AN INTEGRATED BARN-BIOFILTER-GREENHOUSE SYSTEM

By

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A Thesis submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfilment of the requirements of the degree of

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Department of Biosystems Engineering
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Winnipeg

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Abstract

A prototype was built to evaluate the performance of an integrated barn-biofilter-greenhouse system. In order to determine the material for solar storage, a preliminary experiment was conducted in which three identical bins ($0.024m^3$) were used to compare the potential of gravel, soil, and woodchips for passively storing energy inside a solar greenhouse. All three materials stored maximum heat at a depth of 76 mm, with gravel storing approximately 7.25 and 7.73 W more daily average sensible heat energy as compared to soil, and woodchips, respectively. A vertical airflow biofilter (3.34 x 3.34 m) was constructed inside a solar energy greenhouse (floor area of 15 x 6.7 m); exhaust air from a barn was passed through the biofilter for odour treatment before being released into the greenhouse. A booster fan was used to provide a steady airflow rate of 1.4 m^3/s to the biofilter. Data were collected from October 19 to December 6, 2007. The maximum temperature drop along the 15.5m length of the insulated (R-20) duct carrying the exhaust air from the barn to the biofilter was 7°C. The lowest temperature recorded on top of the biofilter surface was 1.3°C when the biofilter booster fan was not working, while the lowest floor temperature was -3°C. On the coldest day in December, the daily average temperature inside the greenhouse was 4.3°C even when the biofilter booster fan was not in service, whereas the outdoor daily average temperature was -25°C. In order to keep the minimum greenhouse temperature at 10°C, the maximum required volumetric flow rate of barn exhaust air at 15°C was $1.60m^3/s$. Maximum hydrogen sulfide (H_2S) removal efficiency was 55%. The weekly average concentration of carbon dioxide (CO_2) inside the greenhouse varied from 841 to 1536 ppm. The system has shown promise for creating an environment suitable for plant growth inside the greenhouse using a

waste gas stream from a hog barn to provide both auxiliary heat and enhanced CO_2 levels.

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1. Introduction

Emissions of gaseous and odorous compounds from intensive livestock operations have raised serious concerns in neighbouring communities about the possible environmental impact of these emissions on air quality (Barth and Melvin 1984; Williams et al. 1989; Warner et al. 1990; O'Niell and Phillips 1992; Zhu 1999). To some extent these concerns have become one of the major obstacles to the expansion of the $1-billion hog industry in Manitoba. Odorous emissions from a hog barn are not only offensive but are also treated as a waste-product, because the heat energy contained in the air exhausted from a hog barn is not used for any purpose.

Greenhouse operators need supplemental heating during the winter months (Tiwari 2003; Beshada and Zhang 2006). Although, solar energy is an attractive substitute for conventional fuels for greenhouse heating (Badescu 2002; Ozturk 2005), previous research on solar energy greenhouses in Manitoba has concluded that solar energy is insufficient to maintain suitable temperatures inside the greenhouse during the night (Beshada et al. 2006). According to the Manitoba Hydro statistics, approximately 6.0 x 106 kW.h energy was provided to the Manitoba's greenhouse sector in 2005 (Manitoba Hydro 2005).

Building a greenhouse next to a hog barn provides an excellent opportunity to use the heat energy in the barn exhaust air to heat the greenhouse, potentially eliminating the need for supplemental heating. However, ducting exhaust air into a greenhouse would create an undesirable work environment. To become acceptable, the odour must be removed from the air stream.

The process of biofiltration is known to obtain high levels of odour reduction in livestock facilities (Nicolai and Janni 1998; Burgess et al. 2001; Hartung et al. 2001; Kennes

and Viega 2001). It is a biological process that consists of a reactor packed with moist, porous filter medium on which a biolayer containing a suitable microbial population is formed. When a contaminated air stream is diffused in the biofilter, the pollutants (such as CH_4, H_2S, NH_3) in the stream are adsorbed onto the biolayer and biodegraded to simple end-products such as water and carbon dioxide (Janni et al. 1998; Devinny et al. 1999; Chaudhary et al. 2003). Although biofiltration is a proven technology, cold winter temperatures may limit the efficiency that can be obtained with an external biofilter. Mann et al. (2002) concluded that exhaust air from a hog barn contained sufficient heat to prevent an uncovered biofilter bed from freezing during ambient temperatures below -20°C. However, the effectiveness of the biofilter was inconsistent. Placing a biofilter inside a greenhouse should, in theory, provide protection from cold weather conditions.

In addition to heat, plants also require adequate amounts of carbon dioxide (CO_2) for the process of photosynthesis. Carbon dioxide is a by-product of the respiration (by pigs) that occurs in the barn, and carbon dioxide is one of the major end-products of the biofiltration process. Consequently, air leaving the barn and passing through a biofilter will have elevated levels of CO_2 when it enters into the greenhouse environment. The carbon dioxide concentration in fresh air varies between 300 and 600 ppm. The current threshold limit value (TLV), or maximum level that is considered safe for healthy adults for an eight-hour work day, is 5000 ppm (Robertson 2006). Elevated CO_2 concentrations are widely expected to enhance the growth and productivity of many greenhouse crops (Kimball 1986; Hinklenton 1988; Allen 1990; Groninger et al. 1996; Schapendonk et al. 2000; Tisserat 2002; Tisserat and Vaughn 2003; Rodgers et al. 2004; Cermak et al. 2005; Phippen et al. 2006). High CO_2 levels can also reduce the minimum temperature required by a plant to grow and complete its

life-cycle (Sionit et al. 1981).

