Process studies of odour emissions from effluent ponds using machine-based odour measurement

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Abstract

Replicable experimental studies using a novel experimental facility and a machine-based odour quantification technique were conducted to demonstrate the relationship between odour emission rates and pond loading rates. The odour quantification technique consisted of an electronic nose, AromaScan A32S, and an artificial neural network. Odour concentrations determined by olfactometry were used along with the AromaScan responses to train the artificial neural network. The trained network was able to predict the odour emission rates for the test data with a correlation coefficient of 0.98. Time averaged odour emission rates predicted by the machine-based odour quantification technique, were strongly correlated with volatile solids loading rate, demonstrating the increased magnitude of emissions from a heavily loaded effluent pond. However, it was not possible to obtain the same relationship between volatile solids loading rates and odour emission rates from the individual data. It is concluded that taking a limited number of odour samples over a short period is unlikely to provide a representative rate of odour emissions from an effluent pond. A continuous odour monitoring instrument will be required for that more demanding task.
Keywords: Odour, Electronic nose, Effluent pond, Olfactometry, Swine, Manure, Neural network

1 Introduction

Effluent ponds are widely used for the treatment of wastes from intensive livestock operations because of their low construction cost, convenience of maintenance and labour savings. More than 75% of piggery operations in the USA store and process waste anaerobically and 70% of their dairy production systems have liquid manure treatment systems (Hussey *et al*., 1999; Fisher, 1989). This level of use may be understood in that anaerobic ponds are the most trouble free, low maintenance systems available for effluent treatment. Effluent ponds are also widely accepted as the principle animal waste treatment system in Australia, especially in piggery operations (Smith *et al*, 1999).

A recognised drawback with effluent ponds is the production of offensive odours. The effluent ponds are the major source of odour in typical Australian piggeries contributing about 75% of all odour emissions (Smith *et al*, 1999; Jiang & Sands, 1998). In order to solve this problem, the first step is to quantify the emission rates of odour from effluent ponds. Current methods for estimating odour nuisance use standard emission rates that do not take into account the effect of loading rates and effluent characteristics. Consequently, there is potential for considerable difference between the estimated and real values.

More complete data on gross odour emission rates and effluent characteristics are required for a range of piggery effluent treatment ponds to assist in the planning process of new and expanding piggery developments. It is assumed that appropriately designed and well-managed ponds will produce lower odour emissions than overloaded and undersized ponds.

At present, olfactometry, in which a human panel is employed as the sensor, is regarded as the industry standard method for the measurement of odour concentration. However, olfactometry has a considerable disadvantage in terms of cost and labour requirements (Nimmermark, 2001). In addition, olfactometry is often thought to be an unreliable measurement technique because of its dependence on subjective human responses. Recent developments in the electronic nose technology and newly emerging pattern recognition techniques such as artificial neural networks (ANN), provide an opportunity to extend the scope of odour measurement (Sohn *et al.*, 2003b; Qu *et al.,* 2000).

The purpose of the research reported in this paper was to demonstrate, through replicable experimental studies, the relationship between odour emission rate and the pond factors of loading rate and hydraulic retention time. An experimental facility consisting of reactor vessels to simulate the operation of effluent ponds and a wind tunnel for sampling the emissions was developed specifically for this research (Sohn *et*

al., 2004; Sohn *et al*., 2003a). The machine-based odour quantification technique reported by Sohn *et al.* (2003b) which uses the AromaScan and an ANN was also applied in this research.

2 Experimental design

Two experiments were conducted to investigate the effect of volatile solids loading rate (VSLR) and hydraulic retention time (HRT) on the odour emission rate from piggery effluent ponds. The experimental methodology and operation of the experimental facility differed slightly for each experiment. A brief summary of the two experiments is outlined in **Table 1**.

2.1 Determination of volatile solids loading rate

As the most common method for designing anaerobic treatment ponds is the Rational Design Standard (RDS) (Barth, 1985; FSA Environmental, 2001), it was applied to determine the control volatile solids (VS) loading rate for the reactor vessels.

The RDS method requires the calculation of a maximum volatile solid loading rate based on a 20% odour detection rate. This is calculated from a standard VS loading rate for odour control of 61 g VS m^{-3} day^{-1}, multiplied by the temperature dependent *k* factor, which varies according to piggery location, as shown in equation 1.

$$V_O = \frac{VS_L}{VS_O} \cdot k \qquad (1)$$

where V_O is the volume for odour control (m^3) and VS_O is the standard VS loading rate for odour control (61 g VS m^{-3} day^{-1}).

The following figures were used to determine standard VS loading rate for the reactor vessels : *k* factor of 0.85 for Toowoomba, Queensland, Australia; and the pond volume for odour control of 0.25 m^3 (volume of a reactor vessel: 0.5 m × 0.5 m × 1.0 m high). From these design assumptions, the VS loading rate for a reactor vessel was calculated to be 18.0 g day^{-1}. This figure was used as the control loading rate for this research.

2.2 Determination of hydraulic retention time

One of the key factors for successful design and operation of piggery ponds is the hydraulic retention time (HRT). Wood (1986) indicated that the design of a waste stabilisation pond depends substantially on two factors: an adequate description of its mixing characteristics; and an adequate estimation of its biological degradation rate constant. HRT is closely related to the mixing characteristics of a pond. It is estimated by dividing the pond liquid volume by the average daily flow rate of effluent.

