Biofiltration of Odour and Ammonia from a Pig Unit – A Pilot-scale Study

B. Sheridan; T. Curran; V. Dodd; J. Colligan

Department of Agricultural and Food Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland;

e-mail of corresponding author: Tom.Curran@ucd.ie

A pilot-scale biofiltration unit was constructed at a pig finishing building on the University College Dublin research farm. The biofiltration system was investigated over three trial periods. Exhaust air from a single pen was extracted by a variable speed centrifugal fan and passed through a humidifier and biofilter. A 0.5 m depth of woodchips of over 20 mm screen size was used as the biofilter medium. The moisture content of the medium was maintained at 63±4% (wet weight basis) for trial one and 69±4% (wet weight basis) for trials two and three using a load cell method. The volumetric loading rate varied from 769 to 1898 m^3 [air] m^{-3} [medium] h^{-1} during the three trial periods. Odour and ammonia removal efficiencies ranged from 77 to 95% and 54 to 93% respectively. The pH of the biofilter leachate remained between 6 and 8 throughout the experimental periods. The pressure drop across the biofilter ranged from 14 to 64 Pa. It is concluded that a wood chip media particle size >20 mm is suitable for use in biofiltration systems on intensive pig production facilities. This will minimise the pressure drop on the system fans to reduce overall operation costs. It is recommended that a filter bed moisture content (wet weight basis) of greater than 63% be used to maintain overall efficiency. An efficient air moisturising system (humidification and bed sprinkling) along with a properly designed air distribution system must be incorporated in the overall design when operating at such high volumetric loading rates.

1. Introduction

The main sources of malodour from pig production operations include livestock buildings, external manure storage facilities and land spreading of manure. Van't Klooster and Voermans (1993) estimated that the total odour emissions from animal facilities in Europe are made up of 50% from indoor exhaust air, 25% from manure storage and 25% from manure transport and spreading. Significant efforts have been made in controlling emissions from land spreading and manure storage areas (Pain *et al*., 1991; Li & Owen, 1997; Moseley *et al*., 1998; Pahl *et al*., 2000) but there is still some progress to be made in reducing emissions from pig housing, particularly with regard to odour abatement technology. There are many air pollution control technologies currently available for reducing the emission of odours and volatile organic compounds to the atmosphere but installation and operation costs restrict their installation. These include incineration, chemical scrubbing, absorption and biological methods. Biological methods include bioscrubbers and biofilters. Biofiltration is a proven technology in industrial applications as a method of odour emissions reduction. It is robust, cost effective (Vaith *et al*., 1996) (in comparison to other technologies) and efficient in the treatment of odour emissions from farm facilities (O'Neill *et al.*, 1992; Nicolai & Janni, 1998; Classen *et al*., 2000).

The primary mechanism in biofiltration is the degradation of gaseous contaminants by micro-organisms. As the odorous air passes through the medium, the contaminants in the air stream are absorbed by the biofilm that surrounds the medium's particles. These contaminants are then oxidised to produce biomass, CO_2, H_2O and inorganic salts (Deshusses, 1997). Adequate odour and ammonia removal efficiencies of >70% for

livestock facilities can be achieved at residence times of between three and fifteen seconds (Rodhe *et al*., 1986; Zeisig *et al*., 1987; Classen *et al*., 2000; Nicolai & Janni, 2000; Sheridan *et al*., 2000), but these removal efficiencies depend on the moisture content and characteristics of the media (Cox *et al*., 1996; Auria *et al*., 1998; McNevin & Barford, 1998; Morales *et al*., 1998; Kim *et al*., 2000a; Krailis *et al*., 2000; Tawil *et al*., 2001).

The objective of this research was to assess the efficacy of a pilot-scale biofiltration system in reducing odour and ammonia emissions from the exhaust air of a pig finishing building at different operating conditions, thus giving useful information for optimising the design and operation of large scale biofilters.

2. Materials and methods

2.1. Animal facilities

A pig finishing house on the University College Dublin research farm was chosen as the facility on which to set up the experimental unit. The building consisted of 12 similar pens with partially slatted floors. The slatted floor area was 21% of the total floor area. One pen was sealed off from the rest of the building and was fitted with a variable speed centrifugal fan thermostatically controlled electrical radiant heater and a separate air inlet (*Fig. 1*). These modifications allowed the pen to be heated and ventilated independently of the other 11 pens. Six disease free pigs were placed in the pen for trial one and seven were placed in the pen for trials two and three. All of the pigs used in the trial were Large White by Landrace crossbreed female (*Sus scrofa*) (35 kg initial weight for trial one and two and 80 kg initial weight for trial 3) and were fed manually twice

daily with a feed comprising of 46% barley, 20% maize, 29% Soya bean meal, 1% tallow and 1% lime. The remaining 3% of the feed comprised of additional minerals.

2.2. Biofiltration system

Air was drawn from the pen by a variable speed centrifugal fan and passed through the biofiltration system, which comprised of a humidifier and biofilter as shown in *Fig. 1*. Pig building ventilation rates vary throughout the year, increasing to a maximum during the warmer summer months in order to remove the excess heat and gases from the building to maintain the ideal conditions for the animals. For a pig finishing house in temperate climate zones, the recommended minimum winter ventilation rate is approximately 10 m^3 h^{-1} pig $place^{-1}$ whereas the recommended maximum rate is approximately 100 m^3 h^{-1} pig $place^{-1}$ (CIGR, 1992).

A dust filter and humidifier were included in the overall design to pre-treat the air prior to it entering the biofilter. It was felt that a dust filter might prove beneficial in removing some particles from the exhaust ventilation air, thus removing some odour and also preventing excess dust building up in the biofilter which would lead to increased pressure drop. However, preliminary tests showed that a bag filter removed greater than 99% of particles while the odour was reduced by 19%. Therefore, it was decided that the benefits of including a dust filter were negligible and it was removed for this experiment.

A humidifier was incorporated into the design in order to saturate the air as it enters the biofilter. Air with a relative humidity of less than 100% can result in rapid loss of biodegradation activity as the incoming gas steadily removes water from the medium bed by convection and dries the biofilm first (Auria *et al*., 1998; Bohn & Bohn, 1999;

Krailis *et al*., 2000). A humidifier was constructed using a cylindrical plastic container with a height of 0.91 m and a diameter of 0.56 m. The humidifier was operated in counter-current flow to obtain maximum air moisturising effect. A humidity/temperature sensor (Model D12-20, Airflow Ltd, UK) at the exit of the humidifier allowed for assessment of the inlet air to the biofilter. A 2 m long pipe with an internal diameter of 0.15 m connected the centrifugal fan to the humidifier. This length of ducting was required to facilitate the accurate determination of airflow rate from the pen (Testo, 1998). A solid cone water nozzle with a spray angle of 80^{o} was placed at the top of the humidifier. Water was delivered continuously to the atomising nozzle at a rate of approximately 0.6 l min^{-1} by a centrifugal pump. Spent water, as a result of the humidification, was piped out at the base of the humidifier. This pipe had a U-shape configuration preventing air from escaping through the water outlet.

2.3. Biofilter details

The biofilter was constructed from a cylindrical metal container of height 0.91 m and diameter 0.56 m; this allowed for a medium depth of 0.5 m, typical for many biofilters (VDI, 1991; Scotford *et al*., 1996; Wani *et al*., 1997).

The biofilter container was fitted with a metal mesh floor 0.125 m from the bottom to support the medium. The mesh floor had apertures of approximately 0.015 m by 0.015 m. The container was also fitted with a rubber baffle, placed 0.285 m from the top of the container, and a perspex window to allow viewing of the medium. The baffle was approximately 0.075 m wide and was attached around the internal circumference of the container to prevent short-circuiting of influent gas down the sides of the container. The temperature change within the biofilter medium was monitored using two Pt100

platinum thermocouples in order to determine any temperature variations within the biofilter. Heating tape, covered with fibreglass insulation, was wrapped around the biofilter to provide heat when the average temperature, sensed by the two probes, dropped below a set temperature of 24^0C.

The weight of the biofilter was monitored using a load cell method and automated control of moisture content within the biofilter was performed using a solenoid valve, which was controlled using graphical computer programming software called LabView™ (National Instruments, UK). If the weight of the biofilter was known, then the moisture content of the biofilter could be controlled to ± 4% (Young *et al*., 1998; Classen *et al*., 2000).

The contaminated air passed through the media in a down-flow direction as it allowed for easier addition of water directly to the dry zone, which would always occur at the entrance (Krailis *et al*., 2000; Arnold *et al*., 1997) and was found to be approximately twice as efficient as upward flow (Arnold *et al*., 1997). The biofilter weight was recorded every 30 seconds on a computer using the data acquisition software package LabView™.

2.4. System operation

The efficiency of the biofilter at reducing the odour and ammonia emissions from the pig building was assessed over three trial experimental periods. The biofilter medium was inoculated at start up using activated sludge from a sewage treatment works in order to reduce the acclimatisation period (Zeisig *et al*., 1987; Hamer, 1998; Kim *et al*., 2000b). The system was operated for three weeks to allow the biomass to adapt itself to the operating conditions (Degorce-Dumas *et al*., 1997).

Regular measurements (*Table 1*) were taken throughout the system during these three trial experimental periods in order to determine the optimum operating conditions for the removal of odour and ammonia.

2.4.1. Volumetric loading rate measurements

The volumetric loading rate on a biofilter is a key operating parameter and is defined as the volume of gas that passes through per unit volume of filter material per unit time. This is essentially the exhaust ventilation rate of the pen divided by the volume of medium used to treat this exhaust ventilation rate. The ventilation rate of the pen was determined using a 16 mm vane anemometer (Testo, UK). The anemometer was placed into the duct connecting the centrifugal fan and the humidifier. The Testo 400 instrument was programmed to record a reading every three seconds over a period of five minutes. This allowed for a total of 100 readings to be taken during the measurement cycle. The required airflow rate was reached by manually adjusting the inverter (Hawk, Dan Chambers, Dublin) that controlled the centrifugal fan (Novenco CNA 315, Dan Chambers, Dublin).

During the three experimental periods, the volumetric air loading on the biofilter was increased by a total number of six, eight and five steps respectively (*Fig. 2*). For trial one, the initial load on the biofilter was 1282 m^3 [air] m^{-3} [medium] h^{-1}, at which it remained constant for 21 days. Once odour and ammonia concentration measurements were taken before and after the biofilter for this volumetric loading rate, the volumetric load was increased. This procedure was repeated over the course of the experiment for the three trial periods. After trial two, the biofilter was shutdown for one week to allow for cleaning of the pig building and was not re-inoculated. This was performed to

examine the biofilter under dynamic conditions, to which it would be subjected in large-scale situations and to determine if the biofilter required re-inoculation to retain its removal efficiency. These ranges (*Table 2*) of volumetric loading rates were selected as it bracketed the figures of 720, 800, 1600 and 2144 m^3 [air] m^{-3} [medium] h^{-1}, performed by Janni and Nicolai (2000), Siemers and van den Weghe (1997), Mannebeck (1995) and Zeisig (1987) respectively on biofiltration systems that also treated emissions from pig and poultry housing.

2.4.2. Collection of the odour samples

In order to obtain air samples for transport to the olfactometry laboratory for odour concentration assessment, a static sampling method was used whereby air samples were collected in 8.5 *l* Nalophan bags using a vacuum sampling device. This device operates on the 'lung principle' whereby the air is removed from a rigid container around the bag by a battery powered vacuum pump. This caused the bag to fill through a stainless steel tube whose inlet is placed in the odour stream, with a volume of sample equal to the volume of air evacuated from the rigid container. Air samples were taken before and after the biofiltration system and always tested within 6 hours of collection.