An integrated barn-biofilter-greenhouse system has the potential to have a major, positive impact on the hog industry in Manitoba. If such a system is constructed, hog producers will have an opportunity to diversify their agricultural operation; as the biofilter will not only remove the odour but also becomes a key component of a secondary production system. Odour treatment will reduce tension between neighbours and the producer, and the producer will be able to make additional income by selling the greenhouse crop and by reducing operating costs.

In summary, the integration of both a biofilter and a greenhouse to a hog barn creates a synergistic system, in which the exhaust air from a hog barn can be used for both nutrients and energy.

1.1 Objectives

The present research took place at the University of Manitoba's Glenlea Research Station (49°N and 97°W). A solar energy greenhouse was built next to a hog barn. An open bed biofilter was constructed inside the greenhouse and an insulated duct carried exhaust air from the barn to the biofilter for odour treatment before introducing it into the greenhouse. The goal was to be able to generate a micro-climate in the headspace above the biofilter that had elevated levels of CO_2 and warm temperatures near the roots of the potted plants (i.e., on top of the biofilter surface).

The main objectives of this research were:

1. To compare the sensible heat energy stored in gravel, soil, and woodchips inside the greenhouse environment to determine which material stores the most solar energy

2. To evaluate the thermal profile of the integrated barn-biofilter-greenhouse system
3. To quantify the sources of both energy release and storage in the integrated system
4. To develop a model for calculating the required volumetric flow rate of the exhaust air from the hog barn to maintain the interior of a greenhouse at a desired temperature
5. To measure the hydrogen sulfide (H_2S) reduction as an indicator of biofilter odour removal efficiency
6. To measure the carbon dioxide (CO_2) concentrations that can be generated by the integrated system.

2.1 Livestock Odour Production

Odour has always been associated with the livestock and poultry industries (Lehman 1973; Cox 1975; Nielson et al. 1986; Nielson et al. 1991; Pain et al. 1991). Unpleasant odours can affect a population's psychological and physiological well-being (Winneke and Kastka 1977; Rotton 1983; Shusterman 1992; Schiffman et al. 1995; Thu et al. 1997; Schiffman 1998; Steinheider et al. 1998; Schiffman et al. 2000; Wing and Wolf 2000). The odour concentration can be calculated by dividing odour flow by the volume flow of the ventilation system of the livestock house (Schauberger et al. 1999). Emissions of gaseous and odorous compounds from intensive livestock operations have raised serious concerns in the neighbouring communities about the possible environmental impact of these emissions on the air quality (Barth et al. 1984; Williams et al. 1989; Warner et al. 1990; O'Niell and Phillips 1992; Zhu 1999). To some extent these concerns have become one of the major impediments to the expansion of the hog industry and potentially the sustainability, productivity, and profitability of hog producers will be dependent upon whether they can reduce the odorous emissions from hog barns to a level which surrounding communities can tolerate (Lemay 1999; Zhu 1999; Predicala et al. 2007).

There are three main sources of odour from livestock operations:

1. Livestock facilities which includes animal housing facilities and feed storage facilities,
2. Manure storage buildings, and

3. Applications of livestock manure onto agriculture land (Powers 1999).

The odour intensity from livestock housing waste air increases from cattle to poultry to hogs; it is further affected by the age of the animals, the type of housing and the purpose for which they are being kept (Hartung 1992). This section mainly focuses on the odour production in hog barns. Most offensive odours from livestock operations are the result of volatile organic compounds (VOCs) generated during the decomposition of manure. Manure is a complex mixture of undigested dietary residues, endogenous body secretions, bacterial cells and end-products. Microbial activities are considered to be responsible for the generation of different gaseous mixtures and compounds that produce offensive odour from manure. Odour emitted from manure is mainly caused by an incomplete anaerobic degradation of the organic matter, primarily proteins and carbohydrates (Sturaro et al. 1991; Mackie et al. 1998; Sutton et al. 1999; Zhu 2000; Sunesson et al. 2001; Nahm 2002).

2.1.1 Classification of odorous gases and compounds A total of 331 different VOCs and fixed gases from hog facilities have been identified by gas chromatography and mass spectrometry. The compounds identified are diverse in nature, and can be divided into four different chemical classes: (1) Volatile fatty acids (VFAs), that include both straight chain and branched chain VFAs, (2) Aromatic compounds (e.g., indols and phenols), (3) nitrogen-containing compounds, (e.g., ammonia and volatile amines), and (4) sulfur-containing compounds, (e.g., hydrogen sulfide and mercaptans) (Mackie 1994; Persaud et al. 1996; Zhu 2000; Varel and Miller 2001; Whitehead and Cotta 2004). Emissions of ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S) from swine facilities are considered major contributors to the odour, and have been well documented (Heber et al. 1997; McCulloch et

al. 1998; Sharpe and Harper 1999; Heber et al. 2000; Walker et al. 2000; Zhu et al. 2000; Aneja et al. 2001; Childers et al. 2001; Ni et al. 2002; Schmidt et al. 2002; Jacobson et al. 2005).

2.1.2 Measurement of odour intensity and offensiveness Odour intensity is mainly a measure of how strongly an odour smells, or strength of the perceived odour sensation. It depends on the odorant concentration. The odour intensity is usually measured according to a predetermined rating system which ranges from 0.0 (no odour) to 4.0 (overpowering odour).