Piggery effluent ponds are neither precise plug flow reactors nor completely mixed systems. Therefore, it is necessary to consider the actual mean HRT. The effective or useful liquid volume of the pond is usually less than the total liquid volume due to short-circulation. Allan and Jeffreys (1987) reported that for an effluent pond in Whitehorse, Yukon, Canada about 40% of the volume was unused due to short-circuiting (cited from Martin, 1991). Tracer tests conducted in the Whitehorse pond showed that the actual mean HRT (HRT_A) was about 60% of the theoretical HRT (HRT_T). Pena *et al.* (2002) reported HRT_A values around 30 to 50% of HRT_T in their dispersion studies in anaerobic ponds using LiCl as a tracer to show the hydrodynamic behaviour of the pond.

The recommended design HRT for piggery effluent ponds is normally 30 to 60 days (ISU, 2003). Canter and Englande (1970) estimated average HRT values of 31 days for anaerobic effluent ponds used in the warmer southern states of the USA (cited from Martin, 1991). An HRT of 30 days was applied in experiment 1 as the control HRT. In experiment 2, an HRT of 60 days, the longest recommended design HRT, was used to allow comparison with the results from experiment 1.

3 Materials and methods

3.1 Experimental facility

An experimental facility was established on the field experimental station of the USQ in Toowoomba, Queensland, Australia. An experimental building with dimensions 5.8 m × 5.8 m × 2.3 m was customised to provide a controlled laboratory environment. The experimental facility consists of two main parts: the pond simulating reactor vessels, and the wind tunnel.

The reactor vessels were designed to simulate the workings of effluent ponds. Since anaerobic ponds are comparable to single-stage, unmixed, unheated digesters, the design of the reactors was based on the simple single-stage digester system model (Shuler & Kargi, 1992). With five independent reactor vessels, five different loading rates can be tested at the same time under controlled environmental conditions.

The wind tunnel was developed specifically for evaluating the kinetics of offensive odour emissions from area sources including liquid effluents. It was designed to allow control of factors such as wind speed, and the meteorological conditions (temperature and humidity) that directly effect the emission of odours. In addition, as the wind tunnel has a modular design, it can be easily modified to achieve specific experimental requirements. A detailed description of the wind tunnel and its evaluation has been presented in Sohn *et al.* (2003a) and Sohn *et al.* (2004).

3.2 Reactor vessel start-up

Prior to each experiment the reactor vessels were loaded identically and allowed a period of initiation to establish identical and stable conditions in each vessel. This initiation served to prevent shock loading and to give sufficient time for anaerobic microbes to propagate.

The reactor vessels were filled initially with anaerobic effluent and mature sludge, collected from a mature piggery effluent pond. During transport, exposure of the anaerobic sludge to oxygen was minimised by using an airtight container. Each reactor vessel was given 50 L of sludge (which is 20% of reactor volume) and 200 L of effluent (80% of reactor volume) with minimal aeration. Once the digesters were filled, they were allowed to equilibrate.

Fresh piggery effluent was collected from beneath the slatted floor of a commercial intensive piggery operation, twice a month, and used as the raw feed material to the reactor vessels. A regular programme of adding this fresh effluent to the reactor vessels commenced soon after the initial filling. A small volume (2.5 L) of effluent was added to each reactor vessel daily after the same volume of effluent was removed from the reactor to maintain a constant liquid level and headspace volume.

The values of pH and electrical conductivity (EC) were measured routinely to check the effluent condition in each reactor vessel. The results showed minimal variations between reactor vessels. After completion of the initiation process of 45 days duration, experiment 1 commenced.

3.3 The experiments

After the reactor vessels were initiated, experiment 1 was conducted for 12 months from 8th August 2001 to 14th August 2002. The reactor vessel 2 was used as the control reactor and was operated at a volatile solids loading rate (VSLR) of 72 g VS m^{-3} day^{-1} (as recommended for odour control by the RDS method). Reactors 1, 3, 4 and 5 were operated with VSLRs of 36, 108, 144 and 180 g VS m^{-3} day^{-1}, respectively. HRT was calculated by dividing the effective liquid volume of a reactor vessel by the average weekly feed rate of piggery effluent. Average HRT was 30 days.

At the conclusion of experiment 1, the reactor vessels were allowed to equilibrate for 60 days each with the same VSLR of 72 g VS m^{-3} day^{-1}. Experiment 2 was then conducted for six months from 13th November 2002 to 26th March 2003. The same VSLRs used in experiment 1 were applied in experiment 2. Average HRT was 60 days.

3.4 Odour sampling

Odour samples were collected in Melinex^{TM} (Polyethylene Terephthalate, DuPont, Australia) sample bags. The sample bags were placed into rigid 30 L or 120 L sample containers which were customised for

this research work. The 30 L and 120 L sample containers were used for the AromaScan and olfactometry analysis, respectively. The complete experimental facility and odour sampling are shown in *Fig 1.*

All components used for sampling were composed of stainless steel or Polytetrafluoroethylene material. The bags were pre-conditioned by filling them with odorous air from the wind tunnel prior to the sample being collected. The sampling container was then sealed and transported to the Aromascan A32S instrument for analysis, and then onto the olfactometer for final testing. The time between sample collection and testing was less than 24 hours in order to minimise any degradation of the odours.