2.4.3. Measurement of odour threshold concentration

An ECOMA TO7 olfactometer (ECOMA, Kiel, Germany) was used throughout the experimental period to determine the odour threshold concentration of the ventilation air before and after biofiltration. Duplicate samples were taken. The odour threshold concentration is defined as the dilution factor at which 50% of the panel can

just detect the odour (CEN, 1999). Only those panel members who passed screening tests with n-butanol (certified reference gas, CAS 72-36-3) and who adhered to the code of behaviour were selected as panellists for olfactometry measurements (CEN, 1999).

The odour threshold concentration is calculated according to the response of the panel members and is displayed in $Ou_E\ m^{-3}$, which refers to the physiological response from the panel equivalent to that elicited by 40 ppb/v n-butanol evaporated in one cubic metre of neutral gas (CEN, 1999). Odour units are in fact a dimensionless unit, but the pseudo-dimensions of $Ou_E\ m^{-3}$ are commonly used for dispersion modelling taking the place of 'grams m^{-3}' (McGinley *et al*., 2000).

2.4.4. Measurement of ammonia concentration

For trial one, ammonia concentrations were determined before and after the biofiltration system using ammonia 2/a Draeger tubes. Draeger tubes have a measuring range of 2 to 30 ppm. A hand operated bellows pump was used to draw a 500 ml sample of air through the detector tubes. The concentration of ammonia in the air was read from a scale marked on the tube. Duplicate samples were taken. The repeatability of this method according to Draeger (1998) is ± 10-15%.

For trials two and three ammonia analysis was performed before and after the biofiltration system using electrochemical cells (7AM CitiCeL, Citytech, UK) and data was logged online using the software package LabView™. The electrochemical cell had a measuring range of 0 to 50 ppm. They were connected to the fieldpoint modules of LabView™ and when placed in the waste air stream, the ammonia concentration was recorded via a PC. The sensors were precalibrated using standard gaseous ammonia concentrations (Citytech, UK). After stabilisation of the sensor, a sampling time of 30

minutes was used to determine the ammonia concentration in the waste air stream. Sensor resolution was ± 0.5 ppm.

2.4.5. pH measurements

Samples of biofilter leachate and supply water were returned to the laboratory for pH measurement on average every four days. Three pH buffer solutions; four, seven and nine were used to calibrate a Russell combination pH electrode which was linked to an Orion 520A pH/mV meter. An electrode slope was produced and the pH of each of the samples was determined. As reported by Murray (2001), the biofilter leachate is representative of pH conditions within the medium bed.

2.4.6. Nitrate measurements

A nitrate ion selective probe (Model Orion, 9707 ionplus) was also attached to an Orion 520A pH/mV meter. A standard curve was developed for nitrate concentration determination using nitrate standards at a 10 fold increasing concentration, to remove any inaccuracies due to sensor drift. When the electrode was placed in the solution a millivolt reading was produced, which was then converted into ppm using the software package Microsoft Excel®.

3. Results and discussion

3.1. Odour and ammonia emissions from pen

The geometric mean odour concentrations measured for trials one, two and three were 476 ± 141, 829 ± 237 & 2149 ± 1351 Ou_E m^{-3} respectively (*Fig. 3*). The geometric mean odour emission rates measured for trials one, two and three were 41 ± 18, 42 ± 28, and 65 ± 38 Ou_E s^{-1} LU^{-1} respectively (where one LU (livestock unit) is equivalent to 500 kg liveweight) (*Fig. 4*). The geometric mean odour emission rates for trials one, two and three were not significantly different (P = 0.25) and were comparable to that of other researchers. Martinec *et al*. (1998) found a wide range of published data describing odour releases from fattening pigs and the odour emission reported varied between 38 and 495 Ou s^{-1} LU^{-1} for fully slatted floors. Hartung *et al*. (1998), Heber *et al*. (1998) and EPA (2000) reported odour emission rates of 126, 96 and 108 Ou s^{-1} LU^{-1} from fully slatted floor housing systems. Holste (1998) communicated an odour emission rate of 39 Ou s^{-1} LU^{-1} from partially slatted floor housing system and Muller *et al*. (1994) reported an odour emission rate of between 32.8 and 58.8 Ou s^{-1} LU^{-1} (unspecified floor type) respectively. The figures of 41 ± 18, 42 ± 28, and 65 ± 38 Ou_E s^{-1} LU^{-1} were in the same range as those of Holste (1998), Martinec *et al*. (1998) and Muller *et al*. (1994) but were lower than that of Hartung *et al*. (1998), Heber *et al*. (1998) and EPA (2000). This may be explained by the fact that the odour emission rates in this experiment were from a pig fattening house with partially slatted floors while those obtained by the aforementioned researchers were from fully slatted floors. It has been suggested by researchers that inside temperature, slatted surface area, ventilation rate, management of pig facility and feed regimes significantly effect odour emission rates from pig facilities (Hartung *et al*., 1998; Heber *et al*., 1998; Schauberger *et al*., 1999). Mass odour loading rates (Ou_E s^{-1} LU^{-1}) on the biofiltration system were comparable for all three trials.

The arithmetic mean ammonia emission rate for trials one, two and three was 7.1 ± 2.8, 9.9 ± 2.5 & 8.3 ± 5.3 g animal^{-1} day^{-1} respectively and therefore, there was no significant differences (P = 0.30). The mass ammonia emission obtained was comparable to that of other researchers. Hendriks *et al*. (1999) estimated that fattening pigs produce 8.22 g animal^{-1} day^{-1}. Demmers (1991) reported mass ammonia emission rates of 4.4, 6.5, 7.4, 7.7 and 9.2 g animal^{-1}day^{-1}. Aarnink and Elzing (1998) reported mass ammonia emissions of 6.84 g animal^{-1} day^{-1}. *Figure 5* represents plots of mass ammonia emissions for trials one, two and three as airflow increases. It can be observed from the plot that as airflow increases, overall mass ammonia emission rate increases (R^2 correlation coefficient 0.24, 0.41 & 0.61 for trial one, two and three respectively). It is important to note that there was slight soiling of the solid floor in trial one. Krause and Jannsen (1991) reported that highest ammonia concentrations were present at 0.6 metres above floor height. Aarnink and Elzing (1998) reported that a ventilation rate change of 0.01 m^3 s^{-1} per m^2 floor area can cause a 21.2% change in ammonia emission and that air velocity above the slurry in the pit had substantial effects on ammonia emission. In an experiment using 80 kg pigs, increasing the air change rate from two to four air changes per hour increased the quantity of ammonia released from 250 to 350 mg h^{-1} (Swine Odour Task Force, 1995). As the ventilation fans were situated one metre above the slatted area, that increase in airflow rate caused an increased air velocity within the pen and hence enhanced ammonia volatilisation from the floor and slurry surface. It is important to note that pH, temperature and ammoniacal nitrogen content of the slurry also significantly affect ammonia volatilisation. Mass ammonia loading on the biofiltration system was not significantly different for trials one, two and three. The average temperature in the pen during the experimental periods was 18-23^{0}C.

3.2. System performance in terms of odour removal

The biofiltration system performed well at treating odour emissions in trials one, two and three, attaining average removal efficiencies of greater than 85 ± 5%, 92.5 ± 5% and 91.3 ± 1.2% respectively (*Fig. 6*). These were similar to the removal efficiencies of 71.5, 81 and 90% attained by Janni and Nicolai (2000), Martinec *et al*. (2000) and Sheridan *et al*. (2000) respectively. There was no decrease in odour removal as volumetric loading rate increased (*Fig. 7*), therefore the efficiency of odour reduction of the biofiltration system was mainly influenced by the odour concentration in the influent gas at the entrance of the biofilter (Hartung *et al*., 1998). It is important to note that the odour concentration of the effluent gas of the biofiltration system (*Fig. 7*) for each measurement point was quite steady despite rather large fluctuations in the odour concentration entering the biofilter (*Fig. 3*). This suggests that the biofilter was capable of achieving relatively similar levels of outlet odour emission rates even when handling a wide range of inlet mass odour loading rates.

Morales *et al*. (1998) demonstrated that the addition of gaseous ammonia in the inlet stream saturated with toluene increased its elimination capacity noticeably. Gribbins and Loehr (1998) reported that soluble nitrogen concentration in the medium can limit biofilter performance after long periods of operation and even at low inlet VOC loading rates, the biofilter requires a threshold amount of soluble nitrogen to maintain pseudo steady-state operation. Since ammonia and nitrates are present in biofilters operating on pig facilities (Janni and Nicolai, 2000; Martinec *et al*., 2000; Sheridan *et al*., 2000), it can be suggested that a greater removal efficiency can be obtained for these reasons. Williams & Miller (1992) reported that basic odour removal mechanisms in a biofilter

are thought to be adsorption/absorption and biooxidation. Deshusses (1997) suggested that water-soluble compounds were first sorbed on to the packing material and then biodegraded. There was no difference in the specific odour elimination capacity for trials one, two and three (*Fig. 8*). It can be suggested that odour elimination capacity is influenced by inlet odour concentration (*Fig. 9*). This was also demonstrated by Martinec *et al*. (2000). Upon comparison of each trial, the 5% increase in the medium moisture content significantly increased ($P = 0.005$) the removal efficiency of the biofiltration system by approximately 7% and stabilised its performance. It is important to note that the odour character of the purified air was earthy up to a volumetric loading rate of 1693 m^3 [air] m^{-3} [medium] h^{-1} and resembled a slight piggery and ammoniacal odour at volumetric loading rates above 1847 m^3 [air] m^{-3} [medium] h^{-1} for trials one and two.

3.3. System performance in terms of ammonia control

Since the biofilter medium was maintained at a moisture content of approximately 64% for trial one and 69% for trials two and three respectively, it acts as a biosorber. As ammonia has a high Henrys constant, it is easily adsorbed on to the packing material of the biofilter forming ammonium. The bacteria within the biofilm utilise the ammonium and degrade it to nitrite with the production of H^+ ions reducing the pH of the system. This increases the capacity of the biofilter to adsorb and absorb more ammonia therefore increasing/equalising the pH. Simultaneously, nitrite is being degraded to nitrate. According to Anthonissen (1976), the nitrification reactions are mainly inhibited by unionised ammonia (FA) and free nitrous acid (FNA).

Martin *et al*. (1996) suggested increasing CO_2 concentration in the feed gas increased ammonia elimination capacity. As the CO_2 concentration in a pig building is approximately 600-1000 ppm (Ni *et al*., 1998; Campbell, 2000; Martinec *et al*., 2000), this waste air is ideal for biofiltration of ammonia gas.

Bioscrubbers operated at retention times of approximately 1.5-2.7 seconds have achieved ammonia reduction efficiencies of approximately 90-95% (Schirz *et al*., 1987; Scholtens *et al*., 1987). This retention time is sufficient for the transfer of ammonia from the gas phase to the liquid. Sublette and Sylvester (1987) indicated that micro-organisms could metabolise gas within a short time (several seconds). Deshusses (1994) suggested a minimum retention time of 2 seconds for biodegradation. Hagopian and Riley (1998) reported that nitrifiers demonstrate a markedly greater survival rate (approximately 10 times) when attached to a particle as compared to being unattached and Scholtens *et al*. (1987) suggested that biofilters have a greater capacity for converting ammonia to nitrate when compared to bioscrubbers.

The biofiltration system was efficient at removing ammonia with average removal efficiencies of 73% (54%-89%), 85% (64%-92%) and 87% (81%-93%) for trials one, two and three respectively (*Fig. 10*). For trial one, the initial volumetric loading rate on the biofiltration system was 1282 m^3 [air] m^{-3} [medium] h^{-1}, continuing to increase to 2001 m^3 [air] m^{-3} [medium] h^{-1}. The ammonia loading on the biofiltration system fluctuated between 967 and 2057 mg h^{-1} up to a volumetric loading rate of 1898 m^3 [air] m^{-3} [medium] h^{-1} (*Fig. 11*). The removal efficiency steadily declined by 19% (*Fig. 10*). When the volumetric loading rate increased to 2001 m^3 [air] m^{-3} [medium] h^{-1}, the removal efficiency dropped by a further 16%. As volumetric loading rate increased, retention time decreased and contact between the waste air stream and the biofilm may have become diffusion limiting. The mass ammonia loading also increased a further

46% and the rate of transfer of ammonia may have become diffusion and reaction limiting (*Fig. 11*).