The human perception of odour offensiveness is influenced by the nature and concentration of the perceived odour (CEN 1999; St. Croix Sensory 2000; McGinley et al. 2000a). Annoyance level is one of the parameters that can be used to define odour offensiveness. It is the measure of human perception about odours. According to St. Croix Sensory (2000) a scale ranging from non-annoyance to extreme annoyance can be used to characterize the annoyance level. Another method used to measure offensiveness is the hedonic tone. Its consists of 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 necessarily offensive.

2.1.3 Measurement of odour concentration Odour concentration is the most commonly used parameter to indicate the strength of a livestock odour (McGinley et al. 2000a; NCMAWM 2001). Although analytical techniques have been employed to categorize individual odorants in the odour, there is no specific correlation between the concentrations of these individual odorants and human response to odour. Thus, non-analytical techniques using the human olfactory sense are commonly employed to measure the strength of odours

(Kephart and Mikesell 2000; NCMAWM 2001). The odour concentration or 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 olfactometry. Olfactometry is an organoleptic technique that utilizes the human sense of smell to determine the odour concentrations (CEN 1999; McGinley et al. 2000b). The different mixtures of odour and diluent (odourless gas such as nitrogen) are presented to a human panellist or group of panellists for sniffing and their responses are recorded (CEN 1999; NCMAWM 2001). N-butanol is often used as a reference odour in the screening process, to select the panellists based on their sensitivity and consistency (CEN 1999; NCMAWM 2001). Odour concentration calculated by olfactometry is expressed as odour units (OU) (CEN 1999; NCMAWM 2001).

The odour concentration (measured as a threshold dilution value) can be calculated as the number of dilutions at which 50% of the panel members can just detect an odour. The results of this procedure can be reported as the ratio of the volume of odorous air divided by the volume of odour-free air. Therefore, the threshold dilution value is referred to as a concentration (Ritter 1989).

Olfactometers can only measure the concentration. However, there are considerable inconsistencies in the design and operation of olfactometers. A photoionization detector (PID) and an electronic nose (EN) both have potential for measuring odour concentration, but the sensitivity of the two instruments is low compared with olfactometry (Hobbs et al. 1995).

2.2 Livestock Odour Control

Primary or secondary control techniques can be employed to control livestock odour.

Primary control techniques involve elimination of the odour by changing the chemical nature of the odorants or by maintaining good housekeeping and an adequate environment for animals. Primary control methods also include pit additives, such as masking agents, digestive deodorants, feed additives, absorbents and oxidants (Debruyn 2000).

Secondary control methods treat odorous air before exhaust to the atmosphere. Secondary control reacts with the odorous stream to break down the contaminants biologically or chemically (Debruyn 2000).

Various techniques can be used as secondary control for the treatment of polluting vapours and gases. Economical constraints and the nature of pollutants in the gaseous waste stream define the choice of secondary actions. A combination of techniques may be required to treat the pollutants in the odorous stream (Debruyn 2000).

2.3 Overview of Biofiltration

The process of biofiltration is known to obtain high levels of odour reduction in livestock facilities (Nicolai and Janni 1998; Burgess et al. 2001; Hartung et al. 2001; Kennes and Viega 2001;). Biofiltration has many economical and environmental advantages over conventional technologies such as chemical scrubbing, catalytic oxidation, incineration, and adsorption (Swanson and Loehr 1997; Zarook and Shaikh 1997; Cox and Deshusses 1998). It is a biological process that consists of a reactor packed with filter material on which a biolayer containing a suitable microbial population is formed. When a contaminated air stream is diffused in the biofilter, the pollutants (such as CH_4, H_2S, NH_3) in the stream are adsorbed onto the biolayer and biodegraded to simple end-products such as water and carbon dioxide (Janni et al. 1998; Devinny et al. 1999; Chaudhary et al. 2003). The efficiency of a

biofilter relies on the bacterial population that forms in the reactor. The type of medium used for microbial growth also affects the long term stability and performance of the biofilter (Kennes and Thalasso 1998; Rene et al. 2005). Depending on the nature of the pollutants present in the waste air stream, the most widely used media types are compost, peat, activated carbon, tree bark, mulch, and mixtures of these media (Hodge et al. 1991; Williams and Miller 1992; Bohn 1993; Swanson and Raymond 1997; Sene et al. 2002).

2.4 Biofilter Design Parameters

2.4.1 Elimination capacity Elimination capacity is an important performance and design criterion for biofilters. Previous research has demonstrated that biofilters can successfully treat a wide range of VOCs; and their application range can be diversified by increasing their VOC-degrading capacity (van Groenestijn and Hesselink 1993; Kinney et al. 1999; Song and Kinney 2000; Jang et al. 2004; van Groenestijn and Kraakman 2004).

The VOC-degrading capacity of biofilters is usually defined as a function of pollutant loading by determining the contaminant elimination capacity (EC):

$$EC = \frac{(C_{g,in} - C_{g,out}) \times Q}{V} \qquad (2.1)$$

Where: EC = elimination capacity (g m^{-3} s),

$C_{g,in}$ = inlet VOC concentration in the gas phase (g m^{-3}),

$C_{g,out}$ = outlet VOC concentration (g m^{-3}),

Q = airflow rate ($m^3 s^{-1}$), and

V = biofilter bed volume (m^3).