3.5 Odour analysis using olfactometry

Odour concentrations were determined using an eight-panellist, triangular, forced choice dynamic olfactometer developed by the Department of Primary Industries and Fisheries, Queensland, Australia (Galvin *et al*., 2002a). Using the odour concentration, the odour emission rate (OER) was calculated using equation 2 (modified from Galvin *et al*., 2002a).

$$OER = C_s V_t \frac{A_t}{A_s} \quad (2)$$

where C_s is the odour concentration in the bag (OU m^{-3}), V_t is the wind speed inside the tunnel (m s^{-1}), A_t is the cross sectional area of the tunnel (m^2), and A_s is the effluent surface area sampled by the tunnel (m^2).

Equation 2 assumes that the incoming air is odour free and that there is complete mixing between the emissions and the airflow in the tunnel (Smith & Kelly, 1996).

3.6 Odour analysis using the AromaScan

The AromaScan A32S, a commercial electronic nose, was used as the main odour measurement instrument. The AromaScan is a commercial electronic nose consisting of 32-conducting polymer sensors. The polymers are based on heterocyclic compounds such as aniline and pyrole and are usually the derivatives of polypyrole and polythiophene. Because of their high sensitivities to volatile organic chemical compounds, polymer sensors are suitable for odour detection. The development of the analysis protocol for the AromaScan A32S, was described in detail in Sohn et al. (2003b).

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

The results of the olfactometry and Aromascan responses from experiment 2 were used to train the ANN. Thirty odorous air samples were collected from experiment 2 and measured concurrently with both the Aromascan and dynamic olfactometer. Five sets of sensor outputs were collected from each air sample to minimise noise and errors from the 32 sensors of the Aromascan, giving a dataset of 150 sensor outputs and 30 olfactory results from the 30 air samples. The entire dataset was divided into three subsets totally randomly, *i.e*. 50 % for training, 25 % for validation and 25% for testing. After the network was trained, the unused data sets were presented to the trained ANN to predict the odour emission rates for experiment 2. The prediction technique, using the trained ANN and sensor output results from the AromaScan, was then used to predict the odour emission rates for experiment 1 (for which olfactometry was not available).

3.7 Liquid sampling and analysis

In experiment 1, the liquid effluent in each of the reactor vessels was sampled for analysis every two weeks. A 500 mL sample was collected from four levels of each reactor vessel, through their respective sampling taps, and aggregated to make a 2 L sample. The sampling taps were located at 200, 400, 600, and 800 mm from the bottom of the one metre high reactor vessels.

In experiment 2, the reactor vessels were also sampled every two weeks. In this case, grab samples were taken from within the top 300 mm of the surface of the reactor vessels, taking care to exclude any scum on the surface. This sampling method was used for two main reasons. Firstly, the chemistry of the

surface layer of an effluent pond was assumed to be the main contributor to odour emissions (Hudson *et al.*, 2002). Secondly, other related research on odour emissions from piggery effluent ponds used the surface effluent sampling method (Galvin *et al.*, 2002a; FSA Environmental, 2001; Hudson *et al.*, 2002).

Liquid samples were stored at 4ºC and analysed within three days to minimize any change in concentration caused by microbiological processes. Various chemical and physical analyses were conducted. They can be classified under four groups: physical and chemical characteristics of raw feed material (pH, Alkalinity, EC, TS, VS, VS / TS, Total-Nitrogen (T-N), Ammonia nitrogen (NH_3-N), Chemical oxygen demand (COD), Potassium (K), Total phosphorus (T-P), Sulphide, and Sulphate); determination of volatile solids (VS); physical operating condition of reactor vessel (pH and EC); and chemical operating condition of reactor vessel (Alkalinity, EC, TS, VS, VS/TS, T-N, NH_3-N, COD, K, T-P, Sulphide, and Sulphate).

3.8 Statistical analysis

All data were analysed with SPSS Version 11.5. It was used to derive the relationship between odour emission rate and the experimental variables through paired samples Student's T-test, Pearson's correlation and linear/non-linear regression statistical analysis.

4 Results and Discussions

4.1 Characteristics of raw piggery effluent

The results of the chemical and physical analysis for the raw piggery effluent, used as the feed material to the reactors, are summarised in **Table 2** below.

As shown in **Table 2**, significant variation was observed in the characteristics of the raw effluent. These variations are mainly due to the irregular maintenance of the piggery waste system. Moreover, there are additional factors affecting the physical and chemical characteristics of raw piggery effluent. These factors include seasonal variance, changing feedstuff, growth stage, and manure storage time in sump.

The range of values for the chemical and physical parameters was similar to that reported by other researchers (FSA Environmental, 2001; Pieters *et al.*, 1999; MWPS, 1985).

4.2 Odour quantification using the AromaScan

The scatter plot of the actual odour emission rates measured with the olfactometer and predicted by the neural network (scaled into the odour emission rate domain) for the test data is shown in *Fig 2*. The value for the correlation coefficient (r^2) in *Fig 2* was 0.98. In addition, the predicted odour emission rates obtained by the neural regression are well distributed around the ideal 1:1 straight line as shown in *Fig 2*. Therefore, the results of the training simulation demonstrate that the trained ANN model can predict the odour emission rate of unknown air samples correctly with a low mean squared error.

The unused sensor data for each odour sample were presented to the trained ANN to predict the odour emission rates. The predictions were compared with the results of the olfactometry to verify the performance of the trained ANN model. The comparison of the actual and predicted odour emission rates from the olfactometry and the Aromascan,respectively, in reactor vessel 5 over the experiment 2 are shown in *Fig 3*. From the comparison plots, it is observed that the predicted odour emission rates have high correlation with the actual odour emission rates measured by olfactometry.