For trial two, the initial activity of the biofiltration system was low in relation to the production of nitrate (*Fig. 12*). The pH of the leachate was 7.6 for the biofilter, demonstrating the adsorption and absorption of ammonia. As mass ammonia loading increased, nitrate concentration in the leachate increased. There was a slow decrease in the pH of the leachate showing the production of nitrite, which was simultaneously degraded to nitrate. This production of nitrite increased the absorption capacity of the medium for ammonia. When the volumetric loading rate was reduced to 769 m^3 [air] m^{-3} [medium] h^{-1}, the mass ammonia loading decreased by 58% and 71% respectively. The removal efficiency for the biofiltration system fully recovered at this point (*Fig. 10*). At a volumetric loading rate of 923 m^3 [air] m^{-3} [medium] h^{-1}, there was a drastic drop in ammonia removal efficiency to 69%. This was due to a fault in the water sprinkler system resulting in media moisture content decreasing by 16% (wet weight basis). This demonstrated how important it was to maintain proper moisture content within the biofilter bed. As can be seen for trial two, (apart from volumetric loading rate 923 m^3 [air] m^{-3} [medium] h^{-1}), as volumetric loading rate increased, mass emission rate from the biofilter increased as contact time between the waste air and filter medium was probably diffusion and reaction limiting (*Fig. 13*).

Trial three demonstrated similar characteristics as trials one and two. The mass ammonia loading fluctuated between 1021 and 2811 mg h^{-1} up to a volumetric loading rate of 1436 m^3 [air] m^{-3} [medium] h^{-1} (*Fig. 11*). On the next sampling day at this volumetric loading rate, the mass ammonia loading on the biofiltration system increased by 35%. The mass ammonia emission from the biofiltration system increased and continued to increase due to significant increases in mass ammonia loading on the

biofiltration system (*Fig. 13*). Once the mass ammonia loading decreased (approximately 48%) the corresponding mass ammonia emissions from the biofiltration system decreased (approximately 56%).

Upon comparison of trials one, two and three, it would appear that the 5% increase in the medium moisture content significantly increased (P = 0.006) the ammonia removal efficiency of the biofiltration system by approximately 12% and stabilised its performance. Janni and Nicolai (2000) and Sun *et al*. (1999) suggested that medium moisture content significantly affected the removal of ammonia in biofilters and demonstrated that biofilters with higher moisture content had a greater removal efficiency of ammonia. Colanbeen and Neukermans (1992) demonstrated ammonia removal of between 56-98% in a biofiltration system operated at a retention time of four seconds and a medium moisture content of 65%. Kim *et al*. (2000a) reported that organic packing materials had a higher maximum removal rate than inorganic packing materials for ammonia.

3.4. Pressure drop results

The pressure drop is linearly proportional to increasing airflow loading on the biofiltration system for trials one, two and three (*Fig. 14*). No sudden decrease or increase in pressure drop occurred across the biofiltration system for any of the volumetric loading rates throughout the course of the experiments. This demonstrated that the medium had good mechanical strength that lead to negligible bed compaction and no short channelling in operation. Other researchers concluded wood chip offers the cheapest acceptable option with excellent stability properties even after wetting (Phillips *et al*., 1995). When compared to other packing media (compost & peat,

coconut fibre, etc.), the pressure drop across wood chip is minimal and will reduce overall power consumption for operation of biofiltration systems (Martinec *et al*., 2000; Phillips *et al*., 1995).

3.5. pH results

The pH of the leachate fluctuated between 6 and 8 (*Fig. 15*). This fluctuation was probably due to the production of acid intermediates (i.e. nitric acid from the degradation of ammonia and sulphuric acid from the degradation of hydrogen sulphide and sulphur organics). As microbial species are sensitive to rapid pH fluctuation (Devinny *et al*., 1999), it would be necessary to add buffering agents such as pelleted calcium carbonate/calcium magnesium carbonate (Demmers, 1991) for long term large scale operation. According to Swanson and Loehr (1997), this range is optimal for biofiltration processes. Such pH values meant that it was not necessary to add buffer solutions to the pilot scale filter beds in an attempt to maintain pH near neutral.

3.6. Design of a large scale biofiltration system

When designing a biofiltration system utilising wood chip (greater than 20 mm particle size) as the medium for large scale operation on pig facilities, it is recommended that a maximum volumetric loading rate of 1350 m^3 [air] m^{-3} [medium] h^{-1} be used in order to achieve removal efficiencies greater than 90% for odour. Pain (1994) recommended that for effective abatement of odour nuisance greater than 90% odour abatement is required. This is calculated by multiplying 1693 m^3 [air] m^{-3} [medium] h^{-1} by 0.8 in order to implement a 20% safety factor suggested by Devinny *et*

al. (1999). This equates to a filter size area of 0.148 m^2 pig^{-1} in summer conditions. This is quite similar to the filter size area of 0.125 m^2 pig^{-1} reported by Mannebeck (1995), but much smaller than the figures of 0.23 and 0.33 m^2 pig^{-1} reported by Scholtens *et al*. (1987).

It is recommended that buffering agents such as pelleted calcium carbonate/calcium magnesium carbonate (Demmers, 1991) be incorporated within the medium at a ratio of 10 % w/w to control any pH fluctuations during long term large scale operation (Tawil *et al*., 2001).

4. Conclusion

A pilot scale biofiltration system was designed and built in the University College Dublin research farm, Newcastle, Co. Dublin. Wood chips were used as the medium type with a chip size of greater than 20 mm.

The biofiltration system achieved odour reduction efficiencies of greater than 85, 92.5 and 91.3% for trials one, two and three respectively. Ammonia removal efficiencies of 73, 85 and 87% were achieved for trials one, two and three respectively. It can be concluded that biofiltration is an effective technology for the removal of odours and ammonia from the exhaust ventilation air of pig rearing facilities.

Upon investigation of the pressure drop across the biofilter, it was concluded that it was negligible when compared to values reported in literature for alternative filter bed mediums such as coconut fibre and peat. The pH of the biofiltration system remained between 6-8 for all three trials.

At such a high volumetric filter load, the biofilter is more sensitive to system disturbance. In large scale operation, it is necessary to incorporate an efficient air

moisturising system such as humidification and filter bed sprinkling in order to maintain high removal efficiencies. As demonstrated in trial two, when the filter medium bed moisture content decreased by 16%, odour and ammonia removal efficiency decreased by 7 and 23% respectively. Trials two and three were approximately 12% more efficient for the removal of ammonia than trial one due to the higher filter medium bed moisture content.

It is important to note when constructing a large scale biofiltration system that careful consideration be given to the air distribution system as this can affect many factors including odour removal efficiency (Lou & Lindsey, 2000), pressure drop and air short circuiting and channelling.

5. Acknowledgements

The authors would like to thank the Irish Government Department of Agriculture, Food and Rural Development who with the assistance of the European Union provided funding from the Research Stimulus Fund under the 1994-99 Operational Programme for Agriculture, Rural Development and Forestry. They would also like to acknowledge the assistance of Dr. William Magette, olfactometry panel members, Woodfab Ltd., Glanbia plc, Dr. John O'Doherty and his research students from the Faculty of Agriculture, University College Dublin.

6. References

Aarnink A J A; Elzing A (1998). Dynamic model for ammonia volatilisation in housing with partially slatted floors for fattening pigs. Livestock Production Science, **53**, 153-169

Arnold M; Reittu A; von Wright A; Martikainen P J; Suihko M L (1997). Bacterial degradation of styrene in waste gases using a peat filter. Applied Microbiology and Biotechnology, **48**, 738-744

Auria R; Aycaguer A C and Devinny J S (1998). Influence of water content on degradation rates for ethanol in biofiltration. Journal of Air & Waste Management Association, **48**, 65-70

Bohn H L; Bohn K H (1999). Moisture in biofilters. Environmental Progress, **18**(3), 156-161

Campbell D (2000). Assessment of gaseous emissions from integrated pig units. M.Sc. Thesis, University College Dublin, Dublin 4, Ireland

CEN (1999). Air quality - Determination of odour concentration by dynamic olfactometry. Draft European Standard prEN 13725, Comité Europeén de Normalisation, Brussels, Belgium.

CIGR (1992). Climatisation of animal houses. CIGR (Commission Internationale du Génie Rural)

Classen J J; Young J S: Bottcher R W; Westerman P W (2000). Design and analysis of a pilot scale biofiltration system for odorous air. Transactions of the ASAE, **43**(1), 111-118, Paper No. 97-4039

Colanbeen M; Neukermans G (1992). Stankbestrijding van ventilatielucht door het gebruik van biofilters en biowasfilters. [Odour control using biofilters and bioscrubbers.] Landbouwtijdschrift - Revue de l'Agriculture, **45**, (5), 909-927

Cox H H J; Magielsen F J; Doddema H J; Harder W (1996). Influence of the water content and water activity on styrene degradation by *Exophiala jeanselmei* in biofilters. Applied Microbiology and Biotechnology, **45**, 851-856

Degorce Dumas J R; Kowal S and Cloirec P L (1997). Microbiological oxidation of hydrogen sulphide in a biofilter. Canadian Journal of Microbiology, **43**, 264-271

Demmers T G M (1991). Ammonia removal from exhaust air in intensive animal housing. In: Symposium on 'Biotechniques for air pollution abatement and odour control policies', Maastricht, Netherlands

Deshusses M A (1994). Biodegradation of mixtures of ketone vapours in biofilters for the treatment of waste air. Ph.D. Thesis, Swiss Federation Institute of Technology, Zurich, Switzerland

Deshusses M A (1997). Transient behaviours of biofilters: Start-up, carbon balances and interactions between pollutants. Journal of Environmental Engineering, **123**(6), 563-568, Paper No. 13242

Devinny J S; Deshusses M A; Webster T S (1999). Biofiltration for Air Pollution Control. Lewis Publishers, Florida, USA, 299

Draeger (1998). Draeger-Tube Handbook, 11th edition, Draeger Sicherheitstechnik GmbH, Luebeck, Germany

EPA (2000). Personal communication. Wexford, Ireland

Gribbins M.J; Loehr R C (1998). Effects of media nitrogen concentration on biofilter performance. Journal of Air & Waste Management Association, **48**, 216-226

Hagopian D S; Riley J G (1998). A closer look at the bacteriology of nitrification. Aquacultural Engineering, **18**, 223-244

Hamer G (1998). Personal communication. University College Dublin, Dublin 4, Ireland

Hartung E; Martinec M; Lais S; Jungbluth T (1998). Testing measures to improve the ammonia reduction of bioscrubbers and biofilters. AgEng 98, Oslo, Norway, Paper Number: 98-E-008

Heber A J; Bundy D S; Lim T T; Ni J; Haymore B L; Diehl C A; Duggirala R K (1998). Odour emission rates from swine finishing buildings. In: Animal Production Systems and the Environment: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues. Des Moines, Iowa, USA, July 19-22, 305-310

Hendriks H J M; van de Weerdhof A M (1999). Dutch Notes on BAT for Pig and Poultry Intensive Livestock Farming. Ministry of Agriculture, Nature Management and Fisheries, National Reference Centre Agriculture, Netherlands. Electronically available at http://www.infomil.nl/lucht/index.htm

Holste D (1998). Personal communication, Schauenburger Str. 116, 24118 Kiel, Germany