Elimination capacity tests are typically performed by increasing the inlet pollutant loading stepwise and then evaluating the EC corresponding to each pollutant loading. An EC versus pollutant loading curve is used to determine the maximum EC value and the critical EC value. The point at which the EC curve achieves its highest value is known as maximum EC, whereas critical EC is measured as the point at which the EC curve begins to deviate from the 100% removal line (Deshusses and Johnson 2000). These two indicators are not only helpful to evaluate biofilter performance under a specific operating condition, but also to set design criteria such as size of the biofilter and empty bed residence time. This design approach is established on the assumption that EC is a stable assessment of biofilter performance. However, declines in biofilter performance frequently occur in biofilters (Smith et al. 1996; Weber and Hartmans 1996; Kinney et al. 1999).

There are several possible reasons for a decline in biofilter performance, including excess microbial growth or changes in the pollutant degrading microbial culture. These changes can cause biofilter operating problems such as clogging and high pressure drops leading to low contaminant removal efficiency and ultimately lower system performance (Sorial et al. 1995; Weber and Hartmans 1996; Song and Kinney 2000). Lab-scale systems are built and tested in the laboratory to predict a biofilter's EC for a specific pollutant stream (Gribbins and Lohn 1998).

2.4.2 Empty bed residence time and true residence time Empty bed residence time (EBRT) is the time a parcel of exhaust air will remain in an empty biofilter and over

estimates the actual treatment time. EBRT relates the air flow rate to the size of the biofilter (Devinny et al. 1999).

$$EBRT = \frac{V_f}{Q} \qquad (2.2)$$

Where: EBRT = empty bed residence time (s)

V_f = filter bed volume (m^3), and

Q = air flow rate ($m^3\ s^{-1}$).

Even though the medium (compost and woodchips) occupies a substantial fraction of the biofilter, EBRT is a commonly used parameter because it is easily calculated (Devinny et al. 1999).

The true residence time is the actual time a parcel of air will remain in the biofilter. True residence time relates the air flow rate to the total filter bed volume and bed porosity of the filter medium (Devinny et al. 1999):

$$\tau = \frac{V_f \times \theta}{Q} \qquad (2.3)$$

Where: τ = true residence time (s), and

θ = porosity = volume of void space (%).

The difference between empty bed residence time (EBRT) and true residence time (τ) is the porosity factor (θ), which can be quite substantial. Both, the empty bed

residence time and true residence time have a similar effect on the performance of the biofilter. Increasing the EBRT or τ, either by reducing the volumetric flow rate or by increasing the volume of media, results in enhanced system performance. In most biofilter systems, flow rate is kept constant and hence, reactor volume is the only variable that can be increased.

Typical gas residence times for commercial and industrial applications range from 30 to 60 s depending on the concentration of VOCs. However, an EBCT of 5 s is sufficient for odour reduction in open-bed biofilters for confined livestock buildings (Zeisig 1987; Nicolai and Janni 1998; 1999).

2.4.4 Selection of biofilter media Selecting the proper biofilter packing material (media) is an important step towards developing an efficient biofiltration process. The following constraints should be considered during media selection (Liu et al. 1994):

- The media should exhibit optimal microbial environment for the resident microbial population in order to achieve and maintain high degradation rates:
- It should have maximum area of contact and sorption capacity
- It must have high moisture retention
- It should have high porosity as it keeps retention time high and backpressures low
- It should have low bulk density as it reduces the medium compaction potential
- The support material should exhibit suitable properties for bacterial attachment

- A low specific density of the packing is recommended to avoid the breakdown of the material

Naturally-occurring materials such as peat, loam soil and compost normally contain sufficient microorganisms for treating the exhaust air from livestock buildings or manure storage. However, a short conditioning period is required to allow the microorganisms to adapt to the odorous gases in the polluted air stream. Organic media are economically feasible and readily available (Boyette 1998). Wood provides high porosity values and compost provides a better environment for microorganisms and nutrients. Usual packing operating life is two to four years (Devinny et al. 1999). During this time media degradation occurs depending on temperature, moisture, contaminant concentrations, and loading rates (Boyette 1998).

2.4.5 Biofilter sizing Surface area of a biofilter can be calculated by determining the volumetric flow rate, the empty bed contact time (EBCT), and the preferred media depth. With knowledge of airflow rate and EBCT, the biofilter media volume can be determined using the following equation (Devinny et al. 1999):

$$V = Q \times EBCT \qquad (2.4)$$

Where:

V = media volume (m^3)

Q = airflow rate ($m^3 s^{-1}$), and

EBCT = empty bed contact time (s).

If area of the biofilter is not limiting, a media depth can be selected and used to find the space needed.

$$A = \frac{V}{D} \qquad (2.5)$$

Where: A = area of biofilter media (m^2), and

D = media depth (m).

Unit airflow rate (UAR) is calculated by using the media area and airflow rate.

$$UAR = \frac{Q}{A} \qquad (2.6)$$

Where:

UAR = unit airflow rate ($m^3\ h^{-1}\ m^{-2}$)

If the space available for the biofilter is limited, the area can be selected as the first design criteria. Media depth can then be calculated by the following equation (Schimdt et al. 2004):

$$D = \frac{V}{A} \qquad (2.7)$$

2.5 Biofilter Operation Parameters

The effectiveness of a biofilter depends on different operating parameters. Because biofilters use living cultures, they are affected by many variables in their environment such as temperature, pH, moisture content and air stream characteristics. Even a small change in one variable can affect the behaviour of others. The main focus of controlling any parameter is to provide a suitable environment for microorganisms to biodegrade the contaminants present in an air stream.