The odour quantification technique using the ANN gives the ability to predict odour emission rates from the sensor responses of the AromaScan. However, one must keep in mind that the regression process must only be used for interpolations. In addition, this odour quantification technique needs sufficient reliable odour data from olfactometry to train the ANN.

4.3 Effect of volatile solids loading rate on the physical and chemical characteristics of reactor vessels

To investigate the effect of VSLR on the physical and chemical characteristics of the reactor vessels, paired-sample T-test were used to analyse the results. The results for experiment 1 and 2 are summarised in **Table 3**.

Strong relationships between VSLR and the physical and chemical parameters were observed except for pH, alkalinity and NH_3-N in experiment 1. In terms of VS, as the VSLR has been determined by the concentration of VS, it is a logical conclusion that the results of VS have a direct relationship with VSLR. The results of TS have a similar tendency to VS because the concentration of TS in piggery effluent has a linear relationship with VS. Piggery effluent has a relatively constant VS / TS ratio of about 60% (MWPS, 1985).

It was observed that pH has no relationship with VSLR. This is due to the buffering capacity of piggery effluent. Piggery effluent used in this research had a high alkalinity value ranging from 2280 to 12240 mg L^{-1} as $CaCO_3$. Another contributing factor is the process stability of the reactor vessels. Even under the highest loading rate of 250% of recommended VSLR (in reactor vessel 5), the process was stable. A rapid decrease of pH caused by 'shock loading' did not occur in any reactor vessel.

The T-test results for EC show clear differences between reactor vessels with varying VSLR ($P < 0.05$). Similar results were observed in the results for COD ($P < 0.05$), *i.e.* these two parameters have strong relationships with VSLR. Therefore, it indicates that these parameters can be used as an indicator of the operating condition of a piggery effluent pond.

In the T-test for TKN in experiment 1, the effect of VSLR is significant under high loading conditions (200% and 250% of the recommended VSLR, $P < 0.01$) *i.e.* reactor vessel 4 and 5. However, the lower loading rates (ranging from 50 to 150%) show a poor relationship.

It was observed that there is no relationship between NH_3-N and VSLR. Under aerobic conditions, NH_3-N is converted to NO_2^--N and NO_3^--N through the nitrification process. The bacteria groups of *Nitrosomonas* and *Nitrobacter* are involved in this nitrification process. Under anaerobic conditions, denitrification occurs, where NO_2^--N and NO_3^--N are the terminal electron acceptors to produce nitrogen gas as a final product. Thus, NH_3-N can be converted to NO_2^--N and NO_3^--N at the surface layer of reactor vessels because the surface layer (less than about 50 cm) may contain dissolved oxygen, depending on such factors as wind, temperature and VSLR (Thirumurthi, 1991). Therefore, NH_3-N should not show a strong relationship with VSLR because it is unstable. In addition, some portion of nitrogen is used for microbial cell synthesis. Thirumurthi (1991) indicated that microbial cells contain about 50% carbon, 20% oxygen, 10 to 15% nitrogen, 8 to 10% hydrogen, 1 to 3% phosphorus, and 0.5 to 1.5% sulphur on a dry weight basis.

The results of experiment 2 made an interesting comparison with the results of experiment 1. The parameters of TS, VS and COD showed no relationship with VSLR. However, these same parameters revealed strong relationships in experiment 1. A contributing factor may be the application of different methods of liquid sampling, *i.e.*, from multi-layer sampling to surface sampling. This finding is discussed in more detail in the following section because it is closely related to the odour emission rates.

The additional chemical parameters of total phosphorus, potassium, sulphide and sulphate were analysed in experiment 2. It was observed that total phosphorus and potassium showed a strong relationship with VSLR ($P<0.05$). On the contrary, sulphide showed a weak relationship. Like NH_3-N, sulphur compounds are converted and restored in the 'Sulphur Cycle'. Hence, this may cause the weak relationship with VSLR. No statistical analysis was carried out for sulphate because of missing data and the low sensitivity of the method of analysis.

Pearson's correlation analysis was used to determine the correlation between the raw feed effluent and the liquid samples collected from the reactor vessels in experiment 2. The physical and chemical parameters analysed in this research work showed no correlation with the raw feed effluent except pH, which showed a weak correlation ($P < 0.05$). However, the results of pH were not significant because the value of the correlation coefficient r was low ranging from 0.47 to 0.58.

Consequently, it can be concluded that it is not possible to predict the concentration of physical and chemical parameters in the reactor vessels based on the concentration of raw feed effluent. This conclusion was confirmed by the results in experiment 2.

4.4 Effect of volatile solids loading rate on the odour emission rates

The odour emission rates (determined by olfactometry) from the five reactor vessels in experiment 2, are depicted in *Fig 4*. Though it was expected that a relationship would exist between odour emission rate and volatile solids loading rate, the regression analysis showed that the relationship was not strong in each individual trial. Galvin *et al.* (2002b) reported similar results from his field study on the effect of loading rate on odour emissions from anaerobic effluent ponds.

The odour emission rates in experiment 1 were acquired by the odour prediction process described in section 4.2. The results are shown in *Fig 5*.

As shown in trial sets 7, 8 and 9 in *Fig 5*, it is observed that the missing or erroneous data were predicted by the trained ANN. These erroneous data were mainly due to fuzzy sensor responses from the AromaScan. These data are excluded from the following statistical analysis. In *Fig 5*, the predicted odour emission rates do not obviously increase as a function of volatile solids loading rate, while the physical and chemical properties show strong relationships with volatile solids loading rate. Odour emissions vary significantly in each trial and in time. One of the suggested reasons is that high rates of odour emission may be closely related to activity in the pond sludge layer. FSA Environmental (2001) noted odour concentrations up to three times higher than average emissions where sludge up-welling had occurred.

