BIOFILTRATION FOR ODOUR CONTROL FROM SWINE HOUSING IN MANITOBA

BY

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A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

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ABSTRACT

Biofiltration is an odour removal technology in which an odorous air stream is passed through a moist, porous medium prior to emission into the atmosphere. Odorous compounds are removed in the filter medium through absorption and bio-oxidation. Four experimental biofilter units were retrofitted to a 2000-hog, 4 room feeder facility in southern Manitoba. The biofilters were designed to eliminate odour from the barn emissions during the winter while minimizing cost. The biofilter bed temperature remained in a temperature range suitable for odour removal, even during very ambient temperatures below -20 °C. Odour removal efficiency from September to February averaged between 69 and 87%. Ammonia and hydrogen sulfide levels were reduced by 56 to 100%. Different air distribution and biofilter media combinations resulted in little difference in odour reduction. This project demonstrates that biofiltration is a viable odour emission reduction technique for mechanically ventilated swine housing in the cold Canadian climate.

Additionally, two experimental biofilters were constructed to determine whether the biofilter media material contributed a residual odour to the outlet air from the biofilters. Six different blends of compost and bulking agents were used at two different retention times and were found to have low residual odour levels. Outlet odour levels at or below ambient farmyard odour levels were found for all varieties of compost blended in a 50%/50% mixture (by mass) with woodchips, as well as for a 50/50 mixture of hemp hurds and compost. Outlet odour levels did not differ significantly for odorous and non-odorous air biofilters, indicating that it was not the processes associated with biofiltration that caused the residual odours.

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1 INTRODUCTION

1.1 Background

With the recent increase in the number and size of pork production facilities in Manitoba, odour emissions have become a concern to rural communities. This thesis outlines the research being conducted by the Department of Biosystems Engineering at the University of Manitoba to determine the viability of reducing odour emissions from swine production facilities using low-cost biofilters. Four experimental biofilter units were retrofitted to a 2000-hog, 4 room finisher facility southwest of Landmark, Manitoba to control emissions from the minimum ventilation rate fans during the winter. Two additional small-scale biofilters were constructed at Glenlea, Manitoba to quantify residual odour in the biofilter media.

1.2 Biofiltration

Biofiltration is an odour removal technology in which an odorous air stream is passed through a moist, porous filter medium prior to emission into the atmosphere. Odorous compounds are removed from the airstream by absorption and diffusion into a moist film on the surface of the filter media known as the biofilm. Odorous contaminants either accumulate in the biofilm, or are digested by the resident microorganisms. The process of digestion, called bio-oxidation, occurs when microorganisms digest the gases, particulate matter, and volatile organic compounds in the presence of oxygen. Water, carbon dioxide, other non-odorous gases, biomass, and mineral salts are the products of these reactions (Williams 1993). The result of the biofiltration process is a decrease in odour emissions.

The biofilters used in this research were designed based on the low-cost biofilters described by Nicolai and Janni (1999) of the University of Minnesota. Nicolai and Janni have successfully operated an open-bed (no roof or cover) biofilter, using woodchips and compost as the filter medium, on a 700-sow production facility since November 1997. The Minnesota model for an open biofilter was chosen because of its design simplicity and its success in reducing odours.

The Minnesota model incorporates a number of design modifications which differ from industrial biofilters in order to simplify the design and cost (including minimal control and maintenance requirements, shallow bed depth, and low cost materials). According to Williams (1993), soil and compost are the most common media used in industrial biofilters. Because of the high pressure required to force air through compost or soil (resulting in significant costs associated with fans), the Minnesota model uses woodchips as a bulking agent in the filter bed. The compost is required to "innoculate" the system with bacteria. Other measures taken to simplify the system and reduce cost include the elimination of dust filters. Common garden sprinklers are used for surface moisture application instead of humidifying the airstream prior to entry into the biofilter. The air distribution plenum under the biofilter is created using standard shipping pallets. There are no walls or covers for the biofilter. The simplicity and low cost of this system make it ideal for livestock production facilities where limited funds are available for odour removal, and minimal maintenance and monitoring are desirable.

1.3 Objectives

1.3.1 Biofiltration in cold temperatures The primary objective of this project was to assess the feasibility of using a low-cost biofilter to remove odour from a hog barn under Manitoba's cold winter conditions. Since biofiltration is already known to work in warmer climates, the biofilters were run during the cold winter months. The feasibility was assessed according to the following factors:

- the biofilter bed temperature during the cold winter months;
- the change in odour concentration of the exhaust air from the barn;
- the decrease in ammonia and hydrogen sulfide emissions; and,
- the odour reduction resulting from different mixtures of woodchips and compost, and from different airflow configurations.

1.3.2 Filter media residual odour The air leaving the biofilters in Landmark was not completely odour-free. The remaining odour was thought to be caused by either incomplete biofiltration of the barn exhaust air, or due to the odour of the filter media itself (the biofilter outlet air had a distinctly earthy/woody smell). Two biofilters were constructed at the University of Manitoba Glenlea Research Station to assess the following:

- the odour concentration of relatively non-odorous air passing through a biofilter bed
- the odour concentration of odorous swine barn exhaust air passing through a biofilter at high retention times (to eliminate as much of the swine odour as possible)
- the odour concentration of different biofilter media mixtures, including different compost, woodchip, straw, and topsoil mixtures, at high retention times.

2. LITERATURE REVIEW

2.1 Livestock Odour Control

Livestock housing odours are caused by chemical compounds created as a result of normal biological processes occurring in the livestock waste. While odour emissions from barns are not generally harmful to livestock, humans, or the environment, concern over the nuisance impact necessitates the study of odour production and elimination. A quantitative and qualitative understanding of odour and odour production allows for the application of methods to decrease odour emissions. Odour can be controlled by altering the odour-causing source or controlling the environment in which the odorant is produced (referred to as primary odour control), or by treating the odorous air prior to emission into the atmosphere (secondary odour control). Biofiltration is a form of secondary odour control.

2.2 Livestock Odour Production

2.2.1 Livestock housing odour sources Odour in livestock housing units is caused by decomposing proteinaceous wastes such as faeces, skin, hair, feed, and bedding. Faeces are the most important component because they usually make up the largest volume of waste, and are biologically active (O'Neill and Phillips 1991). Generally, waste decomposition under anaerobic conditions results in more odour than decomposition under aerobic conditions. Anaerobic conditions result in incomplete digestion of waste by microbes, producing complex, odorous compounds. Accumulated waste on the barn floor contributes the most to barn odour conditions, although accumulation in drainage channels and storage pits also contribute significantly (O'Neill and Phillips 1991). Much research has been done on odour

production from different types of livestock, however, this chapter will focus primarily on odour production in pig barns.

2.2.2 Odour measurement To determine the effectiveness of odour-reducing measures, the ability to define the odour quantitatively and qualitatively is necessary. Ritter (1989) identified the following approaches used by researchers to detect and measure odour:

1. ranking of odour intensities by empirical scales based on odour offensiveness,
2. determination of odour concentration,
3. determination of threshold odour intensity by vapour or liquid dilution, and
4. identification of odorous gases or compounds.

2.2.3 Ranking odour intensity and offensiveness Odour intensity is a measure of how strongly an odour smells, or how readily it is perceived. Intensity is often explained using categories which range from "barely perceptible" up to "very strong" (Ritter 1989). Intensity is not a measure of the acceptability of an odour.

Odour offensiveness is used to characterize whether an odour is good or bad. Williams (1984) used a linear scale ranging from 0.0 (inoffensive odour) to 5.0 (very strongly offensive odour) and concluded that an offensiveness below 2 is acceptable. Another measure similar to offensiveness is the hedonic tone, featuring an arbitrary scale ranging from 10 (pleasant) to 0 (neutral) to -10 (unpleasant) (St. Croix Sensory Inc. 2000). An odour can be intense but not offensive (for instance, the smell of food) and thus not be considered a nuisance. Odour

from livestock housing may not be intense, but it is often offensive and thus a nuisance.

2.2.4 Determination of odour concentration The odour concentration, or threshold dilution value (or dilutions to detection threshold, D/T), is related to odour intensity. The threshold dilution value is a measure of how much an odour can be diluted and still be perceptible. The primary method of measuring the threshold dilution value is called dynamic dilution olfactometry. Olfactometry involves a group of human panellists and an olfactometer (a device which mixes carbon-filtered air with an odorous air sample). By diluting an odorous air sample (vapour dilution) to the point where 50% of the panellists can only just begin to detect the odour, the odour concentration (measured as the threshold dilution value) can be determined. Because the results of this procedure can be expressed as the ratio of the volume of odorous air divided by the volume of odour-free air, the threshold dilution value is referred to as a concentration. Olfactometry can be referred to as an organoleptic technique; a technique which makes use of a human organ (the nose) for detection (Ritter 1989).

Odour concentration can be related to odour intensity using a number of mathematical models. Bundy et al. (1997) compared several predictive models with experimentally measured values and found that the Beilder model fit the experimental data best. The Beilder model equation is:

$$I = \frac{k_1 k_2 C}{1 + k_2 C} \tag{2.1}$$

where k_1 and k_2 are constants of proportionality, I is the intensity of sensation (subjectively ranked from barely perceptible to very strong, and then assigned a numerical scale), and C represents the concentration of the stimulus. In this case, instead of using the olfactometric concentration, C is referenced to a concentration of a measurable compound, parts per million (ppm) of butanol. The power law,

$$I = k_1 C^{k_2} \tag{2.2}$$

was also found to have a good correlation to the model data, but not as good as the Beilder model (Bundy et al. 1997).

Other methods of concentration determination include gas chromatography, wet chemistry, and liquid dilution (similar to vapour dilution, but with water). These methods all determine the concentrations of chemical compounds which cause odour by measuring the quantity of compounds in a given sample. Methods of relating these concentrations of individual compounds to odour intensity are not well developed (Ritter 1989).

2.2.5 Identification of odorous gases or compounds O'Neill and Phillips (1992) reviewed 12 investigations of the chemical composition of ventilation air from livestock housing. A total of 168 compounds have been identified as contributors to livestock odour emissions. The compounds that are most important to livestock odour because of low detection thresholds are: volatile fatty acids (organic acids), *p*-cresol, indole, skatole, diacetyl, and ammonia. Six of the 10 compounds with the lowest detection thresholds are sulfur-based

compounds (O'Neill and Phillips 1992).

2.2.6 Modelling odour production using compound concentrations and biochemical properties Attempts to model odour production from waste require that the change in concentration of the product being modelled must match the kinetics of waste degradation (Spoelstra 1980). Williams (1984) found that, although indole and *p*-cresol are significant odorants often found when pig slurry is highly odorous, the concentrations of these compounds are not suitable indicators of odour (slurry mixes may contain neither of these contaminants and still be highly odorous). While *p*-cresol is a strong odorant, it will degrade within 48 h of batch treatment and the slurry offensiveness will remain high. Correlations of odour to the concentration of easily measured compounds such as ammonia also fail because of variability of the concentrations in equally odorous waste samples. Williams (1984) found that compounds such as sulfides, which are not good indicators of odour under certain circumstances such as aerobic treatment, may be good indicators under other circumstances, such as post-treatment storage.

Odour offensiveness can be predicted using several biochemical indicators including supernatant biochemical oxygen demand (BOD) for storage pits, volatile fatty acids, and total organic acids. These biochemical indicators are composite factors that may be the same for wastes of different compositions. As a result, these indicators are more reliable than predictive models based on specific concentrations of compounds in waste (Williams 1984).

2.2.7 Definition of primary control and secondary control of odour emissions In an effort to control livestock housing odour, primary or secondary control techniques can be employed. Primary odour control seeks to eliminate the odour by altering the chemical nature of odorants, or the way in which odour is generated or volatilized from a source. Primary control methods include manure and slurry additives, feed additives, and barn management techniques.

Secondary control methods treat airborne odour prior to emission from the barn. Methods of secondary control may break down odour compounds biologically or chemically once the odour has been released. Alternately, the odorous compounds (or the dust or water which carry them) may be removed from the airstream and disposed of as a waste product. Secondary control methods include biological methods such as biofiltration, biotrickling filters, and bioscrubbers, and non-biological methods such as adsorption, ionization, ferroelectric techniques, and incineration.

In general, livestock producers do not rely on secondary control systems to eliminate odours because of the high cost traditionally associated with treating large volumes of dilute odorants. Recently, however, there has been an increase in the use of secondary control systems on livestock housing units because of complaints arising from odour emissions in rural areas where residential housing has increased through urban sprawl, or where large intensive livestock operations produce very large volumes of odorous air. The result has been increased research and application of simple, effective secondary control systems like

biofilters.

2.3 Biofiltration

2.3.1 The process of biofiltration Biofiltration is an effective means of controlling odour emissions from intensive livestock housing (Hartung et al. 1997; Nicolai and Janni 1998; Young et al. 1997). Biofiltration is an odour removal technology in which an odorous air stream is passed through a porous filter bed prior to emission into the atmosphere (Fig. 2.1). Odorous compounds are removed from the airstream by absorption and diffusion into a moist film on the surface of the filter media known as the biofilm. Odorous contaminants either accumulate in the biofilm, or are digested by the resident microorganisms. The process of digestion, called bio-oxidation, occurs when microorganisms (primarily bacteria, actinomycetes, and fungi) digest the gases, particulate matter, and volatile organic compounds in the presence of oxygen. Water, carbon dioxide, other non-odorous gases, biomass, and mineral salts are the products of these reactions. Evaporation of the biofilm results in desiccation and death of the bacteria, causing the biofilter to fail (Lau et al. 1996).

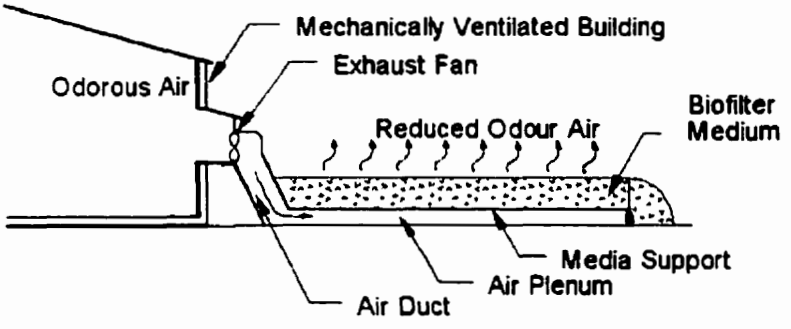


Fig. 2.1 Schematic of an open-bed biofilter (from Nicolai 1998)

2.3.2 Advantages of biofiltration As mentioned, other forms of odour removal technology include chemical wet scrubbing, ionization, and activated-carbon filters. These may not be appropriate for agricultural emissions because of their high capital and maintenance costs. Additionally, the large volume of exhaust air with low concentrations of pollutants from agricultural buildings is not suited to treatment by these technologies (Chapple and Howard 1999). According to Otten and Gibson (1994), biological filtration systems, such as biofilters, biotrickling filters, and bioscrubbers are most effective at removing odour from large volumes of dilute air.

According to Lau et al. (1996) the primary advantages of biofiltration include:

1. simple operation,
2. effectiveness for a wide range of compounds, and
3. little residue or waste product, because the organic compounds are decomposed.

Unfavorable aspects of biofiltration identified by Lau et al. (1996) include:

1. large land-area requirements, and
2. media aging and decomposition, which cause fluctuations in airflow resistance and change the airflow characteristics in the biofilter.

2.3.3 Odorous airstream requirements The airborne pollutants being treated by biofiltration must exhibit the following traits (Spang 1998):

1. the pollutants must be water-soluble to be sorbed into the biofilm,
2. the pollutants must be biodegradable to enable bio-oxidation to occur,

3. the pollutants cannot be toxic, which would result in death of the microorganisms, and

4. the airstream must have sufficient oxygen to facilitate bio-oxidation.

Emissions from confined livestock housing satisfy these conditions and are, therefore, suitable for biofiltration.

