-fitting' and 'under-fitting' using other calibration algorithms (e.g., with artificial neural network); or by implementing a multi-step modelling technique considering the dilution steps of dynamic olfactometry. This technique may be useful for preventing the error range increasing as the range of odour concentrations increases (as what happened with Farm A compared to Farm C).

11.2 Continuous odour records for Farm A (winter) and Farm C

Odour concentration data from the AOS was combined with ventilation rate, olfactometry and weather data (when this data was available) to produce continuous records of odour emission rate.

Figure 207 displays the combined data sets for Farm A (winter, June to July 2006).
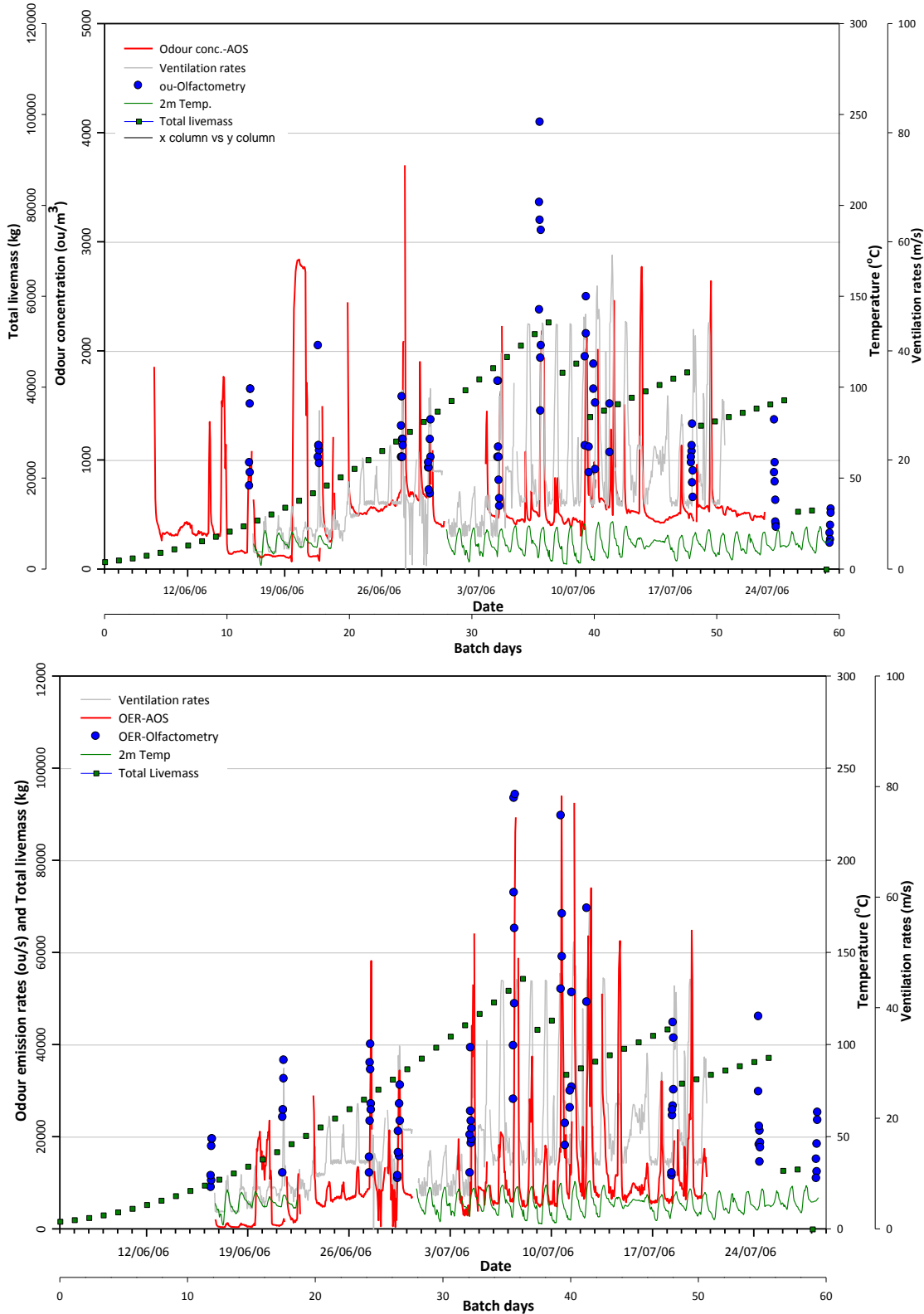
Figure 207: AOS, olfactometry, ventilation and weather data for Farm A (winter) (odour concentration (*top*) and odour emission rate (*bottom*))

Figure 208 displays the combined data sets for Farm A (the batch following the winter batch). Use of the AOS was continued during this batch because there were periods of missing data from the winter batch (as shown in Figure 207).
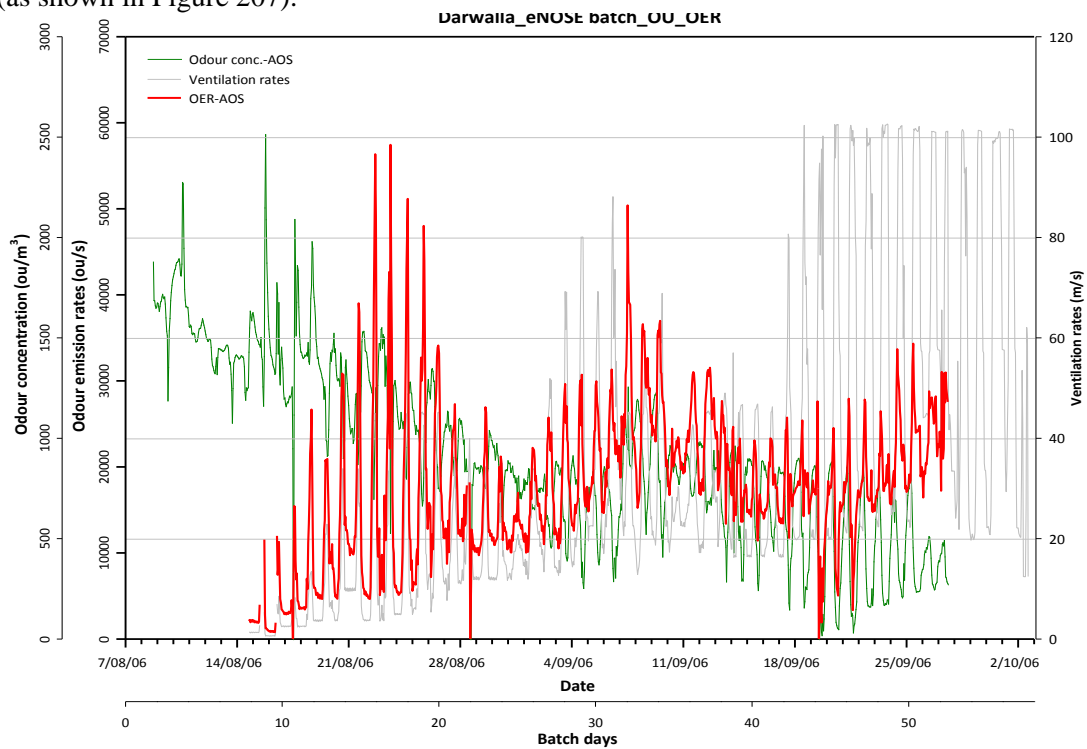
Figure 208: AOS, ventilation and weather data for Farm A (batch following the winter batch)

Figure 209 displays the combined data sets from Farm C (single use litter batch, January to March 2007). Odour emission rate was not available because ventilation rate data was not available during this batch.
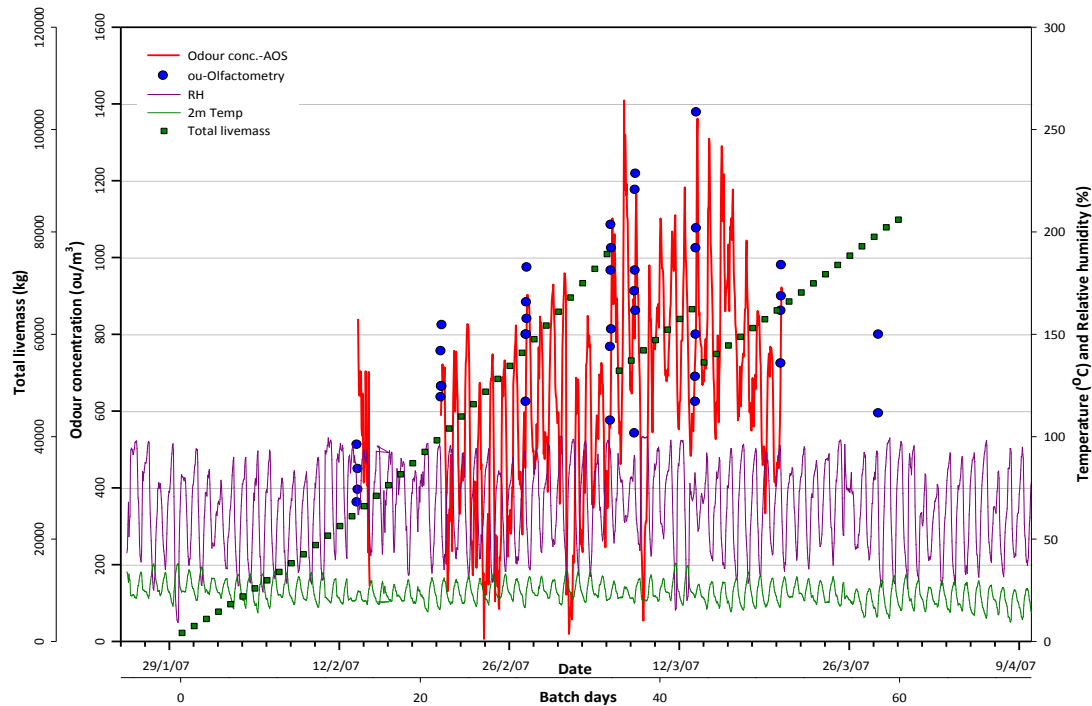
Figure 209: AOS, olfactometry, ventilation and weather data for Farm C (single use litter)

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Figure 210 displays the combined data sets from Farm C (batch following the fresh litter batch, when the litter was partially reused, April to June 2007).
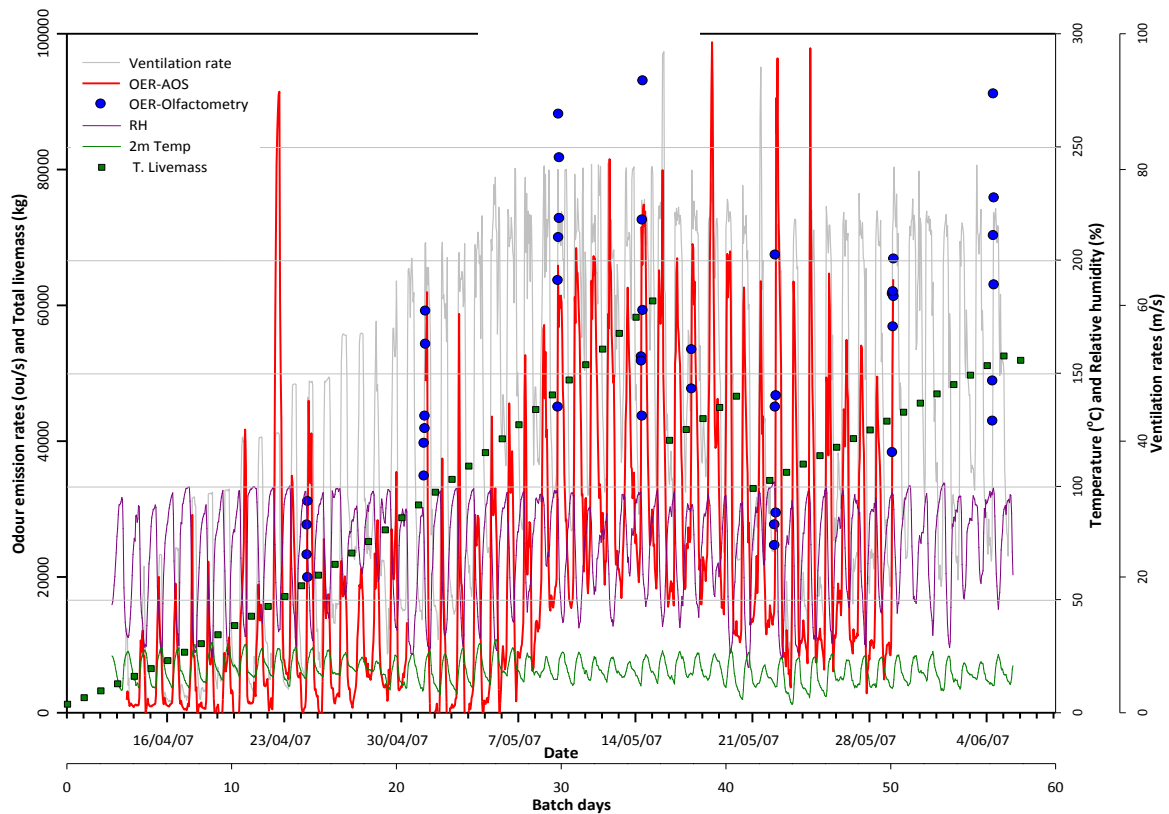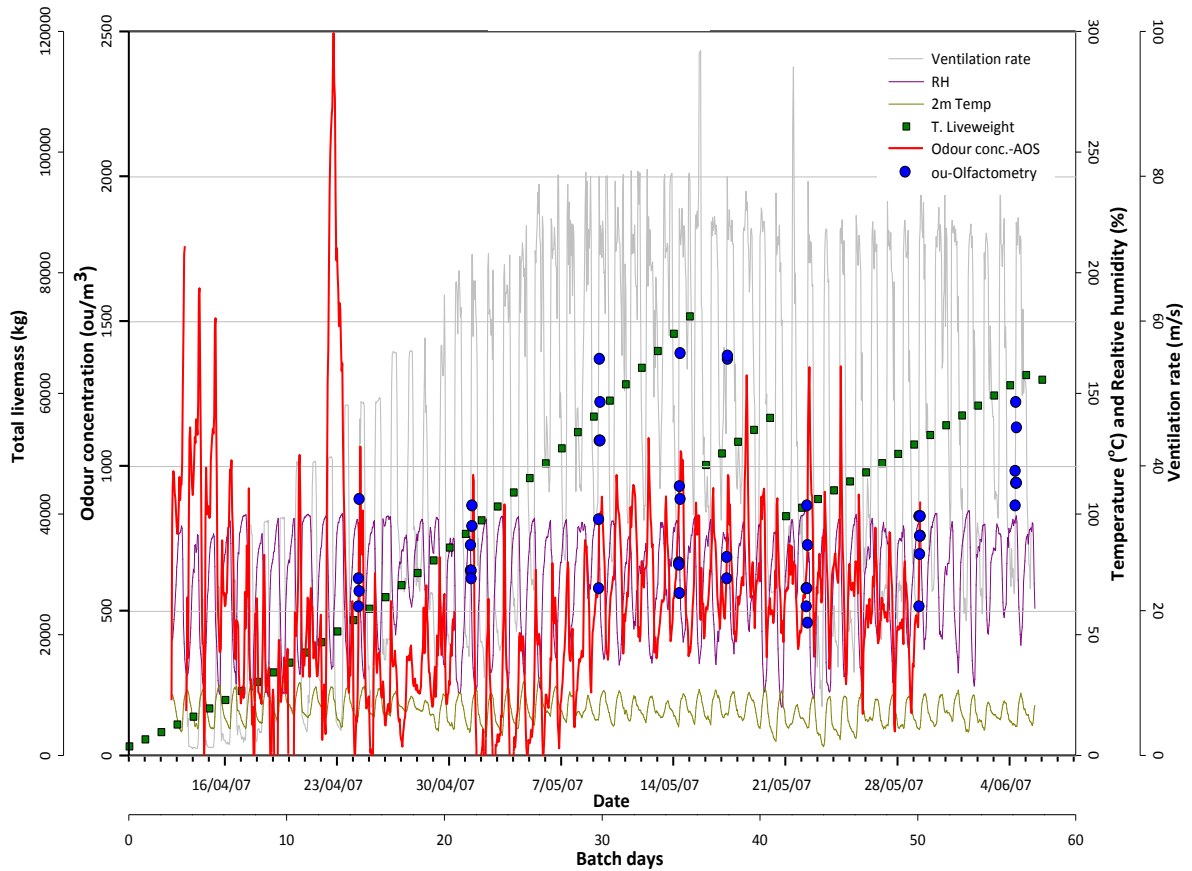
Figure 210: AOS, olfactometry, ventilation and weather data for Farm C (partially reused litter) (Odour concentration (*top*) and odour emission rate (*bottom*))

Continuous collection of odour, ventilation and weather data at Farms A and C demonstrated that:

- in-shed odour concentration and odour emission rates were much more variable than has been previously seen;

- OER changed throughout the batch, with a general trend to increase throughout the batch, but reduce following each pickup;

- odour concentration and OER fluctuated diurnally, presumably due to changes in ventilation rate; and

- odour emission rates sometimes spiked, for reasons that could not be explained by the data that has been collected.

The continuous odour records presented in this section need to be considered cautiously because it was not possible to collect data on all of the parameters that may affect odour emission rate (e.g. bird activity and litter moisture content).

11.3 Diurnal variation of the shed air quality

Figure 211 displays hourly average odour concentration, ventilation rate and odour emission rate data collected on days 29–35 of the production cycle for Farm A (the second of the winter batches, displayed previously in Figure 208) and Farm C (partial litter reuse batch, displayed previously in Figure 210). These charts show that ventilation rate and in-shed odour concentration varied diurnally in the week leading up to day 35 of the batch.

At Farm A, in-shed odour concentration was inversely related to ventilation rate. Odour emission rate generally increased with ventilation rate.

At Farm C, in-shed odour concentration began to increase when the ventilation rate began to reduce at approximately 8-11 pm. When ventilation rate began to rise at 4–7 am, the odour concentration continued to rise and did not begin to decrease until about 11 am to 1 pm. This complex relationship demonstrates that in-shed odour concentration does not have a simple relationship with ventilation rate (dilution effect) and is most likely influenced by other factors such as temperature and bird activity, which will influence the production and release of odour from the litter and birds. While the relationship between odour concentration and ventilation rate was not straight forward, odour emission rate was generally related to ventilation rate.

Ventilation activity was clearly different during these batches at Farm A and C. At Farm A, ventilation rate tended to increase daily between 8–10 am and then began to decrease between 4–6 pm whereas at Farm C, ventilation rate increased daily between 4-7 am but did not decrease until 8-11 pm. It is likely that the extra hours of high ventilation contributed to the different in-shed odour concentration trends, but did not appear to have an appreciable effect on daily trends in odour emission rate, which tended to reach a daily maximum around noon.
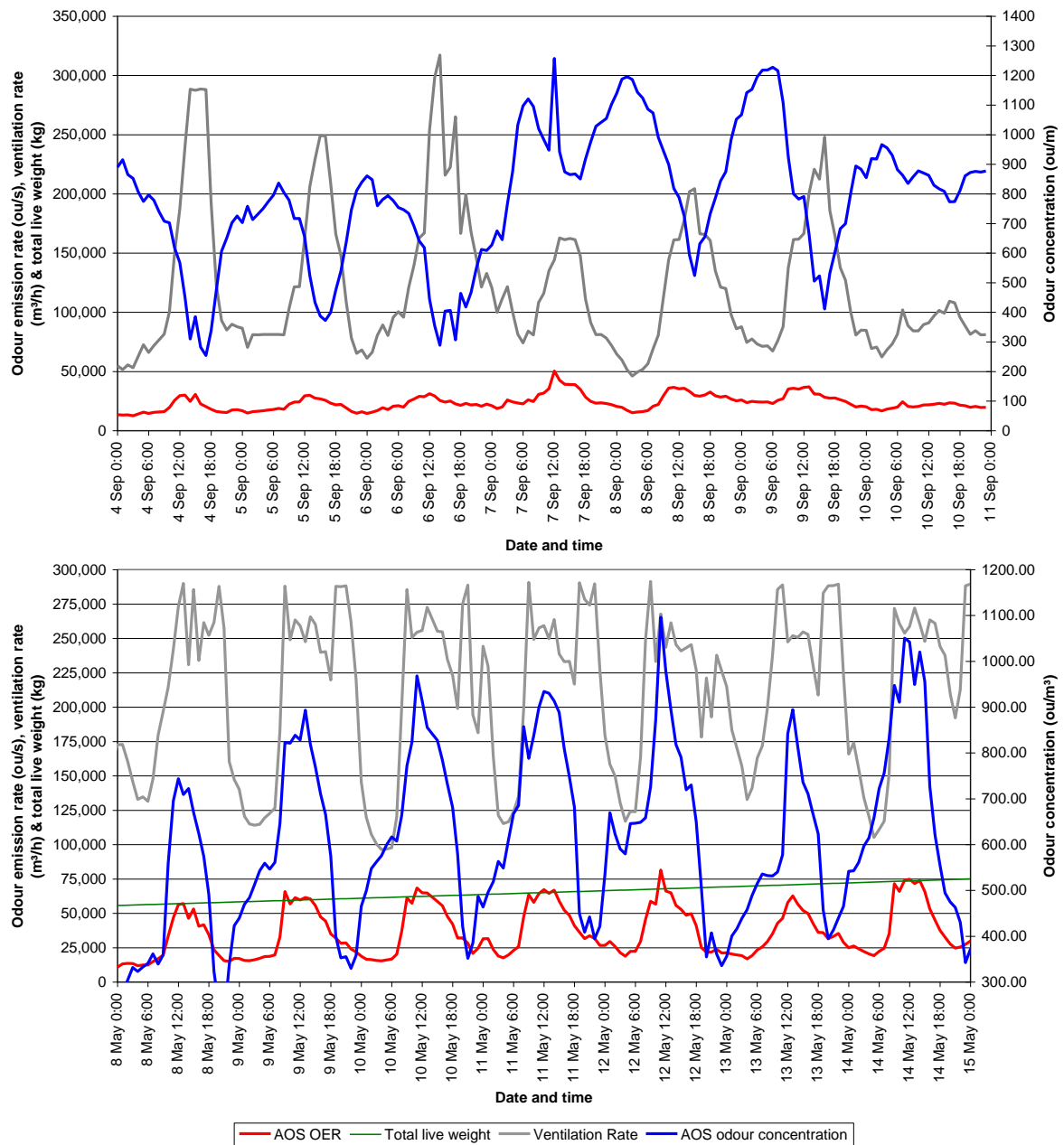
Figure 211: Odour concentration, odour emission rate and ventilation rate at Farm A-spring (*top*) and Farm C-partially reused litter batch in autumn (*bottom*) for days 29–35 of each batch

To simplify presentation of daily trends in odour concentration, ventilation rate and odour emission rate, the hourly average values were averaged across the week leading up to day 35 and re-presented in Figure 212. This figure shows the contrasting relationships between odour concentration and ventilation rate at Farms A and C.