While individual measurements show no trend, the time averaged odour emission rates do increase with volatile solids loading rate though they show high values of standard deviation. It also revealed that the odour emission rates did not necessarily increase linearly with VSLR. From the linear regression analysis between VSLR and time averaged odour emission rate in experiments 1 and 2, the time averaged odour emission rates increase with VSLR with high values for the correlation coefficient, r^2 of 0.96 and 0.95, respectively. Despite the variability in the individual emission rates, the results demonstrate clearly the likely magnitude of emissions from heavily loaded effluent ponds.

As observed previously, it was not possible to obtain the same relationships between VSLR and odour emission rates from the individual data. Taking a few odour samples during a short time period is unlikely to provide a representative odour emission rate from an effluent pond. A continuous odour monitoring instrument will be required for that kind of more demanding task.

No correlation was found in the Pearson's correlation results between odour emission rate and chemical parameters in experiment 1. However, the correlation results presented in **Table 4** show that in experiment 2, the odour emission rates measured by the AromaScan show a correlation with the chemical parameters ($P < 0.05$) except TS, VS, and Sulphur (S^{2-}). However, because of the lower number of data, the odour emission rates measured by olfactometry show no correlation with the chemical parameters except for total phosphorus.

One reason for the difference between experiment 1 and 2, is the change of liquid sampling method to 'surface liquid sampling'. It is observed that odour emissions are more strongly related to the chemistry of the surface layer of effluent ponds.

As seen in **Table 4**, the odour emission rates measured by the AromaScan show a stronger correlation to the chemical parameters ($P < 0.05$) than those from the olfactometry. It suggests that the sensor of the AromaScan may be more sensitive than the human nose to some specific volatile chemical compounds, *i.e.,* it tends to show a stronger response to those volatile chemical compounds than the human nose. However, there are insufficient data to allow a firm conclusion to be drawn.

4.5 Effect of hydraulic retention time on the odour emission rates

The effect of HRT was examined using the results from machine-based odour prediction in experiment 1 and the results from olfactometry in experiment 2. The results are presented in **Table 5**. The HRT was increased from 30 days for experiment 1 to 60 days for experiment 2, resulting in a significant decrease in odour emission rates from the reactor vessels. The reactor vessel 2 was used as a control with 72 g m^{-3} day^{-1} of standard VSLR. The means of the odour emission rates from reactor vessel 2 in experiments 1 and 2

were 7.53 and 3.08 OU m^{-2} s^{-1}, respectively, which is a decrease of about 60% in experiment 2. The decrease over all reactor vessels ranged from 59.1 % to 54.9 %, with an average of 57.1 %. Therefore, it can be concluded that an increase in HRT will decrease the odour emission rate. However, caution is required in the use of this conclusion due to the high variance in the measured odour emission rates as indicated by the standard deviations in **Table 5**.

5 Conclusions

The aim of this research work was to demonstrate the relationship between odour emission rates and pond loading rates through replicable experimental studies using a novel experimental facility and a machine-based odour quantification technique.

The results of olfactometry and the AromaScan in experiment 2 were used successfully to train the ANN. The trained network was able to predict the odour emission rates for the test data with a correlation coefficient of 0.98.

A strong relationship between VSLR and the physical and chemical parameters of the effluent in the reactor vessels was observed except for pH and NH_3-N. The pH was not affected by VSLR. This is mainly due to the buffering capacity of piggery effluent. The results for EC show a clear difference between reactor vessels depending on the change of VSLR ($P < 0.05$). Similar results were observed for COD ($P < 0.05$).

The odour emission rates measured by the AromaScan showed a stronger correlation to chemical parameters ($P < 0.05$) than the results of olfactometry. It suggests that the sensor of the AromaScan is more sensitive than the human nose to some specific volatile chemical compounds.

The effect of HRT was examined. The HRT was increased from 30 days in experiment 1 to 60 days in experiment 2, resulting in a significant decrease in odour emission rates from the reactor vessels. The decrease for the five reactor vessels ranged from 59.1 % to 54.9 %. Therefore, it can be concluded that an increase of HRT will decrease odour emission rates.

While the individual odour emission rates exhibited a high variance, time averaged odour emission rates were strongly correlated with VSLR. Consequently, it can be concluded that a heavily loaded effluent pond would produce more odour. However, no relationship between VSLR and odour emission rate or odour concentration can be seen from the individual data. Because of the variability in emission rate data, taking a few odour samples during a short time period is unlikely to provide a representative odour emission rate from an effluent pond.