2.3.4 Biofilter design parameters Biofilters are designed to eliminate contaminants from an airstream. The elimination capacity (EC) is defined as the pollutant removal capacity per unit volume of bed per unit time. EC is calculated as:

$$EC = \frac{\Delta C \bullet Q}{V} \tag{2.3}$$

where: EC = elimination capacity ($g \bullet m^{-3} \bullet h^{-1}$);

ΔC = change in concentration of pollutant (g/m^3);

Q = airflow rate (m^3/h);

V = filter bed volume (m^3).

The elimination capacity is difficult to determine because different filter media conditions and different contaminant inputs will result in different rates of contaminant removal. Existing empirical models are dependent on the specific design characteristics of a particular type of biofilter and are not easily generalized for different pollutant streams or media types. To predict a biofilter's EC for a specific pollutant stream, pilot scale systems are built and tested in a laboratory (Gribbins and Loehr 1998).

Where lab-scale testing is not economically feasible, biofilters are often designed by "rule of thumb" criteria, assuming that for certain filter materials, acceptable removal efficiencies can be achieved with a standard design (Yang and Allen 1994).

2.3.5 Selection of filter bed media The active portion of the biofilter is the filter bed media. Several parameters must be considered to optimize the environmental conditions for the microorganisms living in the media and to ensure consistent airflow through the filter bed. Biofilter media should satisfy the following conditions (Liu et al. 1994; Spang 1998):

- uniform pore and particle size to reduce gas channeling and air flow resistance, and increase reactive surface area,
- supply of inorganic nutrients to support microorganisms,
- pH, salinity, and alkalinity suitable for microorganism survival,
- high surface area / volume ratio to maximize gas - biofilm interaction,
- good water retention characteristics to maintain wetted surfaces,
- minimal compactability over time to prevent channeling and high pressure drop, and
- no or little self-odour to avoid secondary emissions.

Possible media include organic substances such as (Lau et al.1996):

- mature compost,
- soil,
- straw,
- tree bark,
- woodchips,
- pelletized peat granules.
- loam,
- heather,

The advantage of organic media is that they typically host a microbial community suitable for bio-oxidation, eliminating the need to add microorganisms capable of bio-oxidation of contaminants. Organic media are usually locally available, and not costly (Boyette 1998).

Organic media may undergo decomposition, affecting the uniformity of airflow through the biofilter. Organic media must be replaced after several years of operation when the airflow characteristics degrade significantly, or when the accumulation of metabolic bi-products hampers microbial growth. The degree of media degradation depends on temperature, moisture, contaminant concentrations, and loading rates (Boyette 1998). Once their useful life has been exceeded, organic media are easily disposed of.

2.3.6 Biofilter sizing Once a filter material has been selected, the size of the filter bed must be determined. Biofilter size is based on the elimination capacity of the filter material, and on the volume of air passing through the filter bed. Where the elimination capacity has not been determined through pilot scale studies, the primary "rule of thumb" for biofilter design is to base filter bed size on the opportunity for air to interact with the biofilm in the filter bed. The main parameter used is the residence time (Nicolai and Janni 1998; Swanson and Loehr 1997).

2.3.7 Residence time Residence time is defined as the time exhaust air spends passing through the filter media. Although actual contact time between the air and the biofilm is a function of biofilter volume and the available pore space within the filter media, the empty bed

contact time (EBCT) is commonly used for design calculations. The EBCT calculation assumes that the filter bed is an unobstructed volume containing nothing but air (Williams 1993). Actual residence time is less than EBCT because pore space makes up only a portion of the actual bed volume. The EBCT can be calculated as follows:

$$EBCT = \frac{V}{Q} \tag{2.4}$$

where: EBCT = empty bed contact time (s);

V = biofilter bed volume (m^3);

Q = airflow rate (m^3/s).

Confined livestock ventilation consists of large volumes of air with varying, but low contaminant concentrations. Designing for specific elimination capacities for selected compounds is difficult in such situations. Designing to a specific EBCT (an EBCT based on previous biofilters with successful emission reductions) is a convenient method which will likely result in adequate contaminant removal.

2.3.8 Suggested residence time Based on work by Zeisig (1987), and Nicolai and Janni (1998; 1999), an EBCT of 5 s is sufficient for odour reduction in open-face biofilters at confined livestock housing. Nicolai and Janni (1999) found that there is no significant increase in odour reduction with a residence time of 6 s or more, while a 4-s residence time is not adequate for odour reduction.

Yang and Allen (1994) achieved 100% H_2S removal in a 23-s retention time. A 94% H_2S removal was achieved with only 7-s retention times. Yang and Allen (1994) suggest that since H_2S can be metabolized in under 2 s, it is the diffusion of H_2S from the gas phase into the biofilm that limits this process, and not a lack of digestion time for the microorganisms. Increasing the residence time facilitates complete diffusion of airborne contaminants into the biofilm for digestion.

While knowing the EBCT and airflow rate permits the calculation of the filter bed volume (Eq. 2.1), the depth and area of the biofilter must also be decided. An understanding of the pressure drop through the bed depth is the first requirement to determine the biofilter dimensions.

2.3.9 Pressure drop and surface loading The static pressure drop across the filter bed depth relates to the ease with which air passes through the filter media. The pressure drop can be used as a selection criterion when choosing media for the biofilter. For a selected material, laboratory testing can be used to compare the pressure drop per unit depth of filter medium with the surface loading on the biofilter (Nicolai 1997). Surface loading (or face velocity) is the velocity of the air moving perpendicular to the surface of the filter bed (Devinny et al. 1999). For a given contaminant concentration in the air, the surface loading is proportional to the contaminant loading at the entry surface of the biofilter (assuming uniform inlet airflow across the biofilter area).

Mathematically, the surface loading is given as:

$$SL = \frac{Q}{A} \tag{2.5}$$

where: SL = surface loading (m/s or $(m^3/s)/m^2$);

Q = airflow rate (m^3/s);

A = biofilter area (m^2).

Higher surface loading occurs with decreased retention time and results in decreased contaminant removal efficiency. Devinny et al. (1999) suggest using a surface loading of less than 0.06 m/s.

2.3.10 Relating pressure drop to surface loading The pressure drop per unit depth of medium material is related in a log-log fashion to the surface loading. By determining the available static pressure from the air supply source (for example, from the exhaust fans in livestock housing), and selecting a filter bed depth, the surface loading rate can be determined from experimental data. Figure 2.2 shows the relationship between surface loading rate (identified as "Airflow through the media" in the figure) and pressure drop per unit depth for different filter media. Knowing the surface loading and airflow rate, the surface area of the biofilter can be calculated. Thus, the dimensions of the biofilter are determined based on the EBCT and the surface loading rate.

2.3.11 Direction of airflow through the biofilter Having determined the biofilter dimensions for a selected media type, the layout of the biofilter must be determined. Air may

be fed into the media from the top or bottom of the filter bed. According to Devinny et al. (1999) there are several issues to consider when choosing up-flow or down-flow air distribution systems.

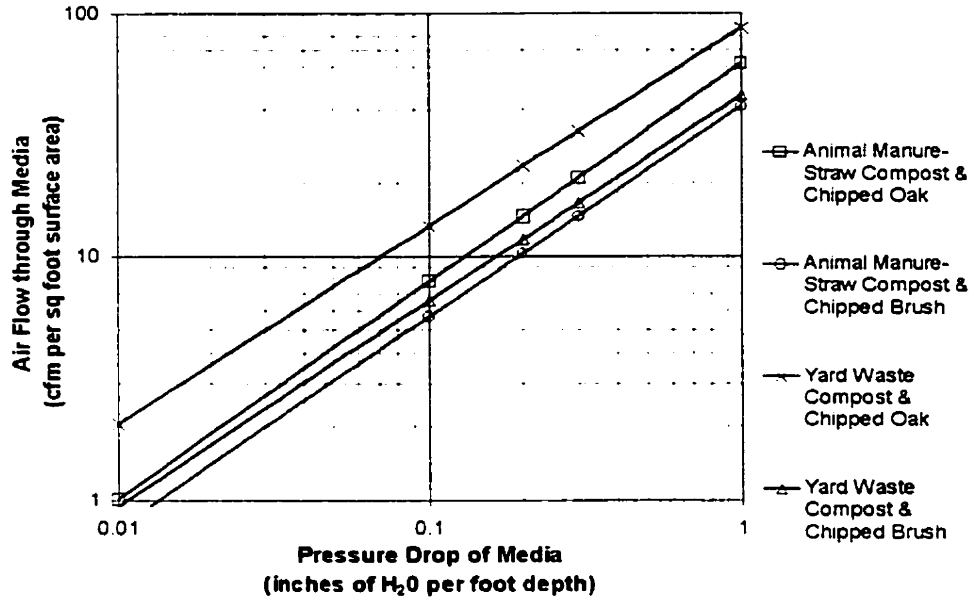


Fig. 2.2 Surface loading rate versus pressure drop for different filter media (Nicolai 1998)

Down-flow systems have the following characteristics (Devinny et al. 1999):

- moisture application and biological activity occur in same region,
- percolation of acids occurs down through the entire bed, damaging the filter material and microbial community in the lower zones of the bed,
- particulate (dust) clogging occurs at the inlet where microbial activity is, and
- hazardous chemicals can accumulate at the surface, making maintenance dangerous.

Up-flow systems have the following characteristics (Devinny et al. 1999):

- removal of accumulated chemical by-products can be achieved by over-applying water without having the contaminants move through the whole filter bed,
- easy examination of the biofilter surface is possible because only treated air reaches the outlet surface, and
- irrigation and biological activity occur in opposite extremes of the bed depth, causing differential rates of drying in the upper and lower portions of the biofilter, resulting in uneven moisture distribution.

In general, agricultural biofilters are up-flow systems.

2.3.12 Airflow and short circuiting Once the biofilter size, layout, and airflow rate have been determined, the airflow pattern through the filter bed must be determined. Symmetrical air distribution minimizes short-circuiting (preferential airflow through one part of the filter bed), ensuring uniform microbial activity and contaminant removal throughout the biofilter (Boyette 1998). Short circuiting can be detected by feeding smoke into the biofilter and observing the airflow at the biofilter surface (Boyette 1998; Young et al. 1997).

2.3.13 Enclosing the biofilter Covering the biofilter surface with a roof is recommended in areas of high rainfall in order to prevent saturation (Lau et al.1996). Roof structures strong enough to support snow loads increase the cost of a biofilter significantly. Boyette (1998) found that open bed systems are generally less costly than enclosed systems and yet have

similar odour removal efficiencies. Hartung et al. (1997) suggested that where odour samples have to be collected, covering the biofilters avoids mixing of the outlet air with natural air currents, which affects ammonia and odour collection (for measurement or regulatory requirements).

2.4 Biofilter Operation

2.4.1 Operational characteristics Biofilters require control of a number of parameters to ensure proper conditions for contaminant removal. Some operational characteristics, such as airflow characteristics and accumulation of biomass are difficult to control. Others, such as moisture application and the chemical balance in the biofilter are more readily controlled. The objective of any control technique is to optimize conditions for the microorganisms and to ensure continued uniform airflow.

2.4.2 Moisture content Lau et al. (1996) found that biofilter performance is most sensitive to changes in moisture content. Both drying and over-wetting the filter media reduce biofilter performance. Drying results in (Boyette 1998; van Lith et al. 1997):

1. drying of the biofilm, reducing microbial activity,
2. a reduction of mass transfer of hydrophobic substances, and
3. a decrease in airflow resistance, resulting in increased airflow and further drying.

Over-wetting results in (van Lith et al. 1997):

1. clogging of pore space and slime formation, reducing surface area for biofilm development,

2. increased pressure drop, and

3. washing out of fine particles, causing irreversible structural damage.

2.4.3 Moisture application methods The two primary methods of moisture application are:

1. prehumidifying incoming air before it comes into contact with the filter media, and
2. sprinkling the surface of the biofilter and permitting the water to percolate through the filter bed.

The appropriate method of moisture application can be chosen depending on biofilter layout and the mechanisms of drying that are dominant. The cost and ease of use also play a deciding role.

2.4.4 Mechanisms affecting filter bed moisture content According to van Lith et al. (1997), three mechanisms affect the moisture content of the filter bed.

1. Incomplete prehumidification results when the air entering the biofilter is at less than 100% relative humidity. Moisture is evaporated from the entrance zone of the filter bed until saturation of the air is achieved. This decreases the moisture content of the filter bed. Raising the relative humidity of the incoming air to 90-95% by prehumidification prior to entry into the biofilter will result in reduced rates of drying.
2. As bio-oxidation occurs, heat is generated, increasing the temperature of the air travelling through the biofilter. Warmer air has increased capacity to absorb moisture, causing drying in the filter bed.

3. When the incoming air is warmer than the media and has a higher moisture content than the media (as in winter), condensation occurs within the bed, increasing the moisture content. When the biofilter exhaust air is cooler than the ambient air (rare in agricultural applications), bed moisture evaporation will occur (van Lith et al. 1997).

Thus, moisture demand varies with the incoming air's temperature and relative humidity, contaminant loading (which is proportional to bio-oxidation), ambient conditions outside the biofilter, and airflow configuration.

Most agricultural applications of biofiltration have upward-flowing air (Hartung et al. 1997; Nicolai and Janni 1998, 1999; Zeisig 1987). For this configuration, prehumidification is preferred to prevent drying at the entrance zone in the bottom of the filter bed. Prehumidification of dusty (unfiltered) livestock housing air results in fouling of the sprayers with dirt, decreasing the viability of this technique. Thus, surface irrigation (sprinkling) is the most common method in agricultural biofilters (van Lith et al. 1997; Boyette 1998).

2.4.5 Optimum filter bed moisture content von Bernuth et al. (1999) found that the moisture content of the filter bed must be maintained between 40 and 70% to maintain stable microbial growth. Similarly, van Lith et al. (1997) found that the optimum moisture conditions range from 40 to 60% by wet mass. For hydrophobic VOC's, however, a moisture content at the low end of this range is preferred. For H_2S, Yang and Allen (1994) achieved nearly 100% removal for moisture contents from 30 to 62%. Below 30% moisture content,

they found that H_2S removal efficiency decreased proportionally with moisture content.

2.4.6 Flushing the biofilter Over-application of water can result in the flushing of microorganisms, decreasing bio-oxidation in the biofilter. Flushing may be necessary, however, when too much biomass growth causes a decrease in surface area and pore space, known as sloughing (Liu et al. 1994). Flushing may also be necessary to remove accumulated mineral salts. Impermeable liners are often laid down to collect leachate to allay environmental concerns, although Boyette (1998) suggests that this is not necessary.

2.4.7 Moisture monitoring and control There are a number of ways in which moisture content in the filter bed can be controlled (Table 2.1). For agricultural applications, the semi-automatic or periodic manual methods of moisture application are most common.

Table 2.1 Moisture control options (van Lith et al. 1997)

Method	Description
Automatic	Moisture content is measured automatically by bulk or spot methods. Sprinklers are triggered for low moisture content. Alarms sound for excessively high or low moisture levels.
Semi-automatic	Sprinkling frequency and duration are controlled by a periodic timer which is set from periodic manual or automatic moisture sampling.
Periodic manual	Sprayers are periodically turned on manually, based on media moisture sampling.
Manual ad hoc	No spraying system exists. Moisture content is adjusted occasionally with spray hoses based on semi-annual monitoring.

2.4.8 Temperature The mesophylic aerobic bacteria living in the filter require temperatures between 10 and 50°C to ensure biological activity. Yang and Allen (1994) found that optimum H_2S removal occurred in the range of 20 to 50 °C (Fig. 2.3). Typically, exhaust air from livestock housing will be in the range of 15 to 40 °C based on livestock needs. Warm exhaust air from the barn will keep the filter bed warm enough for continued contaminant removal, even if temperatures drop below freezing (Nicolai and Janni 1998). While increased temperatures increase contaminant degradation, Lau et al. (1996) suggest that diffusion into the biofilm slows because solubility of gases decreases with increasing temperature.