Janni K A; Nicolai R E (2000). Designing biofilters for livestock facilities. In: Proceedings of the 2000 USC-TRG Conference on Biofiltration (Reynolds F E Jr. eds.), pp. 11-20, California, USA

Kim N J; Hirai M; Shodo M (2000a). Comparison of organic and inorganic packing materials in the removal of ammonia gas in biofilters. Journal of Hazardous Materials B72, 77-90

Kim N J; Sugano Y; Hirai M; Shodo M (2000b). Removal characteristics of high load ammonia gas by a biofilter seeded with marine bacterium *Vibrio alginolyticus*. Biotechnology Letters, **22**, 1295-1299

Krailis S; Pham Q T; Amal R; Jiang J K; Heitz M (2000). Effects of inlet mass loading, water and total bacterial count on methanol elimination using upward flow and downward flow biofilters. Journal of Chemical Technology and Biotechnology, **75**, 299-305

Krause K H; Janssen J (1990). Modelling the dispersion of ammonia within animal houses. In: Odour and Ammonia Emissions from Livestock Farming (Nielsen V C; Voorburg J H; L'Hermite P eds.), pp. 71-78, Cranfield University, Silsoe, UK

Li X W; Owen J E (1997). Feed and feeding method effects on livestock environment. In: Livestock Environment V (Bottcher R W; Hoff S J eds.), pp. 599-606, Minnesota, USA

Lou J; Lindsey S (2000). Biofilters for controlling rendering odour emissions. In: (Reynolds F E Jr. eds.), Proceedings of the 1998 USC-TRG Conference on Biofiltration, pp. 247-248, California, USA

Mannebeck, D (1995). Biofilter an Schweinestallen-Analyse der Wirkungsweise und Konsequenzen. [Biofilters for pig housing - analysis of operation and results.] PhD Thesis, University of Kiel, Germany

Martin G; Lemasle M; Taha S (1996). The control of gaseous nitrogen pollutant removal in a fixed peat bed reactor. Journal of Biotechnology, **46**, 15-21

Martinec M; Hartung E; Jungbluth T (1998). Daten zu Geruchsemissionen aus der Tierhaltung. [Odour emissions data from animal housing.] KTBL Arbeitspapier 260, ISBN 3-7843-1998-2

Martinec M; Hartung E; Jungbluth T (2000). Optimising biofilters to reduce odor and gas emissions from livestock buildings. In: Air Pollution from Agricultural Operations, Proceedings of the 2nd International Conference, (Auvermann B W; Shaw B W; Maghirang R G; eds.), ASAE, St. Joseph, Bloomington, MN, USA, Oct 9-11, 391-398

McGinley C M; McGinley M A; McGinley D L (2000). Odor basics - understanding and using odour testing. In: The 22nd Annual Hawaii Water Environmental Association Conference, Honolulu, Hawaii, 6-7 June

McNevin D; Barford J (1998). Modelling adsorption and biological degradation of nutrients on peat. Biochemical Engineering Journal 2, 217-228

Morales M; Revah S; Auria R (1998). Start-up and the effect of gaseous ammonia additions on a biofilter for the elimination of toluene vapours. Biotechnology and Bioengineering, **60**(4), 483-491

Moseley P J; Misselbrook T H; Pain B F; Earl R; Godwin R J (1998). The effect of injector tine design on odour and ammonia emissions following the injection of biosolids into arable cropping. Journal of Agricultural Engineering Research, **71**, 385-394, doi: 10.1006/jaer.1998.0337

Muller H J (1994). Rates of odour and pollutant gas emission from animal housing: Measurement and analysis. Landtechnik, **49**(6), 360-371

Murray N (2001). The use of a laboratory scale biofilter to study the removal of gaseous ammonia. M.Sc. Thesis, Dublin City University, Glasnevin, Dublin 9

Ni J; Lim T T; Heber A J; Diehl C A; Duggirala R K (1998). Gas release from deep manure pits in emptied and cleaned swine finishing buildings. In: Animal Production Systems and the Environment: An International Conference on Odor, Water Quality, Nutrient Management and Socioeconomic Issues. Des Moines, Iowa, July 19-22, 321-326

Nicolai R; Janni K (1998). Biofiltration - Adaption to livestock facilities. In: Proceedings of the 1998 USC-TRG Conference on Biofiltration (Reynolds F E Jr. eds.), pp. 99-106, California, USA

Nicolai R; Janni K (2000). Designing biofilters for livestock facilities. In: Air Pollution from Agricultural Operations, Proceedings of the 2nd International Conference (Auvermann B W; Shaw B W; Maghirang R G; eds.), ASAE, St. Joseph, Bloomington, MN, USA, Oct 9-11, 376-383

O'Neill D H; Stewart I W; Phillips V R (1992). A review of the control of odour nuisance from livestock building: Part 2, The cost of odour abatement systems as predicted from ventilation requirements. Journal of Agricultural Engineering Research, **51**, 157-165

Pahl O; Williams A G; Sneath R W; Goodman J; Taylor L; Godwin R J; Hann M J (2000). Reducing ammonia emissions from pig production - experiences with oil

and foam as a cover material for slurry under slats. In: Air Pollution from Agricultural Operations, Proceedings of the 2nd International Conference (Auvermann B W; Shaw B W; Maghirang R G; eds.), ASAE, St. Joseph, Bloomington, MN, USA, Oct 9-11, 100-107

Pain B F (1994). Odor nuisance from livestock production systems. In: Pollution from livestock production systems (Ap Dewi I; Axford R F E; Fayez I; Marai M; Omed H eds.), pp. 241-264, UK

Pain B F: Clarkson C R; Philips V R; Klarenbeek J V; Misselbrook T H; Bruins M (1991). Odour emissions arising from the application of livestock slurries on land: measurement following spreading using a micrometeorological technique and olfactometry. Journal of Agricultural Engineering Research, **48**, 101-110

Phillips V R; Scotford I M; White R P; Hartshorn R L (1995). Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 1, Basic airflow aspects. Journal of Agricultural Engineering Research, **62**, 203-214, doi: 10.1006/jaer.1995.1078

Rodhe L; Thyselius L; Berglund U (1986). Biofilters for Odour Reduction – Installation and Evaluation. JTI – rapport 76, 1-20

Schaubeger G; Piringer M; Petz E (1999). Diurnal and annual variation of odour emission from animal houses: a model calculation for fattening pigs. Journal of Agricultural Engineering Research, **74**, 251-259, doi: 10.1006/jaer.1999.0457

Schirz S (1987). Practical application of bioscrubbing technique to reduce odour and ammonia. In: Volatile Emissions from Livestock Farming and Sewage Operations (Nielsen V C; Voorburg J H; l'Hermite P eds.), pp. 82-91, New York

Scholtens R; Klarenbeek J V; Bruins M A (1987). Control of ammonia emissions with biofilters and bioscrubbers. In: Volatile Emissions from Livestock Farming and Sewage Operations (Nielsen V C; Voorburg J H; l'Hermite P eds.), pp. 196-208, New York

Scotford I M; Burton C H; Phillips V R (1996). Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 2, A model to analyse the influence of design parameters on annual cost. Journal of Agricultural Engineering Research, **64**, 155-164, doi: 10.1006/jaer.1996.0057

Sheridan B A; Colligan J G; Curran T P; Dodd V A (2000). Biofiltration of exhaust ventilation air from pig units. In: Air Pollution from Agricultural Operations, Proceedings of the 2nd International Conference (Auvermann B W; Shaw B W;

Maghirang R G; eds.), ASAE, St. Joseph, Bloomington, MN, USA, Oct 9-11, 384-390

Siemers V; van den Weghe H (1997). Biofilter/wetscrubber combinations for the reduction of ammonia, odour and dust emissions of pig fattening houses. In: Proceedings of the International Symposium 'Ammonia and Odour Control from Animal Facilities', Vinkeloord, Netherlands, 537-544

Sublette K L; Sylvester N D (1987). Oxidation of hydrogen sulphide by *Thiobacillus denitrificans*: desulphuration of natural gas. Biotechnology and Bioengineering, **29**, 249-257

Sun Y; Clanton C J; Janni K A (1999). Nitrogen and sulphur balances in biofilters affected by media moisture content and gas retention time. Paper No. 99-4131, American Society of Agricultural Engineers, St. Joseph, Bloomington, MN, 49085

Swanson W J; Loehr R C (1997). Biofiltration: Fundamentals, design and operations principles, and applications. Journal of Environmental Engineering, **123**(6), 538-546

Swine Odor Task Force (1995). Options for managing odor. North Carolina Agricultural Research Service, North Carolina State University

Tawil A A (2001). Bioxidation of n-proponal and acetone in biofilters and bioscrubbers. Ph.D Thesis, University College Dublin, Dublin 4, Ireland

Testo (1998). Personal communication, UK

Vaith K; Cannon M; Milligan D; Heydorn J (1996). Comparing scrubbing technology. Water Environment & Technology, **8**(6), 35-38

Van't Klooster C E; Voermans J M (1993). European perspectives - how are they solving their problems? In: Symposium: Meeting the environmental challenge, The National Pork Producers Council, Minneapolis, MN, USA

VDI (1991). VDI 3477: Biologische Abgas-/Abluftreinigung Biofilter. [Biological waste gas/waste air purification; biofilters.] Verein Deutscher Ingenieure, Dusseldorf, Germany

Wani A H; Branion R M R; Lau A K (1997). Biofiltration: A promising and cost-effective control technology for odors, VOCs and air toxics. Journal of Environmental Science and Health, **A32** (7), 2027-2055

Williams T; Miller F (1992). Biofilters and facility operations. Biocycle, **32**(11), 75-79

Young J S; Classen J J and Westerman P W (1996). Biofiltration system for testing the reduction of odor from swine buildings. In: Proceedings of the International

Symposium 'Ammonia and Odour Control from Animal Facilities', Vinkeloord, Netherlands, 521-528

Zeisig H D; Munchen T U (1987). Experiences with the use of biofilters to remove odours from piggeries and hen houses. In: Volatile Emissions from Livestock Farming and Sewage Operations (Nielsen V C; Voorburg J H; l'Hermite P eds.), pp. 209-216, New York

List of Figures and Tables

Fig 11. Graph of ammonia mass loading versus volumetric loading rate; —●— , trial 1; —○— , trial 2; —▼··, trial 3

Fig.12. Graph of nitrate concentration and pH for trial 2 versus volumetric loading rate; —▲— , nitrate concentration; —●— , pH

Fig 13. Graph of mass ammonia emission after biofilter versus volumetric loading rate; —●— , trial 1; ··○·· , trial 2; —▼— , trial 3

Fig.14. Graph of pressure drop versus volumetric loading rate; ● , trial 1 (R^2 = 0.97); ○ , trial 2 (R^2 = 0.89); ▼ , trial 3 (R^2 = 0.91); —— , best fit line

Fig.15. Graph of pH versus volumetric loading rate; —●— , trial 1; —○— , trial 2; —▼— , trial 3

Table 1
Measurements taken throughout the biofiltration system during trials one, two and three