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Table 1 Summary of the experimental design

	Experiment	
	Exp. 1	*Exp. 2*
Variable 1	VSLR[1]	VSLR
Variable 2	HRT[2] (30 days)	HRT (60 days)
Materials	Piggery effluent	Piggery effluent
Operation periods	12 months	6 months
Season	4 seasons	Summer - Autumn
Temperature	8 – 25 °C	25 – 15 °C
Odour measurement	Aromascan A32s	Aromascan A32S & Olfactometry

1. VSLR: volatile solids loading rate
2. HRT: hydraulic retention time

Table 2 The chemical and physical analyses of the raw piggery effluent

Parameter	*Unit*	*Mean*	*N*[1]	*Min*	*Max*	*SD*[2]
PH		7.42	35	6.68	8.28	0.34
Total Alkalinity	mg L^{-1} as $CaCO_3$	7227	21	2280	12240	3146
EC	dS m^{-1}	19.64	35	13.80	25.12	3.22
TS	mg L^{-1}	21796	35	5628	77249	19042
VS	mg L^{-1}	13442	35	1968	54349	13583
VS/TS	%	54.3	35	36.0	76.0	14.37
Total Nitrogen	mg L^{-1}	2479	18	1920	3420	446
Ammonia Nitrogen	mg L^{-1}	2164	18	1480	3110	455
COD	mg L^{-1}	10629	18	4460	22220	5084
Potassium	mg L^{-1}	1125	5	985	1330	126.6
Sulphates	mg L^{-1}	18	3	8.2	34.8	14.62
Sulphides	mg L^{-1}	5.53	4	2.4	14.1	5.76
Total Phorphorus	mg L^{-1}	294.2	5	150	401	94.35

1. N: Number of samples
2. SD: Standard deviation

Table 3 The results of paired-sample T-test to investigate the effects of volatile solids loading rate on the physical and chemical parameters in the reactor vessels in experiment 1 and 2

		TS	*VS*	*pH*	*Alkalinity*	*EC*	*COD*	*TKN*	*NH_3-N*	*TP*	*K*	*S*
		T-test significant (2-tailed)										
Experiment 1	*R1:R2*	0.005†	0.005†	0.501	0.089	0.000†	0.017†	0.420	0.437			
	R3:R2	0.022†	0.078	0.228	0.285	0.000†	0.735	0.704	0.340			
	R4:R2	0.000†	0.001†	0.803	0.000†	0.000†	0.022†	0.005†	0.814			
	R5:R2	0.001†	0.001†	0.194	0.001†	0.000†	0.001†	0.005†	0.661			
Experiment 2	*R1:R2*	0.089	0.898	0.905	0.009†	0.000†	0.055	0.149	0.112	0.014†	0.007†	0.077
	R3:R2	0.255	0.196	0.086	0.054	0.056†	0.595	0.192	0.085	0.017†	0.001†	0.198
	R4:R2	0.443	0.291	0.827	0.002†	0.006†	0.083	0.020	0.012†	0.012†	0.042†	0.065
	R5:R2	0.046†	0.169	0.650	0.014†	0.000†	0.285	0.027	0.022†	0.009†	0.020†	0.053

†: 95% probability ($P < 0.05$)

Table 4 The results of Pearson's correlation analysis between odour emission rates and chemical parameters in experiment 2

	TS	*VS*	*pH*	*Alkalinity*	*EC*	*COD*	*TKN*	*NH_3-N*	*TP*	*K*	*S*
OER[1]											
Correlation	-.021	-.104	.266	.191	.297	-.097	.095	.205	.487†	.186	-.092
N[2]	30	30	30	30	30	25	25	25	25	25	19
OER_EN[3]											
Correlation	-.017	-.030	-.360†[4]	-.366†	.308†	.325†	.262†	.245†	.482†	.157	-.117
N	30	30	30	30	30	25	25	25	25	25	19

1. OER: actual odour emission rate by olfactometry, OU m^{-2} s^{-1}
2. N: number of samples used for the statistical analysis
3. OER_EN: predicted odour emission rate by the AromaScan, OU m^{-2} s^{-1}
4. †: 95% probability ($P < 0.05$)

Table 5 Effect of hydraulic retention time on the odour emission rates

	VSLR (*VS g m^{-3} day^{-1}*)	*Experiment 1*		*Experiment 2*		*Ratio of OER decrease (%)*
		OER_EN[1] *(OU m^{-2} s^{-1})*	*SD*	*OER*[2] *(OU m^{-2} s^{-1})*	*SD*	
Reactor 1	36	6.67	3.54	2.93	1.39	56.2
Reactor 2	72	7.53	2.92	3.08	1.29	59.1
Reactor 3	108	7.67	2.93	3.27	1.65	57.3
Reactor 4	144	8.51	2.70	3.57	1.04	58.1
Reactor 5	180	8.91	3.12	4.02	0.70	54.9

1. OER_EN: predicted odour emission rate by the AromaScan, OU m^{-2} s^{-1}
2. OER: actual odour emission rate by olfactometry, OU m^{-2} s^{-1}