Daily fluctuations of in-shed odour concentration are presumably related to the biological, chemical and physical mechanisms that control the generation, storage, release and transport of odours (these concepts were introduced in Section 2.2.6). In Figure 212, periods of the day have been highlighted as the times when odours may have been accumulating in the shed as well as when they may have been diluted or stripped from the shed.
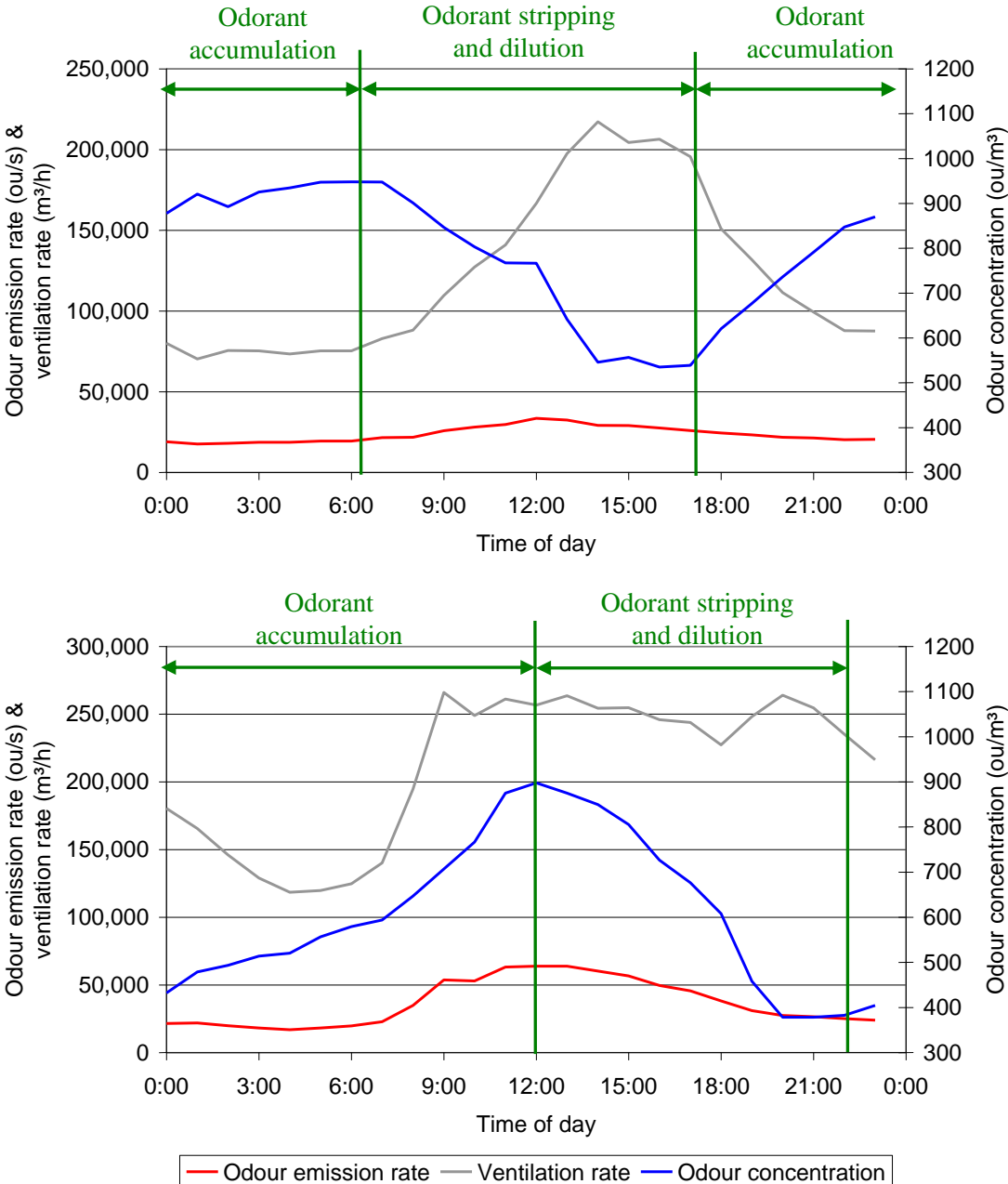
Figure 212: Hourly average odour concentration, odour emission rate and ventilation rate, averaged from day 29–35: Farm A-following winter batch (*top*); and Farm C-partially reused litter (*bottom*)

Odour concentration and odour emission rate for the week leading up to day 35 at Farm A and C (previously presented in Figure 211) have been plotted against ventilation rate in Figure 213. If the generation and release of odour from the litter and birds (i.e. odour flux) had remained constant

throughout the day, it would be expected that odour concentration would decrease and odour emission rate would remain constant as ventilation rate increased; however, as displayed in Figure 213, while these relationships partly held true at Farm A, they were not observed at Farm C. At Farm A, odour concentration generally decreased with increasing ventilation rate; however, odour emission rate was seen to increase with ventilation at low levels of ventilation (less than 100,000 m³/hr) but was relatively constant at higher levels of ventilation. At Farm C, however, odour concentration remained relatively constant up to a ventilation rate of approximately 220,000 m³/h, when there was a noticeable increase. Consequently odour emission rate increased linearly with ventilation rate until 220,000 m³/h, when OER appeared to suddenly increase.
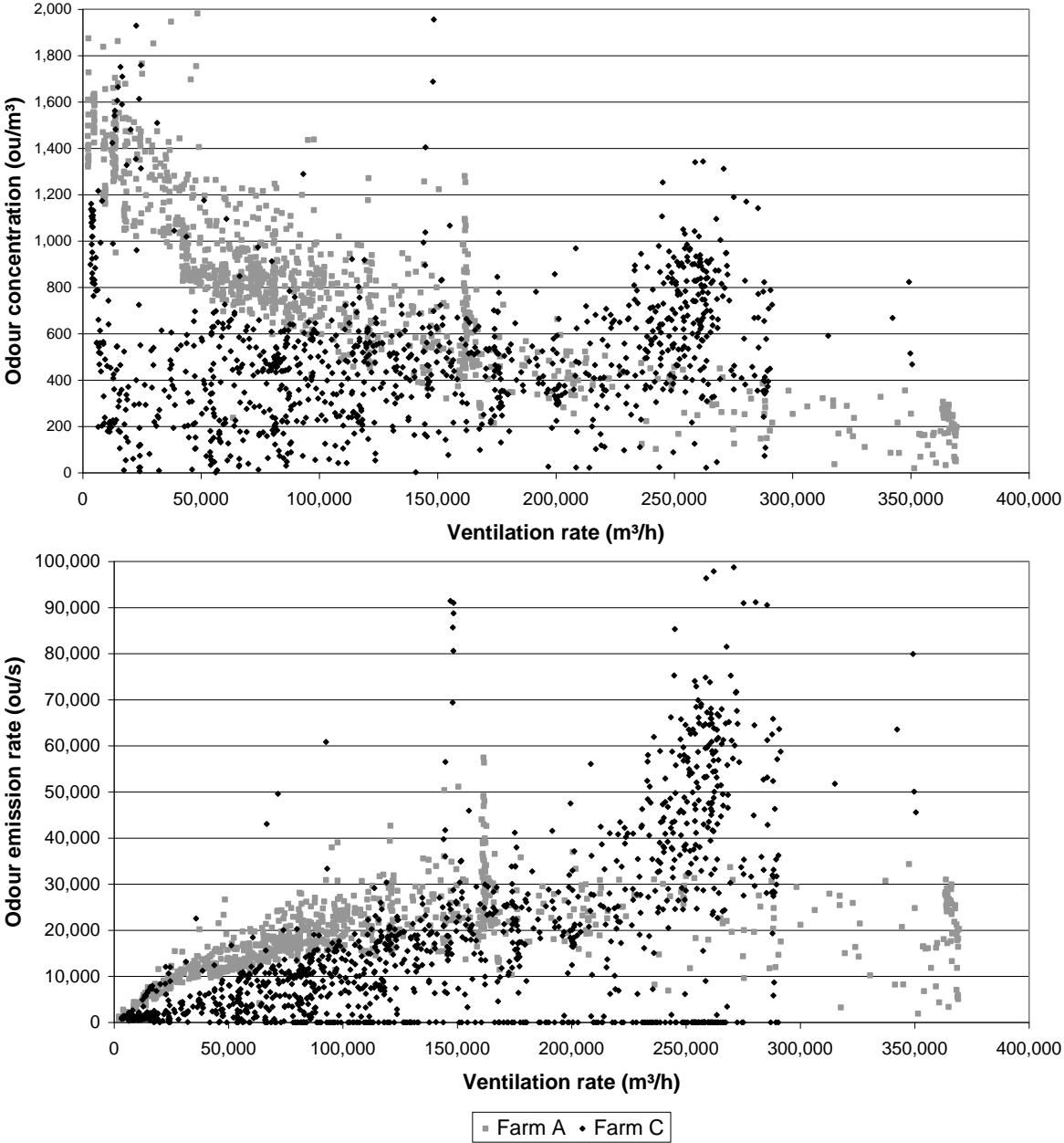
Figure 213: Odour concentration (*top*) and odour emission rate (*bottom*) trends with increasing ventilation rate for Farms A and C

The observed daily fluctuations of in-shed odour concentration and emission rate were almost certainly influenced by ventilation rate; however, other factors that influence the generation, storage, release and transport of odour—such as bird activity, temperature, humidity, litter moisture content, odorant concentration gradients between the litter surface and shed air; airspeed and microbial activity—will also influence odour emission rate.

Continuous monitoring of odour using the AOS has been useful in demonstrating the complex fluctuations of odour concentration and odour emission rate, which highlights the need for further research to improve understanding and to quantify the effects of all of the factors contributing to odour emissions.

11.4 Comparison of odour emission profiles from two consecutive batches at Farm C

Odour concentration was measured for two consecutive batches at Farm C using the AOS, as presented in Figure 209, Figure 210 and Figure 214. The purpose for measuring odour for these two consecutive batches at Farm C was to investigate whether partially reusing litter will increase odour emissions. In general, odour concentrations fluctuated between the two batches in a similar pattern. Prior to day 21 of Batch No. 1, except for days 14 and 15, odour concentration measurements were not made with the AOS due to equipment malfunctions, so it was not possible to make comparisons during this period. Odour measurements on these two days, however, displayed similar trends for both batches. Ventilation activity was not able to be collected during the first batch, so odour emission rates were not able to be compared.

The data presented in Figure 214 demonstrated that there was no substantial increase in odour concentration throughout the entire batch due to the practice of partially reusing litter.
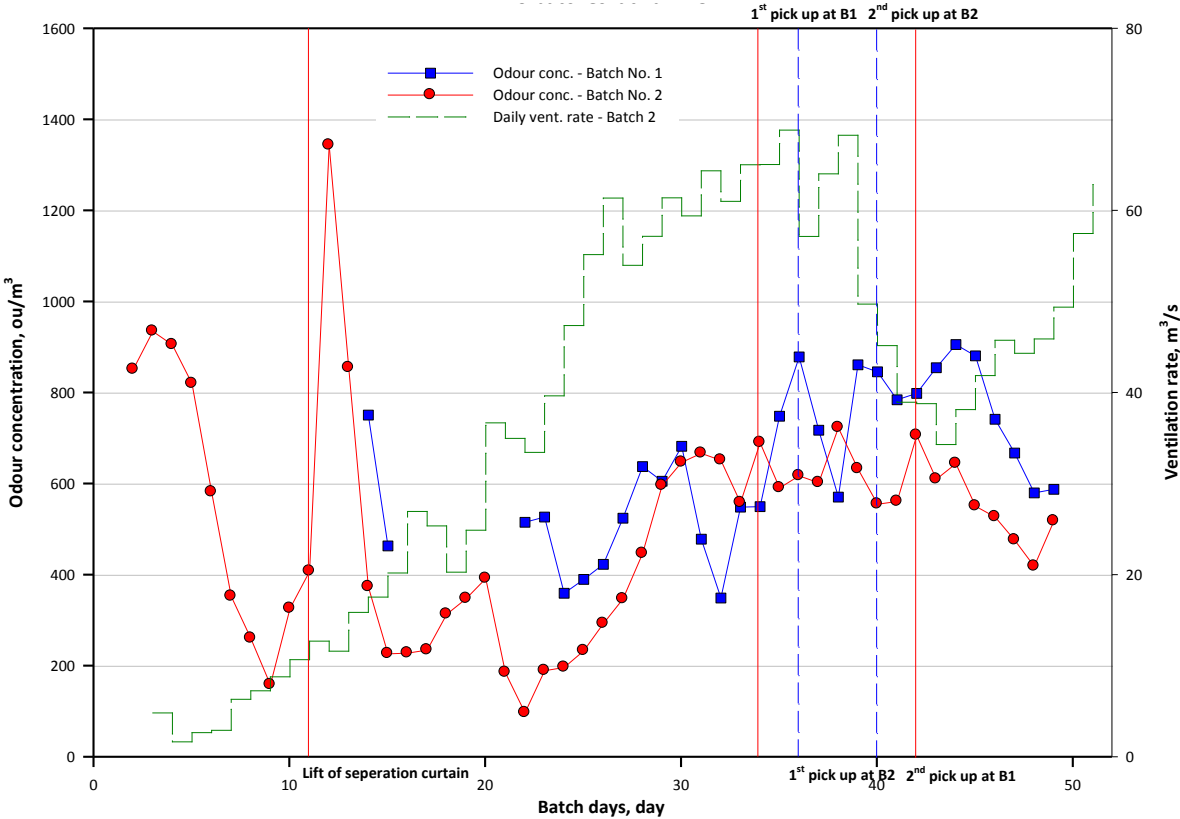
Figure 214: Comparison of odour emission profiles from two consecutive batches in Farm C (Batch No. 1 is single use litter, Batch No. 2 is partially reused litter)

11.5 Comparison of odour emissions between Farm A and Farm C

Odour concentrations were measured at Farm A (winter) and C (partially reused litter). Daily average odour concentration and ventilation rate are presented in Figure 215. Daily averaged odour emission rates were calculated and are presented in Figure 216.

Allowing for expected differences due to shed design and management, season and shed ventilation requirements, odour concentrations from both farms followed a typical odour fluctuation pattern during the production cycle; however, the AOS odour concentrations in Farm A were usually higher and more variable than those of Farm C.
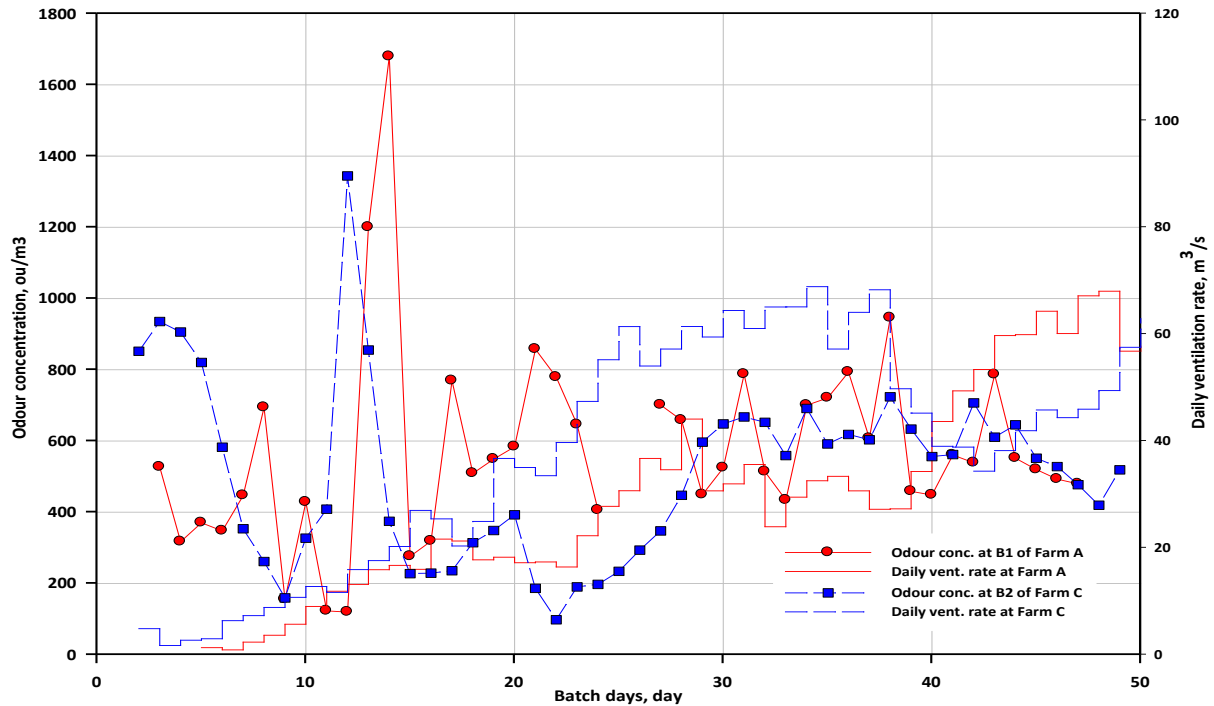
Figure 215: Comparison of odour concentrations at Farm A (winter B1) and C (partially reused litter B2) measured continuously using the AOS
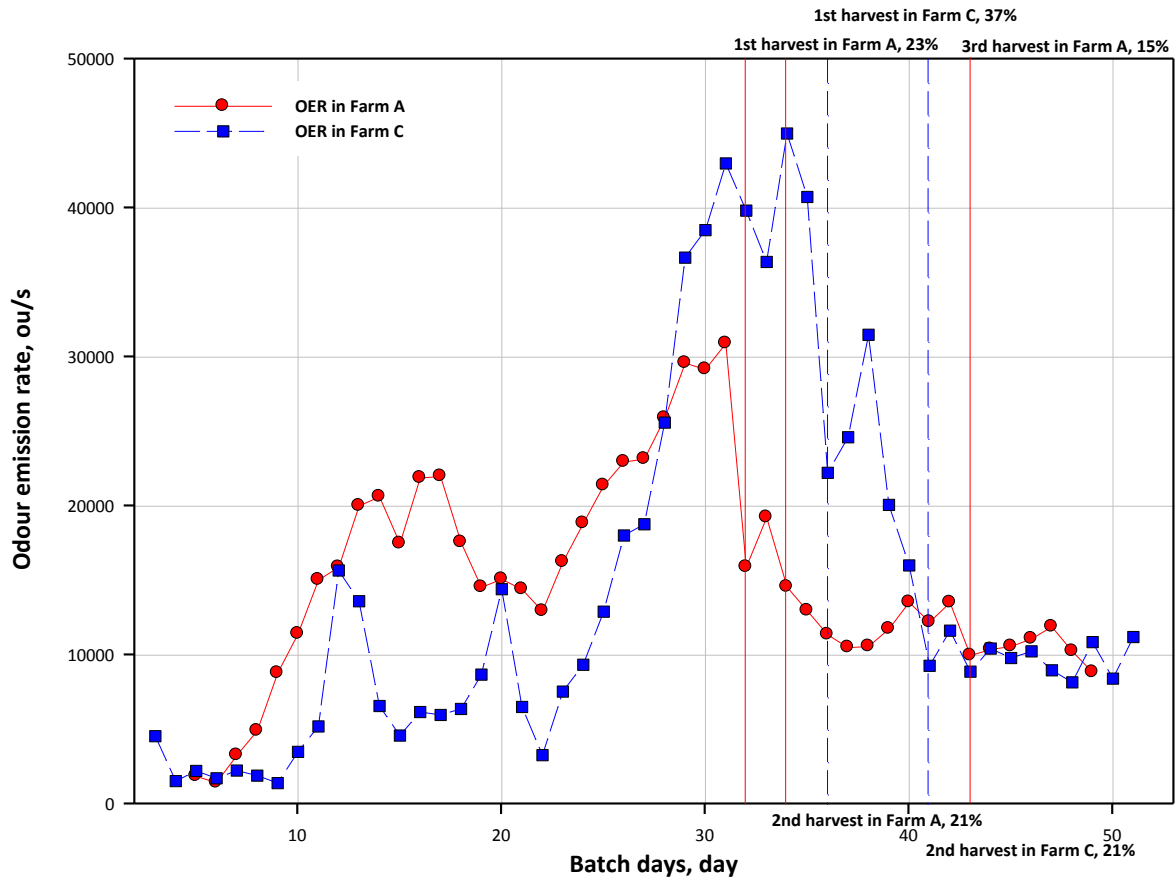
Figure 216: Comparison of daily averaged odour emission rate profiles using the AOS at Farm A (winter B1) and C (partially reused litter)

For both farms, odour emission rates increased until the first pickup. The highest odour emission rate was observed just before the first pickup—30,912 ou/s at Farm A on day 32 and 45,013 ou/s at Farm C on day 36. After the first pickup, odour emission rates for both farms decreased as the number of birds decreased. Odour emissions from Farm C were lower than Farm A until the end of week 4. From week 5, odour emission rates from Farm C were higher than Farm A, possibly due to the later first pickup at Farm C— four days later than Farm A. The second pickup was also 7 days later than at Farm A. After the second pickup around 41st day of the batch, odour emission rates from Farm A and C decreased and remained at a similar level of total odour emission rate.

11.6 Combining continuous odour emission rate measurement with weather station data

Continuous odour emission rate measurement at Farm A (batch following the winter batch) was combined with on-site weather data. This combined data set may be useful for improving understanding how odour emissions are interacting with the weather and atmospheric conditions that influence dispersion and dilution.

Dispersion of odour occurs between a source (the farm) and receptor (neighbours) and ideally dilutes the odour to a concentration where it isn't detected. Dispersion is strongly influenced by atmospheric stability—stable conditions commonly occur at night and result in poor dispersion whereas unstable conditions usually occur on warm, sunny days and encourage great dispersion.