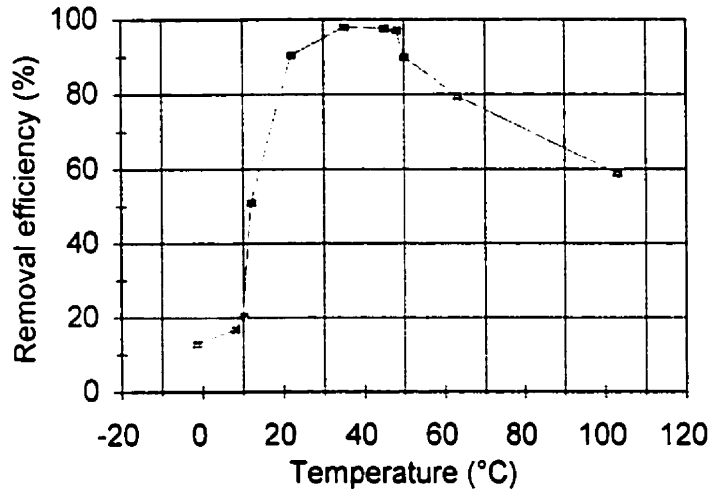


Fig. 2.3 Effect of temperature on H_2S removal efficiency (Yang and Allen 1994)

2.4.9 Control of chemical characteristics The chemical condition of the filter bed can be affected as a result of the byproducts of degradation of the contaminants from the airstream. Mineral salt accumulation can result in adverse conditions for microorganisms. Yang and

Allen (1994) found that a sulfate concentration above 25 mg-S/g in a compost filter bed is toxic to the microbial community.

Degradation of chlorine- (in industrial applications), sulfur-, and nitrogen-containing compounds in the biofilter media can result in acid intermediates or end products, lowering filter media pH. Some organic odorous compounds will not be biodegraded at the resulting low pH levels (Boyette 1998). However, Yang and Allen (1994) found that a pH of 3.2 optimized H_2S removal. Lau et al. (1996) found maximum microbial activity at a neutral pH. Additives such as calcium carbonate, marl, lime, and oystershells can act as pH buffers (Lau et al. 1996; Chou and Cheng 1997).

2.4.10 Toxicity of the air stream In general, toxicity of the air stream is not a concern in agricultural biofilters because the contaminant concentrations treated are usually not high (< 1000 ppm) (Gribbins and Loehr 1998). Effective odour treatment occurs only when odorous compound concentrations are below 2000 ppm, which is virtually guaranteed for agricultural biofilters (Boyette 1998).

2.4.11 Nutrient availability in the filter media Inorganic nutrient availability for microorganisms living in the biofilm can limit microbial growth. Gribbins and Loehr (1998) found that nitrogen (N) becomes limiting due to microbial activity during high VOC loading. The rate of mineralization of organic N to ammonia N can be too slow to keep up with the uptake of soluble nitrogen by microorganisms to make new biomass. When VOC loading

rates are very high, adding nitrogen fertilizers (soluble in sprinkler water) ensures that N levels are not depleted. Where non-organic filter media are used, nutrients must be added (Lau et al.1996).

2.5 Summary of Literature

Design and operation of a biofilter for livestock odour removal requires an understanding of the physical and biological operations of the biofilter. Airflow characteristics through the biofilter are dependent on the biofilter size, and the time required for contaminant digestion by microorganisms. On-going operation of the biofilter requires the maintenance of uniform airflow, as well as adequate conditions for microbial activity. Biofiltration during Manitoba's cold winter will require that the bed temperature be maintained in the appropriate range to ensure on-going microbial activity.

3. MATERIALS AND METHODS FOR BIOFILTRATION IN LOW TEMPERATURES

3.1 Location

Four experimental biofilters were constructed in August, 1999 at a 2000-animal Elite Swine Inc. (ESI) finisher barn near Landmark, MB. These biofilters will be referred to herein as the "Landmark biofilters". The barn at Landmark had four rooms with 500 pigs in each room. The facility was mechanically-ventilated and had partially-slatted floors over gutters. A lagoon was located adjacent to the south side of the barn. The biofilters captured and treated the exhaust air from the Stage 1 fans in each room. Fan staging involves turning fans on and off depending on airflow requirements in the barn. Stage 1 fans run continuously, providing the minimum ventilation rates required for animal respiration during the winter. Since the objective was to determine the viability of biofiltration in cold weather, sufficient data could be collected using the Stage 1 fans. Two of the biofilters were constructed on the north side of the barn, and two on the south side of the barn, corresponding to the locations of the Stage 1 fans. Fig. 3.1 shows a schematic of the barn and the location of each biofilter. The biofilters began full operation during the last week of August, 1999 and were operated until the end of February 2000.

3.2 Landmark Filter Bed Media Composition

The filter bed media consisted of compost and woodchips. The compost used in the media was produced at a composting facility using grocery store vegetable waste (Rockwood Agri-Business, Stony Mountain, MB). Copost is a very non-homogenous material, and the

compost produced at the Rockwood facility varied in texture, particle size, and chemical composition from month to month as a result of the changing input materials.

Fig. 3.1 Layout of Landmark biofilters

Three randomly selected samples collected from a large compost windrow prior to our project were tested at Norwest Labs (Winnipeg, MB). The three samples had the characteristics shown in Table 3.1, demonstrating the variability of the compost used, even from the same windrow. Note: the analysis conducted was for agricultural soil additives, not for typical compost nutrients.

Table 3.1 Nutrient analysis for Rockwood Compost

Parameter	Sample 1	Sample 2	Sample 3
nitrate (ppm)	> 80	> 80	> 80
phosphate (ppm)	> 80	> 80	> 80
potassium (ppm)	> 600	> 600	> 600
sulphate (ppm)	> 20	> 20	> 20
calcium (ppm)	2580	5780	6200
sodium (ppm)	1240	85	8580
magnesium (ppm)	1350	1610	2220
pH	8.3	7.7	8.2
electrical conductivity	8.0	1.9	18.0
organic matter (%)	10.1	8.7	37.1

The woodchips were chipped debris wood from Cedar Lake, a northern Manitoba lake flooded by a hydro-electric project. The Easterville First Nation operates a woodchip production operation. The debris used for the woodchips consists of wood from pine, spruce, fir, cedar, larch, aspen, birch, willow, and alder trees. Manitoba Hydro technicians tabulated the length (i.e. the longest dimension) of the woodchips (Table 3.2). The percentage was calculated by mass of the woodchips, although the woodchips were not oven-dried prior to sorting.

3.3 Airflow Characteristics of the Woodchip/Compost Media Mixtures

The expected airflow characteristics of the filter bed were determined using a packed sampling column concept developed by Nicolai (1998). Air was blown through columns of filter material. By varying the depth of material in the column and the pressure and velocity

provided by the fan, a characteristic curve was developed comparing surface loading rate and pressure drop across the media. The tests were conducted on compacted and non-compacted samples of 50/50% and 75/25% mixtures of woodchips and compost (discussed further in section 3.6). Compressing the samples showed how airflow characteristics would change as the material compacted over time. The compacted samples were compressed by placing a large mass (23 kg, arbitrarily decided based on a large water jug which fit into the tube) on the surface of the material in the column for 24 h. The moisture content of the samples varied from 49 – 60% to represent expected conditions. The characteristic curves developed (Fig. 3.1) were used in conjunction with the available fan pressure at the barn and the required airflow rates for the barn fans to determine the biofilter bed dimensions.

Table 3.2 Woodchip length as a percent of total, by wet mass

Length (mm)	% of total
< 64	42.8
64 - 127	29
127 - 191	16.2
191 - 254	5.7
> 254	6.3

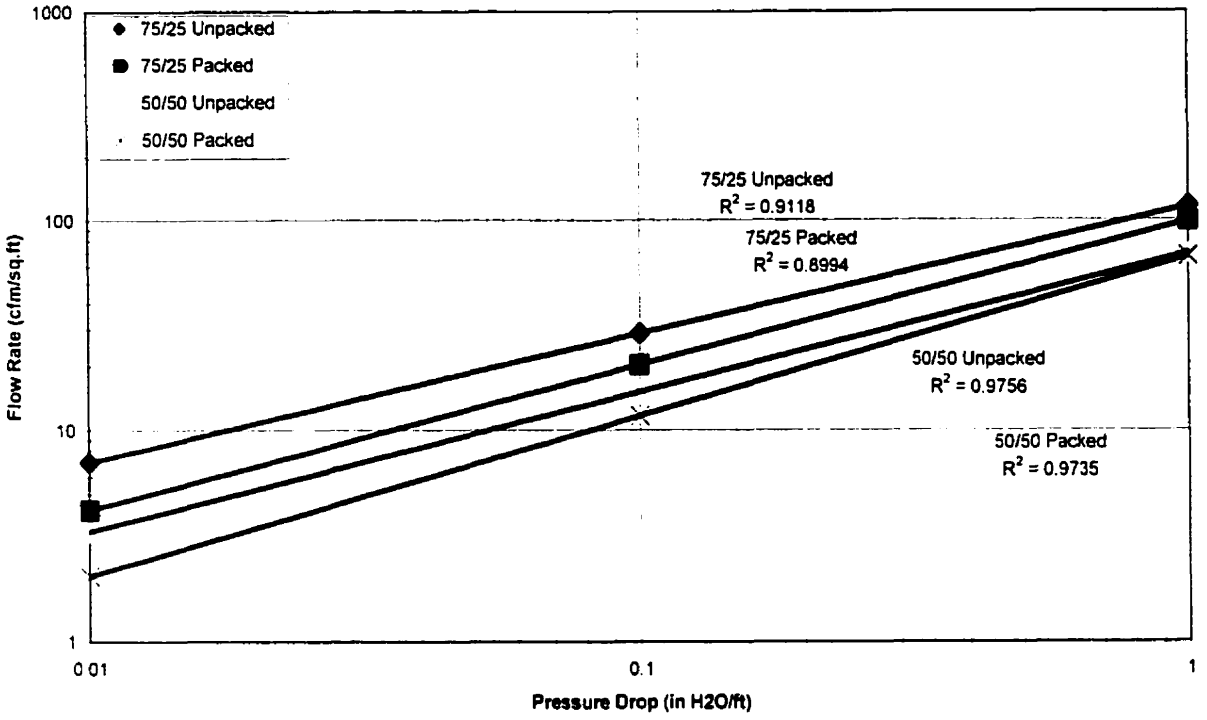


Fig. 3.2 Biofilter media characteristics measured according to procedure developed by Nicolai (1998). 75/25 and 50/50 refer to the mass ratio of woodchips and compost used in the filter bed. Packed and unpacked refer to compression of the material in the testing column. Note: non-SI units were used because agricultural fan specifications are provided in Imperial units.

3.4 Filter Bed Construction

The woodchip and compost media mixture was placed on a vinyl mesh netting which rested on standard shipping pallets. The pallets, which consist of three parallel support members with evenly-spaced slats perpendicular to these members (Fig. 3.3), acted as an air plenum and distribution system, with air being blown through the spaces between the support members. The vinyl mesh netting acted as a media support, preventing the

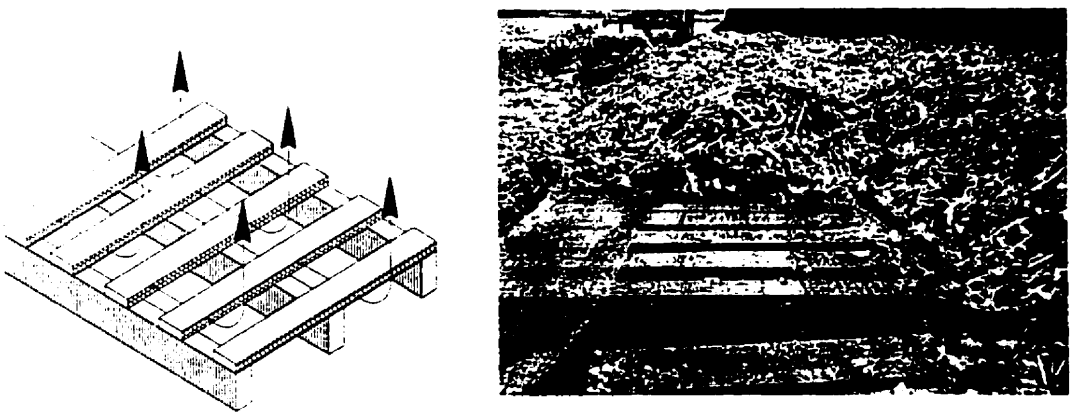


Fig. 3.3 Standard shipping pallet used for air plenum

woodchips and compost from falling through the pallet slat spacing. Airflow was directed from the barn exhaust fans through booster fans (see description in section 3.7). Sealed plywood ducts directed the air into the biofilters. A schematic of the layout is shown in Fig. 3.4. Polyethylene was wrapped around the outer portion of the exterior pallets to prevent blowout of the medium at the edges and the subsequent short circuiting of the airflow through these openings.

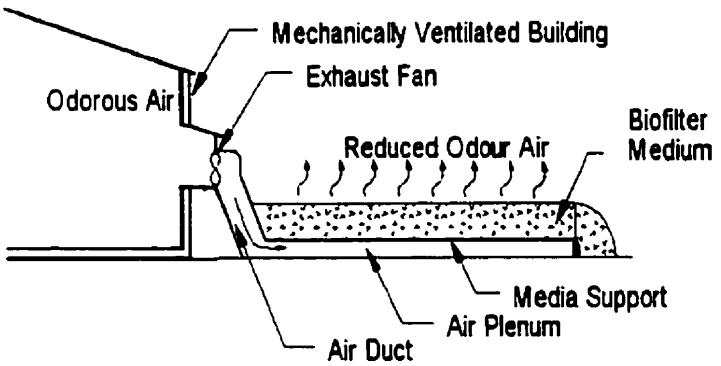


Fig. 3.4 Biofilter for mechanically ventilated agricultural buildings (modified from Nicolai 1998)

3.5 Pallet Arrangement

Two of the biofilters had a pallet arrangement similar to the system used by Nicolai and Janni (1998) in which pallets were placed directly on the ground (referred to herein as "standard biofilters") (Fig. 3.5). The remaining two biofilters were designed to improve initial air distribution across the width of the filter bed. These biofilters, referred to as "modified biofilters", had a transition zone where the air was spread across the width of the biofilter prior to contact with filter material (Fig. 3.6). Additionally, these biofilters had a larger cross-sectional area at the inlet which decreased along the length of the biofilter, decreasing pressure losses associated with air travelling through long narrow

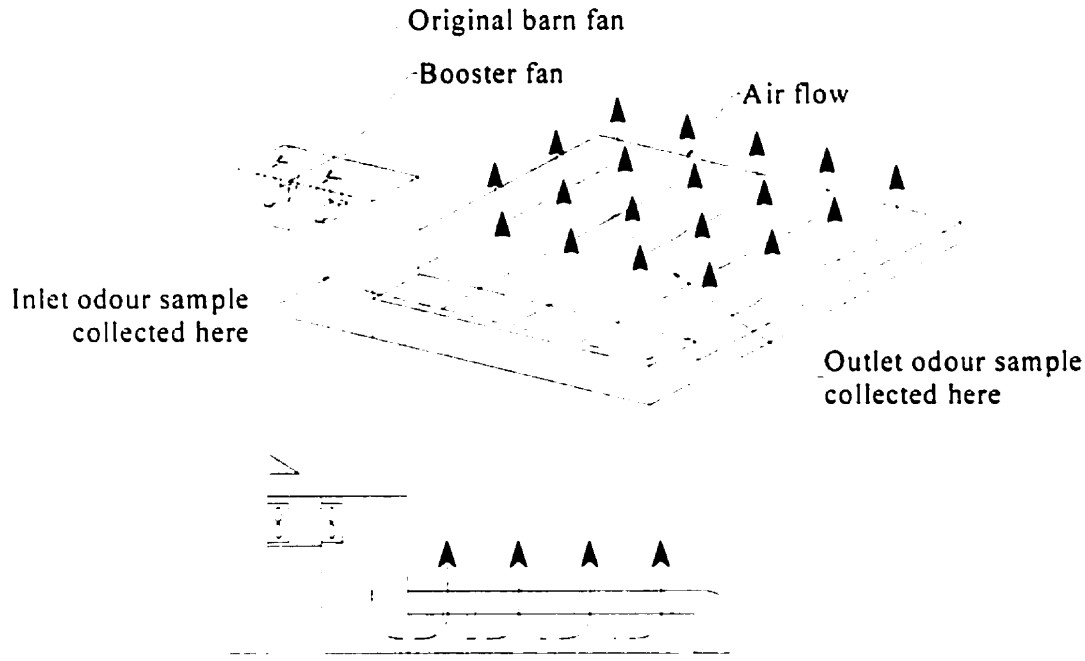


Fig. 3.5 Schematic of "standard biofilter" layout

passages. The larger inlet cross sectional area was provided by raising standard shipping pallets on wooden legs. This design was also selected because Boyette (1998) found that symmetrical air distribution helped to minimized the development of short-circuiting channels in the biofilter bed.