2.5.1 Temperature Microorganisms can only tolerate a definite range of temperatures. Enzyme kinetics suggests that most reaction rates approximately double when temperature rises 10°C, up to an optimum of 37°C (Williams and Miller 1992). Waste gas preheating may not be cost effective unless its temperature falls below 10°C. However a blast of hot air (above 40°C) is the most lethal variable for microbes and cooling is generally required to maintain microbial activity (Leson and Winer, 1991). Cold air is also harmful for microorganisms, but it does not kill microbes. Cold air can significantly reduce bacterial activity to the point that they stop biodegrading the contaminants and go into a state of suspended animation. However, continuous flow of warm air from the building helps biofilters to maintain temperatures well above freezing, even during the winter season. Biofilters generally don't need supplementary heat in livestock applications. The heat of exhaust air and exothermic microbial activity in the filter bed is usually sufficient to keep an open bed biofilter at an appropriate operating temperature range. For instance, Mann et al. (2002) concluded that similar biofilters functioned reasonably well even in the more extreme winter conditions, maintaining temperatures of 16°C during ambient temperatures below -20°C. However, the efficiency of the biofilter was inconsistent.

2.5.2 Moisture Content Biofilter medium moisture content has been recognized as the most important performance parameter in biofilter operation (Marsh 1992). Microbes need a moist environment to survive and moisture creates a biofilm that absorbs pollutants from an air stream so that they can be biodegraded by microbes. Both over-wetting and drying the filter media reduce biofilter performance (Janni et al. 1998).

Biofilters are usually operated damp, without any running or standing water.

Inadequate moisture can allow the media to dry out. Low moisture level in the bed, for short periods, will not kill the microbes, but it will greatly reduce efficiency. However, permanent dryness results in deactivating the microbes, and creating cracks and channelling of air that leads to bed distortion. It also causes a decrease in airflow resistance, resulting in increased airflow and further drying. Efficiency remains below optimum while microbes recover (re-acclimate) after a period of dry bed conditions (Van Lith et al. 1997; Boyette 1998).

Flooding a reactor with water, on the other hand, will cause increased pressure drop across the biofilter bed. Excess moisture can plug some of the pores in the media, causing channelling and limiting oxygen flow in saturated areas of the filter, thereby creating anaerobic conditions. Clogging of pores also causes slime formation and reduction in surface area for biofilm development (Hodge et al. 1991; Marsh 1992; Van Lith et al. 1997).

There are two primary methods of moisture application:

- Pre-humidification of inlet gas air stream before it comes in contact with the filter medium. This can be done by steam injection, passing it through a tank with fine mist sprayers, or by passing it through an air stripping tower.
- Direct humidification by uniform sprinkling of water throughout the biofilter bed.

Humidity and temperature characteristics of the inlet gas affect the rate of drying.

Water consumption of about18.9 to 37.8 liters per 2832 cubic meter of inlet gas is usual for both pre-humidification and direct addition combined. The selection of an appropriate method for moisture application depends on biofilter design, nature of contaminants, and drying mechanisms. Capital and operating costs of the system also play a vital role in the decision.

2.5.3 Optimum moisture content Leson and Winer (1991) reported that the moisture content of the biofilter bed must be maintained between 40 and 60% (wet mass) to sustain stable microbial growth. Likewise, Bernuth et al. (1999) found that the optimum moisture conditions range was from 40 to 70% (wet mass). The raw gas would quickly dry out the filter bed if additional moisture is not provided. Moisture content of the waste air stream with more than 95% relative humidity reduces the rate of drying to a level where it no longer causes rapid changes in bed moisture.

2.5.4 Factors affecting moisture contents Following are some mechanisms that could affect the efficient control of a biofilter.

1. Exothermic microbial activity heats up the bed (Williams and Miller 1992). Thus, increase in off-gas enthalpy leads to an increase in off-gas temperature and consequently, evaporation of moisture to maintain off-gas saturation, thereby causing dryness and preventing the efficient operation of the biofilter
2. Water is one of the by-products of a bioreaction during the process of biofiltration. Warm and saturated inlet air will result in water condensation in the media. This will increase the moisture content and generate high back pressures (Van Lith et al. 1997).
3. Increased airflow rate and warmer temperatures during the summer months causes the media to dry out. Dry areas promote air channeling and limit odour reduction efficiency
4. Excessive water from storms or a failure in the watering system can cause moisture to seep out of the media. This water is known as leachate. It contains a high

concentration of nitrate. A space in the plenum should be provided to collect and remove it from the biofilter

5. Incomplete pre-humidification results in moisture evaporation from the entrance zone of the filter bed and decreases the moisture content

In most of the agricultural applications, surface irrigation is used to control the filter bed moisture content because pre-humidification of dusty livestock exhaust air promotes fouling of the sprayers with dirt (Van Lith et al. 1997; Boyette 1998).

2.5.5 Moisture control Due to a significance of moisture content for microbial activity and filter performance, effective bed irrigation must be controlled and monitored efficiently. The four most commonly used monitoring and control techniques for bed moisture content are (Van Lith et al. 1997):

i) Automatic: The moisture content of the filter bed is measured automatically by bulk or spot methods. The monitoring results control an automatic sprinkling system. Excessively low or high moisture content may trigger an alarm.

ii) Semi-Automatic: sprinkling frequency and duration are controlled by a timer, which has a set point based on manual or automatic moisture sampling.

iii) Periodic manual: A manual valve is used to operate spraying periodically, based on media moisture sampling.

iv) Manual/Ad hoc: No instrumentation of the spraying system is installed and moisture content is adjusted by using spray hose, based on monitoring media content, several times per year.