Figure 217 shows the combined data set including odour emission rate, ventilation rate, ambient temperature, total live weight and atmospheric stability class at Farm A from days 30–37 (9–16 September 2006). The data demonstrates how the OER was still at an elevated level when stable atmospheric conditions (with associated poor dispersion) began in the late afternoon. This is just one example of how the AOS data may be combined with other data sets to improve understanding of broiler shed odour emissions beyond what is possible with discrete olfactometry sampling methods.
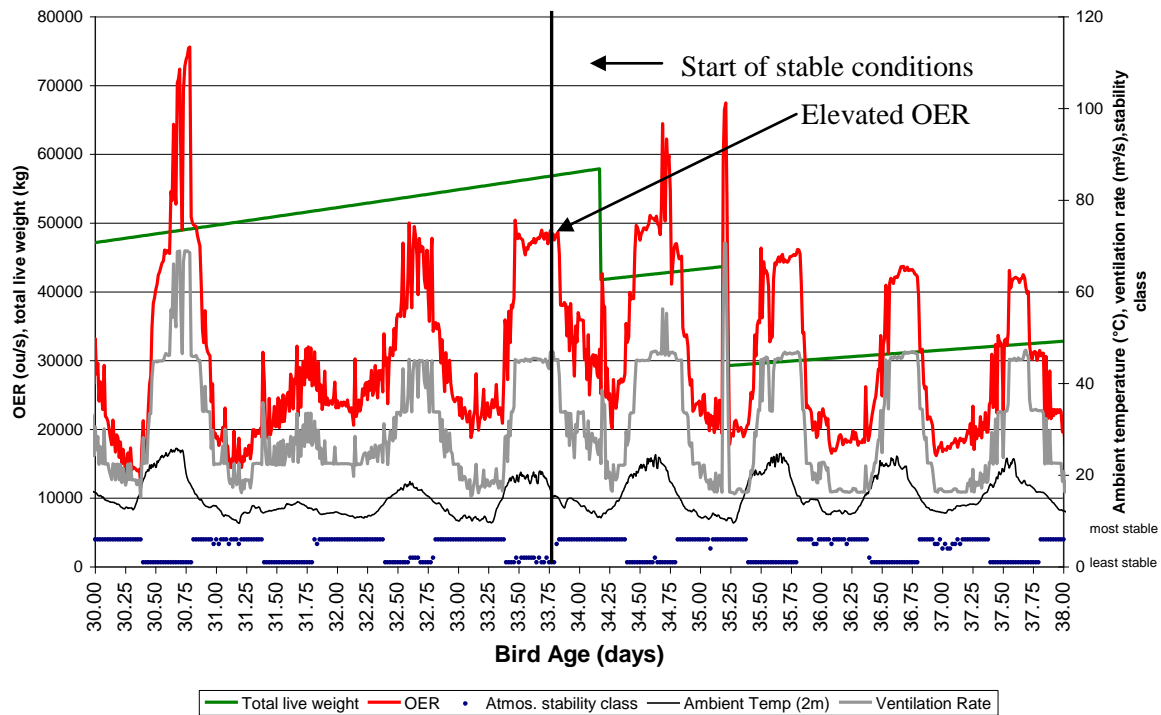
Figure 217: Combination of poultry shed odour emission rate, ventilation rate and atmospheric stability class on days 30-37 at Farm A (the second winter batch) (9–16 September 2006)

11.7 Summary of continuous odour monitoring using the artificial olfaction system

- AOS measurements of odour concentration correlated well with olfactometry measurements (and had relatively small error ranges).

- Calibration formulae were slightly different for Farm A and Farm C.

- When combined with continuous measurement of ventilation rate, the AOS was a valuable tool for continuously measuring odour emission rates.

- The AOS measured substantial diurnal variation in odour concentration and odour emission rate, presumably due to ventilation trends and other factors that control the production, accumulation, release and transport of odours from the source (litter and birds) to the in-shed air and out of the shed.

- Using the AOS, different relationships between odour concentration, odour emission rate and ventilation rate were observed at two different farms. These differences would not have been identified without the continuous monitoring capability provided by the AOS.

- The AOS was used to compare the in-shed odour concentration of sequential batches using different litter management practices—fresh litter and partially reused litter. The AOS was well suited to this application and provided significantly more information about odour than infrequent olfactometry odour analysis.

- AOS was combined with continuous ventilation rate and on-site weather data to produce a unique data set including odour emission rate and atmospheric stability class—two of the factors that contribute to odour nuisance potential.

- Comparison of AOS and olfactometry data highlights an issue—the majority of odour samples were NOT collected during the periods of the day when poor odour dispersion would be likely. The AOS showed that odour emission rates are usually lower at these times compared to the times when olfactometry samples were collected.

11.8 Recommendations for future use of AOS in poultry sheds

- Using AOS to monitor in-shed odour concentration will not directly influence shed management or reduce emissions into the surrounding environment. A farm operator will usually be aware of an increase in odour (using their nose) but there is often little that can be done to reduce odour emissions. We therefore do not recommend that AOS be installed into broiler sheds except for research purposes.

- Use of the AOS should be considered in future research assessments of odour in poultry sheds because it produces a more comprehensive record of the highly variable emissions than is possible with olfactometry alone.

- AOS must be calibrated using poultry odour samples, ideally collected from the farm/source of interest.

- To measure odour emissions from the shed, the sample collection point for the AOS should be positioned closer to the fans to ensure that the air measured by the AOS is the same as the air being emitted from the shed.

- For odour emission measurement, AOS must be combined with a ventilation monitoring system.

- Additional research should be directed toward combining AOS with weather data to improve understanding of when odour emissions combine with poor dispersion conditions.

12 Conclusions

This project had the following objectives:

- *Development of a database of odour and dust emissions from tunnel ventilated broiler sheds.*

- *Development of a dust and odour emissions model for representative broiler sheds based upon management factors.*

- *Examining the relationship between dust and odour emissions, in particular, the importance of dust as a carrier of odour.*

- *Development and testing of cost effective instrumentation to measure dust, odour and other production factors on commercial poultry farms.*

- *Application of an artificial olfaction system (AOS) to continuously monitor odour emissions.*

- *Identification of specific poultry shed non-methane volatile organic compounds and odorants.*

- *Quantification and evaluation of specific poultry shed odorants.*

Achievement of these objectives is summarised in the following sections.

12.1 Development of an odour and dust emission database

12.1.1 Summary of methods and sampling program

- Eleven tunnel ventilated broiler farms were included in this project. At three of the broiler farms; odour, dust and VOC emissions were measured at approximately weekly intervals. At the remaining eight broiler farms, only odour was measured and only on one day when bird mass in the shed was maximum.

- In total, 434 odour samples were included in the odour emission rate database:
    - 349 samples from broiler farms
    - 85 additional samples from broiler farms for method development (diurnal study, dust and odour relationship, and odour decay)
    - 34 samples were discarded due to excessive olfactometry variability (6.2% of total collected)

- Semi-continuous dust measurements were conducted on 50 separate days at 3 broiler farms.

- The majority of odour, dust and VOC samples were collected from within a temporary flexible duct that was attached to one of the tunnel ventilation fans at each farm.

- Odour concentration was measured using dynamic olfactometry to AS/NZS 4323.3:2001. Two laboratories were used, and comparative testing was conducted between the laboratories to ensure comparability of odour concentration measurement.

- Dust was measured using a DustTrak™ and an aerodynamic particle sizer (APS) and reported in terms of mass concentrations (PM_{10} and $PM_{2.5}$), particle number concentrations and count median diameters (mid-point of the number size distribution). Isokinetic sampling techniques were used.

- VOCs were collected using sorption tubes for subsequent analysis with a GC-MS/O.

- Ventilation rate was estimated by measuring in-shed or fan airspeeds, or by calculating the flow rate through each active fan using manufacturer supplied fan flow rate date (and adjusting for shed static pressure), which was selected as the preferred method.

- Two instrumental approaches were used to monitor in-shed conditions and odour concentration—wireless sensor networks and an artificial olfaction system (AOS).

- The differences in emissions between single use and partially reused litter were assessed at one farm.

- All odour samples were analysed within 8.5 hours of collection.

12.1.2 **Odour emissions summary**

Odour emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight).

- Broiler odour emission rates are summarised in Table 51.

Table 51:   Summary of measured broiler odour emission rates using olfactometry

Units	Full measured range	Range for majority of data
ou/s	2070–135,375	5000–105,000
ou/s/1000 birds placed	68–5187	100–3000
ou/s/1000 birds (while sampling)	86–6335	100–5000
ou/s/kg (total live weight)	0.18–5.13	0.25–2.5

- Broiler farm odour emission rates were highly variable. OER varied by farm, bird age, bird weight, season, time of day, ventilation rate, bird weight distribution and litter moisture. Not all variability could be explained by these factors: consequently other factors were likely to be involved.

- Diurnal variation in odour emission was observed. Changes to temperature, ventilation rate and bird activity (presumably coinciding with light programs) may have contributed to the variable emissions.

- 'Morning flush' of odorants accumulated during the night was not observed.

- OER increased with bird weight up to the day of the first pickup—commonly day 35.

- OER dropped sharply following each pickup.

- There was no clear relationship between OER and shed-average litter moisture content. Odour emission rates measured in this study **did not** increase with increasing moisture content.

- Odour emission rates were observed to vary throughout the day (20 hour continuous period); however the majority of samples were collected between 5:30 am and 2:00 pm, consequently the majority of the measured odour emission rates may not be representative of the daily spread of odour emission rates (evident from the AOS results). Few, if any, olfactometry measurements corresponded with periods of the day when odour emission rates would be minimal. These times are also when poor odour dispersion conditions are most likely to occur.

- Odour emission rates before bird placement (on fresh litter) and after litter removal were found to be lower than when birds were present in the shed. Odour emission rates decreased once birds were removed from the shed.

- Some of the measured odour emission rates were suspected of being unrealistic due to the ventilation rate being manually increased above 'normal' levels (given the ambient temperature and batch age) by the research team while attempting to measure the full range of possible odour emission rates. These data points have been identified in the data set and should be disregarded.

- Odour emission rates tended to be higher during summer, compared to winter, presumably due to greater ventilation requirements.

- Odour emission rates were similar for broiler farms located in Queensland and Victoria; however, this conclusion is based on a very limited number of farms that may not represent other farms in each of the respective states.

- Reusing litter in broiler sheds did not appear to increase odour emissions; however, weather, litter moisture content and stocking density were slightly different between the single use and partially reused batches, which confounded the analysis of the data.

- Odour emission rates measured at eight broiler farms in SE Queensland were found to be slightly different at each of the farms, even though shed design and management were similar. Weather may have been a contributing factor, but it is likely that odour emission rates will be highly variable between farms.

- Odour emission rate measurements from three farms were used while attempting to develop an odour emission model with stepwise regression techniques. Unfortunately, a robust model was not able to be developed.

- Relationships between odour emission and individual factors:
  - In-shed odour concentration generally tended to decrease with increasing ventilation rate, presumably because of dilution.
  - Odour emission rate generally tended to increase with ventilation rate.
  - There was no clear relationship between shed-average litter moisture content and odour emission rate. Maximum odour emission rates tended to occur when shed-average litter moisture content was 26–40%.
  - There was no clear relationship between odour emission rate and live weight density.
  - There were only weak relationships between odour emission rate and ambient temperature, even though ventilation rates tended to increase with ambient temperature.
  - It is unlikely that any of the aforementioned factors will influence odour emission rate in isolation with other factors. Consequently, variability in odour emission rate must be considered in conjunction with all contributing factors.

12.1.3 Dust concentration and emission summary

Dust emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, litter moisture content, bird age and total bird live weight).

- Broiler dust concentration and emission rates are summarised in Table 52.

Table 52:   Summary of measured broiler dust concentrations and emission rates

Dust fraction	Units	Full measured range	Range for majority of data
PM_{10}	mg/m³ (concentration)	0.04–1.62	0.1–0.8
	mg/s (ER)	1.8–158.5	5–50
	mg/s/1000 birds placed (ER)	0.04–3.90	0.1–1
	mg/s/kg (total live weight) (ER)	$(0.08–2.05) \times 10^{-3}$	$(1–8) \times 10^{-4}$
$PM_{2.5}$	mg/m³ (concentration)	0.001–0.515	0.02–0.14
	mg/s (ER)	0.08–50.3	1–10
	mg/s/1000 birds placed (ER)	0.003–1.24	0.025–0.25
	mg/s/kg (total live weight) (ER)	$(0.02–1.84) \times 10^{-4}$	$(0.4–1.6) \times 10^{-4}$
Particle number	particles/m³ (concentration)	$(0.13–4.34) \times 10^{7}$	$(0.4–2.5) \times 10^{7}$
	particles/s (ER)	$(0.015–2.34) \times 10^{9}$	$(0.1–1.5) \times 10^{9}$
	particles/s/1000 birds placed (ER)	$(0.045–6.3) \times 10^{7}$	$(0.1–4) \times 10^{7}$
	particles/s/kg (total live weight) (ER)	$(0.03–7.45) \times 10^{4}$	$(0.1–3) \times 10^{4}$
Count median diameter (CMD)	µm	1.4–3.4	1.5–2.5

- The concentration of dust in the air exiting the broiler sheds was highly variable. Consequently, dust emission rates from the sheds also varied widely. Dust emissions varied by ventilation rate, farm, bird age, season, microenvironment, litter management practice and other factors.

- Dust mass concentration and emission rate tended to increase with bird age (or weight). However this was not proven statistically.

- Seasonal differences in dust levels could be partly explained by seasonal differences in ventilation rates; however, this relationship was inconsistent between the farms.

- Dust particle mass and number concentrations and emission rates were generally higher when partially reused litter was employed compared to when single use litter was used. In addition, a greater proportion of fine dust particles (< 1 μm) were generated with partially reused litter.

- When no birds were present in the shed, dust emissions were substantially lower than emissions when birds were present.

- Diurnal variation in dust emission rates was observed.

- 'Morning flush' of dust accumulated during the night was not observed.

12.1.4 Possible effects of methodology on the measurement of odour and dust

- Manually overriding the automatic ventilation system during sample collection may have influenced some of the measured emission rates, producing 'unrealistic' data. The practice of manually controlling fan activity during sample collection was abandoned once this effect was suspected.

- Dust particles collected into odour sampling bags were rapidly attracted to the bag material, excluding them from analysis in the olfactometer; consequently, olfactometry was not an appropriate instrument to assess the influence of dust on perceived odour concentration.

- When using olfactometry to analyse poultry odour, samples must be analysed with 21.5 hours of collection. Divergence in odour concentration was evident 6 hours post sample collection, with significantly different odour concentration measured 21.5 hours post sample collection.

12.2 Development of an odour and dust emissions model

It was originally anticipated that data collected by the sensor networks would be suitable for the development of odour and dust emission models. Unfortunately, as the project progressed, it became apparent that the in-shed VOC and dust concentration data collected by the sensor networks did not correlate well with measured odour and dust emission rates and was therefore not suitable for use during model development.

In an attempt to develop an odour emission rate model, stepwise regression methods were applied to the odour emission measurements (olfactometry) using environmental and production factors—season, batch age, ventilation rate, ambient temperature, live weight distribution and litter moisture—to explain the variability in the data. Individual models were developed for the three primary broiler farms; however, not all of the variability in the odour emission rate data could be explained. **Use of these models to predict odour emission rates at other farms is not recommended due to significant differences between the models—especially with different interactions between the various factors—and uncertainty over which of these models should be selected.**

12.3 Relationship between dust and odour

The relationship between dust and odour emissions was examined; in particular, the importance of dust as a carrier of odour. During a series of experiments, poultry air samples were filtered using HEPA and glass fibre filters, and compared against unfiltered samples through olfactometry analysis. Also, attempts were made to regenerate odour samples from dust collected on the filters. It was found that the methods used during this project were not able to determine the effect of dust on perceived odour concentration:

- Dust particles collected into odour sampling bags were rapidly attracted to the bag material, excluding them from analysis in the olfactometer; consequently, olfactometry was not an appropriate instrument to assess the influence of particulates on perceived odour concentration.
- Odour could not be reliably regenerated using particulate matter captured on filters.

12.4 Development and testing of cost effective instrumentation to measure dust, odour and other production factors on commercial poultry farms

Wireless sensor networks were found to be useful from an academic perspective for continuously the in-shed environment (in a largely qualitative sense); however they suffered from poor reliability.

Investigation of the sensor data showed that:

- relationships could not be found between the sensor outputs and conventional odour and dust measurements;
- the chosen sensors used for monitoring air quality were not stable and were a limiting factor to the overall performance of the sensor network; and
- the sensors were unreliable and the network occasionally malfunctioned, resulting in extended periods where no data was collected.

Due to these issues, it was not possible to develop robust odour and dust calibration models from the data produced by the sensor networks.

Sensor networks are not ready for deployment into poultry sheds, other than for research purposes.

12.5 Application of an artificial olfaction system to continuously monitor odour emissions

An artificial olfaction system (AOS) was successfully deployed into two broiler sheds and used to monitor in-shed odour concentration on a semi-continuous basis. When combined with continuous ventilation rate data, the AOS provided a highly detailed record of odour emission rate from the sheds.

The AOS was trained using olfactometry data collected throughout the project. Odour concentration measurements by the AOS correlated well with olfactometry measurements and had relatively small error ranges. The calibration formula was revised several times during the project, resulting in slightly different formulas for different farms; however the refinements were minimal and the AOS could be used at other broiler sheds with reasonable confidence for research purposes.

The AOS measured significant diurnal variation in odour concentration and odour emission rate, presumably due to ventilation trends and other factors that control the production, accumulation, release and transport of odours from the source (litter and birds) to the in-shed air and out of the shed.

Using the AOS, different relationships between odour concentration, odour emission rate and ventilation rate were observed at two different farms. These differences would not have been identified without the continuous monitoring capability provided by the AOS.

The AOS was used to compare the in-shed odour concentration of sequential batches using different litter management practices—fresh litter and partially reused litter. The AOS was well suited to this application and provided significantly more information about odour than infrequent olfactometry odour analysis.

AOS was combined with continuous ventilation rate and on-site weather data to produce a unique data set including odour emission rate and atmospheric stability class—two of the factors that contribute to odour nuisance potential.

While the AOS was used successfully in this project to monitor odour, and produced considerably more detailed odour emission rate data than was possible with olfactometry alone, it is a research tool that is still undergoing development and significant amounts of manual data processing are required to convert the raw sensor responses into odour concentration values—use of AOS by consultants or producers is not currently feasible. Prospective users of alternative instrumental odour sensing systems to measure poultry shed odour need to ensure that the equipment has been thoroughly calibrated and has demonstrated measurement capabilities specifically with poultry shed odour.

12.6 Quantification and evaluation of specific poultry shed odorants

The gas phase emissions broiler sheds were analysed in three stages: chemical speciation; odorant identification and prioritisation; and NMVOC quantification. Table 53 lists the chemicals and odorants frequently identified in the NMVOC samples collected. The results of the NMVOC analysis from the broiler houses revealed that there was an impact from the soiling of the litter material within the broiler house.

The chemical species that dominated the NMVOC analysis of the broiler house samples were acetone, 2-butanone, 3-methyl-butanal, 2,3-butanedione, 3-hydroxy-2-butanone and acetic acid. Beyond the definition of NMVOC, the presence of sulphide species should not be disregarded. Sulphides present within the results included dimethyl sulphide, dimethyl disulphide and dimethyl trisulphide.