(a) experimental facility

(b) odour sampling container for olfactory analysis

Fig 1 Experimental facility and odour sampling

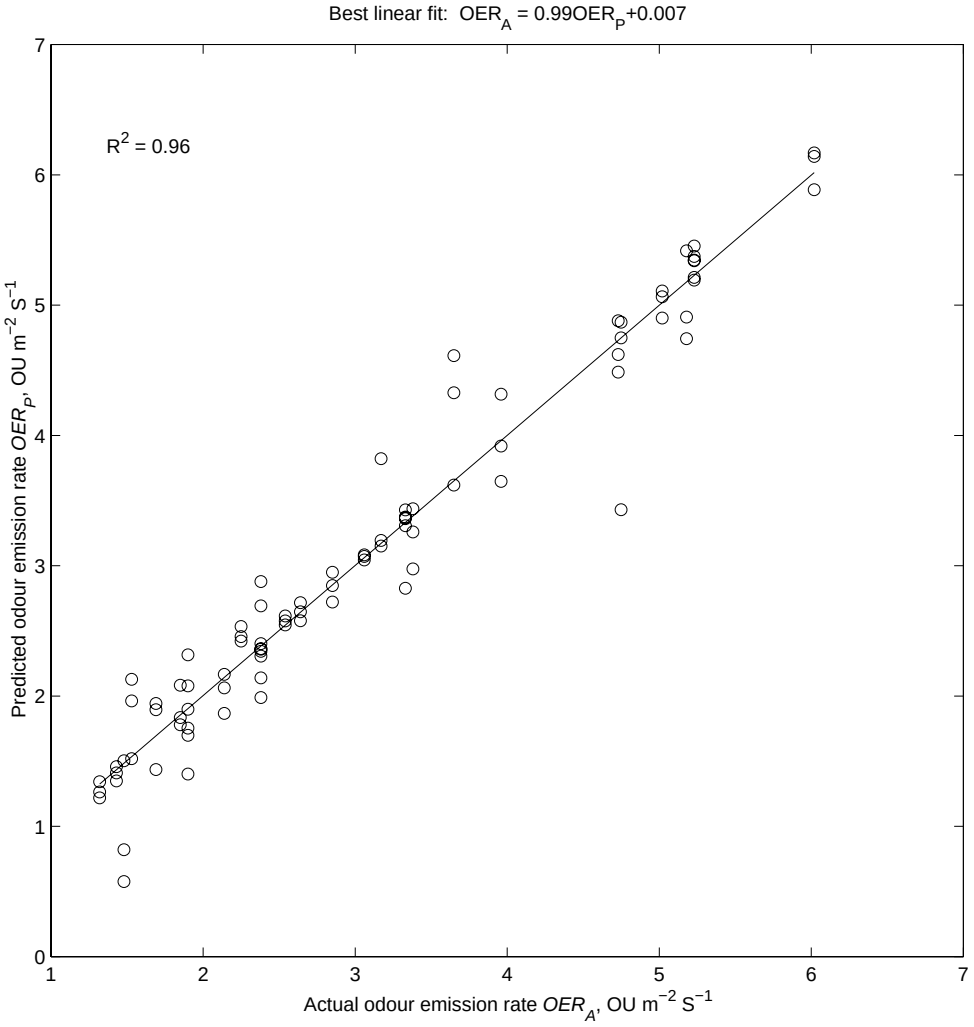

Fig 2 Odour emission rate prediction results using AromaScan and artificial neural network

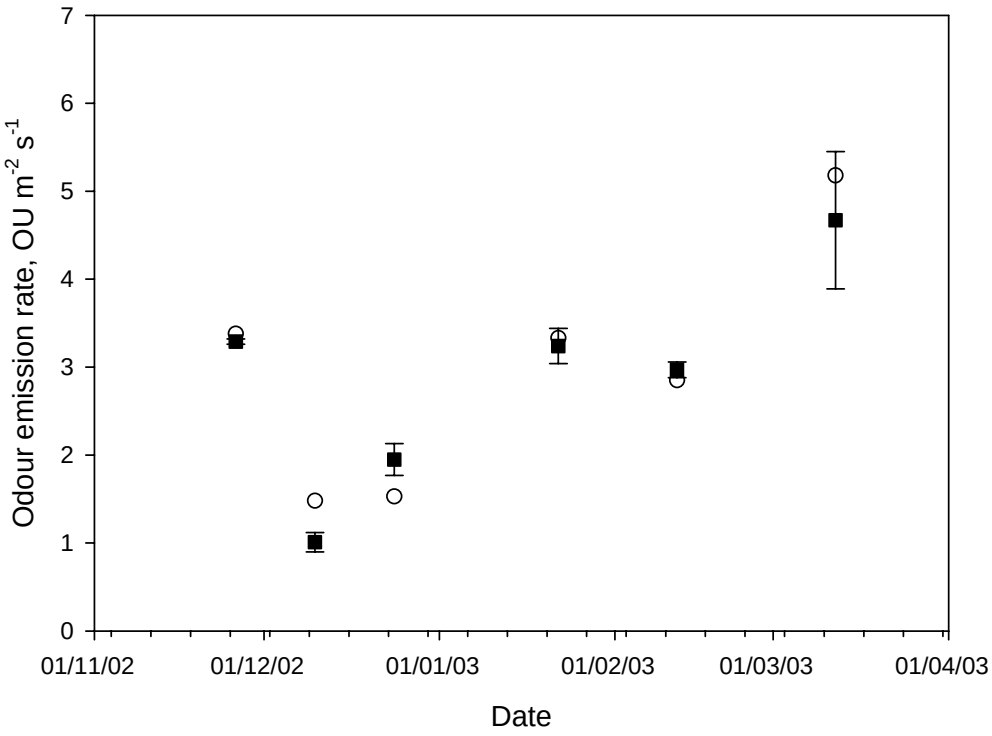

Fig 3 Comparison of odour emission rates in Reactor 5 over experiment 2: ○, odour emission rate measured by olfactometry; ■, odour emission rate predicted by the Aromascan and ANN