Table 2
Biofiltration system operation for trials one, two and three

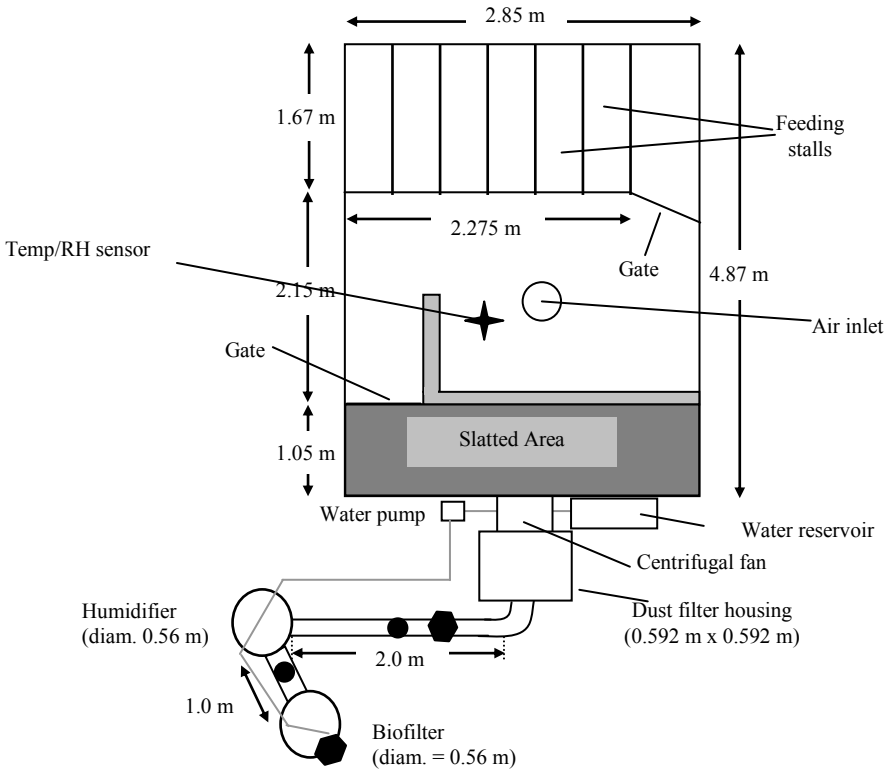

Fig. 1. Plan of biofiltration system; ● , airflow/temp/RH sensors; ⬢ , odour/ammonia sampling

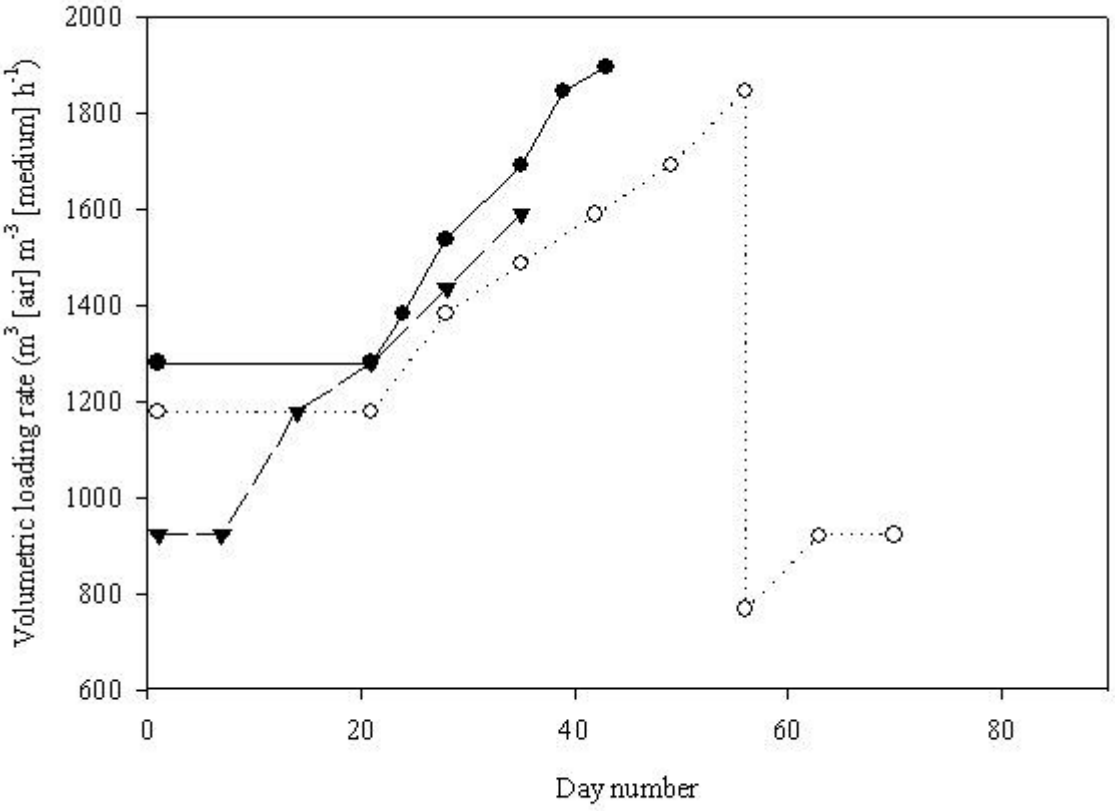

Fig. 2. Graph of volumetric loading rate versus day number; —●— , trial 1; ··○·· , trial 2; —▼— , trial 3

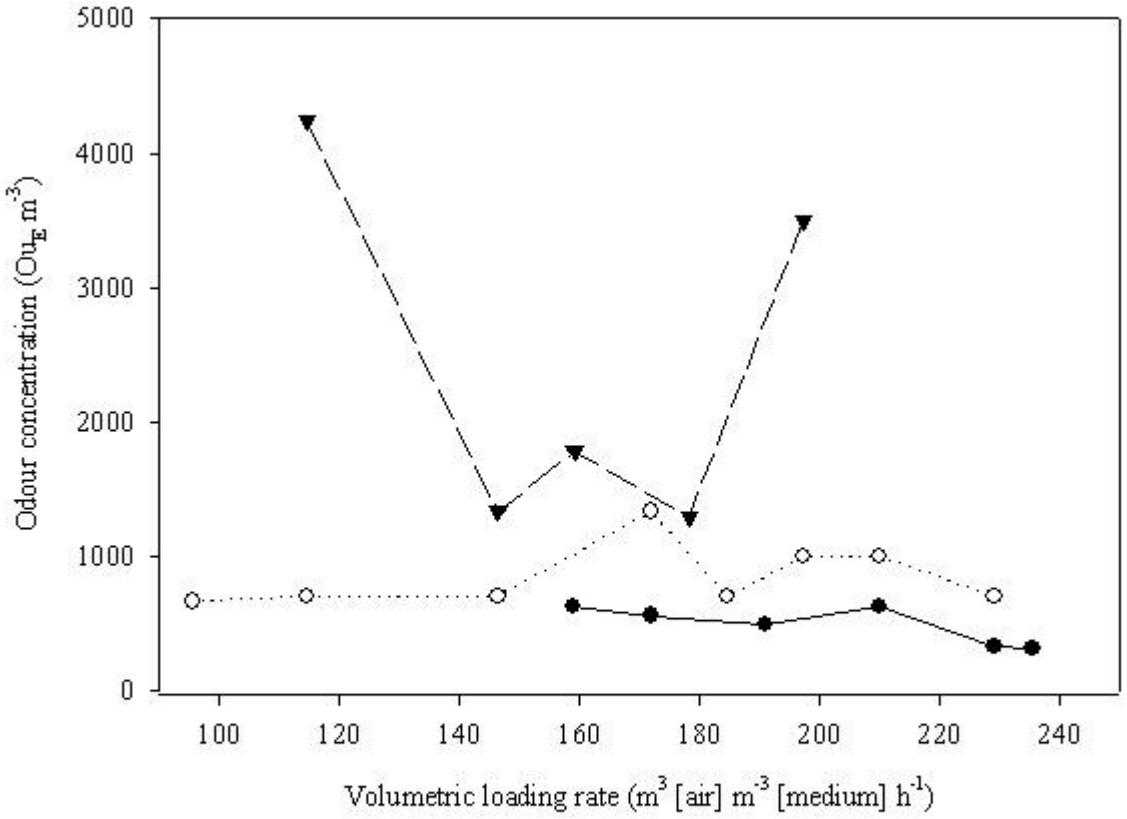

Fig. 3. Graph of inlet odour concentration versus airflow rate; —●— , trial 1 (6 pigs 35-90 kg); ···○··· , trial 2 (6 pigs 35-90 kg); —▼— , trial 3 (7 pigs 80-120 kg)

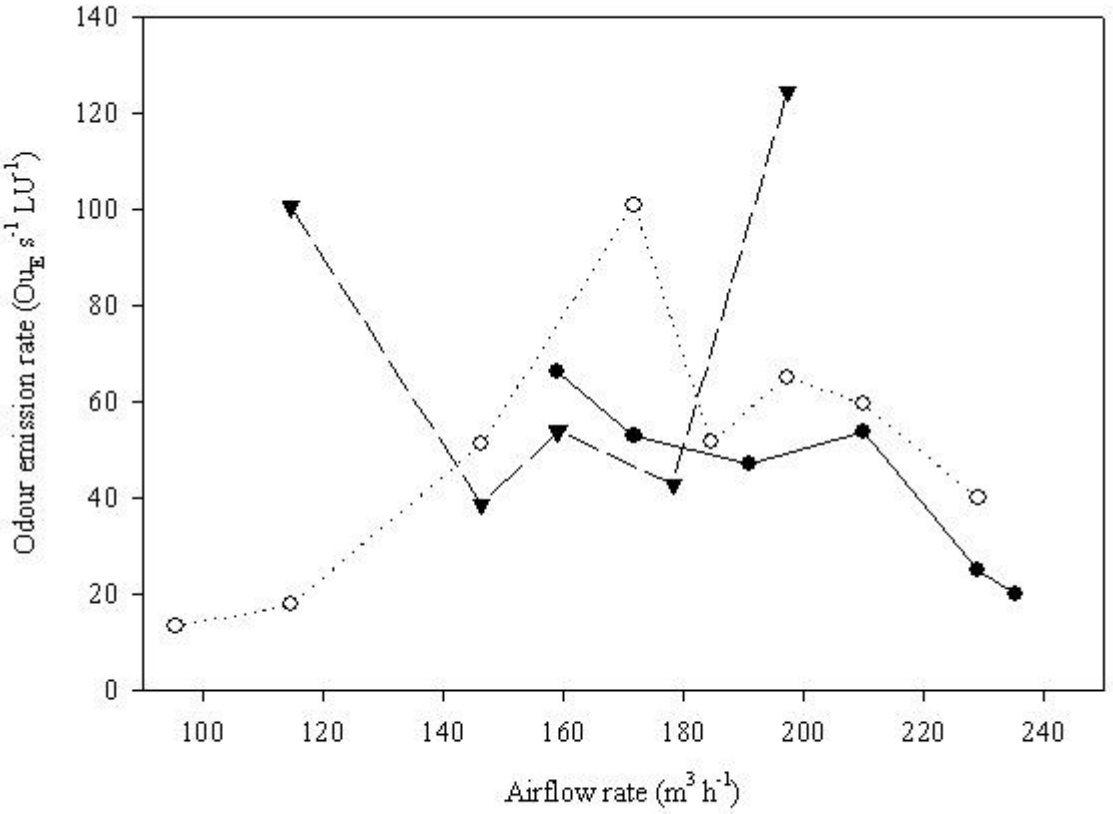

Fig. 4. Graph of odour emission rate versus airflow rate;—●— , trial 1; ···○··· , trial 2; —▼— , trial 3