Table 53: Chemical compounds frequently occurring in poultry house samples

Compound Family	Compounds Identified	Odorants Identified[1]	Odorant Descriptor[2]
Aromatics	Benzene Toluene Xylene (*o*-,*m*-,*p*-) Trimethylbenzene Styrene Acetophenone Benzaladehyde Phenol	Toluene	Solvent/Sweet
Alcohols	1-butanol 2-butanol 2-ethyl-1-hexanol	1-butanol	Sweet/Solvent
Aldehydes	Butanal 3-methyl-butanal Hexanal Heptanal Octanal Nonanal Decanal	3-methyl-butanal Octanal	Pungent/malt Citrus/Green/Detergent
Ketones	2-butanone 2,3-butanedione 3-methyl-2-butanone 3-hydroxy-2-butanone	2,3-butanedione	Rancid/fatty/butter
Carboxylic Acids	Ethanoic acid Propanoic acid Butanoic acid		
Terpines	α-pinene β-pinene Limonene Camphene Camphor Carene Eucalyptol	α-pinene β-pinene Limonene Camphene Camphor Carene Eucalyptol	Pine Pine Citrus/Lemon Camphor Camphor Citrus Pine/Eucalyptus
Other Hydrocarbons	Tetradecane Hexadecane Tetrahydrofuran	Hexadecane	Solvent/Plastic/Alkane
Nitrogen	Trimethylamine		
Sulphur	Dimethyl Sulphide Dimethyl Disulphide Dimethyl Trisulphide	Dimethyl Sulphide Dimethyl Disulphide Dimethyl Trisulphide	Smokey Pungent/metallic

[1]*The third column identifies which of the chemicals are also odorants; and*
[2] *provides a descriptor of the odorant*

The results of the quantification of selected NMVOCs revealed that there is a variation as the birds mature, a general increase as the birds increase; however an almost constant relationship when related to the mass of the birds within the shed. Hence an increase in bird mass will correspond to an increase in NMVOC emissions. Figure 218 illustrates these two relations with respect to the amount of 2,3-butanedione being emitted from a particular broiler house.
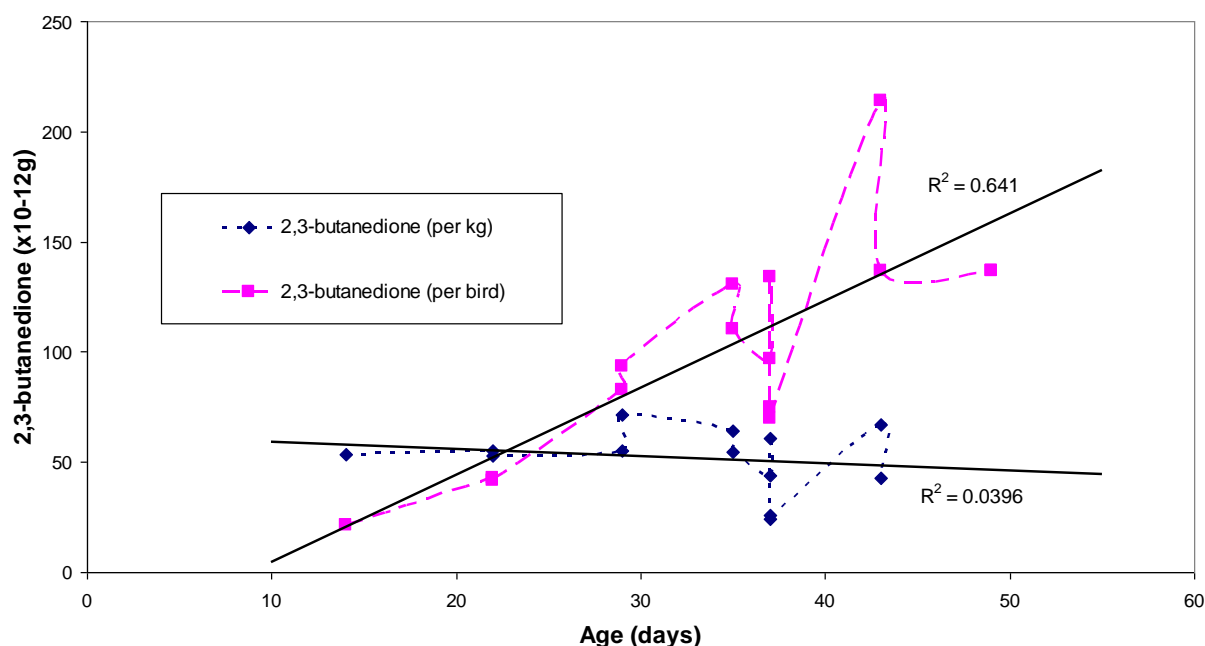
Figure 218: The variation of 2,3-butanedione across a growth cycle of a broiler as observed from the NMVOC sampling

From the results that were obtained from the NMVOC sampling during this project, there was no observed correlation between the season or the geographical location of the poultry facility sampled. There was also no observed impact upon the concentration of the NMVOCs analysed as a result of the ventilation rate applied during the collection of samples from the poultry houses. The round robin and diurnal sampling that was undertaken at the broiler sites revealed that the abundances of chemical species varied significantly. Figure 219 shows the average abundance and standard deviation of key NMVOCs when sampled at similar stages of growth of the birds.
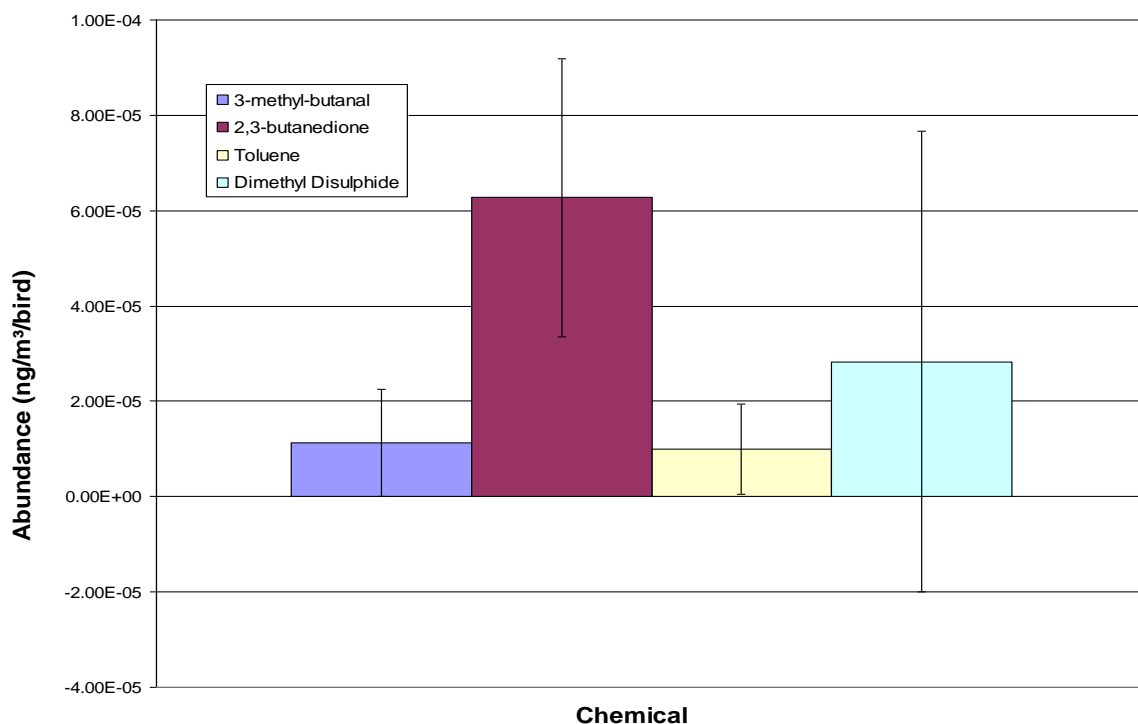
Figure 219: Variation in chemical abundance of key odorants observed from the round robin sampling

These observations led to the investigation of the composition and emissions of the litter material alone as a primary source of emissions. The increasing accumulation of faeces in the litter material corresponded with a change in the composition of NMVOCs and character of the odour. This suggests that degradation of organic matter in the litter is likely to be the principal mechanism influencing the chemical composition of the overall emission matrix.

13 Implications

13.1 The effect of variability and unpredictability of odour emission rates on industry planning and expansion

Odour emission rates were found to be highly variable, and the variability on each sampling day, throughout each batch, between batches and between farms could not always be explained by the environmental or production conditions recorded by the research team. Additionally, the range of odour emission rates was similar or slightly higher than values reported in literature. Consequently, prediction of odour emission rates by consultants for dispersion modelling purposes is unlikely to significantly change.

13.2 Volatile organic compounds in odour

The identification and quantification of non-methane volatile organic compounds (NMVOCs) combined with the prioritisation of odorant species within these NMVOCs will support the development of tailored odour mitigation strategies. By focussing on nuisance odorants, researchers can develop strategies to develop odour abatement and mitigation techniques, with the aim of improving the management of poultry shed emissions. Furthermore the identification of key odorants will support the development of real-time monitoring systems that can be targeted at assessing these nuisance compounds in order to estimate the overall odour emission.

13.3 Modelling of dust impacts

Further modelling work (e.g. dispersion modelling) will be required to use the database of dust emission rates obtained in this project to determine dust concentrations downstream of tunnel-ventilated poultry sheds as a function of distance. This information is necessary to determine dust concentrations in the areas surrounding poultry farms.

14 Recommendations

14.1 Measuring odour emissions at poultry farms

- Odour sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because broiler odour emissions are highly variable.

- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, fan details (dimension, manufacturer), mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, litter moisture content, litter depth, litter reuse status (single use or reused litter), lighting conditions and drinker type.
  - Batch information—bird age, bird numbers, bird live weight, total live weight, number of birds placed at the start of the batch, bird breed.

- Daily fan activity should be understood/surveyed for that time of the batch and year. Odour sampling should be scheduled so that samples are collected at a representative ventilation rate or at several ventilation rates over the normal daily range. Efforts must be made to collect odour samples during the night when odour emission rates are lowest (and is also the time when atmospheric conditions are most stable and poor odour dispersion is likely).

- Fan activity **should not** be manually over-ridden, and stabilisation time should be allowed, if possible, following each change in fan activity. If fan activity changes during the collection of samples, it is recommended to record the changes in fan activity and calculate a time-weighted-averaged ventilation rate rather than manually lock-in the number of active fans. By locking in fans, abnormal shed conditions may be produced—especially in terms of temperature, bird activity and odour production/release mechanisms—that will result in the measurement of unrealistic odour emissions.

- Odour samples should be collected and analysed in duplicate to improve olfactometry confidence and accuracy. Samples should be analysed as soon as possible following collection.

- Efforts should be made not to disturb the chickens prior to, or during, sample collection as additional activity may increase the release of odour from the litter and birds.

14.2 Measuring dust emissions at poultry farms

- Dust sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because poultry dust emissions are highly variable.

- Continuous, size-resolved dust measurements are necessary for studies that attempt to characterise the mechanisms of dust generation in intensive poultry sheds.

- For studies that integrate dust measurements over extended periods of time (e.g. gravimetric filter analysis), it should be recognized that large variations in dust concentrations are likely to occur during the sample collection period.

- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, litter moisture content, litter depth, litter reuse status (single use or reused litter), lighting conditions, drinker type.

- Batch information—bird age, bird numbers, bird live weight, total live weight, number of birds placed at the start of the batch, bird breed.

14.3 Sampling methodology

14.3.1 Dilution olfactometry analysis

- Odour samples should only be analysed at reputable, experienced olfactometry labs that can demonstrate compliance with AS/NZS 4323.3:2001. Olfactometry labs need to report the accuracy and precision of their laboratory, ensuring that $A \leq 0.217$ and $r \leq 0.477$.

- Odour samples are unstable and must be treated carefully. Odour samples should be analysed as soon as possible (preferably within 12 hours, maximum 24 hours) by:
  - choosing an olfactometry laboratory in close proximity to the test site;
  - transporting the samples to the olfactometry laboratory as soon as possible; and
  - pre-arranging delivery time to ensure the samples are analysed as soon as possible after delivery to the olfactometer.

- Where more than one olfactometry laboratory is used for a single trial, it is recommended that a test be performed to ensure similarity in results from all laboratories.

14.3.2 Ventilation rate measurement

- It is recommended that ventilation rate be estimated using manufacturer's performance data (from certified testing laboratories), number of active fans and shed static pressure. This method is recommended assuming that the following conditions are met:
  - fans are clean, well maintained and in good working order;
  - fan details are recorded including fan diameter, number of blades, blade pitch, blade material, motor manufacturer, motor power, voltage, pulley sizes, grills, shutter description, presence of a cone. A tachometer should be used to check rotational speed;
  - static pressure is recorded at the time of ventilation measurement (changes to fan activity and fluctuating wind conditions will affect the reading);
  - all active fan activity, including duty fans, is recorded;
  - on-farm airspeed measurement inside the shed or across each fan face should ideally be made as a cross reference to the manufacturer's published fan performance data.

- Estimating ventilation rate using manufacturer's performance data is recommended because:
  - ventilation rate can be consistently estimated regardless of duty and tunnel fan activity as well as tunnel ventilation status (internal shed airspeed measurement is unsuitable when mini-vents are open or when duty fans are active);
  - manufacturer's fan performance data is usually obtained using standardised methods and certified laboratories (but you need to check which standard was used);
  - airspeed measurements across each active fan are time consuming and prone to errors due to fluctuating winds as well as non-uniform and turbulent air flow;
  - airspeed measurements across each fan face will be affected by the presence of grills and back-draft shutters; and
  - within the poultry shed environment, it is difficult to achieve the conditions required by AS4323.1:1995 when measuring airspeed inside the shed or across each fan face.

- When airspeed measurements are to be taken inside the shed or across each fan face, measurements must be made according to AS4323.1:1995.

- External fan measurements should be undertaken with caution because of turbulent fan air flow.

- External fan measurements should be avoided during gusty wind conditions.

- If measuring air velocity across the fan face, measurements need to be made at each active fan.

- Internal shed velocity measurements should not be undertaken while mini-vents or duty fans are active.

- Internal shed velocity measurements should be avoided during low levels of ventilation (when airspeed is minimal).

- Be aware that errors of 10–20% are likely regardless of the method used.

14.3.3 Measuring litter moisture content

Litter moisture content can be highly variable across the shed floor area. To adequately survey and quantify the range and distribution profile of moisture content, numerous samples of litter need to be collected across the entire floor area. It is recommended that the profile of litter moisture content be reported rather than the shed-average value, as this will enable identification of wet/dry spots, which may significantly contribute to the total odour emission.

14.4 Using the odour emission rate data

- Odour emission rates vary diurnally, seasonally, throughout the batch and will be different at different farms depending on management and infrastructure. **Calculation of daily average, batch average or constant odour emission rate is not appropriate**—unless for a specific purpose.

- Odour emission rates should be presented in terms of total OER (ou/s), OER per 1000 birds placed (ou/s/1000 birds placed) or OER per kg total live weight (ou/s/kg).

14.5 Using the dust emission rate data

- Dust emission rates vary diurnally, seasonally, throughout the batch and will be different at different farms depending on management and infrastructure. Selection of a daily average, batch average or constant dust emission rate should be made with extreme care: considerable variation is likely to occur around the chosen average.

- If possible, dust emission rates should be presented in terms of total emission rate (ER) (e.g. mg or particles/s), ER per 1000 birds placed (e.g. mg or particles/s/1000 birds placed) and ER per kg total live weight (e.g. mg or particles/s/kg). This will enable easier comparison between different studies.

14.6 Instrumental measurement of air quality in poultry sheds

14.6.1 Application of sensing stations in poultry sheds

- Representative sampling locations need to be determined to enable meaningful and useful measurement of air quality and in-shed environmental conditions. Such sampling locations need to be applicable during both tunnel and mini-vent modes of ventilation.

- The position of sensors, and required mobility, need to be determined to enable selection of power supply (battery or mains power)—can the sensor station be built into the shed (e.g. suspended from the ceiling) or does it need to be mobile?

- Sensor measurements need to be integrated with ventilation rate (e.g. using fan activity) to enable the estimation of emissions.

- Whilst sensor based measurements could not be correlated against conventional measures of dust and odour concentration, they did provide relative measures of dust, ammonia, VOC (surrogate for odour) and airspeed (surrogate for ventilation rate) within the shed.

- Potential users of sensing stations need to identify what *really* needs to be monitored in order to reduce the number of sensors, which will improve power usage, mobility, price and size/handling.

- Use of the AOS should be considered for future assessments of odour in poultry sheds because it produces a more comprehensive record of the highly variable emissions than is possible with olfactometry alone.

- AOS must be calibrated using poultry odour samples, ideally collected from the farm/source of interest.

- Additional research should be directed toward combining AOS with weather data to improve understanding of when odour emissions combine with poor dispersion conditions.

14.6.2 Sensor and network selection

- Select sensors that are robust and suited to the environment within poultry sheds, especially in terms of dust accumulation, high humidity, variable air flow and cleaning requirements.

- Sensor networks should be evaluated for suitability of operation in enclosed spaces, and intermittent interruption in operation to ensure robust transmission of data, and prompt recovery from interruptions.

- Utilise 'off-the-shelf' sensors (in un-modified form) to simplify construction and replacement of faulty/exhausted sensors.

- The design of AOS should include sensors that target NMVOCs identified as being primary odorants; including 2,3-butanedione and dimethyl disulphide.

14.7 Future research

- Additional studies to quantify 'typical' odour emission rates from broiler farms measurements need to be made at multiple farms and on multiple days (especially leading up to the first pickup and after pickups); however, significant variability, unexpected and unexplainable odour emission rates—as seen in this project—would be likely. Odour measurements must represent the full spread of 'normal' daily odour emissions, which will require odour samples to be collected at night.

- An artificial olfaction system (AOS) should be used in future odour measuring research activities because the degree of variability and full range of odour emission rates cannot possibly be quantified using olfactometry alone. Research should be directed toward refining the useability, robustness and accuracy of the AOS in detecting the chemicals determined as being the principal nuisance odorants.

- Future research should be directed at quantifying the specific biological, physical and chemical mechanisms that regulate the formation, release and transport of odour and dust within the shed and in the exhaust airstream.

- The effect of litter moisture content on odour formation is still largely unknown—including the delay between wetting and increased emission; changes to microbial community composition and activity; and changes to the litter physical odour release properties due to caking. Further research must investigate these relationships between litter moisture content and odour generation. Techniques to accurately measure the full moisture profile of the litter and to quantify the amount of caking will be required to achieve this.

- Development of robust odour and dust emission models should still be pursued, despite the inability to produce a robust model during this project. The model will need to incorporate the fundamental factors influencing odour emission, and should be formulated from first principles rather than attempting to fit modelling parameters to collected data.

- Future research should be directed at quantifying the conservation/degradation of odorants following emission from the shed (and before reaching receptors). Changes in odorant composition beyond the farm boundary may change the perception of odour by receptors.

- Investigation of the composition and NMVOC emissions from the litter material from the broiler houses would provide useful information relating to the principal odorant emissions from the broiler house.

- Moreover, the investigation of the microbial communities within the litter material and their corresponding NMVOC emissions would enable the elucidation of the species responsible for the key nuisance odorant formation.

15 Glossary

15.1 Abbreviations

AIC	Akaike's Information Criterion
ANOVA	Analysis of Variance
AOS	Artificial Olfaction System (electronic nose; non-specific electronic sensor array)
APS	Aerodynamic Particle Sizer
AS	Australian Standard
AS/NZS	Australian/New Zealand Standard
AWS	Automatic Weather Station
AWSN	Ad hoc Wireless Sensor Networks
CEN	European Committee for Standardisation
CMD	Count Median Diameter
DC	Direct Current
DEEDI	Department of Employment, Economic Development and Innovation (Queensland)
DMDS	Dimethyl Disulphide $(CH_3)_2S_2$
ER	Emission Rate
ETC	Emission Testing Consultants
EtSH	Ethane thiol, ethyl mercaptan CH_3CH_2SH
GC	Gas Chromatograph
GC-MS-O	Gas Chromatograph-Mass Spectrometer-Olfactometer
HEPA filter	High Efficiency Particulate Air filter
IR	Infra-Red
LAN	Local Area Network
LED	Light Emitting Diode
Lpm	Litres per minute (sampling rate measurement)
NMVOC	Non-Methane Volatile Organic Compound
MOS	Metal Oxide Sensor
MS	Mass spectrometer
MSD	Mass selective detector
N_2O	Nitrous Oxide
NER	Number Emission Rate
NH_3	Ammonia
OC	Odour Concentration
ODP	Odour Detection Port
OEM	Original Equipment Manufacturer
OER	Odour Emission Rate
OID	Olfactory input device
ou	Odour Concentration in Odour Units per m³
PCA	Principal Component Analysis
PLS	Partial Least Squares
PM	Particulate Matter
PM_1	Particulate Matter less than or equal to 1 micron
PM_{10}	Particulate Matter less than or equal to 10 microns
$PM_{2.5}$	Particulate Matter less than or equal to 2.5 microns
PN	Particle Number
PPB	parts per billion (µg/l)
PPM	parts per million (mg/l)
PTFE	Polytetrafluoroethylene (Teflon®)
PVC	Polyvinyl Chloride
QUT	Queensland University of Technology
r^2	Correlation Coefficient Value

REML	Restricted Maximum Likelihood
RH	Relative Humidity
RMSEC	Root-Mean-Square Error of Calibration
RMSECV	Root-Mean-Square Error of Cross-Validation
SCD	sulphur chemiluminescence detector
TD	Thermal desorption/Thermal desorber
TIC	Total Ion Chromatogram
TSP	Total Suspended Particulates
UNSW	University of New South Wales
VOC	Volatile Organic Compound
VR	Ventilation Rate
WSN	Wireless Sensor Networks

15.2 Definitions

Broiler	Meat chicken
Count Median Diameter	The mid-point of the size distribution of measured particles
Dry bulb temperature	Air temperature measured by a thermometer
Dynamic Olfactometer	Dilution system used to calculate odour concentration with the use of human panellists
Fogger	High pressure fogging nozzle designed to atomise water droplets and create a fine mist
Live weight density	Unit weight of birds housed in a prescribed area, normally kg per m²
Pickup	An event when some or all of the meat chickens will be harvested for processing
Stocking density	Number of birds housed in a prescribed area, normally birds per m²
VOC and NMVOC	The term volatile organic compound (VOC) refers to any organic compound that under normal conditions will be of sufficient volatility to enter the atmosphere; where normal conditions are typical atmospheric pressure (101.325kPa) and temperature (~300K). Correspondingly non-methane volatile organic compounds (NMVOC) are all volatile organic compounds with the specific exclusion of methane (CH_4). **For the purpose of this document the terms NMVOC and VOC have been used interchangeably, however it should be expressly noted that where VOC is written it is implied that it is the non-methane volatile organic compounds.**
Wet Basis	Volume of moisture present in a sample compared to the total sample weight (can be compared to Dry Basis, which is the volume of dry matter present in the total sample weight)

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Appendix 1 – Summary of reported dust concentrations and emission rates

Reference	Type of operation	Ventilation type	Country	House and manure system	Sampling location	Concentration (mg/m³)					Emission rate, ER (mg/s) [ER per 500kg live weight (mg/s/500kg)]				
						TSP	PM$_{10}$	Respirable (PM$_5$)	PM$_{2.5}$	PM$_1$	TSP	PM$_{10}$	Respirable (PM$_5$)	PM$_{2.5}$	PM$_1$
(Willis et al., 1987)	Broiler	Mechanical	USA					5.43 - 9.71							
(Conceicao et al., 1989)	Broiler	Mechanical			12 sites within the shed	2.0 - 13.2		0.6 - 1.63							
(Morrison et al., 1993)	Broiler									0.0 - 5.7					
(Wathes et al., 1997)	Broiler	Mechanical	UK	Litter floor	7 sites within the shed (inc. 1 site at shed exhaust)	8.0 - 12.0		0.9 - 1.3			200.2-339.8 [1.39-2.36]		24.5-34.6 [0.17-0.24]		
(Hinz and Linke, 1998)	Broiler	Natural	Germany	Litter floor	Centre point of shed at 0.75m height	1.0 - 14.0									
(Takai et al., 1998)	Broiler	Various	Denmark, Germany, England, Netherlands	Litter floor	7 sites within the shed (inc. 1 site at shed exhaust)	7.2		0.8			158.4 [1.1]		20.7 [0.14]		
(Ellen et al., 1999)*	Broiler			Litter floor	Within shed	8.2 - 9.0		1.4 - 1.9							
(Takai et al., 1999)*	Broiler			Litter floor	Within shed	7.06 - 7.18									
(Drost et al., 1999)*	Broiler			Litter floor	Within shed			1.8 - 6.5							
Egis (1999)**	Broiler	Tunnel	Australia (Geelong)	Litter floor		16					1230 [8.54]				
Mirrabooka (2002)**	Broiler	Tunnel	Australia (Tamworth)	Litter floor		4.7 - 16	1.6 - 6.3					17 - 139			
(Redwine et al., 2002)	Broiler	Tunnel	USA	Litter floor	Centre of shed, 40m from output fans	0.74 - 11.4	0.1 - 0.3				2.8 - 504 [0.02-3.5]	0.18-30 [0.001-0.21]			