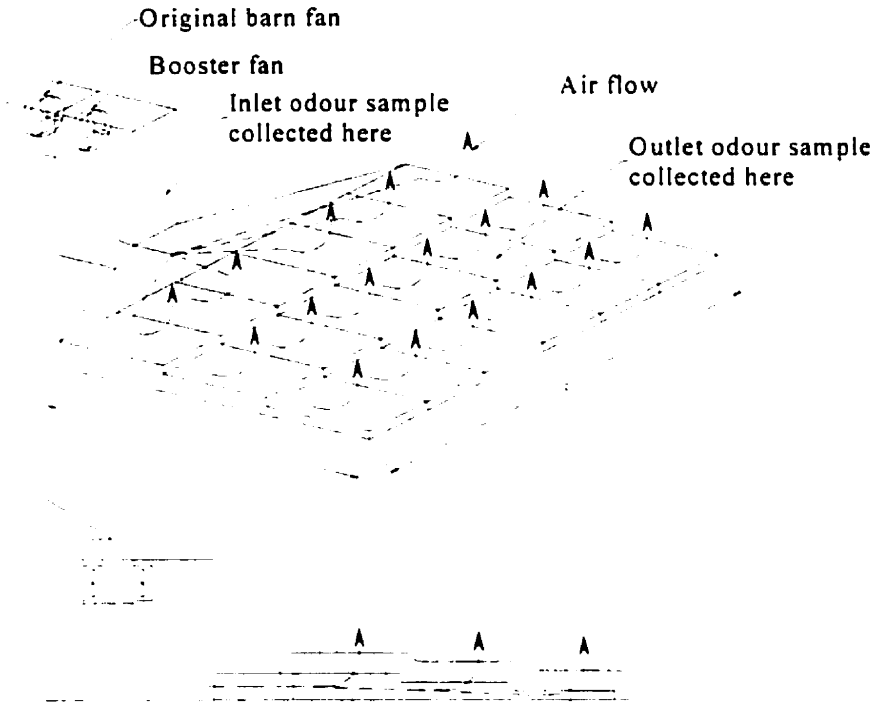


Fig. 3.6 Schematic of "modified biofilter" layout

3.6 Woodchip/Compost Mixtures

The pressure losses and odour removal characteristics of two woodchip/compost (w/c) mixtures were analysed. A 50%/50% ratio (by mass) w/c mixture was used on two biofilters

(as per Nicolai and Janni 1998), and a 75%/25% w/c mixture was used on the two remaining biofilters. Each mixture was placed on one standard pallet biofilter, and one modified biofilter for comparison. The woodchips and compost were mixed using a total mixed ration (TMR) mixer and a front end loader. Table 3.3 shows which mixture was associated with each biofilter.

Table 3.3 Biofilter pallet structure and woodchip/compost mixture

Biofilter #	Pallet structure	Woodchip/compost mixture (percent by mass)
BF1	Modified	50%/50%
BF2	Modified	75%/25%
BF3	Standard	50%/50%
BF4	Standard	75%/25%

3.7 Biofilter Dimensions

The biofilter bed dimensions were based on the contact time of the air in the biofilter, the exhaust fan ventilation rate, the airflow characteristics of the filter medium, the available pallets used in the bed support structure, and the space available around the barn. Appendix A outlines the design calculations. A bed depth of approximately 350 mm was selected based on Nicolai (1998). The fan pressure available permitted a static pressure drop of 30 Pa across the filter medium. This was achieved by placing identical "booster" fans in series with the existing Stage 1 fans. The fans were 0.37 kW, 2.5 Amp, 0.51 and 0.61 m diameter (different sizes for 2 of the rooms), 3-wing K-blade axial fans (Leeson, Toronto, ON). The predicted EBCT was 5 s. The resulting dimensions of each biofilter are shown in Table 3.4.

Actual dimensions varied from calculated dimensions based on available pallet sizes, and limitations in space around the barn. BF4 was especially narrow and long because of the space restrictions beside the parking pad on the north side of the barn.

Table 3.4 Landmark biofilter dimensions

Biofilter	Length (m)	Width (m)	Airflow (m^3/s)
BF1	8	4.8	2.60
BF2	7.3	5	1.88
BF3	6.5	5.5	1.88
BF4	10.4	4	2.60

3.8 Water Application

3.8.1 Sprinklers Water application was achieved using common lawn sprinklers set on timers. Water was applied for 90 minutes every morning at a rate of approximately 0.4 L/s. Sprinklers applied water beyond the edges of the biofilters to compensate for changes in the sprinkling pattern caused by the wind. Thus, not all the sprinkler water was actually applied to the biofilter surface. Water application ceased in the first week of October when heavy frost cracked a plastic hose fitting.

3.8.2 Moisture monitoring In an attempt to automate moisture application to correspond to the moisture content of a large portion of the biofilter bed, moisture monitoring based on the mass of the filter material was attempted. Loadcells were placed under the filter bed to monitor the mass of a portion of filter material. It was theorized that as the filter bed dried, the mass would decrease. Moisture application would be initiated when the mass of the

material changed by a set amount below the saturation mass. Since biofilter operation ceased prior to the spring of 2000, insufficient data was collected to permit meaningful discussion of this technique. Moisture samples were collected and oven dried (see description below).

3.9 Measurement Procedures

3.9.1 Odour measurement Odour reduction was measured by comparing the odour dilution to detection threshold (D/T, also referred to as odour concentration) of the air entering and leaving the biofilter. The concentration (indicated in odour units, OU) is a ratio of the volume of odour-free air to odorous air, where the volume of odour-free air is the volume required to dilute the odorous air sample to the point that only 50% of a group of panellists are able to detect the odour (European Committee for Standardization 1999). The odour concentration was measured using a dynamic dilution olfactometer (AC'SCENT® International Olfactometer, St. Croix Sensory, Stillwater, MN). Odour samples were collected in 10 L Tedlar bags. Odour samples were collected in the duct entering the biofilter for inlet conditions, and using a collection hood on the surface of the biofilter for outlet conditions (Fig. 3.3). The collection hood is described in section 3.9.4. Odour samples were presented to a group of screened panelists within 24 h of collection.

3.9.2 Ammonia and hydrogen sulfide measurement Ammonia concentrations in the air were collected at the same locations as the odour samples. Ammonia was measured using a Gastec gas sampling pump (Gastec Hand Pump 7013113-1, Gastec Corporation, Ayase-City, Japan) and colorimetric tubes (Gastec no. 3L ammonia tubes (0.5-78ppm). The Gastec tubes

had a detecting limit of 0.2 ppm.

Hydrogen sulfide concentrations in the air were collected at the same locations as the odour samples. Hydrogen sulfide concentrations in the air were measured using a Jerome Meter (Jerome 631-X Hydrogen Sulfide Analyzer, Arizona Instrument Corporation, Phoenix, AZ). The Jerome Meter had a detecting limit down to 1 ppb.

3.9.3 Frequency of odour and odorous gas measurement Odour and odorous gas levels were measured once per month. The biofilters had been operational for one month prior to collecting the first odour samples in September, 1999 in order to ensure that a microbial community was established. Hydrogen sulfide was measured in January, when the Jerome Meter was first purchased, and again in February. Ammonia was measured in September and October, and again in January and February when hydrogen sulfide could also be measured. The biofilters were shut down at the end of February 2000 due to complications at the production facility.

3.9.4 Surface airflow measurements The airflow leaving the surface of the biofilter (surface loading) was measured using a large funnel-like hood (Fig 3.7). The hood was placed on the surface of the biofilter and biofilter exhaust air was allowed to pass through the hood for 60 s prior to sampling to ensure that only exhaust air was present in the hood. The design of the hood ensured that contamination by outside air was minimized. Odour and gas samples were collected directly above the cone section, while airflow measurements were

taken at the top of the pipe section. The pipe section was sufficiently long (10 times the diameter) to allow the development of laminar flow. Air velocity measurements taken in the pipe section were 100 times greater than the surface airflow rate (because of the dimensions of the cone and tube). Airflow rates were measured in the pipe using a hotwire anemometer.

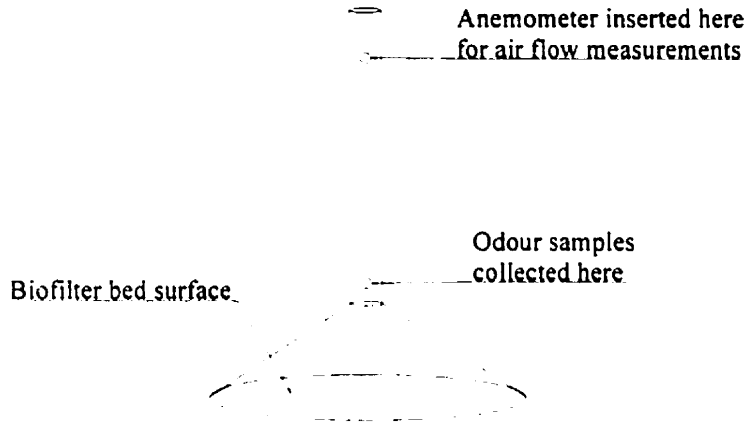


Fig. 3.7 Airflow sampling hood

3.9.5 Temperature measurement The biofilter bed temperature was recorded in the two south-facing biofilters (BF1 and BF2). T-type (copper-constantin) thermocouples were placed at three depths in two locations on each biofilter (Fig. 3.8). The depths were: 50, 175, and 350 mm below the surface of the biofilters (thermocouples T1 and T4, T2 and T5, T3 and T6, respectively). Another thermocouple recorded the inlet air temperature (T7). Ambient temperature was recorded 3 m south of the barn, 1 m above ground. The thermocouple was not shaded and black body radiation from the ground may have affected ambient temperature

readings (there was only thin snow cover in December, and snow cover at the location was not recorded).

Temperature was recorded over two periods: November 26, 1999 to December 15, 1999, and January 7, 2000 to January 26, 2000. Temperature was supposed to have been recorded throughout the life of the biofilters, however difficulties with the data acquisition system resulted in data being collected for only two recording periods. Temperatures were recorded every 30 seconds.

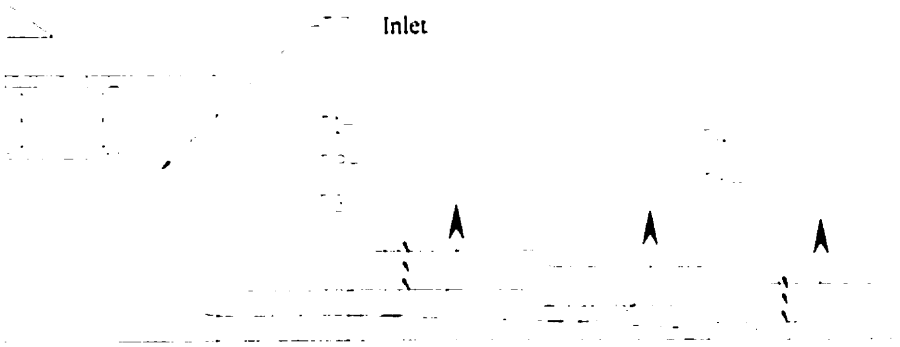


Fig. 3.8 Thermocouple placement in the biofilter bed

3.9.6 Moisture measurement

Biofilter media samples were collected at the location of odour sampling. Media samples were collected at 3 depths (similar to temperature measurements) to gain an understanding of the overall filter moisture conditions. The samples were oven dried at 130°C for 48 h.

3.10 Cost

The cost to construct the four experimental biofilters was approximately $5000 (Table 3.5). This cost does not include data acquisition equipment. It is estimated that if a producer constructed a full scale biofilter which treated all of the barn exhaust air, the cost might range from $5000 - $10 000 for a 500-hog finisher barn (equivalent to a ventilation rate of approximately 250 m^3/s (50 000 cfm)). Any type of monitoring equipment or controllers would add to the cost. Labour costs (construction, electrical) were not included in these estimates.

Table 3.5 Approximate costs of experimental biofilter construction

Material	Cost
woodchips	$1000
compost	$700
fans	$1800
duct and construction materials	$750
hoses, sprinklers, timers	$250
equipment rental	$400

4. RESULTS AND DISCUSSION - BIOFILTRATION IN LOW TEMPERATURES

4.1 Biofilter Bed Temperature

4.1.1 Measured bed temperature The results of temperature monitoring at the Landmark biofilters demonstrate that the biofilter bed temperature was maintained in a range suitable for elimination of odorous compounds throughout the winter. The daily minimum and maximum ambient temperatures, and the minimum and maximum of the mean biofilter temperatures are shown in Figs. 4.1 and 4.2 for the two measurement periods (note: the mean biofilter temperature denotes the mean of the readings at the 3 depths for all locations). Additionally, the maximum and minimum temperatures for each day at any location (noted as "specific biofilter location minimum or maximum") are indicated. The minimum and maximum recorded temperatures in the biofilters over the two recording periods were 10.9 and 22.2°C. The mean biofilter bed temperature was 16.3°C. The minimum and maximum recorded ambient temperatures over the two recording periods were -34.2 and 9.2°C. The mean recorded ambient temperature over this same periods was -7.7°C.

According to the producer, the temperature in the barn was maintained at approximately 20°C. The barn exhaust air passing through a biofilter will typically be maintained between 15 and 40°C (depending on the management practice of the barn and the outdoor temperature). This warm exhaust air, in conjunction with sunlight shining on the uncovered biofilter surface combined in this case to maintain the bed temperature in the range indicated above.