Semi-automatic or periodic manual are the most common strategies for moisture

application in agricultural biofilters.

2.5.6 pH control Efficient pH control is necessary to maintain high microbial activity and good contaminant removal rates. Since each species of microorganisms is most successful over a specific pH range, changes in the pH of the filter material will strongly affect their activity and might kill them if conditions move outside this range; Lau et al. (1996) reported maximum microbial activity at a neutral pH. Typically, pH is maintained between the range of 6 and 9 to obtain good contaminant removal rates (Janni et al. 1998). In some cases the biodegradation of contaminants can generate acidic by-products. Examples are the oxidation of halogenated organics and reduced sulphur compounds.

Depending on the nature of the microorganisms that are present, the resulting pH drop can destroy the resident population and reduce the filter's degradation capacity. In such cases, biofilter material is often supplemented with buffering compounds, such as granulated lime, calcium carbonate, or lime stone to overcome this problem (Ottengraf et al. 1986). Media pH can also be controlled by addition of base in irrigation water.

2.5.7 Nutrient control In addition to a normal operating temperature and moist environment, microbes need a balanced diet of nutrients to survive and propagate. The inlet gas contaminants provide the main source of food, but in some cases, microbes also require macronutrients to sustain life.

Nitrogen is one of the essential nutrients for microbial growth. It is a major constituent of proteins and nucleic acids. Microbes use nitrogen in soluble form to build cell walls, but not all nitrogen is available. Some nitrogen products from biodegradation are gaseous mixtures of nitrogen oxides and ammonia, and small quantities will leave the

process with emissions. However, most of the nitrogen-containing vapours are re-absorbed into the liquid phase, and are consumed by microorganisms.

Other essential mineral nutrients include phosphorus, sulphur, calcium, magnesium, sodium and iron. Nitrogen, phosphorus, and potassium (NPK) may be added into bed media by incorporating agricultural fertilizer. Nutrients can also be added during direct humidification by including them as an aqueous solution in the spray. A compost-based biofilter has the important advantage that sufficient nutrients are present in the media (Janni et al. 1998; Devinny et al. 1999). However, with activated carbon or inert packing, nutrient addition is required (Lau et al. 1996). Sometimes limiting nutrient addition may be helpful for controlling biofilm accumulation. Excessive biomass build up can be successfully controlled by limiting nitrogen salt addition (Janni et al. 1998).

2.5.8 Direction of airflow Vertical airflow biofilter system provides effective moisture control as it allows application of additional water at the point of drying, where it is most needed. In up-flow systems, this can be achieved by using hoses to inject additional water at the point of need whereas in down-flow systems this can be achieved by sprinkling water on top of the biofilter bed (Devinny et al. 1999). However, it is difficult to provide additional moisture in horizontal airflow systems where drying is most likely to occur at the sides of the medium.

2.6 Solar Energy Greenhouse

Supplemental heating is required to maintain moderate temperatures in greenhouses during the winter (Tiwari 2003; Beshada and Zhang 2006). Solar energy may provide the most economical means for greenhouse heating (Ozturk 2005). Solar energy greenhouses not

only collect solar energy during sunny days, but also store heat for use at night (Walten 1976; Bouhdjar et al. 1996).

2.6.1 Solar heat storage Heat arrives from the sunlight in the form of short waves, which strike and transfer heat to the objects in the greenhouse. A south-facing greenhouse with a sloping roof permits maximum diffusion of sunlight. Inside the greenhouse the heated objects radiate heat energy in the form of long waves, which do not readily penetrate the greenhouse covering. These long waves can be trapped and stored as energy. The most widely used storage material for heating a greenhouse is water stored in ordinary 55-gallon drums painted a dark, non reflective color for maximum heat absorption. The smaller-size container has a higher ratio of surface area to volume, resulting in better absorption of heat during the sunny days.

However, piles of rocks in wire-mesh cages are also common heat storage material (Nuess 1997). Clear glass containers do not degrade, and provide the advantages of capturing heat better than dark metal containers, but they can be easily broken (North Carolina Solar Center 2000). Rocks are another common heat storage material instead of water. For better heat storage, the rocks should be 12.7 to 38.1 mm in diameter to provide high surface area for heat absorption (Bartok and John 2000). Rocks can be piled in wire-mesh cages to keep them contained. Since rocks have much lower specific heat value than water (0.2 kcal/kg °C compared to 1 kcal/kg °C), to store an equivalent amount of heat, a rock bed would have to be five times as large as a water tank. Rocks also have higher resistance to airflow than water, resulting in less efficient heat transfer (Pin 1995).

2.6.2 Phase-change Instead of water or rocks, phase-change materials can also be used as

heat storage materials. While phase change materials are usually more expensive than conventional materials, they have 5 to 14 times better heat storage capacity than water or rocks. Thus, they are very useful when space is limited. Phase change materials include: calcium chloride hexahydrate, Glauber's salt (sodium sulfate decahydrate), sodium thiosulfate pentahydrate, disodium phosphate decahydrate, paraffin, and fatty acids (Gates 2000). Phase change materials absorb and store heat when they change from solid to liquid phase, and release this heat when they change back into a solid phase (Bartok and John 2000). Calcium chloride hexahydrate has the capacity to store 10 times more heat than water (Bellows 2003). Glauber's salt has the nice property that it melts at 32°C and can store about 83 kcal/kg °C compared to water which stores only 1 kcal/kg °C. This large energy storage value significantly reduces the space required for thermal storage, thus providing more free space for growing plants. These materials are usually contained in sealed tubes, with several tubes being installed to provide required heat storage.