Reference	Type of operation	Ventilation type	Country	House and manure system	Sampling location	Concentration (mg/m³)					Emission rate, ER (mg/s) [ER per 500kg live weight (mg/s/500kg)]				
						TSP	PM$_{10}$	Respirable (PM$_5$)	PM$_{2.5}$	PM$_1$	TSP	PM$_{10}$	Respirable (PM$_5$)	PM$_{2.5}$	PM$_1$
(Banhazi et al., 2003)	Broiler	Various	Australia (SA)		Within shed	2.27 - 8.58		0.3 - 1.8			85-298.5 [0.6-2.1]		10-100 [0.07-0.7]		
(Lacey et al., 2003)***	Broiler	Tunnel	USA	Litter floor	Centre of shed, 40m from output fans						408 [2.8]	21.5 [0.15]			
(Visser et al., 2006)					Upstream of shed				0.024						
	Broiler	Tunnel	USA	Litter floor	Within shed at exhaust				0.059						
					100ft downstream of shed				0.024						
(Van Der Hoek, 2007)	Broiler	Various	The Netherlands	Litter floor								3.2 [0.2]			
(Roumeliotis and Van Heyst, 2007)	Broiler	Mechanical	Canada	Litter floor	Within shed at exhaust		0.69		0.19	0.16		9.7 ± 0.3 [0.07±0.002]		2.03 ± 0.08 [0.014±0.0006]	1.65 ± 0.07 [0.01±0.0005]
(Takai et al., 1999)*	Broiler and Layer			Various	Within shed	2.22 - 4.58		0.19 - 0.64							
(Donham and Cumro, 1999)*	Broiler and Layer			Various	Within shed	0.02 - 81.33		0.01 - 7.73							

These references can be found within (Ellen et al., 2000). They are taken from the conference proceedings of the international symposium on "Dust Control in Animal Production Facilities"

** As referenced by Pollock and Anderson (2004)

*** This study reports average values from the (Redwine et al., 2002) study

Appendix 2 – Summary of the NMVOC laboratory techniques

Sampling Campaign	Date (MM/YYYY)	Gas Chromatograph Flow	Gas Chromatograph Column	Gas Chromatograph Temperature	Mass Spectrometer (m/z)	% Split to ODP
Preliminary Broiler	Oct-05	1.3ml/min Constant Flow	HP-5ms	50 °C 2 min, 5 °C/min 250°C 2 min	Scan 50-550m/z	0%
Qld. Summer Broiler	11/2005-01/2006	1.3ml/min Constant Flow	HP-5ms	50 °C 2 min, 5 °C/min 250 °C 2 min	Scan 50-550m/z	0%
Vic. Summer Broiler	02/2006 – 04/2006	1.6ml/min Constant Pressure	HP-5ms	50 °C 2 min, 5 °C/min 125°C, 10 °C/min 200 °C 2 min	Scan 35-550m/z	50%
Qld. Winter Broiler (incl. Diurnal)	06/2006 – 07/2006	1.6ml/min Constant Pressure	HP-5ms	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35-550m/z	66.67%
Vic. Winter Broiler	09/2006 – 10/2006	1.6ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35-550m/z	66.67%
Qld. Litter Re-Use (batch 1)	02/2007 – 03/2007	1.6ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35	66.67%
Qld. Litter Re-Use (batch 2)	04/2007 – 06/2007	1.6ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35	66.67%

Appendix 3 – Odour samples discarded due to excess variability within the duplicate, or below detection limit or not analysed to standard

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %
5	A	Single Use	Summer	131205	18	8:50	25.00%	22.8	29.6	-	10.25	27.8	29.9	66.5
5	A	Single Use	Summer	131205	18	8:50	25.00%	22.8	29.6	-	10.25	27.8	29.9	66.5
6	A	Single Use	Summer	131205	18	9:57	50.00%	46	32.3	-	10.25	27.8	31.3	55.2
6	A	Single Use	Summer	131205	18	9:57	50.00%	46	32.3	-	10.25	27.8	31.3	55.2
16	A	Single Use	Summer	110106	47 – Different Shed	12:20	100.00%	91.2	32.4	-	14.76	31.95	28	81.7
16	A	Single Use	Summer	110106	47 – Different Shed	12:20	100.00%	91.2	32.4	-	14.76	31.95	28	81.7
17	A	Single Use	Summer	110106	47 – Different Shed	13:06	100.00%	91.2	31.2	-	14.76	31.95	28	81.7
17	A	Single Use	Summer	110106	47 – Different Shed	13:06	100.00%	91.2	31.2	-	14.76	31.95	28	81.7
19	A	Single Use	Summer	130106	Birds removed litter present	9:34	50.00%	46	32.6	-	-	-	30.6	54.5
19	A	Single Use	Summer	130106	Birds removed litter present	9:34	50.00%	46	32.6	-	-	-	30.6	54.5
20	A	Single Use	Summer	130106	Birds removed litter present	10:10	75.00%	67.6	33.6	-	-	-	31.6	51
20	A	Single Use	Summer	130106	Birds removed litter present	10:10	75.00%	67.6	33.6	-	-	-	31.6	51
26	B	Single Use	Summer	80206	Single Use Litter no birds	9:19	56.00%	29.3	20.4	-	-	44.53	20.3	54.3
26	B	Single Use	Summer	80206	Single Use Litter no birds	9:17	56.00%	29.3	20.4	-	-	44.53	20.3	54.3
27	B	Single Use	Summer	80206	Single Use Litter no birds	10:08	80.00%	41.6	22.8	-	-	44.53	21.5	50.6
28	B	Single Use	Summer	80206	Single Use Litter no birds	10:54	88.30%	46.1	26	-	-	44.53	25	44.6
28	B	Single Use	Summer	80206	Single Use Litter no birds	10:54	88.30%	46.1	26	-	-	44.53	25	44.6
29	B	Single Use	Summer	80206	Single Use Litter no birds	12:01	100.00%	52.3	27	-	-	44.53	26.9	40.8
29	B	Single Use	Summer	80206	Single Use Litter no birds	12:01	100.00%	52.3	27	-	-	44.53	26.9	40.8
46	B	Single Use	Summer	70406	Post Litter Removal Prior Shed Cleaning	8:06	56.00%	29.3	12.6	-	-	-	15.8	66.7
46	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	8:12	56.00%	29.3	12.6	-	-	-	15.8	66.7
47	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	9:03	79.50%	41.6	14.6	-	-	-	15.1	58.7
47	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	9:09	80.00%	41.6	14.6	-	-	-	15.1	58.7
48	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	9:36	88.30%	46.1	15.7	-	-	-	16.3	52.3
48	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	9:43	88.30%	46.1	15.7	-	-	-	16.3	52.3
49	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	9:49	100.00%	52.3	16.1	-	-	-	16.4	51.2
49	B	Single Use	Summer	70406	Post litter removal prior shed cleaning	10:15	100.00%	52.3	16.1	-	-	-	16.4	51.2
81	A	Single Use	Winter	110706	35	12:05	50.00%	46	22.4	43.3	26.76	-	24	42.7
81	A	Single Use	Winter	110706	35	12:05	50.00%	46	22.4	43.3	26.76	-	24	42.7
144	C	Reused	Autumn	170507	37	10:28	78.60%	82	25.7	55.8	21.2	29.88	27.7	64.5
144	C	Reused	Autumn	170507	37	10:28	78.60%	82	25.7	55.8	21.2	29.88	27.7	64.5

Appendix 3 continued - Odour samples discarded due to excess variability within the duplicate, or below detection limit or not analysed to standard

Sample Number	Odour concentration (ou/m³)	OER (ou/s)	OER (ou/s.bird)	OER (ou/s.1000 birds)	OER (ou/s/1000 birds placed)	OER (ou/s.kg)	OER (ou/s.kg.m²)	Reason for Exclusion
5	1024	23376	0.9	899	896	1.28	2281	Outside repeatability criteria
5	2896	66109	2.54	2543	2533	3.63	6451	Outside repeatability criteria
6	3043	140063	5.39	5387	5366	7.7	13668	Outside repeatability criteria
6	912	41978	1.61	1615	1608	2.31	4096	Outside repeatability criteria
16	966	88116	8.84	8843	-	3.36	5971	Different shed
16	1085	98971	9.93	9932	-	3.78	6707	Different shed
17	1085	98971	9.93	9932	-	3.78	6707	Different shed
17	966	88116	8.84	8843	-	3.36	5971	Different shed
19	90	4143	-	-	-	-	-	Outside repeatability criteria
19	28	1289	-	-	-	-	-	Outside repeatability criteria
20	223	15066	-	-	-	-	-	Outside repeatability criteria
20	82	5540	-	-	-	-	-	Outside repeatability criteria
26	30	-	-	-	-	-	-	Below Detection Limit
26	30	-	-	-	-	-	-	Below Detection Limit
27	30	-	-	-	-	-	-	Below Detection Limit
28	30	-	-	-	-	-	-	Below Detection Limit
28	30	-	-	-	-	-	-	Below Detection Limit
29	30	-	-	-	-	-	-	Below Detection Limit
29	30	-	-	-	-	-	-	Below Detection Limit
46	30	-	-	-	-	-	-	Below Detection Limit
46	30	-	-	-	-	-	-	Below Detection Limit
47	30	-	-	-	-	-	-	Below Detection Limit
47	30	-	-	-	-	-	-	Below Detection Limit
48	30	-	-	-	-	-	-	Below Detection Limit
48	30	-	-	-	-	-	-	Below Detection Limit
49	30	-	-	-	-	-	-	Below Detection Limit
49	30	-	-	-	-	-	-	Below Detection Limit
81	2733	125794	5.2	5203	3816	2.65	4700	Outside repeatability criteria
81	1149	52886	2.19	2187	1604	1.11	1976	Outside repeatability criteria
144	594	48704	2.1	2101	1309	0.99	2297	Outside repeatability criteria
144	1599	131107	5.65	5655	3525	2.66	6183	Outside repeatability criteria

Appendix 4 – Odour decay study

Sample Number	Test Number	Litter Reuse Status	Season	Date (ddmmyy)	Collection Time (hh:mm)	Sample Age at Analysis (hh:mm)	Odour concentration (ou/m³)
1A	1	Single Use	Autumn	120505	10:33	2:57	927
1B	1	Single Use	Autumn	120505	10:33	3:31	1188
1C	1	Single Use	Autumn	120505	10:33	3:55	1130
2A	1	Single Use	Autumn	120505	9:22	6:43	912
2B	1	Single Use	Autumn	120505	9:22	7:28	1625
2C	1	Single Use	Autumn	120505	9:22	8:00	1680
3A	1	Single Use	Autumn	120505	9:22	11:00	1097
3B	1	Single Use	Autumn	120505	9:22	11:47	1218
3C	1	Single Use	Autumn	120505	9:22	12:40	1149
1A	1	Single Use	Autumn	120505	10:33	21:16	1248
1B	1	Single Use	Autumn	120505	10:33	21:54	1378
1C	1	Single Use	Autumn	120505	10:33	22:46	1097
2A	1	Single Use	Autumn	120505	9:22	26:21	2261
2B	1	Single Use	Autumn	120505	9:22	26:57	1579
2C	1	Single Use	Autumn	120505	9:22	27:50	2048
3B	2	Single Use	Winter	210705	10:27	2:29	1085
1A	2	Single Use	Winter	210705	10:52	2:40	1290
2C	2	Single Use	Winter	210705	10:27	3:49	1290
3C	2	Single Use	Winter	210705	10:27	5:11	1218
2A	2	Single Use	Winter	210705	10:52	5:35	912
1B	2	Single Use	Winter	210705	10:27	6:56	966
2B	2	Single Use	Winter	210705	10:52	8:55	656
1C	2	Single Use	Winter	210705	10:27	10:08	799
3A	2	Single Use	Winter	210705	10:27	10:47	1076
2B	2	Single Use	Winter	210705	10:52	21:05	724
3C	2	Single Use	Winter	210705	10:27	22:18	676
1A	2	Single Use	Winter	210705	10:27	22:54	676
3B	2	Single Use	Winter	210705	10:27	25:26	813
2A	2	Single Use	Winter	210705	10:52	25:49	689
1C	2	Single Use	Winter	210705	10:27	27:00	624
3B	3	Single Use	Winter	120706	10:55	1:23	1512
1A	3	Single Use	Winter	120706	11:21	1:37	1069
2C	3	Single Use	Winter	120706	11:13	2:30	912
3C	3	Single Use	Winter	120706	10:55	4:10	980
2A	3	Single Use	Winter	120706	11:13	4:29	824
1B	3	Single Use	Winter	120706	11:21	5:09	724
2B	3	Single Use	Winter	120706	11:13	7:52	799
1C	3	Single Use	Winter	120706	11:21	8:24	761
3A	3	Single Use	Winter	120706	10:55	9:30	761
2B	3	Single Use	Winter	120706	11:13	19:47	362
3C	3	Single Use	Winter	120706	10:55	20:50	388
1A	3	Single Use	Winter	120706	11:21	21:09	1024
3B	3	Single Use	Winter	120706	10:55	24:09	1218
2A	3	Single Use	Winter	120706	11:13	24:47	1166
1C	3	Single Use	Winter	120706	11:21	25:09	1218

Appendix 5 – Farm A, summer batch odour and dust

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
1	A	Single Use	Summer	231105	Single Use Litter No Birds	13:40	12.5%	11.9	27.0	60.00	-	10.30	-	-	-	-
2	A	Single Use	Summer	231105	Single Use Litter No Birds	9:20	50.0%	46.0	27.0	61.50	-	10.30	26.1	66.2	-	-
3	A	Single Use	Summer	231105	Single Use Litter No Birds	10:14	75.0%	69.0	27.1	60.80	-	10.30	26	65.7	-	-
4	A	Single Use	Summer	231105	Single Use Litter No Birds	11:36	100.0%	91.2	31.0	44.30	-	10.30	27.6	53.9	-	-
7	A	Single Use	Summer	131205	18	11:10	75.0%	69.0	33.8	53.20	10.25	27.80	28.8	58	18200	26000
8	A	Single Use	Summer	131205	18	12:12	100.0%	91.2	33.0	50.70	10.25	27.80	31.7	51	18200	26000
9	A	Single Use	Summer	221205	27	8:44	75.0%	69.0	27.5	70.50	20.50	26.30	26.2	70.5	36400	26000
10	A	Single Use	Summer	221205	27	9:55	87.5%	80.5	28.0	64.50	20.50	26.30	26.4	73.8	36400	26000
11	A	Single Use	Summer	221205	27	10:22	87.5%	80.5	29.0	61.80	20.50	26.30	26.55	72.15	36400	26000
12	A	Single Use	Summer	221205	27	10:50	100.0%	91.2	30.0	59.10	20.50	26.30	26.7	70.5	36400	26000
13	A	Single Use	Summer	110106	Birds Removed Litter Present	8:54	12.5%	11.8	27.5	73.00	-	29.60	25.3	81.5	-	-
14	A	Single Use	Summer	110106	Birds Removed Litter Present	9:40	50.0%	46.0	27.5	77.00	-	29.60	26.6	82.6	-	-
15	A	Single Use	Summer	110106	Birds Removed Litter Present	10:34	100.0%	91.2	30.5	65.00	-	29.60	27.6	76.7	-	-
18	A	Single Use	Summer	130106	Post Litter Removal Prior Shed Cleaning	8:37	12.5%	11.8	31.0	51.50	-	-	30.4	57.5	-	-
21	A	Single Use	Summer	130106	Post Litter Removal Prior Shed Cleaning	11:01	100.0%	91.2	34.9	41.00	-	-	31.6	51.2	-	-
22	A	Single Use	Summer	200106	Post Shed Cleaning and Fumigation	11:58	12.5%	11.8	28.3	62.50	-	-	27.5	70.5	-	-
23	A	Single Use	Summer	200106	Post Shed Cleaning and Fumigation	10:50	50.0%	46.0	28.1	67.00	-	-	26	74.7	-	-
24	A	Single Use	Summer	200106	Post Shed Cleaning and Fumigation	9:46	75.0%	69.0	26.6	71.50	-	-	25.4	77.5	-	-
25	A	Single Use	Summer	200106	Post Shed Cleaning and Fumigation	8:54	100.0%	91.2	25.3	74.80	-	-	23.6	81.6	-	-

Sample Number	Odour concentration* (ou/m³)	ou Min[#]	ou Max[#]	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER[##] (particles/s/1000 birds placed)	PM$_{2.5}$ ER[##] (mg/s/1000 birds placed)	PM$_{10}$ ER[##] (mg/s/1000 birds placed)
1	60	57	63	716	-	-	-	-	-	-	-	-
2	119	101	137	5477	-	-	-	-	-	-	-	-
3	121	90	152	8354	-	-	-	-	-	-	-	-
4	52	49	54	4698	-	-	-	-	-	-	-	-
7	704	683	724	48571	1.87	1868	1861	2.67	4740	-	0.09	0.35
8	1086	724	1448	99062	3.81	3810	3795	5.44	9667	-	0.09	0.30
9	765	689	840	52783	2.03	2030	2022	1.45	2575	-	0.00	0.17
10	1487	1024	1949	119667	4.60	4603	4585	3.29	5839	-	0.01	0.83
11	1755	1248	2261	147928	5.69	5690	5668	4.06	7218	-	-	-
12	1496	1311	1680	136416	5.25	5247	5227	3.75	6656	-	-	-
13	1073	980	1166	12697	-	-	-	-	-	-	-	-
14	843	824	861	38779	-	-	-	-	-	-	-	-
15	814	767	861	74251	-	-	-	-	-	-	-	-
18	114	80	148	1349	-	-	-	-	-	-	-	-
21	71	64	78	6476	-	-	-	-	-	-	-	-
22	41	33	49	485	-	-	-	-	-	-	-	-
23	41	39	42	1864	-	-	-	-	-	-	-	-
24	38	34	42	2624	-	-	-	-	-	-	-	-
25	42	39	45	3831	-	-	-	-	-	-	-	-

* Average of duplicate olfactometry measurements
[#] Maximum or minimum olfactometry values
Number of birds placed 26,100
[##] Average values from corresponding odour collection times. Averaging time ~10 minutes.

Appendix 6 – Farm A, winter batch odour and dust

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
54	A	Single Use	Winter	160606	10	11:07	12.5%	11.8	21.0	27.00	5.45	31.37	23	42	9685	32282
55	A	Single Use	Winter	160606	10	12:26	12.5%	11.8	26.0	30.00	5.45	31.37	22.6	21	9685	32282
56	A	Single Use	Winter	160606	10	13:11	12.5%	11.8	23.0	18.50	5.45	31.37	26.3	30.2	9685	32282
57	A	Single Use	Winter	210606	15	9:40	12.5%	11.8	18.3	66.00	9.57	37.08	23	71	16991	32179
58	A	Single Use	Winter	210606	15	11:00	25.0%	22.8	18.8	64.30	9.57	37.08	24	62	16991	32179
59	A	Single Use	Winter	210606	15	11:55	37.5%	33.7	20.2	64.50	9.57	37.08	23.6	70.9	16991	32179
60	A	Single Use	Winter	270606	21	9:40	12.5%	11.8	15.9	58.60	15.97	38.32	24.3	61.3	28370	32056
61	A	Single Use	Winter	270606	21	11:07	25.0%	22.8	20.5	48.00	15.97	38.32	22.7	58	28370	32056
62	A	Single Use	Winter	270606	21	11:45	37.5%	33.7	21.2	43.40	15.97	38.32	21.9	49.5	28370	32056
63	A	Single Use	Winter	270606	21	12:40	25.0%	22.8	21.7	38.00	15.97	38.32	23.9	47	28370	32056
64	A	Single Use	Winter	290606	23	8:50	12.5%	11.8	12.4	74.30	18.42	33.83	23.7	65.3	32719	32015
65	A	Single Use	Winter	290606	23	9:45	25.0%	22.8	18.0	61.50	18.42	33.83	21.8	62.1	32719	32015
66	A	Single Use	Winter	290606	23	11:35	25.0%	22.8	21.2	51.30	18.42	33.83	24.6	56.2	32719	32015
67	A	Single Use	Winter	290606	23	12:37	25.0%	22.8	19.6	50.00	18.42	33.83	24.6	56.2	32719	32015
68	A	Single Use	Winter	040706	28	8:53	12.5%	11.8	13.4	59.00	25.05	31.73	25.8	56.5	44487	31913
69	A	Single Use	Winter	040706	28	9:54	25.0%	22.8	18.5	47.00	25.05	31.73	25.3	48.8	44487	31913
70	A	Single Use	Winter	040706	28	10:50	25.0%	22.8	19.0	39.50	25.05	31.73	25.8	49.5	44487	31913
71	A	Single Use	Winter	040706	28	11:41	37.5%	33.7	19.8	40.30	25.05	31.73	24.6	44.5	44487	31913
72	A	Single Use	Winter	070706	31	9:05	12.5%	11.8	14.5	46.50	29.29	33.14	27.2	-	52014	31852
73	A	Single Use	Winter	070706	31	9:50	25.0%	22.8	16.5	42.60	29.29	33.14	24.7	51	52014	31852
74	A	Single Use	Winter	070706	31	10:35	37.5%	33.7	21.6	40.60	29.29	33.14	24.5	46	52014	31852
75	A	Single Use	Winter	070706	31	11:15	50.0%	46.0	23.0	40.00	29.29	33.14	25	46.1	52014	31852
76	A	Single Use	Winter	100706	34	16:18	50.0%	46.0	24.7	31.00	25.62	-	24	35.8	45503	24178
77	A	Single Use	Winter	100706	34	18:20	37.5%	27.4	16.7	49.00	25.62	-	20.3	55	45503	24178
78	A	Single Use	Winter	100706	34	23:15	37.5%	20.5	12.4	56.80	25.62	-	16.2	59.8	45503	24178
79	A	Single Use	Winter	110706	35	6:40	12.5%	15.9	6.9	68.70	26.76	-	15.4	70.7	47534	24178
80	A	Single Use	Winter	110706	35	9:50	37.5%	33.7	18.5	45.50	26.76	-	19.5	54.6	47534	24178
82	A	Single Use	Winter	180706	42	8:33	12.5%	11.8	13.9	62.00	24.59	30.80	25.6	63.5	43674	17067
83	A	Single Use	Winter	180706	42	9:37	25.0%	22.8	17.0	60.00	24.59	30.80	22.5	60.5	43674	17067
84	A	Single Use	Winter	180706	42	10:33	37.5%	33.7	18.8	51.00	24.59	30.80	21.6	52.4	43674	17067
85	A	Single Use	Winter	180706	42	11:20	50.0%	46.0	20.3	44.90	24.59	30.80	21.4	48.5	43674	17067
86	A	Single Use	Winter	240706	48	8:35	37.5%	33.7	14.9	90.10	20.65	30.60	16.9	81	36679	12018
87	A	Single Use	Winter	240706	48	9:30	25.0%	22.8	16.8	67.60	20.65	30.60	19.9	67.8	36679	12018
88	A	Single Use	Winter	240706	48	10:25	37.5%	33.7	18.8	69.50	20.65	30.60	20	69	36679	12018
89	A	Single Use	Winter	240706	48	11:10	50.0%	46.0	20.8	58.40	20.65	30.60	21.2	61	36679	12018
90	A	Single Use	Winter	280706	Birds Removed Litter Present	8:20	50.0%	46.0	16.9	92.00	-	-	16.7	91.4	-	-
91	A	Single Use	Winter	280706	During Litter Removal	9:25	50.0%	46.0	17.6	99.0	-	-	16.7	91.4	-	-
92	A	Single Use	Winter	280706	During Litter Removal	10:30	50.0%	46.0	-	-	-	-	16.7	91.4	-	-