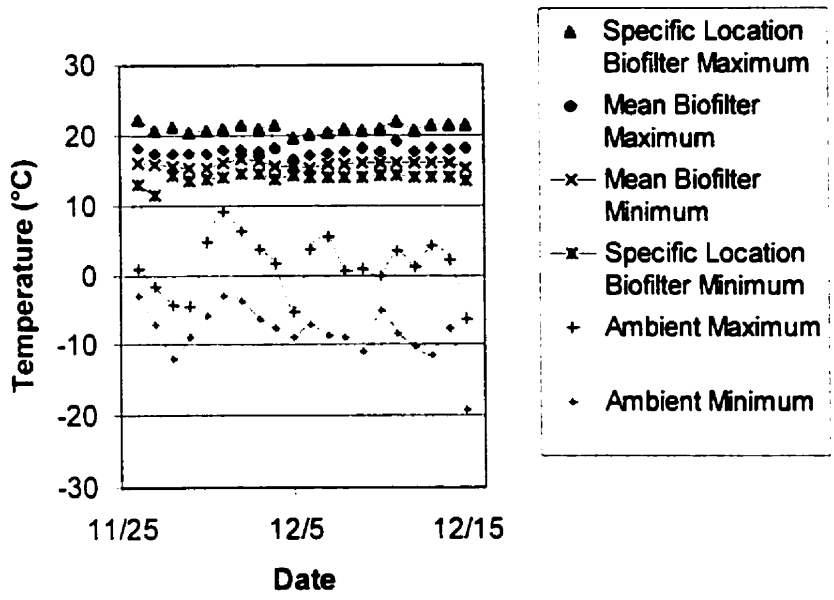


Fig. 4.1 Daily maximum and minimum ambient and average biofilter bed temperatures in November and December 1999

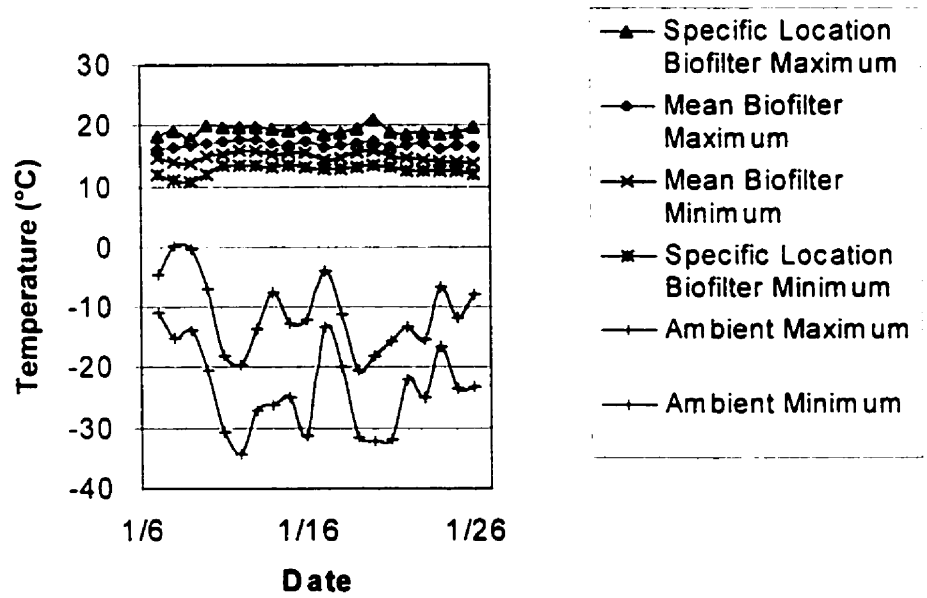


Fig. 4.2 Daily maximum and minimum ambient and average biofilter bed temperatures in January 2000

Based on observations, the majority of the biofilter surfaces remained snow-free as a result of snow melting on the warm filter bed surface. During periods of extreme cold and high winds, some snow drifting was observed. When drifting occurred, airflow channels remained open in the snow drifts.

During a period of extreme cold at the end of December when the daytime and nighttime ambient temperature remained below -20°C for over a week, low airflow and ice crusting were observed at the ends and edges of the biofilters furthest from the fans. Unfortunately, the data acquisition system for temperatures was not in operation during this period of time. Visual observation at a later date showed that normal airflow had resumed and the ice crust had melted, presumably once the period of extreme cold ended. Figure 4.2 shows that even at the coldest ambient temperature recorded (-34.2°C on January 12, 2000) there was no noticeable change in the average biofilter temperature.

4.1.2 Odour level reduction during cold weather Odour measurements taken at the end of December, 1999 resulted in a mean reduction in odour concentrations of 79%even though the daytime and nighttime ambient temperature had remained below -20°C for over a week prior to collecting the samples. Similarly, the odour measurements taken at the end of January resulted in a 78% reduction in odour emissions. This demonstrates that biofiltration is a viable technique for odour reduction at temperatures below -20°C .

4.2 Reduction in Odour Concentration

Over the entire odour collection period (September 1999 through February 2000), odour levels in the air entering the biofilters (inlet air) ranged from 464 to 3036 OU with a mean of 1406 OU (Fig. 4.3, note: the figure shows the mean of the monthly readings for all four biofilters). Odour levels in the air leaving the biofilters (outlet air) ranged from 45 to 785 OU with a mean of 322 OU. The results for the individual biofilters are presented in more detail in section 4.8. The mean reduction in odour concentration was 76%. A summary of percent reduction in odour concentration for each biofilter shows that the monthly odour reduction for individual biofilters ranged from 56% to 94% (Table 4.1). Odour panel data for each measurement are found in Appendix B.

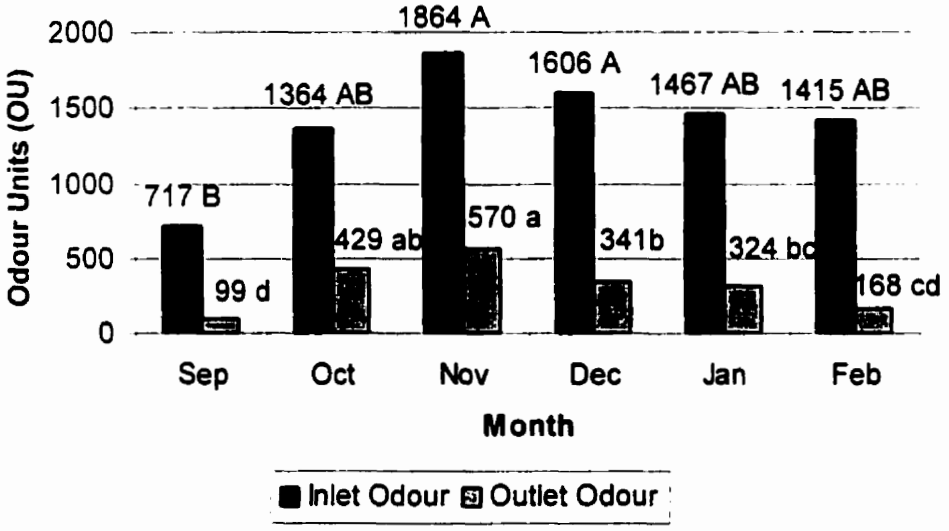


Fig. 4.3 Monthly mean of all four biofilters' odour concentrations for inlet and outlet air. Letters indicate significant differences, based on analysis of variance of individual monthly data ($\alpha = 0.05$ level (SAS 1985)). Capital letters refer to inlet odour levels. Small letters refer in to outlet odour levels.

Table 4.1 Monthly percentage reduction in odour concentration for each biofilter

Biofilter #	% reduction in odour concentration					
	Sep	Oct	Nov	Dec	Jan	Feb
BF1	85	66	84	92	85	94
BF2	92	77	72	60	76	79
BF3	67	61	56	65	66	90
BF4	92	66	64	73	79	85

4.3 Reduction of Ammonia Levels

The mean ammonia concentrations for the four biofilters are shown in Fig. 4.4. The individual monthly ammonia concentrations in the inlet air ranged from 2.3 to 14.3 ppm with a mean of 8.3 ppm. Ammonia concentration in the outlet air ranged from 0 to 2.0 ppm, with a mean of 0.4 ppm. The mean reduction in ammonia concentration was 96%.

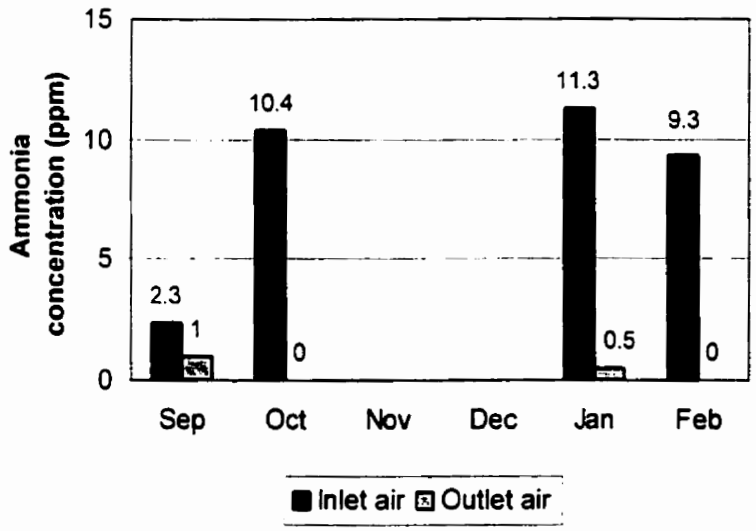


Fig. 4.4 Mean inlet and outlet ammonia concentrations

4.4 Reduction of Hydrogen Sulfide Levels

The mean hydrogen sulfide concentrations for the four biofilters are shown in Fig. 4.5. The

hydrogen sulfide concentration in the inlet air ranged from 0.32 to 1.1 ppm with a mean of 0.65 ppm. The hydrogen sulfide concentration in the outlet air ranged from 0.02 to 0.17 ppm with a mean of 0.085 ppm. The mean reduction in hydrogen sulfide concentration was 87%.

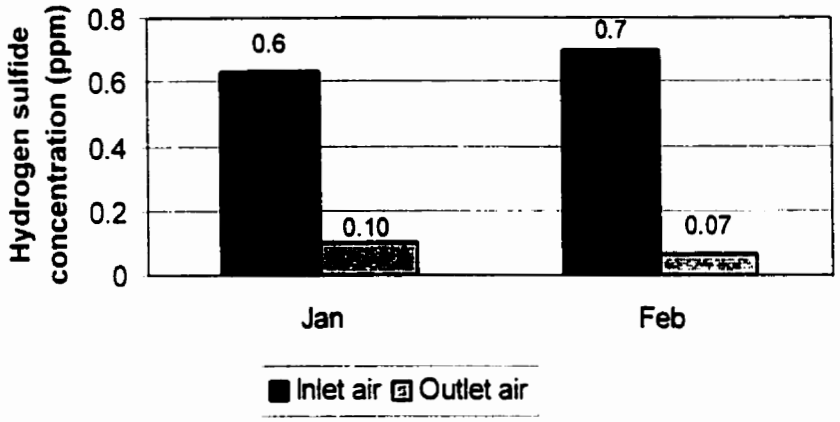


Fig. 4.5 Mean hydrogen sulfide concentrations of air entering and leaving the biofilters

4.5 Retention Time and Airflow

4.5.1 Retention time based on inlet airflow Odour reduction is based largely on retention time. Measurements of airflow at the inlet of each biofilter (i.e., in the barn at the fans which blew into the biofilter ducts) were taken in October to determine actual retention times (Table 4.2). It was found that for all biofilters, less air was entering the biofilters than was intended in the original design. A review of the biofilter construction revealed a larger pressure drop in the air ducts than was originally accounted for. The result was that between 37 and 52% of the design airflow was actually entering the biofilters. This corresponded to a modified EBCT for the air passing through the biofilters of 10 to 12.5 s, instead of 5 s. The expected

result was improved odour reduction. The downside of this situation was that barn ventilation was adversely affected. Since only one ventilation fan was being affected per room, it was decided, in conjunction with the producer, that for this experimental set-up the reduced airflow was not a concern.

Table 4.2 Measured airflow into each biofilter (October, 1999)

Biofilter	Airflow (m^3/s) Design	Measured	% of design airflow
BF1	2.55	0.96	37.6
BF2	1.85	0.78	42.0
BF3	1.85	0.85	45.9
BF4	2.55	1.33	52.2

4.5.2 Retention time based on surface airflow Calculation of the retention time based on surface flow rates (measured with the airflow hood) resulted in different calculated EBCT values (Table 4.3) than for the retention times calculated from the inlet airflow. While the inlet airflow measurements indicated that there was approximately a 10 - 12.5 s EBCT, the measurement of surface airflow at specific locations indicated an EBCT ranging from 41 to 74 s (for October, the only month for which we have both data sets). This difference is substantial! There are several factors which likely influenced this:

1. The procedure used in selecting the location of surface airflow measurements was not very good (in hindsight). Airflow measurements (and odour measurements) were taken away from locations which appeared to exhibit short-circuiting or were dried out. Thus, only low airflow rate (i.e. high retention time) locations were selected.
2. Short circuiting due to rodent holes was a problem until poison was placed

on-site. When short-circuit channels develop, airflow through the remaining biofilter bed would decrease. Thus, the amount of air measured on the surface of the biofilter would not correspond to the airflow into the biofilter at the inlet fan. Airflow measurements taken subsequent to the application of poison and the filling of rodent holes in early November resulted in increased airflow through the filter bed, and decreased retention times (Table 4.2).

3 Compaction in specific areas due to walking on the filter bed likely impacted airflow. With odour samples and airflow measurements conducted repeatedly in the same spots, high compaction may have occurred. At the time, it was felt that increased compaction was not a significant issue because the biofilters were only going to be operated for one year. Hindsight indicates that this may not have been an appropriate attitude. This impact would likely only be seen in the later measurements.

Table 4.3 EBCT (s) calculated from the mean of measured surface airflows

	EBCT (s)				
Month	BF1	BF2	BF3	BF4	Monthly Average
Aug	18	15	18	16	17
Sep	62	56	51	89	64
Oct	41	55	74	59	57
Nov	22	18	23	19	21
Dec	21	35	39	23	30

4.5.3 Impact of reduced airflow on retention time The actual airflow into the biofilters was decreased in mid-November when the producer requested that the booster fans be turned off over concerns that the fans were sucking too much air out of the barn at certain times.

This was because depending on the temperature in the barn, the Stage 1 fan airflow rates sometimes decreased below the required "minimum" ventilation rate. At the same time, the booster fans were configured to simply run full power, all the time. Following shutdown of the booster fans, actual airflow through the biofilter varied with the barn temperature. Anticipating that proper biofilter function might not be resumed until spring, airflow measurements ceased after December. It was assumed that biofilter operation would continue into the spring and summer. Thus, no airflow data was collected for January and February.

In February, the producer requested that the biofilters be shut down and the ducts removed from the fans. Thus ended the Landmark biofilters. Unfortunately, a complete airflow profile of each biofilter bed was not conducted prior to shut-down to demonstrate how the biofilters were performing with respect to airflow.

4.5.4 Moisture content Another theory as to why the calculated EBCTs were so high relates to moisture content (m.c.) and drying of the biofilter beds. Sprinklers were removed from the biofilters in early October when nights began to get well below 0°C. Daytime temperatures sometimes still reached the high teens during this period. The result (based on visual observation) was that the biofilters became dry. If drying of the filter bed resulted in opening of pore spaces previously clogged when moisture was abundant, the result would be an increase in airflow through the filter bed, and decreased retention times (as indicated in Table 4.3). While this theory makes sense, the high retention times at the end of October can not be explained in this way.

Although not a good explanation for high retention times, this drying might explain the higher outlet odour levels in October and November, when water stress would have affected the ability of microbes to eliminate odorous compounds. Once temperatures became cold in December, moisture in the inlet air from the barn would more readily condense in the filter bed. The result would likely be an increase in biological activity and thus a decrease in outlet odour values for December and onwards (as was observed, Fig. 4.3).

While this theory is supported by visual observations of the biofilters (which indicated considerable drying and short circuiting in October and November), it is not supported by actual moisture measurements. The moisture samples collected (Table 4.4) indicate that the m.c. of the filter material varied little from month to month. Moisture content was measured from samples of filter material taken only at the location selected each month for odour sampling. Since, as mentioned previously, odour samples were taken at locations which appeared (visually) to be least affected by short-circuiting, it is likely that the m.c. measured was not representative of the m.c. of the whole bed.

Moisture samples were only collected at one location on each bed because it was intended that m.c. would be determined using loadcell data (as discussed in section 3). However, this technique could not be validated prior to shutdown in February, and thus sufficient data was not collected to understand the moisture characteristics of the entire biofilter bed.

Table 4.4 Moisture content at airflow sampling locations on each biofilter

	Moisture content (% wet basis)						
Biofilter	Sep	Oct	Nov	Dec	Jan	Feb	Average
BF1	45	52	65			56	54
BF2	60	61	64			66	63
BF3	59	63	60			63	61
BF4	63	66	65			65	65

Thus, no firm conclusions can be drawn about why the measured retention times varied, based on the moisture data. Additionally, moisture data does not support theories about drying and increased airflow. Thus, no conclusions will be made in this area. Additionally, the odour reduction data must be considered in light of the lack of understanding about the actual airflow in the biofilters.