2.6.3 Heat storage systems Thermal heating of greenhouses has been investigated by various researchers using both active heat storage systems (Connellan 1986; Santamouris et al. 1996; Bargach et al 2000; Kurpaska and Slipek 2000; Jain and Tiwari 2003) and passive heat storage systems (Tiwari and Dhiman 1986; Abak et al. 1994; Santamouris et al. 1994a,b; Hussaini and Seun 1998; Ismail and Gonclaves 1999). An active system requires a mechanical device to circulate warmed air or water throughout the thermal storage mass whereas a passive system stores energy in the thermal-mass heat sink during the day, and at night, this heat radiates out to keep the greenhouse warm. To reduce operation costs, passive heat storage systems are becoming standard (Tahat et al. 1995).

2.6.4 Active heat storage Active heat storage systems use supplemental energy to maintain the temperature at the required level (Anon 1980). An active method for solar heating of greenhouses uses a geothermal storage system. This method forces solar heated air, water, or phase change materials through pipes buried in the floor. In case of air, the system works by drawing hot air collected in the peak of the roof, brought down through pipes and into the buried tubing. The hot air in the tubes warms the soil during the daytime. At night time, cool air from the greenhouse is pumped through the same tubing, causing the warm soil to heat this air, which then heats the greenhouse (Puri and Suritz 1985; Monk et al. 1987).

2.6.5 Passive heat storage A passive heat storage system consists of a thermal mass, such as gravel or any other heat storage material that captures heat during the day and radiates it back at night (Bredenback 1984; Santamouris et al. 1994). Exposing as much of the storage mass as possible in direct sunlight is the most effective passive heat storage method. A thermal mass under direct sunlight stores approximately three times more heat than an equivalent mass situated in the shade (Agriculture Canada 1987).

Passive heat storage in the north wall of a greenhouse has been studied in Manitoba where the inside surface of the north wall absorbs solar radiation for maximum energy storage during the day hours and radiates it back during the night hours (Beshada et al. 2005; Beshada and Zhang 2006). Although Manitoba has cold winter weather, there is no lack of solar radiation. In Winnipeg, for example, the mean hourly global solar radiation in January can be as high as 450 W/m^2 at noon (Environment Canada 1990). This amount of solar energy may be sufficient to maintain an appropriate greenhouse temperature during daytime. However, the real challenge is to maintain a desirable greenhouse temperature after sunset

with minimum or no supplemental heating (Beshada et al. 2005).

The greenhouse floor is another potential source of heat storage. Many floor designs have been researched for active heat storage systems including direct utilization of geothermal heating sources (Lund and Freestone 2001) or recirculating greenhouse air through buried pipes in the greenhouse floor to increase storage of heat (Kurata and Tatakura 1991). Usually the greenhouse floor consists of a bed of soil in which plants are directly planted. However, gravel can be used as passive system of heat storage in the floor.

2.7 Greenhouse Supplemental Heating

Heating is a major concern to commercial greenhouse producers for year around production. This is due primarily to the costs involved in the purchase and operation of heating equipment. Electricity, coal, oil and gas are the most common forms of energy used for greenhouse heating. The choice of which of these to use is based mainly on economics. Perhaps, there are drawbacks to each, the most important, and least often considered, is fumes (Freeman and Bellanca 1997).

Plants are at least as vulnerable to the noxious gases in the atmosphere as humans are, and all of the heating sources listed above, except electric ones, can give off fumes that will impair the growth of plants, or even kill them. Another drawback is the placement of these heaters; unless careful evaluation is made for air circulation, plants near the heater may be overheated, while plants farthest away may freeze up. Many of these problems can be avoided by moving the combustion site out of the greenhouse (Freeman and Bellanca 1997).

Most of the systems which heat a large amount of space around the plant before heating the root zone tend to be more heat-energy-wasteful. The benefits to plant growth

from root zone heating systems are well researched. Greenhouse air temperature can be lowered approximately 10°C, by maintaining the optimum root temperature. The most common technique used to heat the root zone for greenhouse pot plant production involved placement of a few relatively large caliper (32 to 51 mm) steam or hot water heating lines under raised benches to warm the surface supporting the potted plant material and the air around the plants. These systems are mostly productive when the bench tops are either partially open to convection currents of rising warm air or are excellent heat conductors. If a bench top does not fit one of these categories, the under-bench heating system is likely to be ineffective. Most root zone heating systems work well for closely spaced potted plants (Henley 1991).

2.8 Perpetual Harvest Greenhouse System

A perpetual harvest greenhouse system (PHGS) is a conceptual greenhouse system that incorporates different technologies that have been proven to work separately. The goal of this system is to create the most economical and efficient greenhouse system that should produce more crops than a conventional greenhouse system. The system should be environmentally friendly as well.