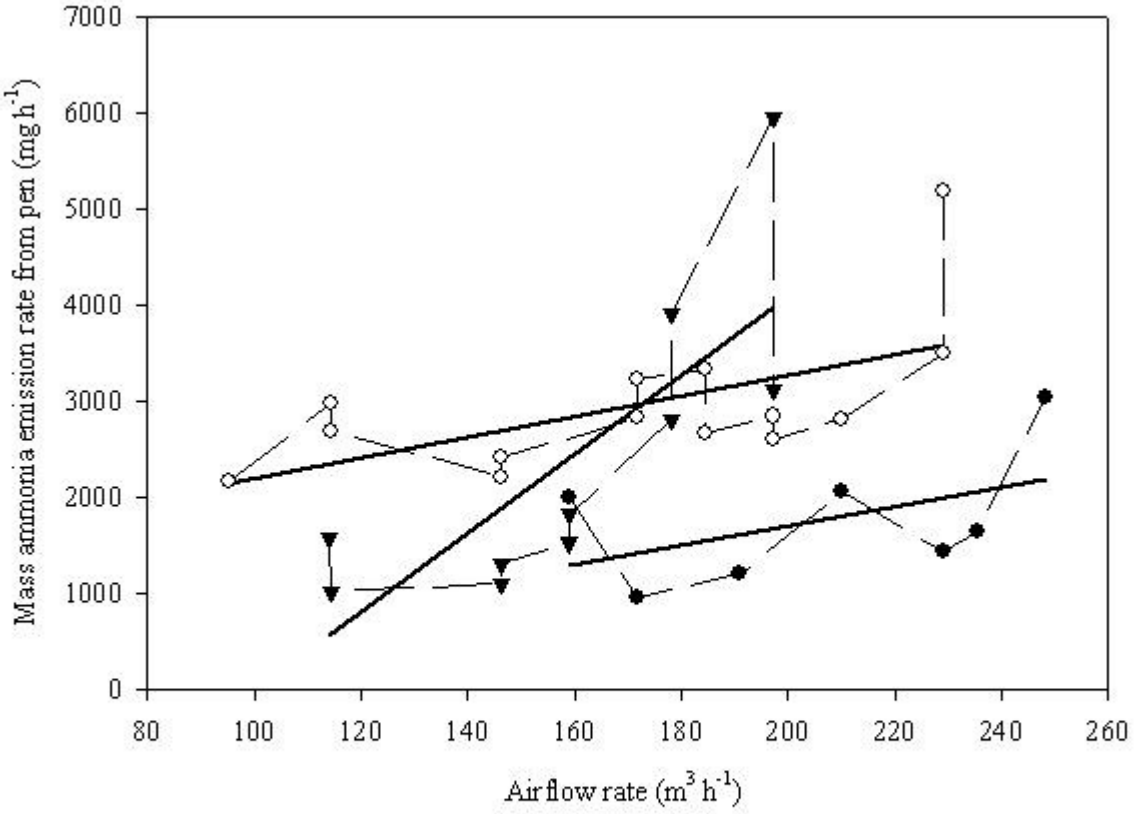

Fig. 5. Graph of mass ammonia emission rate from pen versus airflow rate; —●— , trial 1 (R^2 = 0.24); —○— , trial 2 (R^2 = 0.41); —▼— , trial 3 (R^2 = 0.61); —— , best fit line

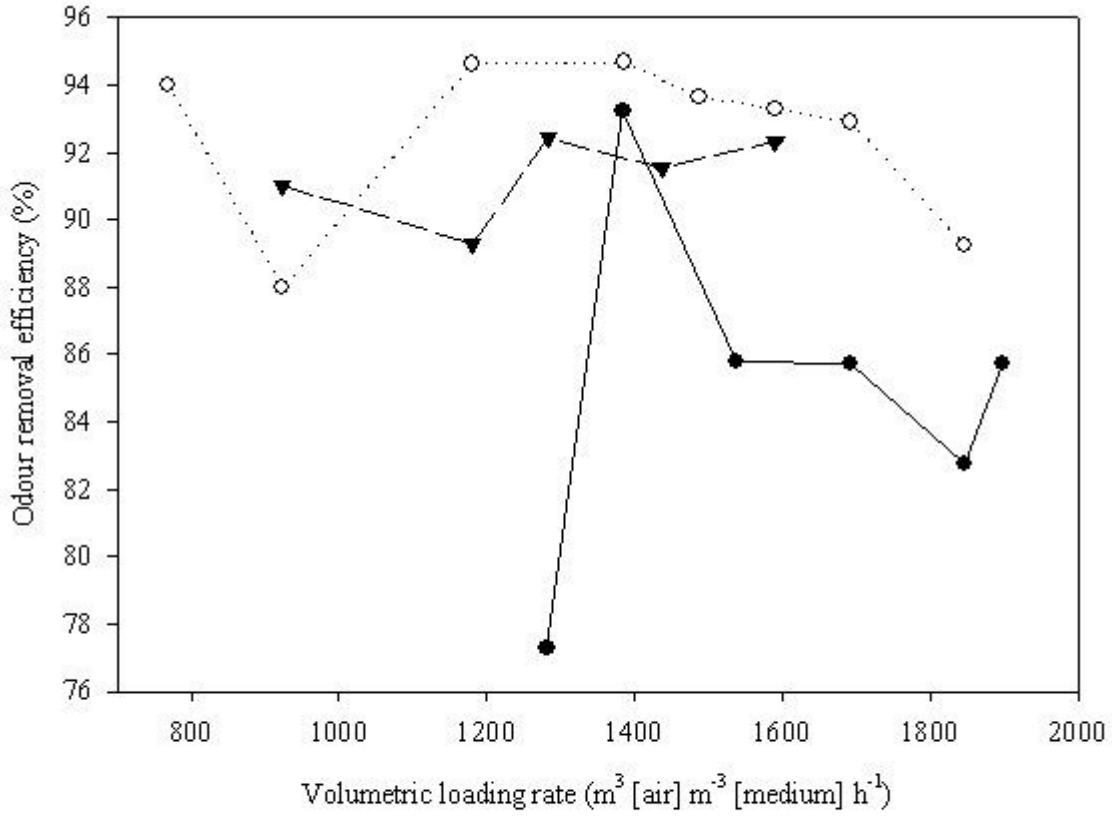

Fig. 6. Graph of odour removal efficiency versus volumetric loading rate; —●— , trial 1; ··○·· , trial 2; —▼— , trial 3

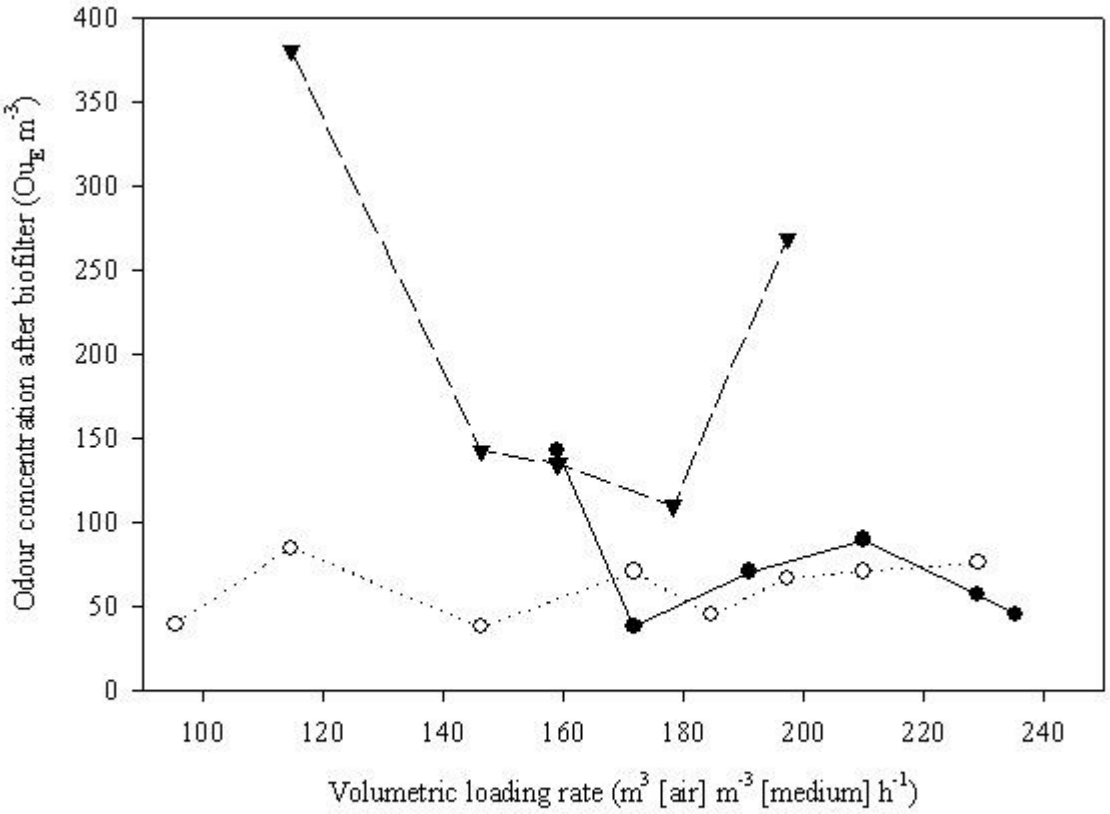

Fig. 7. Graph of odour concentration after biofilter versus volumetric loading rate;—●— , trial 1; ··○·· , trial 2;—▼— , trial 3

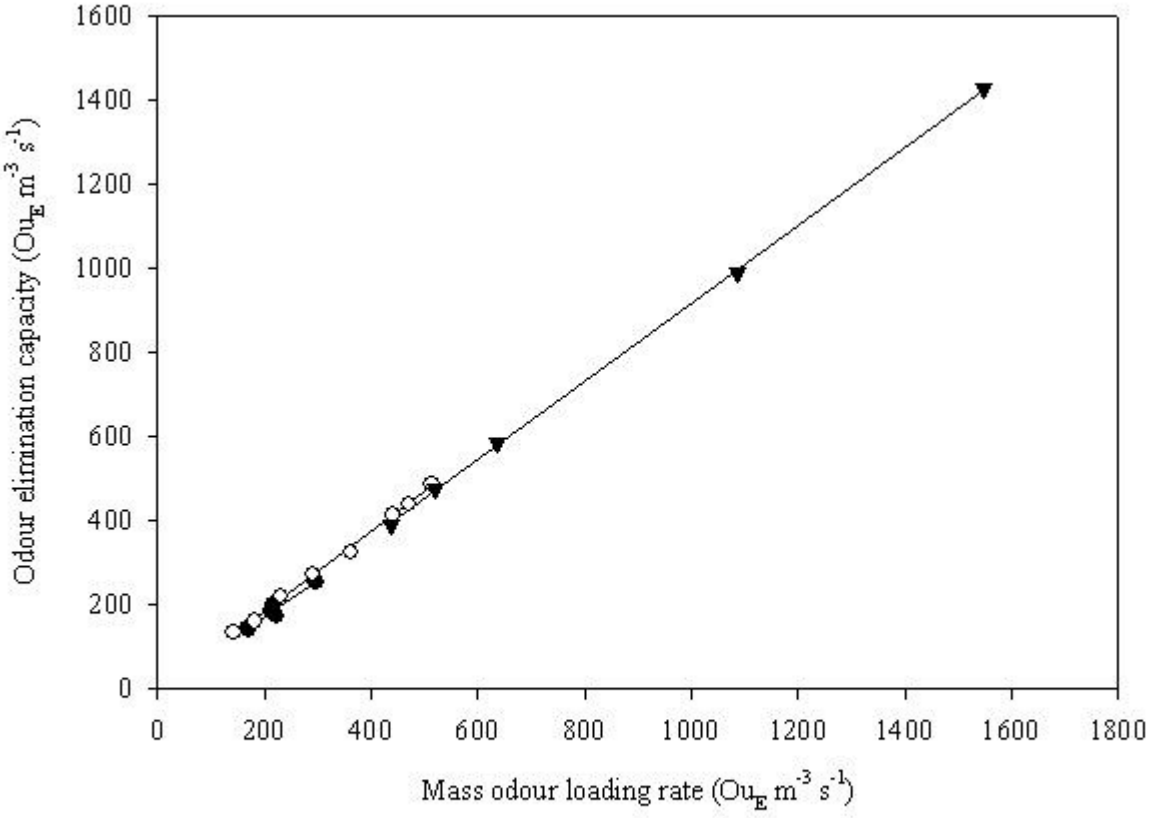

Fig. 8. Graph of odour elimination capacity versus mass odour loading rate; ● , trial 1; ○ , trial 2; ▼ , trial 3; —— , best fit line