Appendix 6 continued — Farm A, winter batch odour and dust

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER## (particles/s/1000 birds placed)	PM$_{2.5}$ ER## (mg/s/1000 birds placed)	PM$_{10}$ ER## (mg/s/1000 birds placed)
54	861	761	974	10188	0.32	316	309	1.05	1868	-	-	-
55	1155	883	1512	13673	0.42	424	415	1.41	2507	-	-	-
56	1649	1649	1649	19513	0.60	604	592	2.01	3578	-	-	-
57	1448	1024	2048	17136	0.53	533	520	1.01	1791	5,588,277	-	0.08
58	1130	1130	1130	25795	0.80	802	783	1.52	2696	7,344,066	-	0.08
59	1024	966	1085	34531	1.07	1073	1047	2.03	3609	-	-	-
60	1159	1024	1311	13710	0.43	428	416	0.48	858	1,662,198	-	0.07
61	1272	1024	1579	29027	0.91	906	881	1.02	1817	-	-	0.09
62	1103	1024	1188	37202	1.16	1161	1129	1.31	2329	-	-	-
63	1159	1130	1188	26449	0.83	825	802	0.93	1656	-	-	-
64	950	927	974	11244	0.35	351	341	0.34	610	-	-	-
65	819	724	927	18701	0.58	584	567	0.57	1015	-	-	-
66	905	689	1188	20653	0.65	645	627	0.63	1121	-	-	-
67	1183	1024	1367	27008	0.84	844	819	0.83	1466	-	-	-
68	1328	1024	1722	15713	0.49	492	477	0.35	627	-	-	0.17
69	1387	1117	1722	31660	0.99	992	960	0.71	1264	3,716,473	-	0.18
70	912	813	1024	20828	0.65	653	632	0.47	832	-	-	0.29
71	609	575	645	20541	0.64	644	623	0.46	820	-	-	-
72	2825	2376	3360	33434	1.05	1050	1014	0.64	1142	-	-	0.18
73	3619	3197	4096	82606	2.59	2593	2506	1.59	2821	-	-	0.34
74	1673	1448	1933	56429	1.77	1772	1712	1.08	1927	9,285,616	-	0.34
75	2521	2048	3104	116051	3.64	3643	3520	2.23	3962	-	-	0.36
76	1484	1130	1949	68307	2.83	2825	2072	1.50	2666	16,762,422	-	-
77	2320	2156	2496	63546	2.63	2628	1928	1.40	2480	12,038,332	-	0.99
78	993	883	1117	20358	0.84	842	618	0.45	795	-	-	0.67
79	1760	1649	1878	28038	1.16	1160	851	0.59	1048	312,674	-	0.12
80	1178	912	1521	39725	1.64	1643	1205	0.84	1484	3,951,810	-	0.33
82	999	974	1024	11818	0.69	692	358	0.27	481	1,985,457	-	0.56
83	1103	1076	1130	25171	1.47	1475	764	0.58	1024	-	-	0.70
84	1024	790	1328	34547	2.02	2024	1048	0.79	1405	-	-	-
85	768	656	899	35347	2.07	2071	1072	0.81	1437	-	-	-
86	1099	883	1367	37057	3.08	3083	1124	1.01	1794	32,364,456	0.21	0.73
87	882	799	974	20138	1.68	1676	611	0.55	975	13,332,347	0.08	0.34
88	520	430	630	17555	1.46	1461	533	0.48	850	17,816,960	-	-
89	394	383	406	18150	1.51	1510	551	0.49	879	16,418,143	0.09	0.45
90	279	238	328	12860	-	-	-	-	-	-	-	-
91	328	269	400	15098	-	-	-	-	-	-	-	-
92	530	512	549	24403	-	-	-	-	-	-	-	-

* Geometric mean of duplicate olfactometry measurements
# Maximum or minimum olfactometry values
Average values from corresponding odour collection times. Averaging time ~10 minutes.
Number of birds placed 32,965

Appendix 7 – Farm B, summer batch odour and dust

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
27	B	Single Use	Summer	080206	Single Use Litter No Birds	10:08	80.0%	41.6	22.8	36.00	-	44.53	21.5	50.6		
30	B	Single Use	Summer	230206	13	9:01	56.0%	29.3	24.5	50.10	7.33	18.60	27.1	62.6	10590	24000
31	B	Single Use	Summer	230206	13	10:09	79.5%	41.6	27.0	44.50	7.33	18.60	27.0	53.3	10590	24000
32	B	Single Use	Summer	230206	13	11:23	88.3%	46.1	30.7	35.20	7.33	18.60	30.0	48.7	10590	24000
33	B	Single Use	Summer	230206	13	12:22	100.0%	52.3	33.3	30.10	7.33	18.60	31.3	40.0	10590	24000
34	B	Single Use	Summer	140306	32	9:05	56.0%	29.3	13.4	68.20	22.84	26.96	25.2	73.5	33000	22000
35	B	Single Use	Summer	140306	32	9:43	79.5%	41.6	15.2	63.20	22.84	26.96	22.1	17.5	33000	22000
36	B	Single Use	Summer	140306	32	11:01	88.3%	46.1	19.3	47.00	22.84	26.96	22.8	16.6	33000	22000
37	B	Single Use	Summer	140306	32	11:55	100.0%	52.3	20.4	34.40	22.84	26.96	24.1	15.1	33000	22000
38	B	Single Use	Summer	280306	46	9:39	68.7%	35.9	19.6	62.50	26.90	26.50	23.2	66.0	38863	13636
39	B	Single Use	Summer	280306	46	10:37	79.5%	41.6	26.5	41.90	26.90	26.50	25.2	50.1	38863	13636
40	B	Single Use	Summer	280306	46	11:19	88.3%	46.1	25.5	37.25	26.90	26.50	25.4	42.8	38863	13636
41	B	Single Use	Summer	280306	46	11:59	100.0%	52.3	31.9	32.10	26.90	26.50	28.2	37.7	38863	13636
42	B	Single Use	Summer	060406	Birds Removed Litter Present	7:49	56.0%	29.3	9.1	76.00	-	24.18	9.9	9.1	-	-
43	B	Single Use	Summer	060406	Birds Removed Litter Present	8:37	79.5%	41.6	10.9	76.40	-	24.18	9.9	10.9	-	-
44	B	Single Use	Summer	060406	Birds Removed Litter Present	9:13	88.3%	46.1	13.0	68.00	-	24.18	12.2	13.0	-	-
45	B	Single Use	Summer	060406	Birds Removed Litter Present	9:43	100.0%	52.3	13.7	62.80	-	24.18	13.8	13.7	-	-
50	B	Single Use	Summer	120406	Post Shed Cleaning and Fumigation	8:13	56.0%	29.3	14.9	58.30	-	-	14.2	62.3	-	-
51	B	Single Use	Summer	120406	Post Shed Cleaning and Fumigation	9:03	79.5%	41.6	14.5	50.80	-	-	15.0	52.3	-	-
52	B	Single Use	Summer	120406	Post Shed Cleaning and Fumigation	9:49	88.3%	46.1	16.1	45.10	-	-	16.7	45.3	-	-
53	B	Single Use	Summer	120406	Post Shed Cleaning and Fumigation	10:35	100.0%	52.3	17.5	40.75	-	-	17.4	41.5	-	-

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER## (particles/s/1000 birds placed)	PM2.5 ER## (mg/s/1000 birds placed)	PM10 ER## (mg/s/1000 birds placed)
27	35	35	35	1454	-	-	-	-	-	-	-	-
30	183	160	210	5363	0.22	223	176	0.51	732	-	0.02	0.04
31	54	51	58	2260	0.09	94	74	0.21	308	-	0.02	0.04
32	45	42	48	2071	0.09	86	68	0.20	283	-	0.03	0.06
33	66	48	90	3436	0.14	143	113	0.32	469	-	-	-
34	1949	1900	2000	57032	2.59	2592	1870	1.73	2497	23,912,865	0.09	0.51
35	2946	2800	3100	122431	5.57	5565	4014	3.71	5360	18,974,259	0.18	0.43
36	1749	1700	1800	80679	3.67	3667	2645	2.44	3532	-	-	-
37	2291	2100	2500	119767	5.44	5444	3927	3.63	5243	-	-	-
38	1597	1500	1700	57283	4.20	4201	1878	1.47	2130	28,543,317	-	0.51
39	2078	1800	2400	86372	6.33	6334	2832	2.22	3211	-	-	0.40
40	846	730	980	39010	2.86	2861	1279	1.00	1450	-	-	0.31
41	1177	990	1400	61537	4.51	4513	2018	1.58	2288	-	-	-
42	140	130	150	4085	-	-	-	-	-	-	-	-
43	45	42	48	1866	-	-	-	-	-	-	-	-
44	96	77	120	4433	-	-	-	-	-	-	-	-
45	164	150	180	8589	-	-	-	-	-	-	-	-
50	605	590	620	17695	-	-	-	-	-	-	-	-
51	38	36	40	1577	-	-	-	-	-	-	-	-
52	42	40	45	1957	-	-	-	-	-	-	-	-
53	43	42	44	2247	-	-	-	-	-	-	-	-

* Geometric mean of duplicate olfactometry measurements

Maximum or minimum olfactometry values

Average values from corresponding odour collection times. Averaging time ~10 minutes.

Number of birds placed 30,500

Appendix 8 – Farm B, winter batch odour and dust

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
93	B	Single Use	Winter	060906	14	11:06	56.0%	29.3	12.5	66.9	8.43	26.2	22.3	70.1	12177	30215
94	B	Single Use	Winter	140906	22	9:35	69.0%	35.9	15.5	49.4	16.25	29.1	19.4	55.6	23470	30013
95	B	Single Use	Winter	140906	22	10:51	80.0%	41.6	17.9	42.0	16.25	29.1	20.8	40.8	23470	30013
96	B	Single Use	Winter	210906	29	9:24	69.0%	35.9	14.0	47.2	27.07	36.7	22.1	58.8	39108	29876
97	B	Single Use	Winter	210906	29	10:45	80.0%	41.6	16.5	44.7	27.07	36.7	21.4	51.8	39108	29876
98	B	Single Use	Winter	270906	35	9:09	69.0%	35.9	18.0	31.5	39.00	39.7	24.6	49.5	60421	29764
99	B	Single Use	Winter	270906	35	10:06	80.0%	41.6	21.5	29.6	39.00	39.7	24.9	39.8	60421	29764
100	B	Single Use	Winter	290906	37	8:38	69.0%	35.9	12.8	43.0	34.30	38.7	27	52	49555	22525
101	B	Single Use	Winter	290906	37	9:27	80.0%	41.6	14.2	57.0	34.30	38.7	20.3	64	49555	22525
102	B	Single Use	Winter	290906	37	10:48	88.0%	46.1	16.0	50.6	34.30	38.7	20.9	53	49555	22525
103	B	Single Use	Winter	051006	43	8:44	69.0%	35.9	16.0	40.0	38.88	34.3	22.2	46.1	56172	19504
104	B	Single Use	Winter	051006	43	9:36	80.0%	41.6	16.1	39.2	38.88	34.3	19.9	45.5	56172	19504
105	B	Single Use	Winter	111006	49	8:27	69.0%	35.9	20.4	24.0	17.22	29.6	21.1	28.6	24874	7773
106	B	Single Use	Winter	111006	49	9:17	88.0%	46.1	22.6	20.0	17.22	29.6	23.5	26	24874	7773
107	B	Single Use	Winter	131006	Birds Removed Litter Present	8:02	56.0%	29.3	20.2	27.6	-	-	20.7	29	-	-
108	B	Single Use	Winter	131006	During Litter Removal	8:52	80.0%	41.6	23.7	28.2	-	-	25	33.5	-	-
109	B	Single Use	Winter	131006	During Litter Removal	9:39	80.0%	41.6	26.1	24.8	-	-	26.1	28.2	-	-

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER## (particles/s/1000 birds placed)	PM₂.₅ ER## (mg/s/1000 birds placed)	PM₁₀ ER## (mg/s/1000 birds placed)
93	1140	1000	1300	33358	1.10	1104	1076	2.74	3958	-	-	-
94	759	730	790	27241	0.91	908	879	1.16	1677	-	-	-
95	485	480	490	20153	0.67	671	650	0.86	1241	-	-	0.16
96	1449	1400	1500	51983	1.74	1740	1677	1.33	1920	-	-	-
97	1149	1100	1200	47744	1.60	1598	1540	1.22	1764	-	-	-
98	1612	1300	2000	57842	1.94	1943	1866	0.96	1483	-	-	1.38
99	1196	1100	1300	49693	1.67	1670	1603	0.82	1274	-	-	0.74
100	2400	2400	2400	86093	3.82	3822	2777	1.74	2510	-	-	1.35
101	1300	1300	1300	54022	2.40	2398	1743	1.09	1575	-	-	0.54
102	1149	1100	1200	52989	2.35	2352	1709	1.07	1545	-	-	0.54
103	961	840	1100	34482	1.77	1768	1112	0.61	887	-	-	-
104	355	350	360	14751	0.76	756	476	0.26	379	-	-	-
105	205	200	210	7352	0.95	946	237	0.30	427	-	-	-
106	140	130	150	6440	0.83	829	208	0.26	374	-	-	-
107	175	170	180	5118	-	-	-	-	-	-	-	-
108	553	510	600	22987	-	-	-	-	-	-	-	-
109	369	310	440	15347	-	-	-	-	-	-	-	-

∗ Geometric mean of duplicate olfactometry measurements

Maximum or minimum olfactometry values

Average values from corresponding odour collection times. Averaging time ~10 minutes.

Number of birds placed 31,000

Appendix 9 – Farm C, Single Use litter batch odour and dust

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
110	C	Single Use	Summer	130207	14	10:58	28.2%	32.3	26.0	60.0	7.12	20.6	27.5	60	16564	39913
111	C	Single Use	Summer	130207	14	12:28	28.2%	32.3	26.0	59.5	7.12	20.6	27	64	16564	39913
112	C	Single Use	Summer	200207	21	8:59	71.4%	76.0	28.9	50.0	14.52	26.3	29	53	33770	39823
113	C	Single Use	Summer	200207	21	10:11	78.6%	82.0	29.3	47.7	14.52	26.3	29.2	54	33770	39823
114	C	Single Use	Summer	200207	21	11:13	71.4%	76.0	29.3	42.7	14.52	26.3	30	-	33770	39823
115	C	Single Use	Summer	270207	28	8:58	85.7%	89.4	28.9	53.3	25.64	30.9	27.6	62.5	59621	39747
116	C	Single Use	Summer	270207	28	9:53	78.6%	82.0	29.0	50.5	25.64	30.9	27.1	68.5	59621	39747
117	C	Single Use	Summer	270207	28	10:43	85.7%	89.4	27.6	48.5	25.64	30.9	27.8	65.3	59621	39747
118	C	Single Use	Summer	060307	35	8:12	92.9%	90.7	28.0	76.0	33.18	34.6	26.7	77	77136	39638
119	C	Single Use	Summer	060307	35	9:23	100.0%	97.6	26.3	68.8	33.18	34.6	28.1	-	77136	39638
120	C	Single Use	Summer	060307	35	10:07	100.0%	97.6	29.3	64.0	33.18	34.6	28	60.8	77136	39638
121	C	Single Use	Summer	080307	37	8:04	85.7%	89.4	26.2	66.5	23.37	-	25.5	74	54327	26631
122	C	Single Use	Summer	080307	37	9:01	85.7%	89.4	27.1	63.8	23.37	-	28	62	54327	26631
123	C	Single Use	Summer	080307	37	9:47	100.0%	97.6	29.5	59.0	23.37	-	27.5	74.9	54327	26631
124	C	Single Use	Summer	130307	42	8:09	85.7%	89.4	28.3	62.4	28.84	34.3	25.7	-	67046	26396
125	C	Single Use	Summer	130307	42	9:05	85.7%	89.4	26.3	66.9	28.84	34.3	26	77	67046	26396
126	C	Single Use	Summer	130307	42	9:55	100.0%	97.6	27.5	62.8	28.84	34.3	27.4	-	67046	26396
127	C	Single Use	Summer	200307	49	8:34	85.7%	89.4	26.4	66.6	27.86	30.2	22	75	64771	21083
128	C	Single Use	Summer	200307	49	10:11	100.0%	97.6	27.9	63.7	27.86	30.2	26.7	70.1	64771	21083
129	C	Single Use	Summer	280307	57	8:31	78.6%	82.0	27.1	55.4	34.04	28.7	25.3	55.4	79143	20609
130	C	Single Use	Summer	280307	57	9:42	78.6%	82.0	25.0	52.0	34.04	28.7	24.5	64.5	79143	20609

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER## (particles/s/1000 birds placed)	PM$_{2.5}$ ER## (mg/s/1000 birds placed)	PM$_{10}$ ER## (mg/s/1000 birds placed)
110	431	362	512	13919	0.35	349	344	0.84	1954	-	-	-
111	421	395	449	13616	0.34	341	337	0.82	1911	-	0.03	0.18
112	693	636	756	52720	1.32	1324	1303	1.56	3630	-	-	-
113	664	664	664	54443	1.37	1367	1346	1.61	3748	2,464,002	0.08	0.28
114	740	664	824	56238	1.41	1412	1390	1.67	3872	5,209,584	0.16	0.52
115	706	624	799	63159	1.59	1589	1561	1.06	2463	-	-	-
116	840	799	883	68870	1.73	1733	1702	1.16	2686	18,753,662	0.13	0.51
117	905	840	974	80907	2.04	2036	2000	1.36	3155	24,764,353	0.15	0.53
118	664	575	767	60206	1.52	1519	1488	0.78	1815	-	-	-
119	1024	966	1085	99968	2.52	2522	2471	1.30	3013	214,628,064	1.37	3.41
120	912	813	1024	89095	2.25	2248	2202	1.16	2685	13,478,155	1.17	4.41
121	703	542	912	62887	2.36	2361	1554	1.16	2691	-	-	-
122	1066	966	1176	95336	3.58	3580	2356	1.75	4080	27,319,445	0.10	0.56
123	1024	861	1218	99996	3.75	3755	2472	1.84	4279	22,569,029	0.18	0.70
124	656	624	689	58650	2.22	2222	1450	0.87	2034	8,754,337	0.08	0.37
125	905	799	1024	80908	3.07	3065	2000	1.21	2806	9,037,891	-	-
126	1218	1076	1378	118901	4.50	4505	2939	1.77	4123	-	-	-
127	790	724	861	70622	3.35	3350	1746	1.09	2535	-	0.13	0.51
128	939	899	980	91654	4.35	4347	2265	1.42	3290	-	-	-
129	512	487	538	41969	2.04	2036	1037	0.53	1233	-	-	-
130	689	594	799	56486	2.74	2741	1396	0.71	1659	-	-	-

* Geometric mean of duplicate olfactometry measurements

\# Maximum or minimum olfactometry values

\#\# Average values from corresponding odour collection times. Averaging time ~10 minutes.