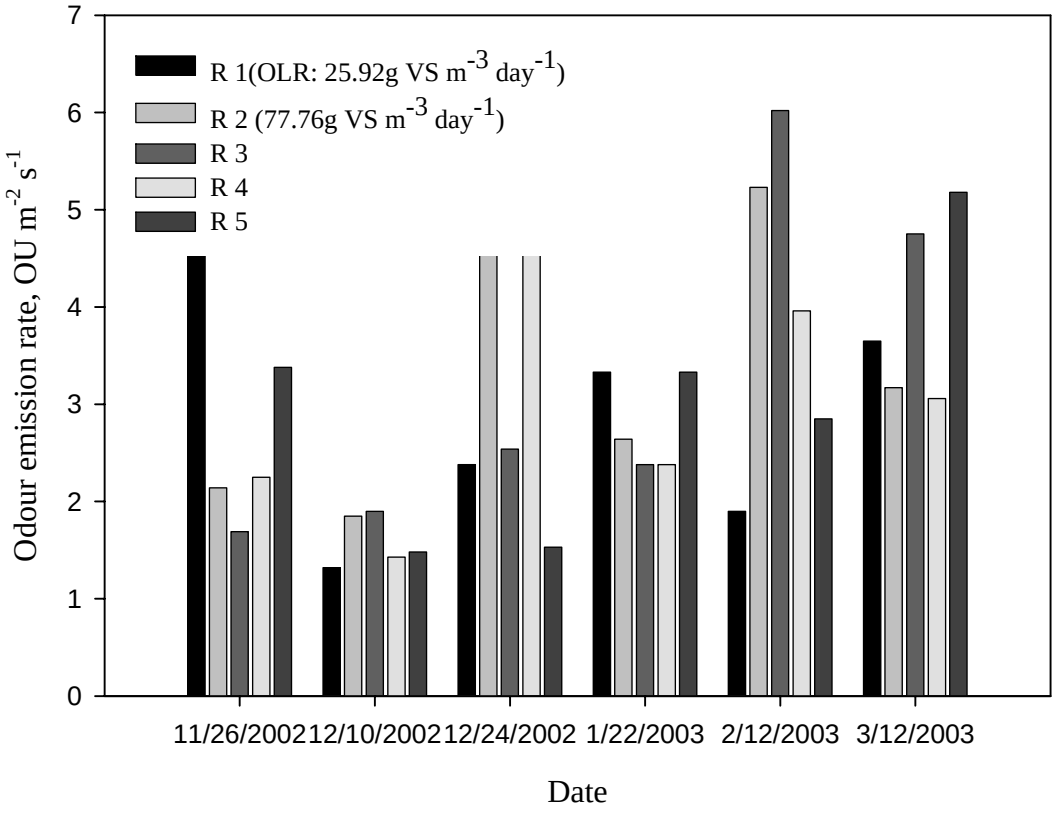

Fig 4 Course of the odour emission rates (analysed by olfactometry) from the five reactor vessels in experiment 2 (R1, VSLR 36 g VS m^{-3} day^{-1}*; R2, 72; R3, 108; R4, 144; R5, 180)*

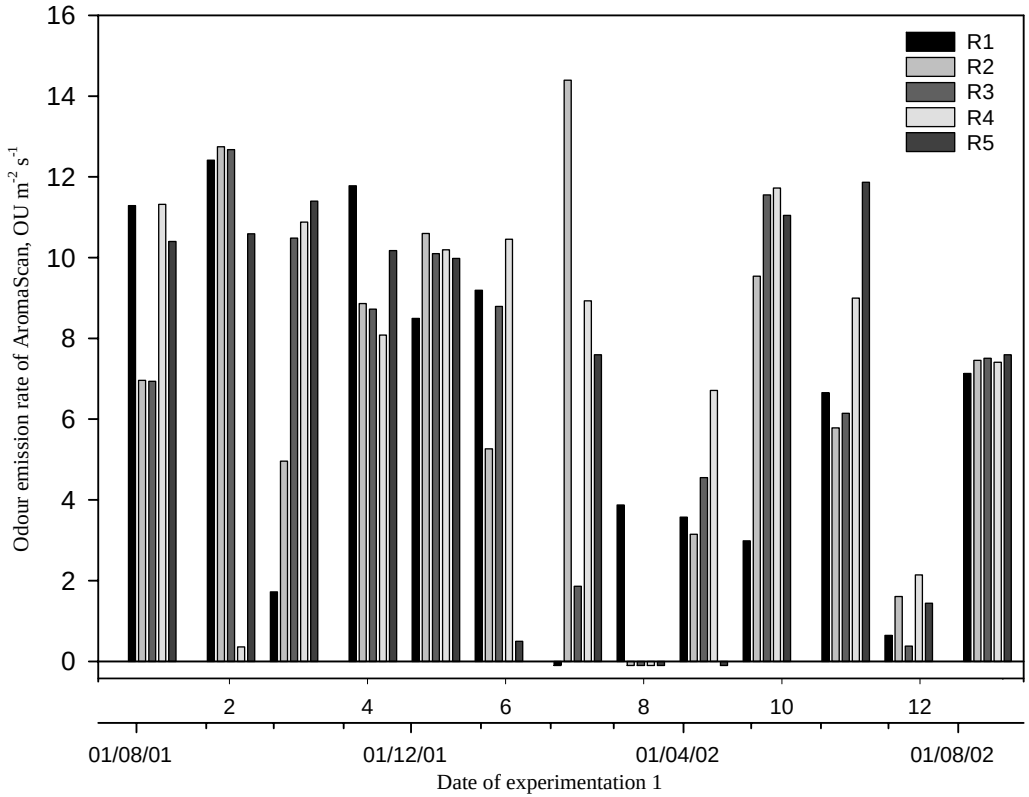

Fig 5 Course of the odour emission rates (predicted by the AromaScan) from the five reactor vessels in experiment 1 (R1, VSLR 36g VS m^{-3} day^{-1}; R2, 72; R3, 108; R4, 144; R5, 180)