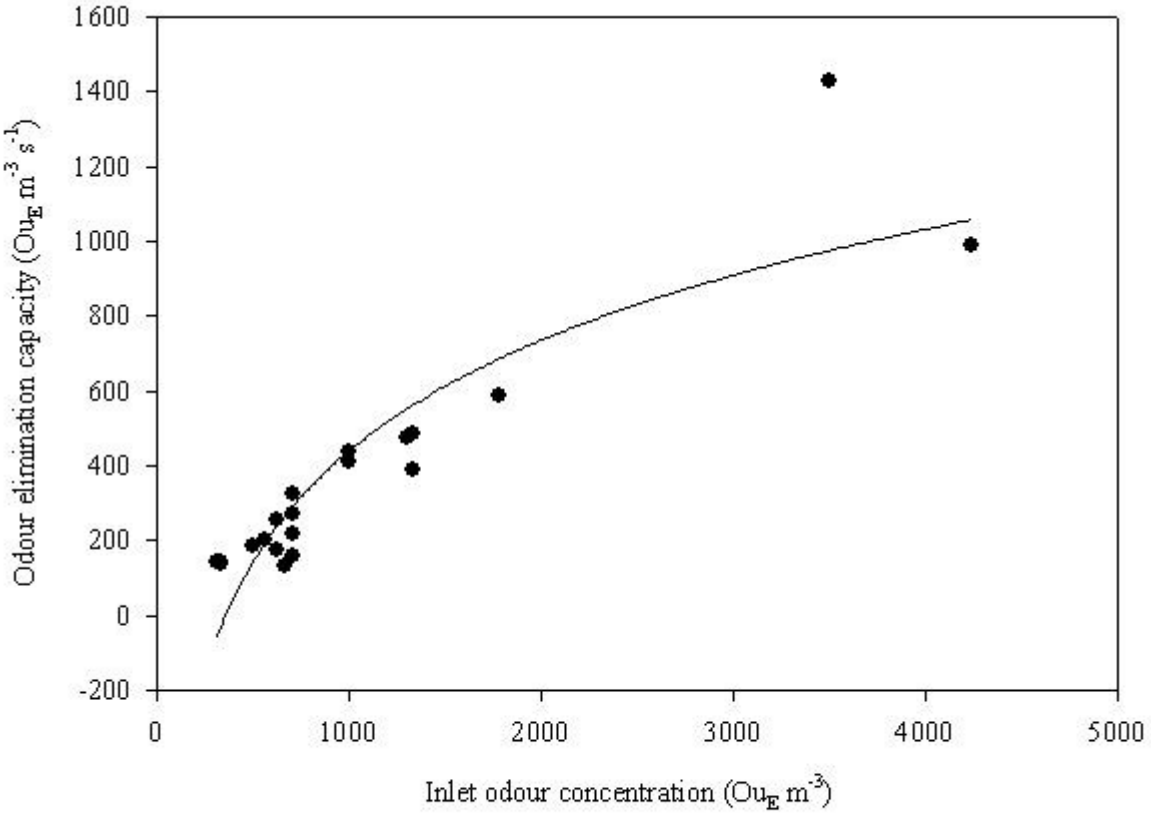

Fig. 9. Graph of odour elimination capacity versus inlet odour concentration; ● *, relationship for trials 1, 2, and 3;* —— *, best fit line (R^2 = 0.80)*

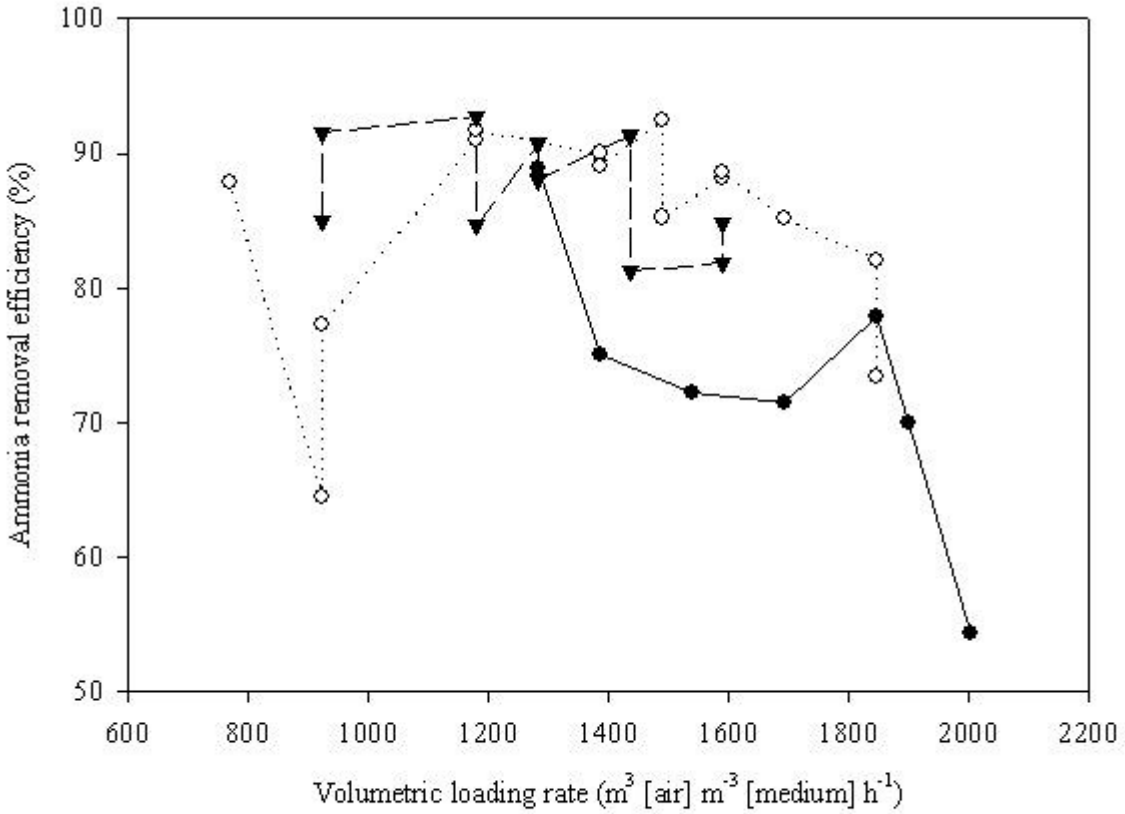

Fig.10. Graph of ammonia removal efficiency versus volumetric loading rate; —●— , trial 1; ··○··, trial 2; —▼— , trial 3

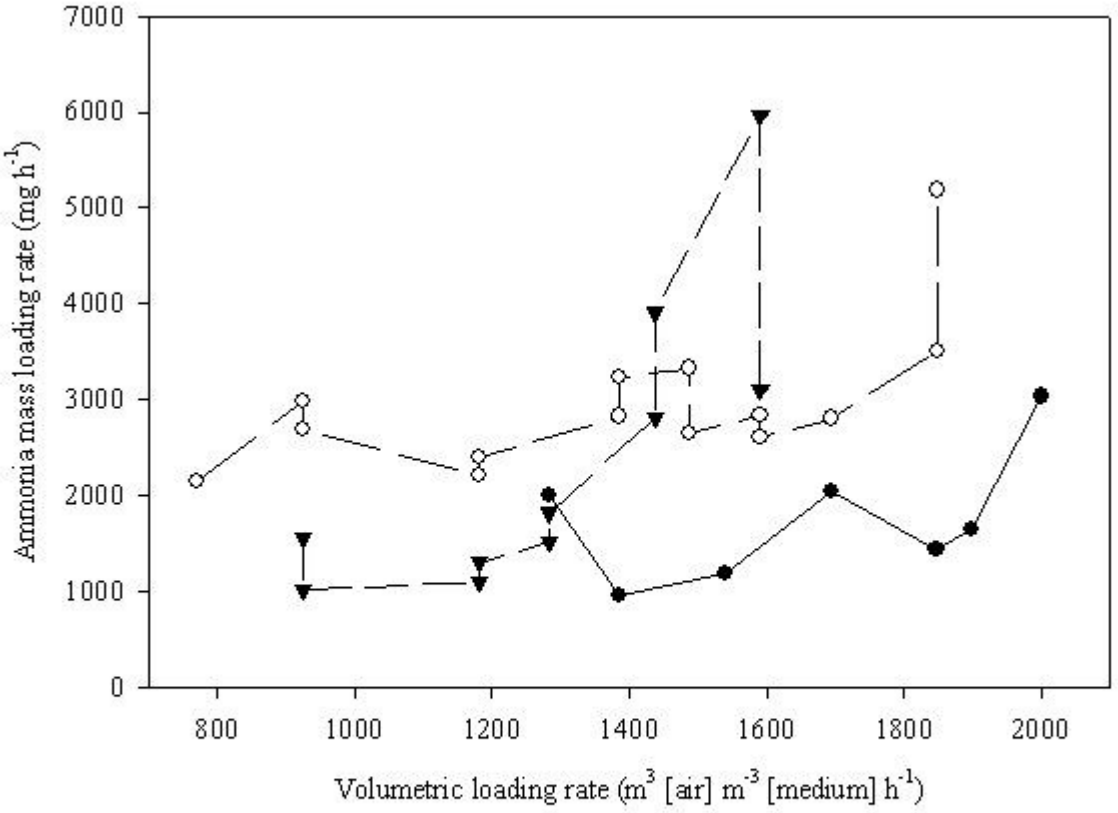

Fig.11. Graph of ammonia mass loading versus volumetric loading rate; —●— , trial 1; —○— , trial 2; —▼— , trial 3

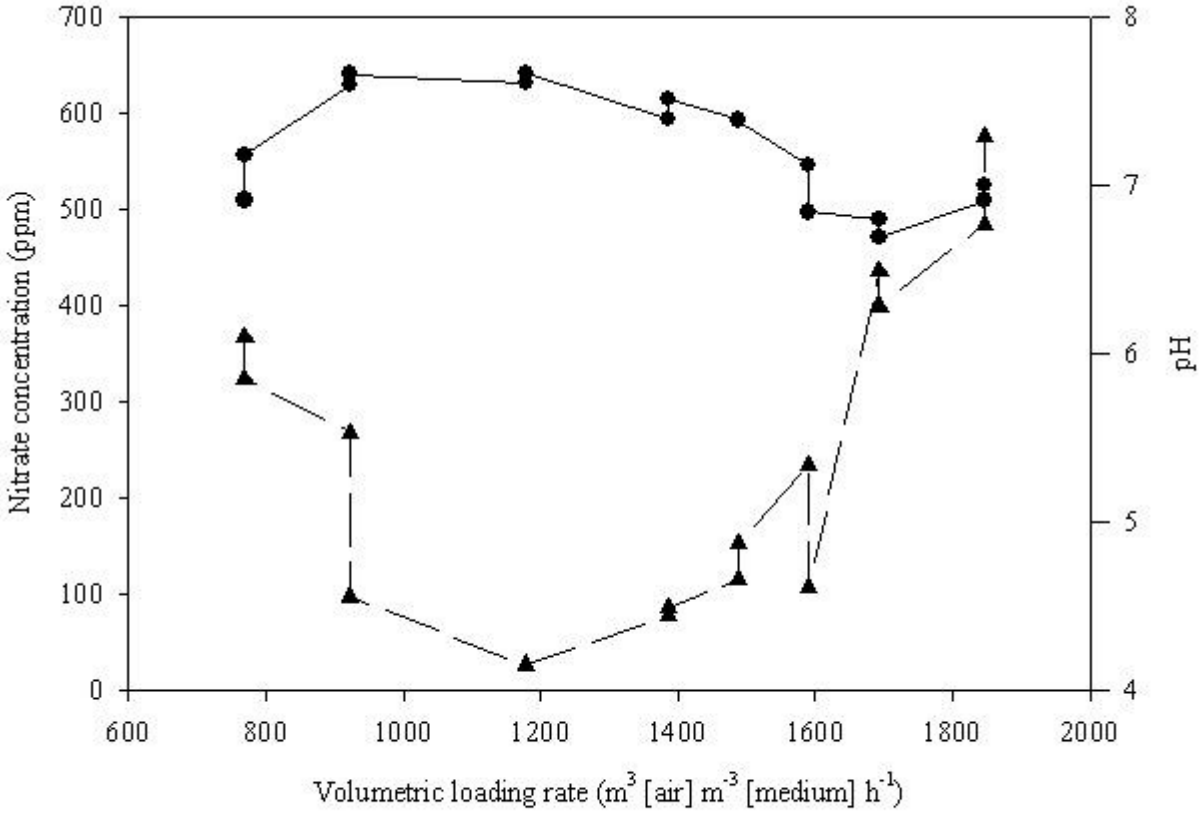

Fig. 12. Graph of nitrate concentration and pH for trial 2 versus volumetric loading rate; —▲— *, nitrate concentration;* —●— *, pH*