Number of birds placed 40,457

Appendix 10 – Farm C, partially reused litter batch odour and dust

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
131	C	Reused	Autumn	240407	14	9:17	39.3%	45.4	26.8	50.7	9.64	22.2	26.9	53.8	22418	36993
132	C	Reused	Autumn	240407	14	10:22	30.2%	35.2	26.9	52.9	9.64	22.2	29.6	47.1	22418	36993
133	C	Reused	Autumn	010507	21	8:46	50.1%	54.8	25.6	49.2	15.71	22.5	27	-	36535	36893
134	C	Reused	Autumn	010507	21	9:36	63.6%	68.7	25.0	41.8	15.71	22.5	26.8	39.2	36535	36893
135	C	Reused	Autumn	010507	21	10:38	63.6%	68.7	26.7	35.4	15.71	22.5	30.5	-	36535	36893
136	C	Reused	Autumn	090507	29	8:49	77.8%	78.3	26.9	46.7	23.94	27.2	29.1	-	55665	36779
137	C	Reused	Autumn	090507	29	9:40	57.1%	64.5	26.8	55.0	23.94	27.2	29	56	55665	36779
138	C	Reused	Autumn	090507	29	10:31	64.3%	67.1	27.4	52.0	23.94	27.2	28.5	53	55665	36779
139	C	Reused	Autumn	140507	34	8:39	71.7%	78.9	26.3	57.5	29.78	27.1	24.5	59	69231	36708
140	C	Reused	Autumn	140507	34	9:33	77.8%	78.3	26.0	59.3	29.78	27.1	25.7	64.5	69231	36708
141	C	Reused	Autumn	140507	34	10:30	64.3%	67.1	27.0	57.1	29.78	27.1	28	-	69231	36708
142	C	Reused	Autumn	170507	37	8:45	77.8%	78.3	26.0	63.8	21.20	29.9	24.5	-	49298	23185
143	C	Reused	Autumn	170507	37	9:36	71.4%	76.0	25.5	67.9	21.26	29.9	25.7	-	49298	23185
145	C	Reused	Autumn	220507	42	8:42	42.4%	48.1	26.0	63.4	17.26	28.4	21.9	-	40141	15712
146	C	Reused	Autumn	220507	42	9:21	77.8%	78.3	22.3	52.9	17.26	28.4	24.2	-	40141	15712
147	C	Reused	Autumn	220507	42	10:13	57.1%	64.5	24.4	42.0	17.26	28.4	25.3	-	40141	15712
148	C	Reused	Autumn	290507	49	8:43	70.7%	74.8	23.3	55.2	21.66	27.4	22.7	70.5	50356	15670
149	C	Reused	Autumn	290507	49	9:42	78.6%	82.0	23.8	64.9	21.66	27.4	23.6	68.5	50356	15670
150	C	Reused	Autumn	290507	49	11:08	71.4%	81.1	26.0	56.8	21.66	27.4	23.6	71.6	50356	15670
151	C	Reused	Autumn	040607	55	8:34	44.5%	49.8	21.8	71.6	25.77	26.9	21.4	-	59917	15633
152	C	Reused	Autumn	040607	55	9:21	70.7%	74.8	19.0	81.7	25.77	26.9	22	-	59917	15633
153	C	Reused	Autumn	040607	55	10:16	64.3%	67.1	21.8	68.9	25.77	26.9	23.7	68	59917	15633

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER## (particles/s/1000 birds placed)	PM$_{2.5}$ ER## (mg/s/1000 birds placed)	PM$_{10}$ ER## (mg/s/1000 birds placed)
131	558	512	609	25338	0.68	685	681	1.13	2628	80,698,687	0.17	-
132	706	565	883	24877	0.67	672	669	1.11	2580	21,780,447	0.04	-
133	679	636	724	37177	1.01	1008	1000	1.02	2366	-	-	-
134	622	609	636	42737	1.16	1158	1149	1.17	2720	53,455,937	0.15	1.01
135	825	790	861	56634	1.54	1535	1523	1.55	3604	-	-	-
136	684	575	813	53512	1.45	1455	1439	0.96	2235	-	-	-
137	1218	1085	1367	78524	2.14	2135	2111	1.41	3280	-	0.11	0.46
138	1150	1085	1218	77120	2.10	2097	2074	1.39	3221	31,470,067	-	-
139	660	656	664	52079	1.42	1419	1400	0.75	1749	-	-	-
140	719	558	927	56290	1.53	1533	1513	0.81	1890	66,005,245	0.27	1.25
141	1107	883	1387	74241	2.02	2022	1996	1.07	2493	46,359,457	0.23	1.02
142	645	609	683	50477	2.18	2177	1357	1.02	2381	-	-	-
143	1372	1367	1378	104350	4.50	4501	2806	2.12	4921	49,628,305	0.34	2.08
145	543	512	575	26086	1.66	1660	701	0.65	1511	-	-	-
146	704	575	861	55069	3.50	3505	1481	1.37	3190	40,348,009	0.15	-
147	575	456	724	37047	2.36	2358	996	0.92	2146	-	-	-
148	650	512	824	48597	3.10	3101	1307	0.97	2244	-	-	-
149	724	693	756	59348	3.79	3787	1596	1.18	2740	-	-	-
150	789	756	824	63979	4.08	4083	1720	1.27	2954	39,270,548	0.20	0.55
151	919	861	980	45789	2.93	2929	1231	0.76	1777	56,786,613	0.22	0.95
152	1069	939	1218	80014	5.12	5118	2151	1.34	3105	43,843,320	0.21	0.76
153	1030	939	1130	69103	4.42	4420	1858	1.15	2681	34,836,813	0.15	0.63

* Geometric mean of duplicate olfactometry measurements

Maximum or minimum olfactometry values

Average values from corresponding odour collection times. Averaging time ~10 minutes.

Number of birds placed 37,193

Appendix 11 – Farms F-M, multiple Queensland farm comparison odour

Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
210	F	Reused	Autumn	040408	36	8:22	100.0%	95.7	22.0	58.5	32.76	47.5	-	-	56095	29680
211	F	Reused	Autumn	040408	36	9:01	100.0%	95.7	23.2	56.2	32.76	47.5	26.3	57.1	56095	29680
212	F	Reused	Autumn	040408	36	10:27	100.0%	95.7	27.6	48.9	32.76	47.5	-	-	56095	29680
213	G	Reused	Autumn	070408	35	8:21	31.0%	53.3	24.0	66.0	33.60	43.5	-	-	70439	36687
214	G	Reused	Autumn	070408	35	9:44	31.0%	53.3	27.0	53.0	33.60	43.5	-	-	70439	36687
215	G	Reused	Autumn	070408	35	11:30	44.0%	57.6	-	-	33.60	43.5	-	-	70439	36687
216	H	Single Use	Autumn	080408	35	8:19	64.0%	81.5	19.8	71.2	32.32	44.5	-	-	75652	42029
217	H	Single Use	Autumn	080408	35	9:28	86.0%	109.0	22.0	65.0	32.32	44.5	24.4	64	75652	42029
218	H	Single Use	Autumn	080408	35	11:20	100.0%	126.4	24.0	60.0	32.32	44.5	-	-	75652	42029
219	I	Reused	Autumn	090408	34	8:17	54.0%	76.6	19.7	81.4	32.65	39.3	-	-	76433	42463
220	I	Reused	Autumn	090408	34	9:30	77.0%	109.5	20.4	77.9	32.65	39.3	23.5	70.8	76433	42463
221	I	Reused	Autumn	090408	34	11:45	77.0%	109.5	22.6	66.0	32.65	39.3	-	-	76433	42463
222	J	Single Use	Autumn	170408	35	8:10	35.7%	41.1	17.0	72.0	30.84	43.1	25	-	72518	42910
223	J	Single Use	Autumn	170408	35	12:49	74.1%	85.3	-	-	30.84	43.1	-	-	72518	42910
224	K	Single Use	Autumn	120508	31	8:29	42.9%	49.4	18.4	79.0	33.44	30.3	-	-	75250	43000
225	K	Single Use	Autumn	120508	31	11:13	57.1%	65.8	-	-	33.44	30.3	-	-	75250	43000
226	L	Single Use	Autumn	210508	34	8:21	25.5%	35.1	-	-	38.30	35.7	-	-	78522	42675
227	L	Single Use	Autumn	210508	34	11:06	42.1%	58.1	-	-	38.30	35.7	-	-	78522	42675
228	M	Single Use	Autumn	260508	32	9:05	25.0%	23.0	-	-	30.35	33.3	-	-	53894	33684
229	M	Single Use	Autumn	260508	32	11:41	62.5%	57.5	-	-	30.35	33.3	-	-	53894	33684

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)
210	583	535	636	55820	1.88	1881	1794	1.00	1704
211	449	430	469	42974	1.45	1448	1381	0.77	1312
212	558	558	558	53397	1.80	1799	1716	0.95	1630
213	679	636	724	36165	0.99	986	932	0.51	1076
214	773	756	790	41188	1.12	1123	1061	0.58	1226
215	664	583	756	38228	1.04	1042	985	0.54	1138
216	650	636	664	52980	1.26	1261	1222	0.70	1639
217	611	538	693	66564	1.58	1584	1535	0.88	2060
218	583	583	583	73713	1.75	1754	1700	0.97	2281
219	452	441	464	34645	0.82	816	800	0.45	1061
220	244	232	256	26681	0.63	628	616	0.35	817
221	214	200	228	23378	0.55	551	540	0.31	716
222	656	624	689	26942	0.63	628	597	0.37	874
223	440	400	483	37514	0.87	874	831	0.52	1216
224	311	291	332	15349	0.36	357	349	0.20	459
225	210	173	256	13843	0.32	322	315	0.18	414
226	761	689	840	26723	0.63	626	614	0.34	698
227	312	243	400	18126	0.42	425	417	0.23	473
228	1188	1024	1378	27338	0.81	812	764	0.51	901
229	1103	1024	1188	63407	1.88	1882	1772	1.18	2089

* Geometric mean of duplicate olfactometry measurements
# Maximum or minimum olfactometry values
Number of birds placed F – 31,120, G – 38,808, H – 43,350, I – 43,333, J – 45,120, K – 44,000, L – 43,500, M – 35,786

Appendix 12 – Worked example for the odour emission model for Farm C

(Based on the information provided in Section 0)

Scenario:

Estimate the odour emission rate (OU/s/1000 birds) at Farm C assuming:

Season	= summer (assigned a value of 1)
Batch age	= 35 days
Ventilation rate	= 100 m³/s
Ambient Temperature	= 29.5 °C
Live weight density	= 34 kg/m²
Litter moisture	= 32 %

OER per bird ≈	Intercept			+
	Season (summer)	×	0.8127175	+
	Batch age	×	-0.0569523	+
	Ventilation rate	×	0.0377881	+
	Ambient temperature	×	-0.7846743	+
	Live weight density	×	-0.4675131	+
	Litter moisture	×	-0.4117151	+
	Season × Live weight density	×	-0.1023154	+
	Batch age × Ambient temperature	×	-0.0028754	+
	Batch age × Live weight density	×	0.0055347	+
	Ventilation rate × Live weight density	×	-0.0009478	+
	Ambient temperature × Live weight density	×	0.0162404	+
	Ambient temperature × Litter moisture	×	0.0234855	

OER per bird ≈	17.0451417			+
	1	×	0.8127175	+
	35	×	-0.0569523	+
	100	×	0.0377881	+
	29.5	×	-0.7846743	+
	34	×	-0.4675131	+
	32	×	-0.4117151	+
	1 × 34	×	-0.1023154	+
	35 × 29.5	×	-0.0028754	+
	35 × 34	×	0.0055347	+
	100 × 34	×	-0.0009478	+
	29.5 × 34	×	0.0162404	+
	29.5 × 32	×	0.0234855	

OER per bird ≈ 2.801 ou/s/bird

Assuming that 40,000 birds are in the shed,

OER ≈ 2.801 × 40,000

OER ≈ 112,030 ou/s

(Remember that the OER per bird is always multiplied by the number of birds placed in the shed at the start of the batch, not the actual number of birds, which changes due to mortality and pickups.)

Appendix 13 – Farm A Litter moisture contours

SUMMER BATCH — 18 Days, 27 Days
WINTER BATCH — 10 Days, 21 Days, 28 Days, 37 Days, 48 Days
Cooling Pads
Tunnel fan end of the shed
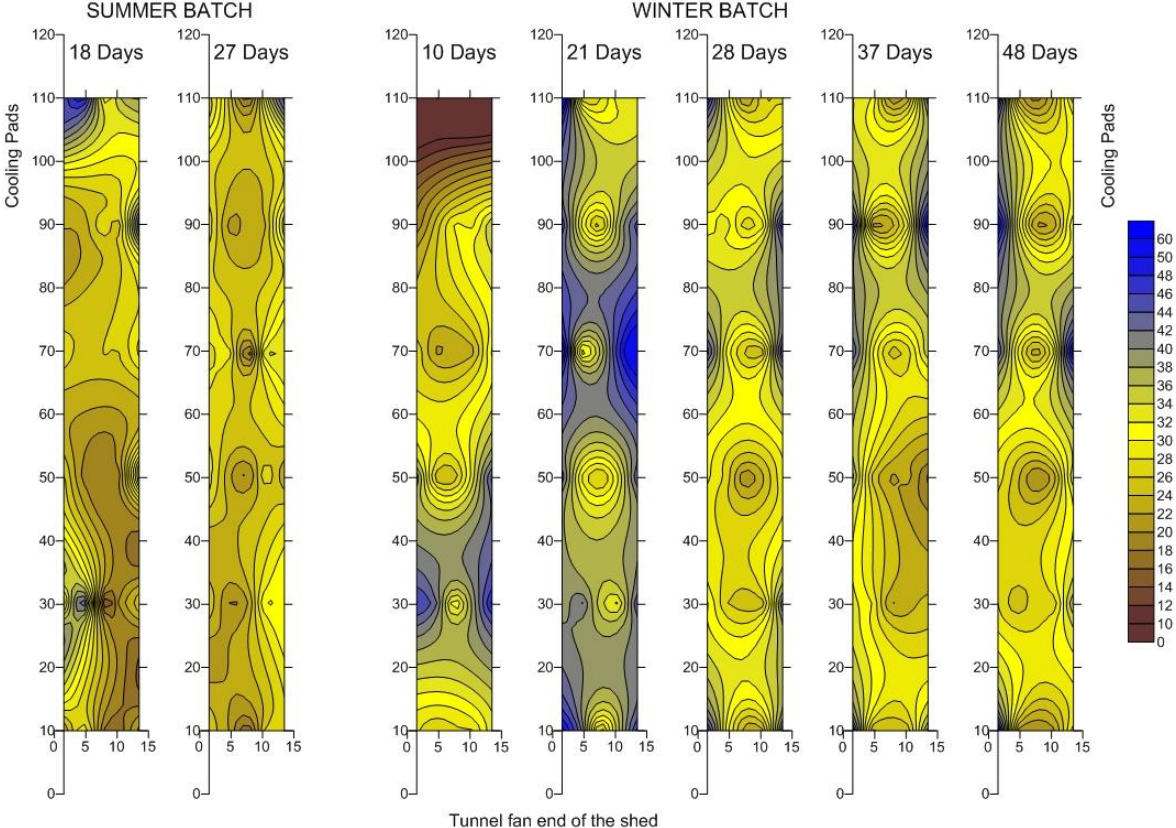
Appendix 14 – Farm B Litter moisture contours

FARM B SUMMER BATCH

13 Days   32 Days   46 Days

Cooling Pads

Tunnel fan end of the shed

FARM B WINTER BATCH

14 Days   22 Days   29 Days   35 Days   43 Days   49 Days

Cooling Pads

Tunnel fan end of the shed
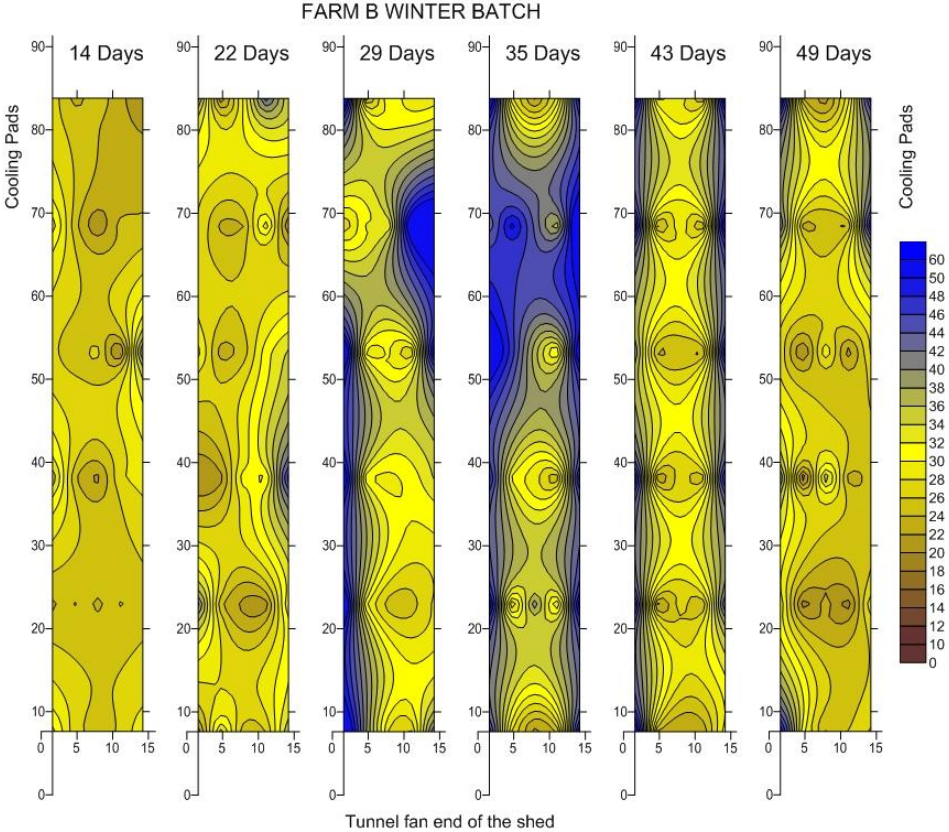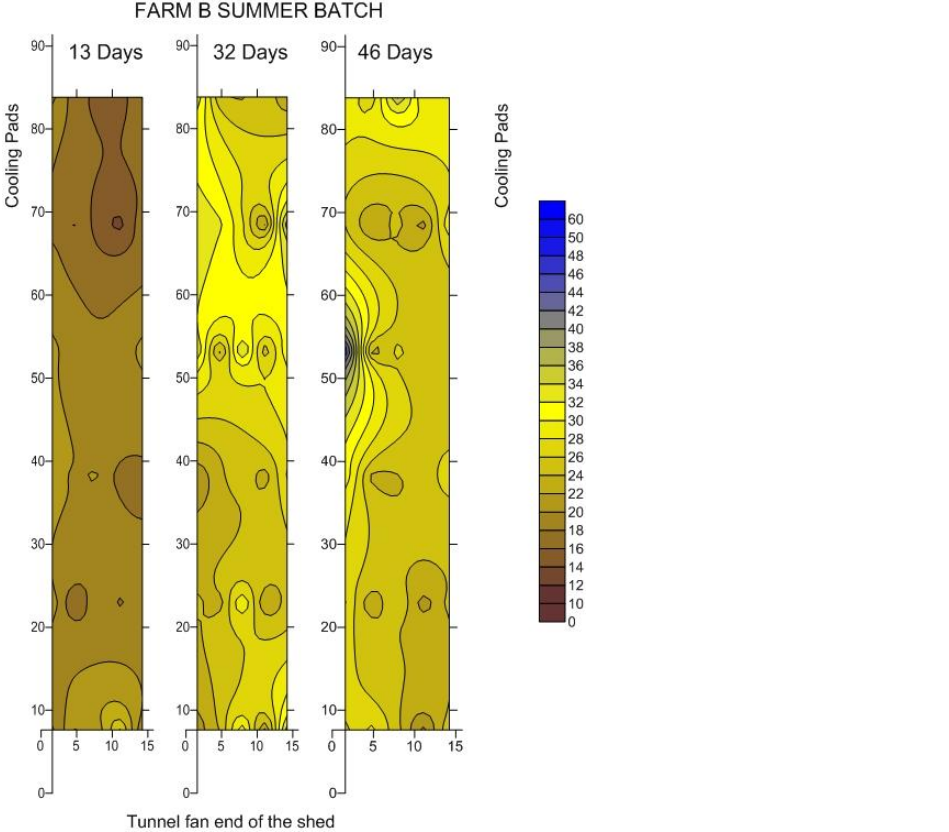
Appendix 15 – Farm C Litter moisture contours

FARM C FRESH LITTER BATCH

Tunnel fan end of the shed

FARM C REUSED LITTER BATCH

Tunnel fan end of the shed
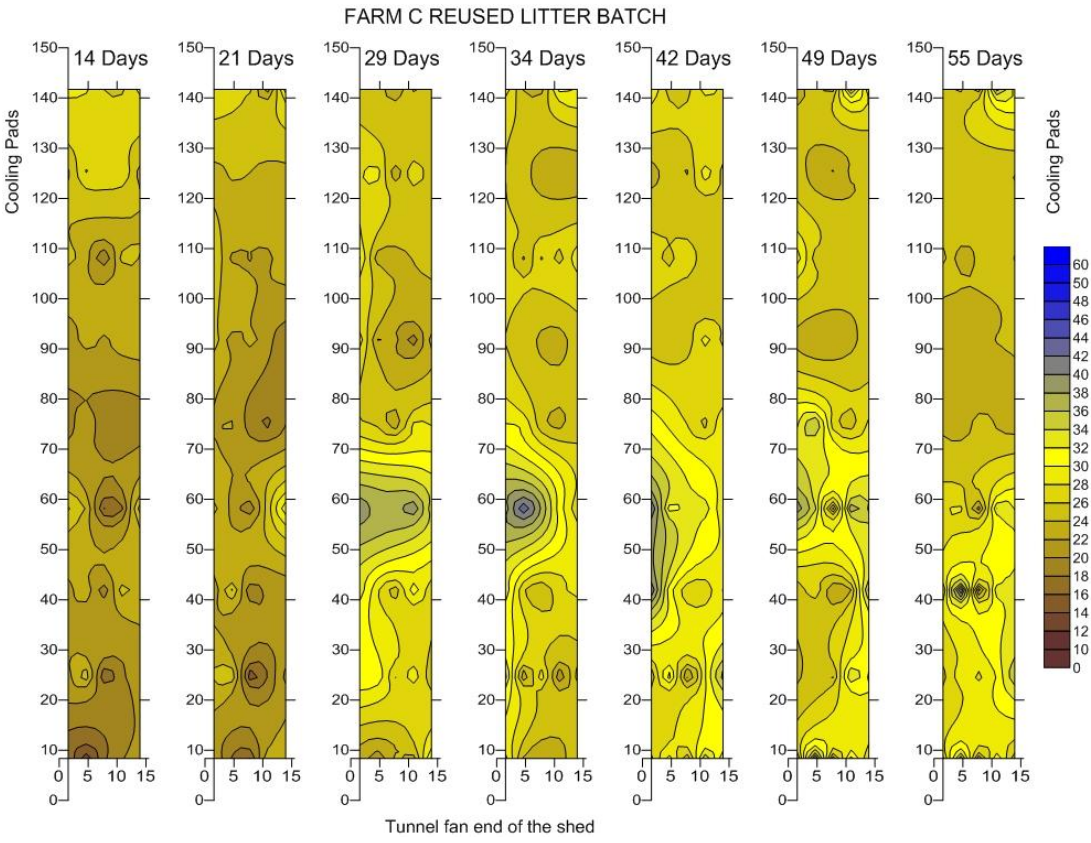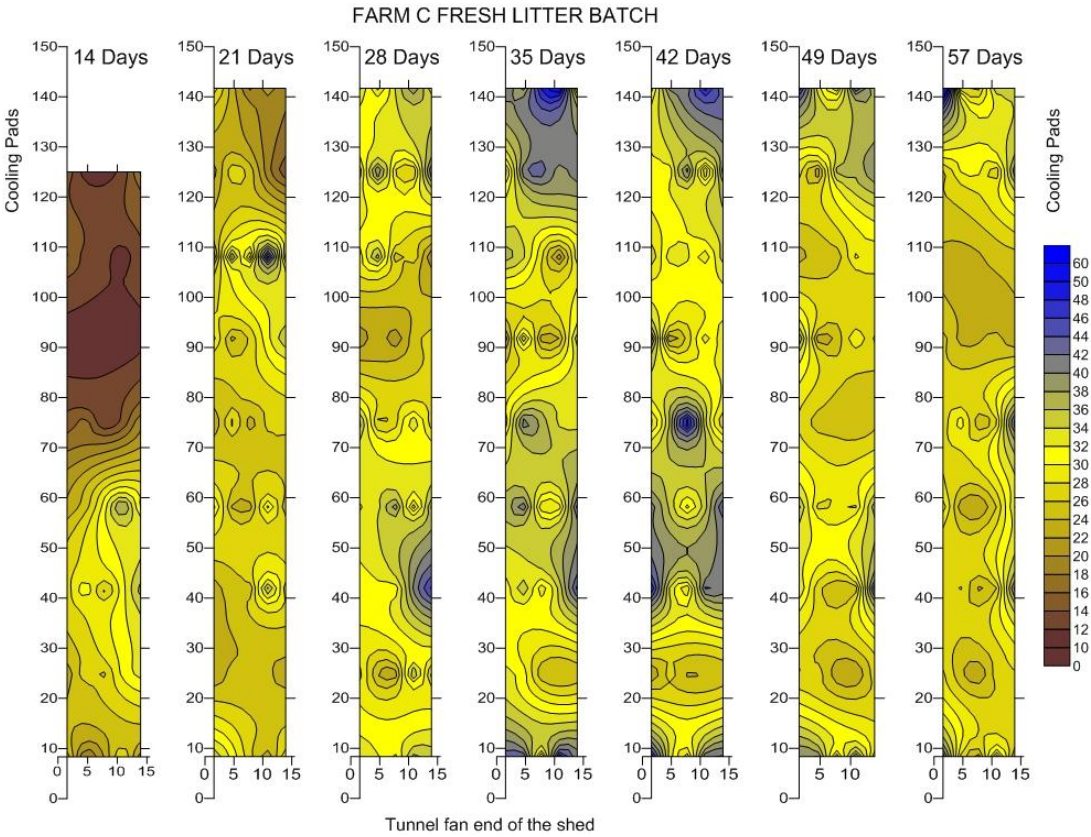
Appendix 16 – Farms F–M Litter moisture contours