4.6 Monthly Changes in Odour Reduction

In spite of the varying airflow, the percentage reduction in odour was fairly constant from month to month, with a standard deviation of 12 for the mean reduction of 77 % (Table 4.1). These results do vary, however, and it is difficult to determine exactly which factors influence the changes. For instance, the actual retention time of the air varied from month to month, as discussed above. However, the data is inconclusive in demonstrating a connection between recorded monthly retention times and residual outlet odour.

It is apparent from Fig. 4.3 that for higher inlet odour levels, the outlet air was also more odorous. The high inlet odour levels may have resulted in incomplete biodigestion, thus resulting in high outlet odour levels. If the microbial community was undergoing water-stress

(as discussed above) and was presented with a heavy loading of odorants, it is conceivable that the result would be incomplete bio-oxidation of odorous compounds. This is speculation only.

Alternately, the nature of the odorant may have been different, specifically for the November inlet odour measurement (which was higher, although not significantly higher than subsequent data points at the $\alpha = 0.05$ level (SAS 1985)). The November measurement was taken 3 weeks after a new batch of weanlings arrived. The nature of the odorous compounds would likely be different because the different feed and digestion processes of young pigs, and because of aging of the manure slurry in the central collection pit. The volume of waste generated by young pigs is very small (compared to large animals), so the central collection pit was pumped much less frequently and the manure in the pit aged more before being pumped. Thus, odorous compounds associated with aging manure were entering the biofilter, as opposed to compounds from relatively fresh manure. This, in conjunction with water-stress could also have contributed to the high odour levels in November.

However, stage of pig growth does not seem to influence odour levels when the pigs are older. When the October measurements were taken, the pigs were at week 15 in a 17 week cycle (i.e. very large animals), producing large quantities of fresh manure. The inlet and outlet odour levels for October were not significantly higher or lower statistically than the other months, in spite of the size of the pigs.

4.7 Minimum Outlet Odour Concentration

Although the monthly mean outlet odour levels from the Landmark biofilters were significantly different from each other (at the $\alpha = 0.05$ level), the mean value of 322 OU (with a sample standard deviation of 188 OU) was high compared with a similar study (Nicolai and Janni 1999). Additionally, as stated above, the mean reduction in H_2S concentration was 87%. At the high retention times occurring in the biofilters, other researchers have found 94-100% reduction in H_2S levels (Yang and Allen 1994). This could be an indication that incomplete treatment of air occurred. Based on the relatively high outlet odour levels observed, several questions were raised:

- In spite of high retention times, did the high outlet odour thresholds occur because the biofilter media material and associated microbial community could only be expected to reduce odour to a certain level?
- Was incomplete treatment of the air occurring (as suggested by the H_2S readings)?
- Was there an odour in the barn air which could not be eliminated by the biofilter?
- Or, does the filter media and associated resident microbial community emit an odour corresponding to the minimum odour levels detected?

The latter was deemed to be the most likely. Nicolai and Janni (1999) found that biofilter exhaust air had a minimum odour concentration associated with the woody/compost-like outlet smell. However, they had outlet odour levels below 100 OU, while those at the Landmark biofilter were much higher. No further research about the residual odour of biofilter media was found in the literature. Thus, the research conducted at the University of Manitoba Glenlea Research Station during the summer of 2000 sought to answer some of

these questions. The experimental procedure and results of this research are found in sections 5 and 6 of this thesis.

4.8 Airflow Layout and Media Mixtures

4.8.1 Differences in odour reduction The average odour reductions for the four different biofilter airflow configurations are shown in Table 4.5. If it is assumed that the changes in conditions (related to airflow and moisture) affected the biofilters in approximately the same manner. it can be assumed that the differences in biofilter layout and media mixtures can be compared.

Table 4.5 Odour concentration reduction (%) for different configurations of airflow and woodchip/compost mixtures (with analysis of variance at the $\propto$=0.05, level based on monthly odour reduction)

Airflow configuration	Woodchip/compost ratio (by mass)	Biofilter number	Odour reduction (%)
Standard	75/25	BF4	76 b
Standard	50/50	BF3	68 ab
Modified	75/25	BF2	76 ab
Modified	50/50	BF1	84 a

When considering odour reduction, the Modified 50/50 (BF1) configuration had considerably higher odour reduction (although not statistically so at the $\propto = 0.05$ level). Additionally, Fig. 4.6 shows that although inlet odour levels were considerably higher in BF1 (although not statistically significant), the outlet odour level was the lowest (although again not significantly different). The individual monthly inlet and outlet odour concentrations for each biofilter are shown in Fig. 4.7 for comparison. Although not conclusive, the higher inlet and lower outlet levels for BF1 may imply that this design is superior to the other configurations (i.e. the other

combinations of mixture and airflow layout). In light of the changing airflow conditions, however, caution should be exercised when making conclusions purely based on the odour data.

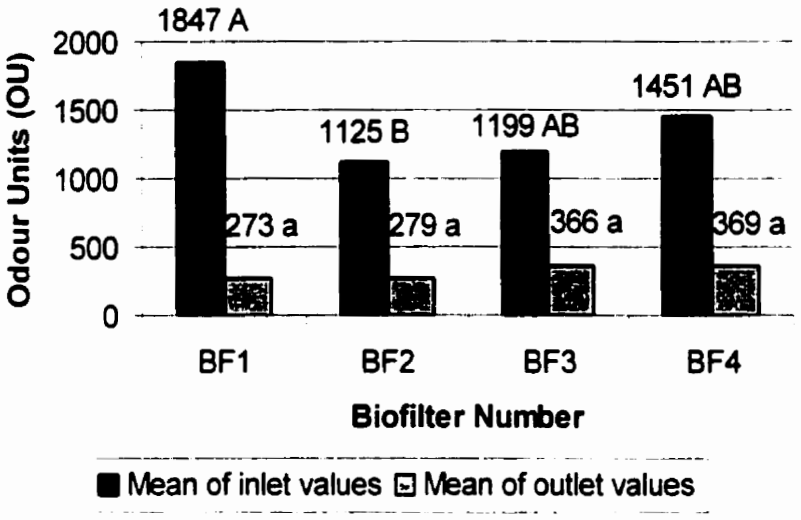


Fig. 4.6 Mean odour concentrations of different biofilter configurations. Letters indicate significant differences, based on analysis of variance (α=0.05) of individual monthly data. Capital letters refer to inlet odour levels. Small letters refer in to outlet odour levels

4.8.2 Airflow and short-circuiting Additional support for the contention that the BF1 design (Modified 50/50) was superior can be found in on-site observations. It was apparent that there was poor airflow through the filter bed in the Standard design biofilters at the furthest part of the bed away from the fan (i.e. at the end of the filter bed). For the long, narrow filter bed on BF4 for example, snow crusting covered the last 1 m of the bed length throughout much of the winter, indicating that very little warm air was circulating through the media at the extreme length. Airflow measurements at the end of the bed were not taken

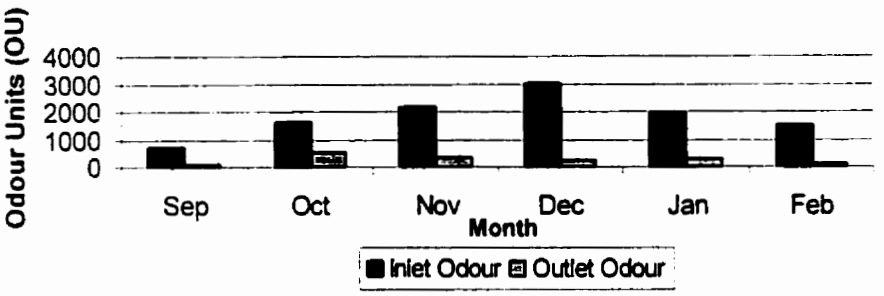


Fig. 4.7a Monthly inlet and outlet odour concentrations for BF1

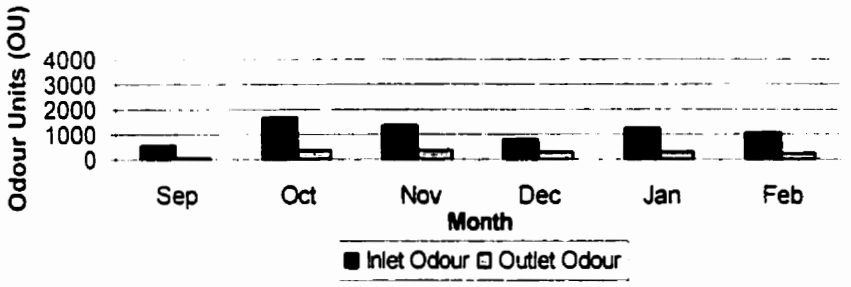


Fig. 4.7b Monthly inlet and outlet odour concentrations for BF2

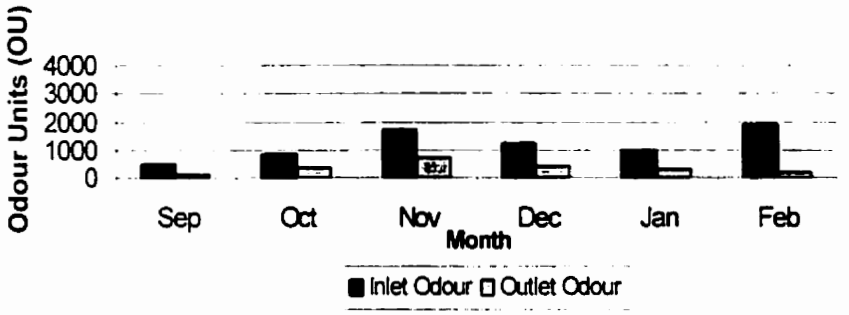


Fig. 4.7c Monthly inlet and outlet odour concentrations for BF3

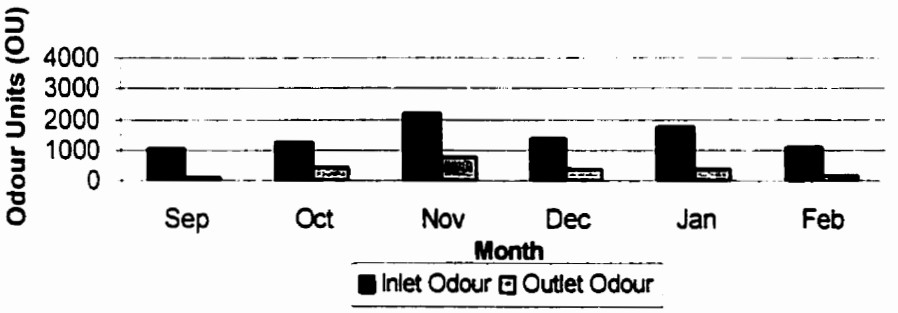


Fig. 4.7d Monthly inlet and outlet odour concentrations for BF4

in February prior to the unexpected shut-down, thus this observation can not be quantitatively supported.

4.8.3 Dust accumulation When the biofilters were taken apart, the Standard design biofilters were found to have significant build-up of dust in the first 1 m of filter media adjacent to the air inlet box. This thickly-caked dust almost certainly impeded airflow, although no airflow measurements were taken in that immediate area prior to disassembly. Once clogging of the pore space with dust occurs, it may be possible to unclog the pores by flushing the biofilter with large volumes of water. However doing so may result in washing away fine particles or the microbial community.

The larger initial contact area between the incoming air and the filter media surface associated with the Modified design resulted in less noticeable caking or accumulation of dust. Differences in dust levels in the air coming into each biofilter (from different rooms of the barn) may have contributed to dust accumulation and clogging; however, dust levels were not monitored because they were not expected to vary since all rooms were operated in the same manner.

Thus, based on a considerably larger reduction in odour concentration, coupled with better airflow behaviour and decreased dust clogging, the Modified 50/50 design was the best design of the four airflow/media mixture combinations.

4.9 Weed Growth

Weed growth at the Landmark biofilters was not a significant problem because the biofilters only ran for two months before sub-zero temperatures became common. For the weeds that did grow, it was found that significant clumping of filter media occurred in the roots. Additionally, it is likely that root growth clogged pore spaces. The result was likely decreased airflow, although this was not quantitatively measured.

4.10 Producer Difficulties

From the outset, the circumstance surrounding where the biofilters were constructed were not ideal. The producer was not convinced that the odour emissions from his barn were a concern (he had never received a complaint about odour from neighbours). He was also not interested in possible media exposure, not wanting to draw any negative attention to his operation. Thus, he was somewhat sceptical and perhaps suspicious about the biofilters, and was a reluctant participant in the process.

From the outset, we assured the producer that if he had concerns that the biofilter was negatively impacting his operation, we would shut down the biofilters. Thus, when difficulties arose (as they usually do in research), he was quite eager to shut down the biofilters. He did exhibit a fair bit of patience at the beginning of the experiments, but ultimately decided that it was too much of a worry for him. A power failure (which the producer's electrician assured us was not caused by our biofilters) resulted in the exhaust fans in one room shutting down. This is a potentially fatal situation for a hog barn. It is important that for future

research that control systems for the biofilter should either be entirely stand alone (in terms of electrical systems and fan operation), or be fully integrated into the existing electrical system so that concerns over power draw and blown fuses can be addressed. It is also important for the participating producer to be keenly interested in the technology.

4.11 Sources of Error

4.11.1 Construction errors Poor mixing of the biofilter media would have resulted in differences in filter material composition. This likely resulted in differences in biofilter function across the filter bed. Airflow differences across the filter bed could be associated with different blends of material. Better mixing prior to application could solve this problem.

4.11.2 Odour panel error Any conclusions based on odour panel results must be taken in light of the fact that some error exists based on differences in panellists' odour perceptions. The more panellists used per sampling period, the increased confidence possible for that sample. The panels had only six participants. Typically odour panels have six to eight panellists, so for these experiments, we used the minimum.

Additional error is associated with having different panellists for the samples from each month. Although all panellists were screened to have neither a high nor low odour detecting ability, there are variations for each panellist. Ideally, the same panellists would have been used each month. This did not occur.

4.11.3 Poor airflow characteristics The airflow rate measured is the average of all airflows entering the collection hood. If the airflow rate measured through the hood consisted of some air moving through a short-circuit along with other air which had moved through a dense, packed portion of the filter material, the airflow rate measured might have been the same as another section where airflow was consistent throughout the filter material under the hood. In general, airflow was measured where there was no obvious short-circuiting for this reason. Unfortunately, the result was a skewing of airflow data in favour of slower values.

Airflow measurements were often very difficult to collect when wind speeds were high because of a suction effect at the end of the funnel. Readings would often fluctuate wildly. A covering hood for the sampling hood was devised to minimize this effect, but it was not eliminated entirely.

Additionally, odour samples were collected over roughly the same parts of the filter bed. These areas would have experienced more walking and thus packing than other portions of the filter bed (as mentioned previously). Since a complete mapping of airflow characteristics was not conducted prior to shutdown, it is impossible to verify whether this occurred.

4.11.4 Lack of replication In order to ensure a collected sample is not anomolous (i.e. due to faulty or superior design, or unusual behaviour), typically three replicate samples are collected at the same time. Thus, 3 similar biofilter setups should have been constructed for each airflow and media mixture. Because this did not occur, it is impossible to isolate the

effect of poor construction, faulty mixing, poor airflow, or short-circuiting for each biofilters tested.

It should be noted that when considering the statistical differences discussed throughout this section, that these results were not reproduced over three replications. Thus, the differences are based only on the results of one replication. The assumption was made that monthly measurements can be considered as replications over time. This, however, may not be valid, as long-term changes in biofilter operation occurred.

In terms of replication for odour measurements, the use of six panellists on a fairly large sample of material (a 10 L bag of air) is assumed to be sufficient to not require replication of individual samples. However, there is no way of knowing whether an air sample was collected over a "bad spot" on the filter bed which had poor or exceptional performance.

For ammonia and hydrogen sulfide measurements, three replicates were taken at each point and the mean of the three samples was used.