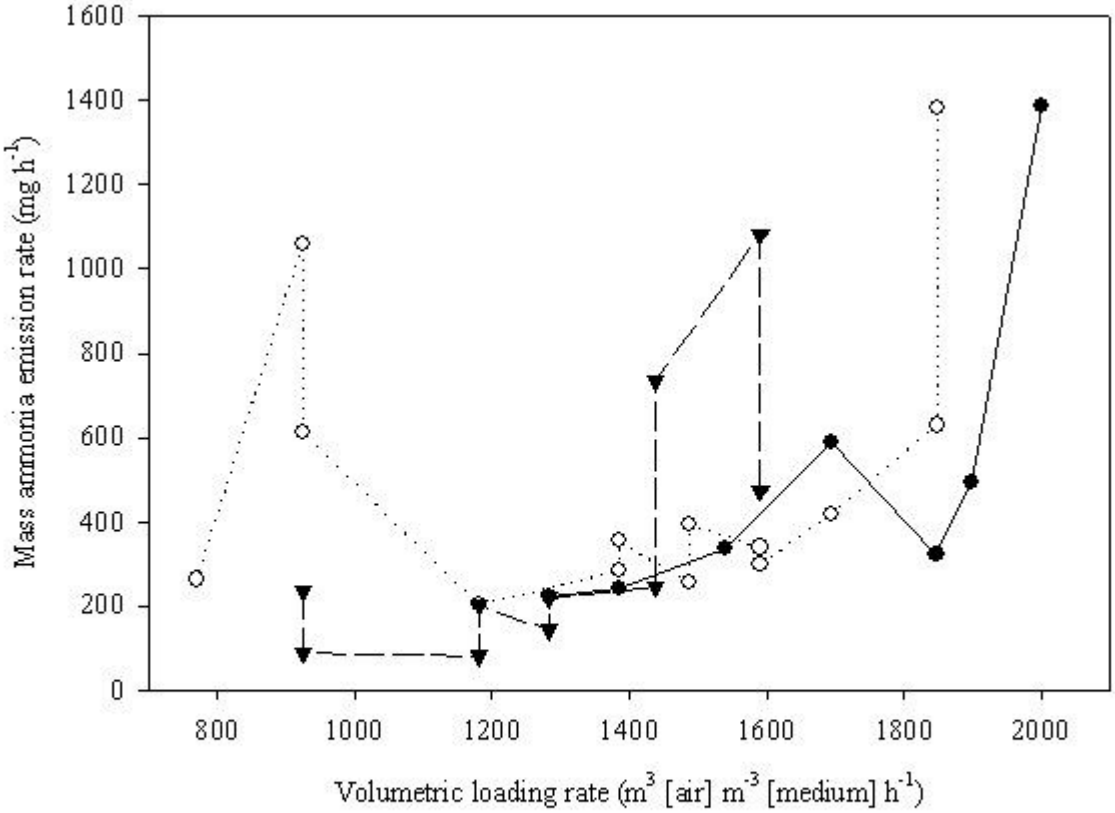

Fig.13. Graph of mass ammonia emission after biofilter versus volumetric loading rate; —●— *, trial 1;* ··○·· *, trial 2;* —▼— *, trial 3*

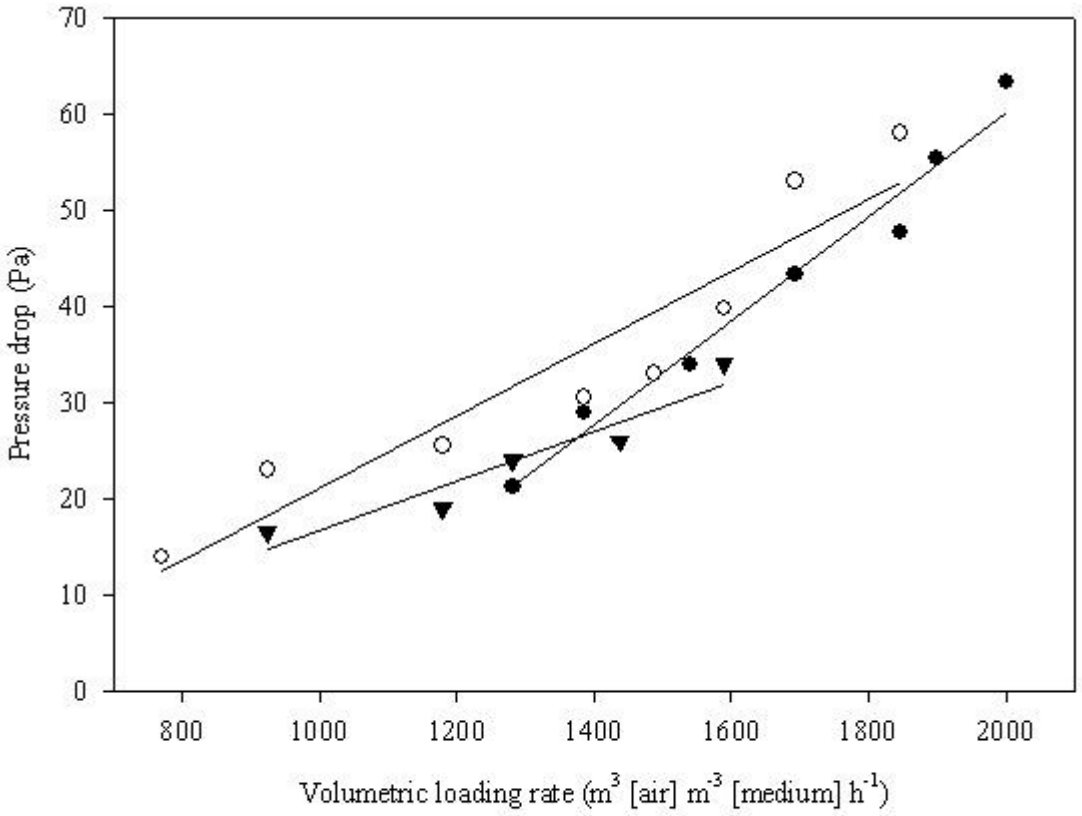

Fig 14. Graph of pressure drop versus volumetric loading rate; ● , trial 1 (R^2 = 0.97); ○ , trial 2 (R^2 = 0.89); ▼ , trial 3 (R^2 = 0.91); —— , best fit line

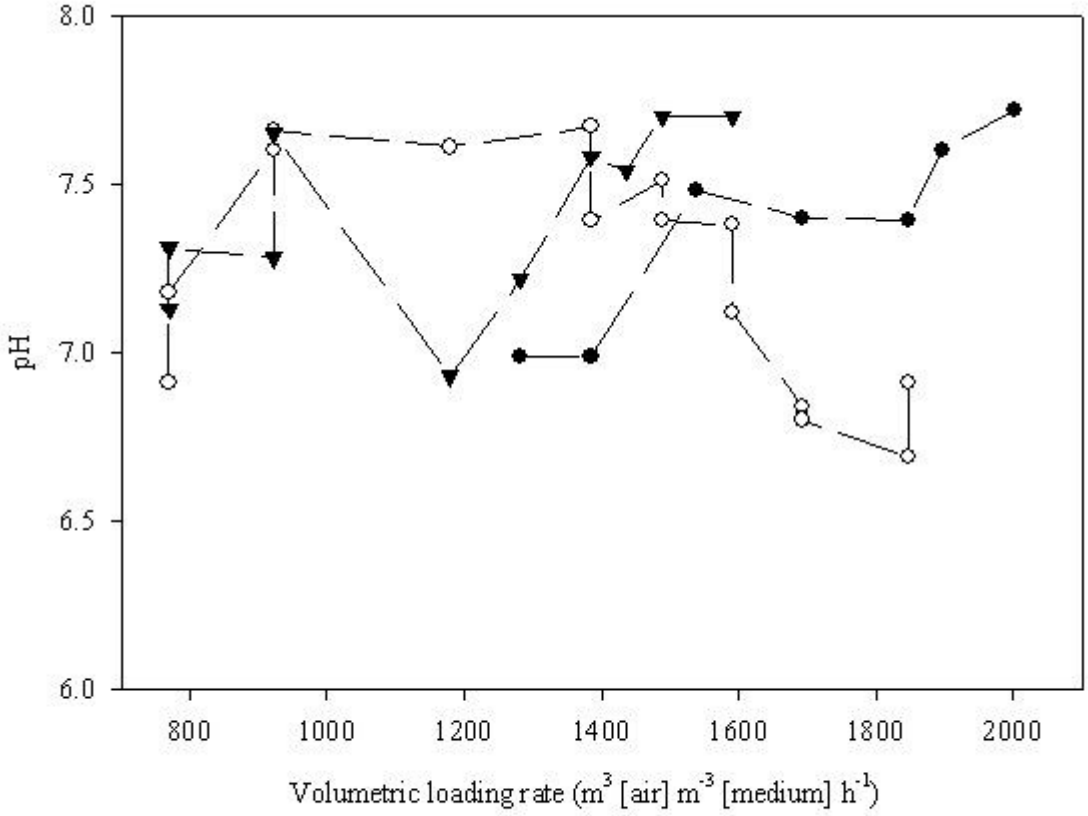

Fig.15. Graph of pH versus volumetric loading rate; —●— , trial 1; —○— , trial 2; —▼— , trial 3

Table 1
Measurements taken throughout the biofiltration system during trials one, two and three

Measurement	*Trial 1*	*Trial 2*	*Trial 3*
Pen temperature/RH	Continuously	Continuously	Continuously
Biofilter inlet air temperature/RH	Continuously	Continuously	Continuously
Pressure drop across biofilter	Continuously	Continuously	Continuously
Biofilter weight	Continuously	Continuously	Continuously
Biofilter temperature	Continuously	Continuously	Continuously
Airflow rate from pen	Every four days	Every four days	Every four days
Biofilter leachate pH	Every four days	Every four days	Every four days
Biofilter leachate nitrate concentration	-	Every four days	-
Inlet and outlet ammonia concentration	Every four days	Every four days	Every four days
Inlet and outlet odour concentration	Every four days	Every seven days	Every seven days

Table 2
Biofiltration system operation for trials one, two and three

Experimental period	*Volumetric loading rate (m^3 [air] m^{-3} [medium] h^{-1})*	*No of sampling periods*	*Acclimatisation period (weeks)*	*Seeding*
Trial 1	1282-1898	6	3	Yes
Trial 2	769-1847	8	3	Yes
Trial 3	923-1590	5	0	No