QUEENSLAND FARMS BEFORE FIRST PICKUP
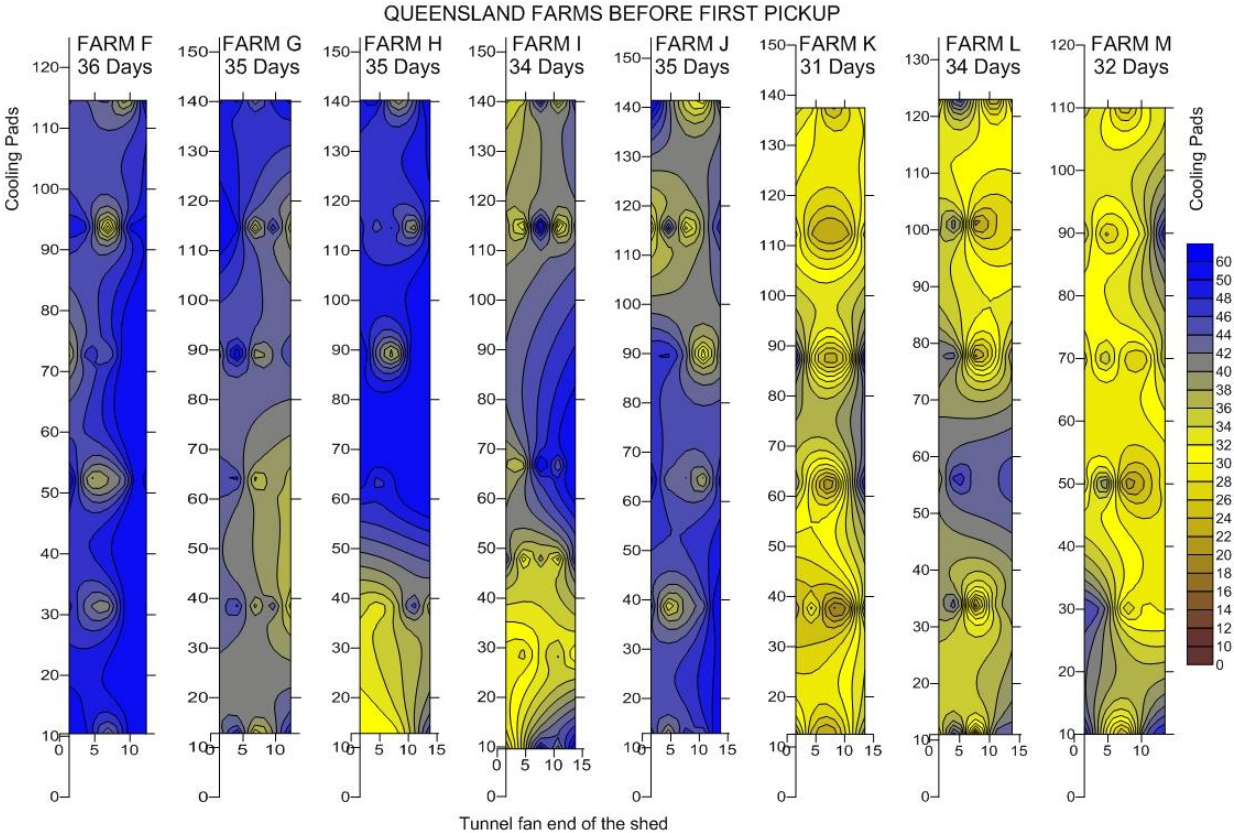
Appendix 17 – Importance of particulates on odour study

Sample Number	Date (ddmmyy)	Test Number	Date (ddmmyy)	Collection Time (hh:mm)	Sample Description	Odour Concentration (ou/m³)
1	110505	1	110505	12:10	Unfiltered	362
2	110505	1	110505	13:05	HEPA filtration	512
3	110505	1	110505	13:30	Unfiltered	609
4	110505	1	110505	16:30	HEPA filtration	1085
5	110505	1	110505	17:35	Unfiltered	974
6	110505	1	110505	18:05	HEPA filtration	1130
7	110505	1	110505	18:50	HEPA filtration	883
8	110505	1	110505	19:45	Unfiltered	1218
9	110505	1	110505	20:20	HEPA filtration	1176
10	110505	1	110505	21:00	Unfiltered	840
1	200705	2	200705	9:45	Unfiltered	761
2	200705	2	200705	10:40	HEPA filtration	799
3	200705	2	200705	11:30	Unfiltered	456
4	200705	2	200705	12:30	HEPA filtration	483
5	200705	2	200705	14:15	Unfiltered	609
6	200705	2	200705	15:00	HEPA filtration	1097
7	200705	2	200705	15:50	Unfiltered	724
8	200705	2	200705	16:30	HEPA filtration	813
1	261005	3	261005	12:50	Unfiltered	1085
2	261005	3	261005	10:13	Unfiltered	575
3	261005	3	261005	16:30	Glass fibre filtration (Filter number 1)	483
4	261005	3	261005	11:20	Glass fibre filtration (Filter number 2)	1024
5	261005	3	261005	12:05	Glass fibre filtration (Filter number 3)	912
6	261005	3	261005	14:15	Glass fibre filtration (Filter number 4)	683
8	261005	3	261005	15:50	Nitrogen sample from filter number 2 - heated at 100 degrees	362
9	261005	3	261005	15:00	Nitrogen sample from filter number 3 - heated at 60 degrees	683
10	261005	3	261005	18:00	Nitrogen sample from filter number 4 - heated at 100 degrees	55
11	261005	3	261005	17:30	Nitrogen sample from blank filter - heated at 100 degrees	147

Appendix 18 – Farm A, summer batch dust

Dust Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Ventilation Status (% of max fan activity)	Ventilation rate (m³/s)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (μm)	Number conc. (particles/m³)	NER (particles/s)	PM₂.₅ conc. (mg/m³)	PM₂.₅ ER (mg/s)	PM₁₀ conc. (mg/m³)	PM₁₀ ER (mg/s)
1	A	Single Use	Summer	231105	Single Use Litter No Birds	50.0%	46.03	-	10.30	-	-	-	-	-	0.022	1.026	0.023	1.073
2	A	Single Use	Summer	231105	Single Use Litter No Birds	75.0%	69.04	-	10.30	-	-	-	-	-	0.017	1.190	0.013	0.910
3	A	Single Use	Summer	231105	Single Use Litter No Birds	100.0%	91.22	-	10.30			-	-	-	0.012	1.122	0.007	0.628
4	A	Single Use	Summer	131205	18	25.0%	25.73	10.25	27.80	18200	26000	-	-	-	0.038	0.969	0.398	10.237
5	A	Single Use	Summer	131205	18	50.0%	44.10	10.25	27.80	18200	26000	-	-	-	0.026	1.138	0.266	11.723
6	A	Single Use	Summer	131205	18	75.0%	69.04	10.25	27.80	18200	26000	-	-	-	0.038	2.637	0.204	14.108
7	A	Single Use	Summer	131205	18	100.0%	91.22	10.25	27.80	18200	26000	-	-	-	0.030	2.693	0.097	8.834
8	A	Single Use	Summer	221205	27	75.0%	69.04	20.50	26.30	36400	26000	-	-	-	0.001	0.082	0.072	4.945
9	A	Single Use	Summer	221205	27	87.5%	80.50	20.50	26.30	36400	26000	-	-	-	0.004	0.298	0.222	17.851
10	A	Single Use	Summer	221205	27	100.0%	91.22	20.50	26.30	36400	26000	-	-	-	0.003	0.299	0.197	17.925
11	A	Single Use	Summer	110106	Birds Removed Litter Present	100.0%	91.22	-	29.60	-	-	-	-	-	0.036	3.245	0.110	10.041
12	A	Single Use	Summer	130106	Post Litter Removal Prior Shed Cleaning	12.5%	11.83	-	-	-	-	-	-	-	-	-	0.008	0.099
13	A	Single Use	Summer	130106	Post Litter Removal Prior Shed Cleaning	50.0%	45.25	-	-	-	-	-	-	-	-	-	0.008	0.349
14	A	Single Use	Summer	130106	Post Litter Removal Prior Shed Cleaning	75.0%	68.20	-	-	-	-	-	-	-	-	-	0.007	0.475
15	A	Single Use	Summer	130106	Post Litter Removal Prior Shed Cleaning	100.0%	91.22	-	-	-	-	-	-	-	-	-	0.008	0.702

Appendix 19 – Farm A, winter batch dust

Dust Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Ventilation Status (% of max fan activity)	Ventilation rate (m³/s)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (μm)	Number conc. (particles/m³)	NER (particles/s)	PM₂.₅ conc. (mg/m³)	PM₂.₅ ER (mg/s)	PM₁₀ conc. (mg/m³)	PM₁₀ ER (mg/s)
28	A	Single Use	Winter	210606	15	12.5%	11.83	9.57	37.08	16991	32179	1.99	15,381,828	182,014,799	-	-	0.209	2.470
29	A	Single Use	Winter	210606	15	25.0%	22.83	9.57	37.08	16991	32179	1.76	11,381,061	259,802,827	-	-	0.126	2.875
30	A	Single Use	Winter	210606	15	37.5%	33.73	9.57	37.08	16991	32179	-	-	-	-	-	0.140	4.713
31	A	Single Use	Winter	270606	21	12.5%	11.83	15.97	38.32	28370	32056	1.90	5,348,050	63,284,037	-	-	0.215	2.545
32	A	Single Use	Winter	270606	21	25.0%	22.83	15.97	38.32	28370	32056	1.81	4,084,807	93,246,525	-	-	0.162	3.692
33	A	Single Use	Winter	270606	21	37.5%	33.73	15.97	38.32	28370	32056	-	-	-	-	-	0.181	6.117
34	A	Single Use	Winter	040706	28	12.5%	11.83	25.05	31.73	44487	31913	2.01	8,014,857	94,840,646	-	-	0.451	5.337
35	A	Single Use	Winter	040706	28	25.0%	22.83	25.05	31.73	44487	31913	2.14	4,652,155	106,197,751	-	-	0.287	6.560
36	A	Single Use	Winter	070706	31	12.5%	11.83	29.29	33.14	52014	31852	1.87	15,564,574	184,177,247	-	-	0.674	7.975
37	A	Single Use	Winter	070706	31	25.0%	22.83	29.29	33.14	52014	31852	-	-	-	-	-	0.486	11.090
38	A	Single Use	Winter	070706	31	37.5%	33.73	29.29	33.14	52014	31852	1.88	8,241,124	277,964,944	-	-	0.364	12.262
39	A	Single Use	Winter	070706	31	50.0%	46.03	29.29	33.14	52014	31852	-	-	-	-	-	0.306	14.074
40	A	Single Use	Winter	100706	34	50.0%	46.03	25.62	-	45503	24178	1.77	8,366,542	385,095,088	-	-	0.326	15.012
41	A	Single Use	Winter	100706	34	37.5%	33.73	25.62	-	45503	24178	1.64	12,331,619	415,933,300	-	-	0.551	18.571
42	A	Single Use	Winter	100706	34	25.0%	22.83	25.62	-	45503	24178	1.55	12,975,358	296,196,862	-	-	0.823	18.789
43	A	Single Use	Winter	110706	35	12.5%	11.83	26.76	-	47534	24178	2.01	1,254,689	14,846,870	-	-	0.319	3.774
44	A	Single Use	Winter	110706	35	37.5%	33.73	26.76	-	47534	24178	1.39	4,335,673	146,237,959	-	-	0.299	10.097
45	A	Single Use	Winter	110707	35	50.0%	46.03	26.76	-	47534	24178	-	-	-	-	-	0.334	15.390
46	A	Single Use	Winter	110708	35	62.5%	54.63	26.76	-	47534	24178	1.45	4,178,391	228,265,475	-	-	0.237	12.961
47	A	Single Use	Winter	180706	42	12.5%	11.83	24.59	30.80	43674	17067	1.52	6,132,035	72,561,017	-	-	1.231	14.564
48	A	Single Use	Winter	180706	42	25.0%	22.83	24.59	30.80	43674	17067	1.62	4,286,218	97,844,273	-	-	0.731	16.694
49	A	Single Use	Winter	240706	48	25.0%	22.83	20.65	30.60	36679	12018	1.87	18,562,807	423,745,165	-	-	0.498	11.371
50	A	Single Use	Winter	240706	48	37.5%	33.73	20.65	30.60	36679	12018	1.88	19,454,368	656,176,571	-	-	0.505	17.046
51	A	Single Use	Winter	240706	48	50.0%	46.03	20.65	30.60	36679	12018	1.95	11,758,587	541,224,087	-	-	0.431	19.846

Appendix 20 – Farm B, summer batch dust

Dust Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Ventilation Status (% of max fan activity)	Ventilation rate (m³/s)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (μm)	Number conc. (particles/m³)	NER (particles/s)	PM$_{2.5}$ conc. (mg/m³)	PM$_{2.5}$ ER (mg/s)	PM$_{10}$ conc. (mg/m³)	PM$_{10}$ ER (mg/s)
16	B	Single Use	Summer	230206	13	56.00	29.26	7.33	18.60	10590	24000	-	-	-	0.031	0.918	0.098	2.860
17	B	Single Use	Summer	230206	13	56.0%	29.26	7.33	18.60	10590	24000	-	-	-	0.019	0.569	0.042	1.231
18	B	Single Use	Summer	230206	13	79.5%	41.56	7.33	18.60	10590	24000	-	-	-	0.017	0.712	0.040	1.658
19	B	Single Use	Summer	230206	13	88.3%	46.12	7.33	18.60	10590	24000	-	-	-	0.019	0.879	0.039	1.784
20	B	Single Use	Summer	140306	32	56.0%	29.26	22.84	26.96	33000	22000	-	30,966,394	906,076,682	0.138	4.032	0.598	17.486
21	B	Single Use	Summer	140306	32	56.0%	29.26	22.84	26.96	33000	22000	-	19,175,871	561,021,835	0.069	2.021	0.380	11.113
22	B	Single Use	Summer	140306	32	79.5%	41.56	22.84	26.96	33000	22000	-	10,105,002	419,919,758	0.050	2.086	0.209	8.703
23	B	Single Use	Summer	140306	32	88.3%	46.12	22.84	26.96	33000	22000	-	8,976,881	414,024,164	0.029	1.333	0.204	9.431
24	B	Single Use	Summer	280306	46	68.7%	35.87	26.90	26.50	38863	13636	-	22,516,171	807,655,068	-	-	0.573	20.561
25	B	Single Use	Summer	280306	46	68.7%	35.87	26.90	26.50	38863	13636	-	9,368,503	336,067,050	-	-	0.218	7.814
26	B	Single Use	Summer	280306	46	79.5%	41.56	26.90	26.50	38863	13636	-	14,377,137	597,451,022	-	-	0.198	8.240
27	B	Single Use	Summer	280306	46	88.3%	46.12	26.90	26.50	38863	13636	-	-	-	-	-	0.221	10.201

Appendix 21 – Farm B, winter batch dust

Dust Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Ventilation Status (% of max fan activity)	Ventilation rate (m³/s)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (μm)	Number conc. (particles/m³)	NER (particles/s)	PM$_{2.5}$ conc. (mg/m³)	PM$_{2.5}$ ER (mg/s)	PM$_{10}$ conc. (mg/m³)	PM$_{10}$ ER (mg/s)
52	B	Single Use	Winter	140906	22	80.0%	41.56	16.25	29.09	23470	30013	-	-	-	-	-	0.120	5.004
53	B	Single Use	Winter	270906	35	69.0%	35.87	41.82	39.70	60421	29764	-	-	-	-	-	1.190	42.701
54	B	Single Use	Winter	270906	35	80.0%	41.56	41.82	39.70	60421	29764	-	-	-	-	-	0.556	23.092
55	B	Single Use	Winter	290906	37	69.0%	35.87	34.30	38.67	49555	22525	-	-	-	-	-	1.164	41.744
56	B	Single Use	Winter	290906	37	80.0%	41.56	34.30	38.67	49555	22525	-	-	-	-	-	0.402	16.718
57	B	Single Use	Winter	290906	37	88.0%	46.12	34.30	38.67	49555	22525	-	-	-	-	-	0.362	16.677

Appendix 22 – Farm C, single use litter batch dust

Dust Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Ventilation Status (% of max fan activity)	Ventilation rate (m³/s)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (µm)	Number conc. (particles/m³)	NER (particles/s)	PM₂.₅ conc. (mg/m³)	PM₂.₅ ER (mg/s)	PM₁₀ conc. (mg/m³)	PM₁₀ ER (mg/s)
58	C	Single Use	Summer	130207	14	28.2%	32.33	7.12	20.55	16564	39913	3.39	5,060,218	163,603,940	0.038	1.224	0.224	7.240
59	C	Single Use	Summer	200207	21	78.6%	81.99	14.52	26.32	33770	39823	2.87	3,135,051	257,052,756	0.059	4.868	0.204	16.754
60	C	Single Use	Summer	270207	28	78.6%	81.99	25.64	30.94	59621	39747	1.89	11,421,564	936,490,246	0.066	5.424	0.233	19.092
61	C	Single Use	Summer	270207	28	85.7%	89.45	25.64	30.94	59621	39747	2.12	10,487,884	938,110,804	0.067	5.954	0.274	24.495
62	C	Single Use	Summer	060307	35	100.0%	97.65	33.18	34.64	77136	39638	1.90	40,500,000	3,954,679,863	0.515	50.288	1.623	158.480
63	C	Single Use	Summer	080307	37	85.7%	89.45	23.37	-	54327	26631	2.14	10,965,411	980,824,174	0.064	5.713	0.407	36.405
64	C	Single Use	Summer	080307	37	100.0%	97.65	23.37	--	54327	26631	2.39	8,169,134	797,686,683	0.089	8.710	0.396	38.649
65	C	Single Use	Summer	130307	42	85.7%	89.45	28.84	34.28	67046	26396	3.01	3,661,430	327,504,263	0.034	3.014	0.152	13.625
66	C	Single Use	Summer	200307	49	85.7%	89.45	27.86	30.24	64771	21083	-	-	-	0.090	8.007	0.344	30.766

Appendix 23 – Farm C, partially reused litter batch dust

Dust Sample Number	Property	Litter Reuse Status	Season	Date (ddmmyy)	Batch Age (days)	Ventilation Status (% of max fan activity)	Ventilation rate (m³/s)	Bird weight distribution (kg/m²)	Average litter moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (µm)	Number conc. (particles/m³)	NER (particles/s)	PM₂.₅ conc. (mg/m³)	PM₂.₅ ER (mg/s)	PM₁₀ conc. (mg/m³)	PM₁₀ ER (mg/s)
67	C	Reused	Autumn	240407	14	39.3%	45.38	9.64	22.24	22418	36993	2.22	36,828,732	1,671,131,989	0.055	2.487	0.354	16.069
68	C	Reused	Autumn	010507	21	63.6%	68.67	15.71	22.46	36535	36893	2.30	28,257,963	1,940,454,062	0.081	5.548	0.544	37.359
69	C	Reused	Autumn	090507	29	77.8%	78.27	23.94	27.19	55665	36779	-	12,760,835	998,742,192	-	-	-	-
70	C	Reused	Autumn	090507	29	57.1%	64.48	23.94	27.19	55665	36779	-	15,729,064	1,014,154,193	0.071	4.546	0.303	19.530
71	C	Reused	Autumn	090507	29	64.3%	67.09	23.94	27.19	55665	36779	-	14,964,752	1,003,915,252	-	-	-	-
72	C	Reused	Autumn	140507	34	71.7%	78.91	29.78	27.12	69231	36708	-	29,676,596	2,341,753,874	0.126	9.970	0.613	48.338
73	C	Reused	Autumn	170507	37	71.4%	76.03	21.20	29.88	49298	23185	1.88	19,447,908	1,478,625,086	0.119	9.061	0.573	43.565
74	C	Reused	Autumn	220507	42	77.8%	78.27	17.26	28.42	40141	15712	1.76	16,054,275	1,256,507,323	0.050	3.944		
75	C	Reused	Autumn	290507	49	71.4%	81.06	21.66	27.42	50356	15670	1.74	18,425,042	1,493,560,329	0.085	6.879	0.276	22.371
76	C	Reused	Autumn	40607	55	35.7%	41.62	25.77	26.93	59917	15633	1.68	43,396,683	1,806,169,954	-	-	-	-
77	C	Reused	Autumn	40607	55	44.5%	49.85	25.77	26.93	59917	15633	1.68	34,672,537	1,728,360,886	0.153	7.640	0.617	30.748
78	C	Reused	Autumn	40607	55	70.7%	74.82	25.77	26.93	59917	15633	1.71	21,470,663	1,606,408,597	0.118	8.815	0.462	34.568
79	C	Reused	Autumn	40607	55	64.3%	67.09	25.77	26.93	59917	15633	1.72	17,076,108	1,145,556,267	0.087	5.840	0.333	22.330