5 MATERIALS AND METHODS - RESIDUAL MEDIA ODOUR

5.1 Background to Biofilter Media Material Odour

Section 4.7 of this report outlines how the odour detection threshold of the outlet biofilter air from the Landmark biofilters was higher than expected based on previous research (Nicolai and Janni 1998; 1999). The biofilter outlet air had a distinctly earthy or musty smell. The owner of the Landmark barn identified the smell as an undesirable odour. Thus, while the biofilters eliminated the normal swine facility odour and decreased the odour detection threshold of the barn emissions, they were modifying on-site odour.

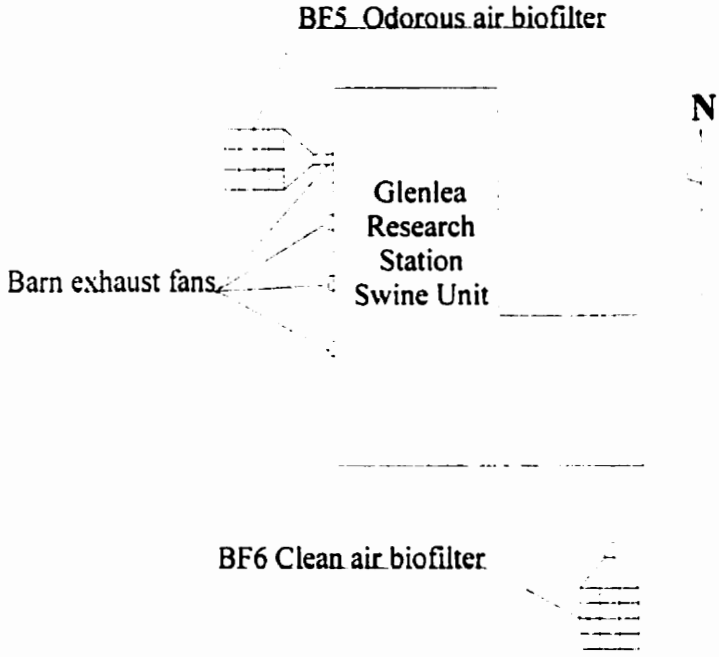
The objective of this portion of the project was to determine whether the biofilter media material was responsible for a residual odour at the biofilter outlet. Additionally, different blends of filter media material were observed to determine whether they had different effects on residual odour emissions.

5.2 Location

Two experimental biofilters were constructed in May, 2000 at the University of Manitoba Glenlea Research Station swine unit (Fig. 5.1). Biofilter 5 (BF5) was constructed to capture the exhaust air from a maximum ventilation fan of a swine barn (the maximum ventilation fan runs during warm and hot weather). BF5 was constructed on the west side of a grower/finisher barn. Biofilter 6 (BF6) was constructed on a gravel parking pad 5 m south of the same barn. BF6 was constructed to blow relatively clean air through the filter material to determine whether incomplete treatment of odorous air was responsible for residual odour,

or whether the residual odour was due to the decay of the filter material. Thus, the location of BF6 was chosen because no exhaust fans blow to the south side of the swine barn. For both biofilters, 0.61 m diameter, 0.37 kW, 2.5 Amp axial fans (Leeson, Toronto, ON) were used to create air movement through the biofilter beds.

Fig. 5.1 Layout of the two experimental biofilters in relation to the swine unit at the University of Manitoba Glenlea Research Station



5.3 Biofilter Media Mixtures

Six different biofilter media mixtures were tested in separate biofilter cells (Table 5.1). Each biofilter cell had a 50%/50% mixture (by mass) of compost and a bulking agent. The 50/50 ratio was selected because this ratio had better resistance to both drying and airflow short-circuiting than the 75/25 bulking agent/compost ratio at the Landmark biofilters. Different mixtures were used to determine whether filter bed composition affected outlet odour levels.

5.4 Biofilter Cell Construction

Each biofilter contained 12 cells: 6 mixtures at 2 depths. Each cell measured 0.9 m by 1.2 m (1.1 m^2, corresponding to the size of an average shipping pallet). Airflow was controlled at the adjustable inlet duct to each cell. The filter bed mixture was placed onto a frame of wooden slats which were covered by mesh netting (Nicolai and Janni 1999). Cells were separated by plywood walls. The shallow cells had a depth of 0.35 m and the deep cells had a depth of 0.7 m (Fig. 5.2). Garden cloth was placed around the perimeter of each cell, 0.15 m below the cell surface to reduce short circuiting along the walls.

Fig. 5.2 Experimental biofilter configuration

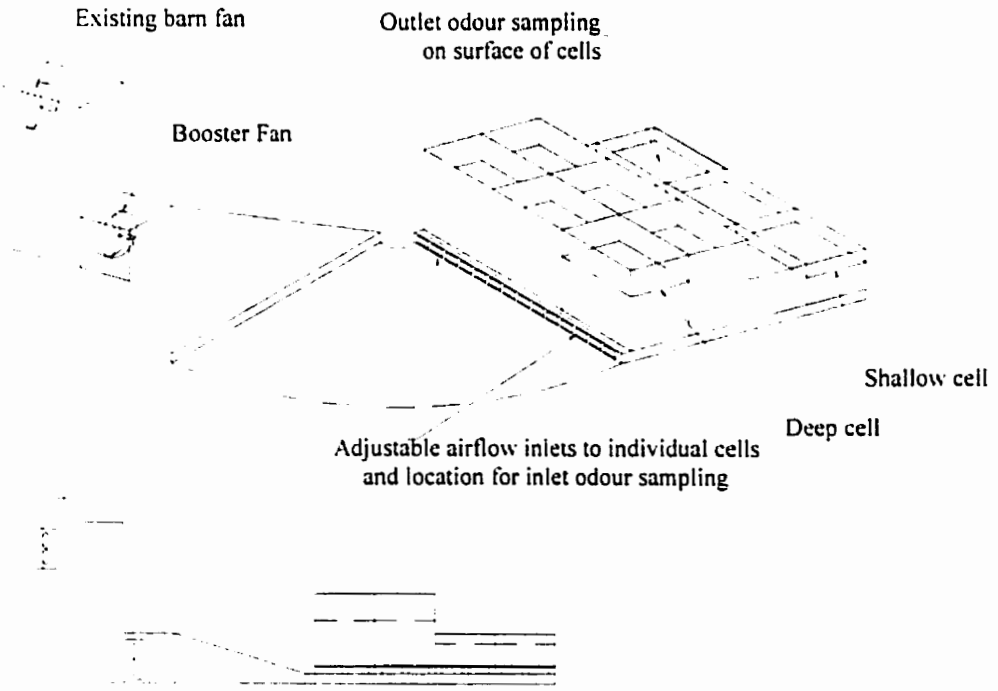


Table 5.1 Compost and bulking agents used in the biofilter media mixtures

Abbreviation	Type of Compost	Type of Bulking Agent
YWW	Yard Waste [1]	Woodchips [2]
GWW	Grocery Waste [3]	Woodchips
PMW	Poultry Manure [4]	Woodchips
GWH	Grocery Waste	Hemp Hurds [5]
GWS	Grocery Waste	Straw [6]
TS	Topsoil [7]	Straw

[1] Leaf and garden waste compost containing shreds of plastic bags, from the City of Winnipeg, MB *Leaf It With Us* composting program.
[2] Woodchips chopped from mixed debris wood collected from a Northern Manitoba Lake. The chips consisted of wood from pine, spruce, fir, cedar, aspen, birch, willow, and alder trees.
[3] Grocery waste compost processed in turned windrows at Rockwood Agribusiness, Stony Mountain, MB.
[4] Poultry manure compost processed in turned windrows at Milleni Egg, Dufrost MB. The compost was not completely composted when used.
[5] Hemp hurds produced by mechanical decortication of industrial hemp stalks.
[6] Unchopped baled wheat straw.
[7] Topsoil was substituted for compost in one sample to determine whether commonly available materials could be used as a biofilter media material.

5.5 Airflow

The surface loading rate was maintained at approximately 0.01 m/s in each cell, producing an EBCT of 35 and 70 s for the shallow and deep cells, respectively. The 35 and 70 s EBCTs were selected to ensure total elimination of odour from the exhaust air (see section 5.8 below). Thus, any remaining odour emission from the biofilter could be assumed to be the residual odour of the biofilter material or biofiltration processes, and not odour from the barn exhaust air.

5.6 Moisture Application

Both biofilters were kept wet using garden sprinklers. The sprinklers were controlled using timers to apply water for 45 min at 0600h and for 45 min at 2000h. Water application was

done twice daily to minimize the effect of short-circuiting of airflow due to dry-out along the plywood walls of the cells.

5.7 Odour Measurement

Odour level reduction was measured by comparing the odour detection threshold of the air entering and leaving the biofilter. Odour samples were collected and analysed as discussed in section 3.9. Samples were first collected after 4 weeks of operation. Subsequent samples were collected every two weeks, until the end of the eighth week.

5.8 Hydrogen Sulfide Measurements

Hydrogen sulfide (H_2S) concentrations were measured from the air samples collected for odour measurements. The presence of H_2S in an outlet air sample indicates that short-circuiting air channels may exist, resulting in partially treated air. Yang and Allen (1994) achieved 100% H_2S removal with a 23-s retention time in a compost biofilter. They achieved 94% H_2S removal with only 7-s retention times. Thus, elevated H_2S levels in the outlet air indicate that a portion of that air is not achieving the appropriate 35 or 70s retention time. Hydrogen sulfide concentrations in the air were collected and measured as described in section 3.9. As with the odour samples, H_2S concentrations were measured every two weeks.

6. RESULTS AND DISCUSSION - RESIDUAL MEDIA ODOUR

6.1 Odour and Hydrogen Sulfide Data

Table 6.1 presents the odour data collected from the odorous air biofilter (BF5). Table 6.2 presents the odour data collected from the clean air biofilter (BF6). Table 6.3 presents the hydrogen sulfide data collected from the odorous air biofilter (BF5). The standard deviation in the tables is the deviation of the weekly sample about the mean of weekly samples. The standard deviation associated with the panel response to an individual odour measurement is high (often larger than the actual measured value). We disregarded that variability (because it is inherent in the process of measuring odour samples) and simply presented the standard deviation of the mean of the three samples. The "Mean Odour Reduction" is the mean of the individual weekly percentage reductions of odour concentration from the inlet to outlet of each cell. Blank readings represent samples which could not be collected.

Statistical differences were compared using SAS analysis of variance (SAS 1985). It was assumed that the three sampling weeks could be considered as replications. This assumption may not be valid if changes in the odour-removing capacity occurred in the cells over this time.

Odour concentration measurements for this research can be found in Appendix C of this thesis.

Table 6.1 Odour concentration results from odorous air biofilter

Mixture	Depth (m)	Odour Concentration (OU) Sampling week 4	6	8	Mean	S.D.	Mean Odour Reduction (%)
Inlet		1166	923	784	958	193	
YWW	0.70	15	39	26	26	12	97
GWW	0.70	49	16	20	28	18	97
PMW	0.70	55	97	40	41	30	96
GWH	0.70	20	26		23	4	97
GWS	0.70	61	134	111	102	37	89
TS	0.70	62	49	50	53	7	94
YWW	0.35	16	35	56	35	20	96
GWW	0.35	35	96	21	50	40	94
PMW	0.35	38	96	112	61	39	93
GWH	0.35	28	16		22	8	97
GWS	0.35	99		229	110	92	87
TS	0.35	86	31	452	190	229	77

Table 6.2 Odour concentration results from clean air biofilter

Mixture	Depth (m)	Odour Concentration (OU) Sampling week 4	6	8	Mean	S.D.	Mean Odour Reduction (%)
Inlet		44	30	28	34	9	
YWW	0.70	18	32	28	26	7	17
GWW	0.70	55	45	20	40	18	-16
PMW	0.70	62	57	52	57	5	-73
GWH	0.70	51	20		35	22	-21
GWS	0.70	31	45	25	34	10	-4
TS	0.70	39	57	36	44	11	-36
YWW	0.35	44	30	16	30	14	14
GWW	0.35	49	51	20	40	17	-18
PMW	0.35	28	90	26	48	36	-53
GWH	0.35	32	69		51	26	-73
GWS	0.35	28	68	16	37	27	-16
TS	0.35	55	56	25	46	18	-35

Table 6.3 Hydrogen sulfide (H_2S) concentrations from odorous air biofilter

Mixture	Depth (m)	H_2S Concentration (ppb) Sampling week					Mean H_2S Reduction (%)
		4	6	8	Mean	S.D.	
Inlet		225	145	255	208	57	
YWW	0.70	6	9	2	6	4	97
GWW	0.70	11	3	3	5	5	97
PMW	0.70	112	235	6	117	115	29
GWH	0.70	8	3		6	4	97
GWS	0.70	47	125	47	73	45	58
TS	0.70	25	42	29	32	9	83
YWW	0.35	15	6	3	8	6	96
GWW	0.35	12	8	2	7	5	96
PMW	0.35	26	6	74	35	35	85
GWH	0.35	15	2		8	9	95
GWS	0.35			85	85		67
TS	0.35	65	13	126	68	57	71

6.2 Discussion

6.2.1 Timing of odour samples Sampling began 4 weeks after biofilter operation began. Based on the results from the Landmark biofilters and Nicolai and Janni (1998), this is sufficient time to ensure the development of a microbial community associated with high odour reductions. By the end of Week 8, moss and mushrooms were growing on the surface of several cells, indicating a varied biological make-up in the cells.

6.2.2 Odorous air biofilter Table 6.1 shows that for both 35 and 70 s retention times (i.e., shallow and deep cells), the YWW, GWW, PMW, and GWH mixtures all had mean odour concentrations at or below 50 OU (with the exception of the PMW (shallow) at 61 OU). Zhou (2000) found that farmyard odours are often in the range of 40 to 50 OU. Thus, at high

retention times, the above-mentioned mixtures do not emit an odour at a concentration distinguishable above ambient farmyard odour levels. Thus, when barn exhaust odours were eliminated (with high retention times), the odour caused by the filter material was not high.

6.2.3 Compost - woodchip mixtures Little difference was found in odour level for the different blends of compost and woodchips. This indicates that the source of compost has little effect on the odour of the media mixture.

6.2.4 Straw mixtures The straw mixtures did not demonstrate the same low mean odour concentrations as the woodchip mixtures (except for the TS (deep) sample). This is because these samples dried out more readily and developed air channels which led to short-circuiting. When short-circuiting occurred, some of the odorous air passed through the filter bed without being fully treated. Thus, unchopped straw is not a suitable material for biofilter beds because of its propensity to develop air channels.

Additionally, the straw mixtures demonstrated rapid growth of grasses (likely wheat, although it was removed before it could be identified). Plant or weed growth on the biofilter surface was observed to cause clumping of filter material around the roots and clogging of pore spaces by roots. These roots hampered biofilter performance by impeding proper airflow. The roots usually extended to cover a circular area around the plant larger than the single blade of grass or stalk of weed, impeding flow over a substantial portion of the filter surface. Based on these observations, uncut straw is not a suitable biofilter media component.

6.2.5 Clean air biofilter Table 6.2 presents the data collected at the clean air biofilter (BF6). Since the air entering this biofilter likely contained only low levels of odorous compounds, the biological community associated with biofiltration would not have had a source of nutrients for growth. Thus, any odour in these samples would be associated primarily with the wet filter media material. The mean odour level of all the samples was 41 OU, while the ambient odour level had a mean of 34 OU. It is apparent for almost all samples (except for the YWW samples) that the air exiting the biofilters was more odorous than the air going in. However, these results were not significant at the $\propto = 0.05$ level. Thus, the biofilter media material neither adds to nor subtracts from the odour concentration of the outlet air.

Every mixture except PMW (deep) and GWH (shallow) had at least one sample where the outlet odour level was lower than the inlet, so perhaps some odour was being eliminated from the inlet air. It may be possible that odour was being eliminated from the air, but then the self-odour of the material became the dominant odour. There is no way of separating these effects, however, because odours may mask other odours, and no observation of the character or nature of the odour was made.

6.2.6 Hydrogen sulfide observations Table 6.3 presents the H_2S data collected from the odorous air biofilter. The mean ambient concentration of H_2S measured on three separate occasions on site was 4 ppb. The mean in-barn concentration (from Table 6.3 Inlet) was 208 ppb. The detection threshold concentration for H_2S odour is 6 ppb (Lodge 1988). The

YWW, GWW, and GWH mixtures all had very high H_2S removal, with outlet H_2S levels at or below 15 ppb. The short-circuiting of the straw cells resulted in higher H_2S levels than for the woodchip-based cells because some of the air was not effectively treated.

The PMW samples had higher H_2S readings than the other woodchip and compost mixtures. This may correspond to some remnant of the poultry manure which was not adequately composted prior to use in the biofilter. However, this would be surprising, because under normal biofiltration conditions any waste should be oxidized and biodegraded to a non-odorous form very rapidly.

Outlet H_2S levels in the clean air biofilter were almost all below the 15 ppb level, with several unexplained outliers (not tabulated in this thesis). It was expected that virtually no H_2S would be present in outlet air from the clean air biofilters because of the lack of in-going H_2S. The PMW (deep) cell again demonstrated high levels of H_2S (with a mean of 106 ppb). It is interesting to note that in spite of elevated H_2S levels, the odour concentration of both clean and odorous air samples for PMW Deep were not significantly different from those for other cells. This is unusual because the H_2S levels emitted from those cells greatly exceeded the detection threshold concentration H_2S. No explanation can be offered for this result. The PMW (shallow) cell in BF6 had H_2S concentrations below the detection threshold.

6.2.7 Comparison of clean and odorous air biofilters When comparing the results in Table 6.1 and Table 6.2, and ignoring the straw samples (which had short-circuiting

problems), the mean odour concentration of the outlet air from the odorous air biofilter was very close to the odour concentrations in the clean air biofilter samples. Above, I concluded that the biofilter media material neither adds to nor subtracts from the odour concentration of the outlet air. Similarly, it can be concluded that when odours are eliminated from the barn exhaust air with high retention times, the associated biofiltration processes do not result in a residual odour which increases the odour concentration of the outlet air above that of ambient farmyard air.

6.2.8 Long-term odour emissions Although these biofilters were operated long enough to permit the development of a microbial community necessary for complete removal of barn-air contaminants. this experiment failed to consider the long-term effect on odour of accumulated by-products of biodigestion or decay of the filter material. Further research into these long-term effects could be conducted.

6.3 Summary of Media Residual Odour Experiments

Outlet odour levels at or below ambient farmyard odour levels were found for all varieties of compost blended in a 50/50% mixture (by mass) with woodchips, as well as for the 50/50 mixture of hemp hurds and compost. Little difference in media odour was found for compost originating from grocery waste, yard waste, or poultry manure when mixed with woodchips.

Biofilter cells exposed to non-odorous air did not emit odour at a level higher than ambient farmyard levels. Thus wet biofilter media material itself does not emit a noticeable odour.

Since the emissions from the biofilter cells exposed to odorous air were at odour levels similar to the emissions from the "clean" cells, it can be concluded that the processes associated with biofiltration do not result in a residual odour which increases the odour level of the outlet air above that of ambient farmyard air.

Unchopped straw was found to be unsuitable for use in biofilter media mixtures because of its propensity to develop short-circuiting air channels. As a result of these channels, odour and H_2S levels were higher in the outlet samples from the straw mixtures than from all the other mixtures.

This experiment did not explain why the Landmark biofilters experienced high outlet odour levels.

7. CONCLUSIONS

7.1 Biofiltration in Cold Temperatures

This project demonstrated that biofiltration is an effective means of eliminating odour and airborne contaminants from the emissions of a mechanically ventilated swine production facility in the cold temperature conditions found in Southern Manitoba. A low cost biofilter using woodchips and compost as the filter media effectively eliminated or reduced the levels of odour, ammonia, and hydrogen sulfide from the exhaust air of a mechanically ventilated finisher barn. Specific conclusions include:

1. Temperatures suitable for microbial activity were maintained in biofilters, even at temperatures below -20°C. A 79% reduction in the odour detection threshold of the exhaust air was observed when the ambient temperature was below -20°C. The mean biofilter bed temperature was 16.3°C, with minimum and maximum bed temperatures of 10.9 and 22.2°C. These temperatures were recorded over a period when the mean ambient temperature was -7.7°C, with minimum and maximum temperatures of -34.2 and 9.2°C.
2. Low cost biofilters effectively eliminated odour from barn exhaust air. Woodchips and compost are effective biofilter media materials. The mean reduction in odour detection threshold of the four biofilters constructed at Landmark was 76%. Odour levels in the air entering the biofilter (inlet air) ranged from 717 to 1864 OU with a mean of 1406 OU. Odour levels in the air leaving the biofilter (outlet air) ranged from 99 to 570 OU and with a mean of 322 OU. These measurements correspond

to a EBCT of 10 to 12.5 s.

3. The outlet odour levels for the Landmark biofilters were considerably higher than those measured by other researchers. This observation led to subsequent research.

4. Low cost biofilters effectively eliminated specific odorous compounds from barn exhaust air. Ammonia concentrations at the biofilter inlet ranged from 2.3 to 14.3 ppm with a mean of 8.3 ppm. Ammonia concentration in the outlet air ranged from 0 to 2.0 ppm, with a mean of 0.4 ppm. The mean reduction in ammonia concentration was 96%. The hydrogen sulfide concentration in the inlet air ranged from 0.32 to 1.1 ppm with a mean of 0.65 ppm. The hydrogen sulfide concentration in the outlet air ranged from 0.02 to 0.17 ppm with a mean of 0.085 ppm. The mean reduction in hydrogen sulfide concentration was 87%.

5. A high degree of variability was observed in the airflow characteristics of the biofilters. Minimizing rodent burrowing and short-circuit channels improved airflow characteristics. Rodent burrowing in the biofilters was effectively stopped using poison.

6. An airflow configuration with a larger initial contact area between the filter media and odorous air was found to have less dust accumulation than a design used by other low-cost biofilter designers.

7.2 Biofilter Media Residual Odour

The research at the Glenlea Research Station resulted in the following specific conclusions about biofilter media residual odour:

1. Low-cost agricultural biofilters media mixtures had very low residual odour levels. Outlet odour levels at or below ambient farmyard odour levels were found for all varieties of compost blended in a 50/50% mixture (by mass) with woodchips, as well as for the 50/50 mixture of hemp hurds and compost. Little difference in media odour was found for compost originating from grocery waste, yard waste, or poultry manure when mixed with woodchips.

2. Biofilter cells exposed to non-odorous air did not emit odour at a level higher than ambient farmyard levels. Thus wet biofilter media material itself does not emit a noticeable odour. Since the emissions from the biofilter cells exposed to odorous air were at odour levels similar to the emissions from the "clean" cells, it was concluded that the processes associated with biofiltration did not result in a residual odour which increases the odour level of the outlet air above that of ambient farmyard air.

3. Unchopped straw was found to be unsuitable for use in biofilter media mixtures because of its propensity to develop short-circuiting air channels. As a result of these channels, odour and H_2S levels were higher in the outlet samples from the straw mixtures than from all the other mixtures.

4. This experiment did not explain why the Landmark biofilters experienced high outlet odour levels.

7.3 Recommendations

Based on the research conducted at Landmark and Glenlea, the following recommendations are presented:

1. Field-scale research should be undertaken only when control can be achieved over many influencing factors. The ability to regularly monitor influencing factors is very important. Choosing a research site close to the University is one aspect of this. Designing a simple experiment with replication and with few interacting factors is another aspect.

2. Study the impact of reduced airflow in biofilters when fans are shutdown in winter. This will be a concern in scaling up biofilters to treat all barn air. Does clogging of pore-spaces permanently affect the biofilter? Does drying re-open clogged pore-spaces?

3. Further research could be conducted into residual odour of biofilter media materials, taking into consideration the long-term effect on odour of accumulated by-products of biodigestion or decay of the filter material.

4. Research could be conducted into whether odour emissions from swine facilities are of concern in the winter. I theorize that the moist component of the barn emissions would simply condense in the cold air and settle to the ground instead of travelling downwind.

5. Farmer acceptance of biofilters depends on low maintenance and ease of operation. Keep it simple. Keep it neat.

6. Alternately, research could be conducted into hi-tech biofilters with low maintenance and ease of operation. Farmers may not want a "cheap" technology mated to their hi-tech barns. Research could be conducted into farmer's attitudes towards low-tech and hi-tech odour control technologies.

7. Based on the difficulties associated with being shutdown part way through completing the research at Landmark, when working with a co-operating farmer or producer, is is necessary to clearly outline every aspect of the project, including possible failures or impacts. Cooperation depends on understanding and patience. Therefore, it is helpful if the producer is supportive of, and keenly interested in the research being conducted.

8. Do not choose to do research into odour. You'll end up stirring buckets of c- -p and your acquaintances will refer to you as "the odour guy". People will begin conversations by asking you "do you have anything to do with that manure thing I saw on television?" You will not notice when your clothing stinks. Other people will notice.

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APPENDIX A Biofilter Design Calculations

1. Select a residence time
The selected design EBCT (residence time) for swine housing was 5 seconds (Zeisig 1987, Nicolai 1998).

2. Determine required media volume
The biofilters should be designed so that the operating flow rate of the existing barn fans is not changed (i.e., no change in the volume of air leaving the barn).

For the 0.61 m fans (BF1 and BF4), the operating flow rate was 2.60 m^3/s
For the 0.51 m fans (BF2 and BF3), the operating flow rate was 1.89 m^3/s

Media volume (m^3) = flow rate (m^3/s) X EBCT (s)

2.60 m^3/s X 5 s = 13 m^3
1.89 m^3/s X 5 s = 9.45 m^3

3. Determine bed dimensions
An arbitrary biofilter width was selected to be 6 m, and the desired depth was 0.35 m (Nicolai, 1998)

Bed length (m) = bed volume (m^3) / (width (m) X depth (m))

Bed length (m) = 13 m^3 / (6 m X 0.35 m) = 6.2 m
Bed length (m) = 9.45 m^3 / (6 m X 0.35 m) = 4.5 m

4. Determine surface loading rate (SL)
SL = flow rate (m^3/s) / area (m^2), from Equation 2.5

SL = 2.60 m^3/s / (6 m X 6.2 m) = 0.070 m^3/s / m^2 (or m/s)
SL = 1.89 m^3/s / (6 m X 4.5 m) = 0.070 m^3/s / m^2 (or m/s)

5. Verify that the fan pressure satisfies the requirements for the pressure drop through the biofilter
Booster fans provide 3.18 mm H_2O (0.125 in H_2O) pressure drop through the biofilter bed and ducting. From Figure 3.1, using worst case scenario (50/50 woodchips/compost packed), the SL above was 0.70 m/s or 13.75 cfm/sqft. When that SL is found from the y axis (called "flow rate" in the figure), the result is a pressure drop of 0.11 in H_2O / ft of depth (from the x axis).
This corresponds to 9.16 mmH_2O / m of depth. The bed depth was selected at 0.35 m, thus,

9.16 mm H_2O / m depth X 0.35 m depth = 3.21 mm H_2O pressure drop

This corresponds to the 3.18 mm H_2O available from the fans. These numbers could be

balanced to be exactly the same if the arbitrarily chosen depth and width were altered slightly.

Therefore, the biofilter satisfies airflow requirements of the barn.

6. Summary of dimensions

The design dimensions for the 0.61 m fans (BF1 and BF4) were: 6 m X 6 m X 0.35 m depth.

The design dimensions for the 0.51 m fans (BF2 and BF3) were: 6 m X 4.5 m X 0.35 m depth.

Since odd sized pallets were used for the air plenums, and some space limitations existed around the barns at Landmark, the actual biofilter dimensions were modified (Table A1).

Table A1 Landmark biofilter dimensions

Biofilter	Length (m)	Width (m)	Airflow (m^3/s)
BF1	8	4.8	2.60
BF2	7.3	5	1.88
BF3	6.5	5.5	1.88
BF4	10.4	4	2.60

APPENDIX B Odour Panel Data for Biofiltration in Low Temperatures

Table B1 Landmark biofilters dilutions to detection threshold (D/T) and standard deviation (SD)

Month		Inlet		Outlet	
		D/T	SD	D/T	SD
Sep					
	BF1	753	2.0	110	1.7
	BF2	588	1.7	45	2.4
	BF3	464	1.5	153	2.2
	BF4	1061	2.4	88	2.6
Oct					
	BF1	1640	2.2	551	2.3
	BF2	1661	2.5	388	2.2
	BF3	884	2.2	343	1.5
	BF4	1271	1.8	434	2.3
Nov					
	BF1	2169	2.1	343	2.4
	BF2	1376	2.7	384	2.0
	BF3	1724	2.3	766	1.7
	BF4	2185	1.8	785	1.8
Dec					
	BF1	3036	1.8	250	1.8
	BF2	812	1.5	323	2.2
	BF3	1216	1.6	420	1.8
	BF4	1361	2.1	369	1.7
Jan					
	BF1	1937	1.7	293	1.4
	BF2	1222	2.1	297	2.3
	BF3	972	2.1	331	1.7
	BF4	1738	1.7	374	1.9
Feb					
	BF1	1544	1.8	93	1.5
	BF2	1092	2.1	233	1.5
	BF3	1934	1.7	184	1.6
	BF4	1092	2.1	164	1.7

APPENDIX C Odour Panel Data for Residual Odour in Biofilter Media

Table C1 Odorous air biofilter dilutions to detection threshold (D/T) and standard deviation (SD)

Sample week	4		6		8	
Source	D/T	SD	D/T	SD	D/T	SD
Inlet	1165.9	1.7	922.6	1.5	784.2	1.4
YWW Deep	14.7	1.8	38.6	1.7	25.9	1.3
YWW Shallow	15.8	1.5	34.5	1.7	55.9	2.3
GWW Deep	49.1	3.0	15.5	1.5	20.0	1.4
GWW Shallow	34.8	2.5	95.7	3.0	20.5	1.3
GWH Deep	19.5	1.7	25.7	1.7		
GWH Shallow	27.6	1.7	16.1	1.5		
TS Deep	61.6	2.0	48.5	2.2	50.0	2.5
TS Shallow	86.1	2.4	30.7	1.8	452.3	1.5
GWS Deep	61.3	1.8	134.3	3.0	111.2	2.5
GWS Shallow	99.3	2.7			229.2	1.8
PMW Deep	55.1	2.5	27.5	2.0	40.0	2.2
PMW Shallow	38.4	3.1	34.5	1.7	111.6	3.0

Table C2 Clean air biofilter dilutions to detection threshold (D/T) and standard deviation (SD)

Sample week	4		6		8	
Source	D/T	SD	D/T	SD	D/T	SD
Inlet	43.9	2.1	29.9	1.8	27.9	1.4
YWW Deep	17.7	2.3	31.9	2.3	28.3	2.0
YWW Shallow	43.9	1.8	29.9	1.8	16.2	1.7
GWW Deep	55.3	3.0	45.1	2.4	20.2	1.9
GWW Shallow	49.2	3.0	50.6	2.7	20.1	1.5
GWH Deep	50.5	3.3	20.2	1.8		
GWH Shallow	32.1	2.0	69.1	1.4		
TS Deep	39.1	1.7	56.8	2.8	35.6	2.2
TS Shallow	55.2	2.8	56.4	2.3	25.1	1.7
GWS Deep	31.2	1.4	45.0	1.6	25.1	1.7
GWS Shallow	28.0	2.0	68.0	1.8	16.2	1.4
PMW Deep	62.0	2.3	56.8	2.8	52.4	1.9
PMW Shallow	27.8	2.3	90.0	2.4	26.2	1.8