Permaculture greenhouse systems are also defined by the above mentioned criteria. A good example of such an energy efficient system is a chicken greenhouse. A chicken greenhouse is based on the idea that excess heat generated by chickens in a coop could be used as a supplemental heat source for a greenhouse. Previous research indicates that the supplemental heat provided by 40 laying hens increased the temperature on average by 8°C (Meisterhiem 1996). Additional benefits are enhanced exchange of carbon dioxide

from the chickens and oxygen from the plants. Chicken manure can be used to fertilize the soil. In a conventional chicken barn all these chicken outputs are seen as a waste output. This is another principle of permaculture that uses the waste as a source of energy rather than polluting the environment. An adequate ventilation system is very important to avoid the rapid build-up of heat and humidity that can be fatal for small animals. There is very little literature available on permaculture greenhouses, and a lot of research is needed to make an energy efficient design.

2.9 Carbon dioxide enrichment

Elevated CO_2 concentrations are widely expected to enhance the growth and productivity of many greenhouse crops (Kimball 1986; Hinklenton 1988; Allen 1990; Groninger et al. 1996; Schapendonk et al. 2000; Tisserat 2002; Tisserat and Vaughn 2003; Rodgers et al. 2004; Cermak et al. 2005; Phippen et al. 2006). Flowers and vegetable plants show very robust effects of CO_2 enrichment by increased photosynthesis, dry weight, plant height, and lateral branching (Mortensen 1987; Campbell et al. 1988). Carbohydrate formed in the leaves is eventually used to sustain the growth of the developing fruits; thus increased yield in crops such as cucumber (Peet and Willits 1987; Willits and Peet 1989), tomato (Slack 1986; Willits and Peet 1989; Reinert et al. 1997), and pepper (Hinklenton 1988) are a common result of CO_2 enrichment. Similarly, production time of lettuce and kohlrabi can be reduced by 15 to 25% under an elevated CO_2 environment (Wittwer and Robb 1964; Hand et al. 1981). Hand and Soffe (1971) recorded 32 to 72% higher tomato yields after six weeks of harvesting when plants were grown in 1200 ppm CO_2. There was only a slight increase in the total tomato fruit set with CO_2 enrichment, but the fruit weight under CO_2 enrichment was

significantly higher (Peet and Willits 1984). Growth and yield responses to enhanced CO_2 concentration might also be influenced by a wide range of environmental factors including light and humidity (Mortensen 1992; Wong 1993), nutrient status (Israel et al. 1990), and temperature (Sionit et al. 1987 a,b; Idso et al. 1988). High CO_2 levels can reduce the minimum temperature required by a plant to grow and complete its life-cycle. For example, Sionit et al. (1981) showed that okra was unable to complete its life-cycle in normal CO_2 at temperatures below 23/17°C (day/night), while okra plants grown in 1000 ppm CO_2 at 20/14°C (day/night), matured and produced fruit.

3. Comparison of Potential Heat Storage between gravel, Soil, and Woodchips

3.1 Abstract

This paper compares the potential of gravel, soil, and woodchips for passively storing energy inside a solar energy greenhouse. The experiment was conducted in February 2007 inside a solar greenhouse at St. Francis Xavier, MB (49°N and 97°W). The maximum and minimum average hourly temperatures inside the greenhouse were recorded as 19.6 and -1.2°C, respectively. Three identical bins (0.024 m^3), insulated by a 152 mm thick layer of R-20 fibreglass insulation, were used to store gravel (bin1), woodchips (bin 2), and soil (bin 3) inside the solar greenhouse environment. Calculations were made to compare the heat energy storage of gravel, woodchips, and soil at depths of 76, 152, and 229 mm. All three materials stored maximum heat at a depth of 76 mm, with gravel reaching the highest temperature gain of 21°C at 14:00h. Fluctuations in temperature decreased as the material depth increased. Approximately 7.25 and 7.73 W more daily average sensible heat energy was stored by gravel as compared to soil and woodchips, respectively.

3.2 Introduction

Supplemental heating is required to maintain moderate temperatures in greenhouses during the winter (Tiwari 2003; Beshada and Zhang 2006). Solar energy may provide the most economical means for greenhouse heating (Ozturk 2005). Solar energy greenhouses not only collect solar energy during sunny days, but also store heat for use at night (Walten 1976; Bouhdjar et al. 1996). Thermal heating of greenhouses has been investigated by various researchers using both active heat storage systems (Connellan 1986; Santamouris et al. 1996;

Bargach et al 2000; Kurpaska and Slipek 2000; Jain and Tiwari 2003) and passive heat storage systems (Tiwari and Dhiman 1986; Abak et al. 1994; Santamouris et al 1994a,b; Hussaini and Seun 1998; Ismail and Gonclaves 1999). Active heat storage systems use mechanical energy to maintain the temperature at the required level (Mazria 1979; Anon 1980). To reduce operation costs, however, passive heat storage systems are becoming standard (Tahat et al. 1995). A thermal mass, such as gravel or any other heat storage material, captures heat during the day and radiates it back at night (Bredenback 1984; Santamouris et al. 1994).

The current research took place in a solar energy greenhouse with a passive heat storage system. The passive storage system in the greenhouse was a concrete wall, which was oriented on the north side. The inside surface of the north wall absorbs solar radiation for maximum energy storage during the day hours and radiates it back during the night hours (Beshada and Zhang 2006). Although Manitoba has cold winter weather, there is no lack of solar radiation. In Winnipeg, for example, the mean hourly global solar radiation can be as high as 450 W/m^2 at noon during the month of January (Environment Canada 1990). This amount of solar energy may be sufficient to maintain an appropriate greenhouse temperature during daytime. However, the real challenge is to maintain a desirable greenhouse temperature after sunset with minimum or no supplemental heating (Beshada et al. 2005).

The greenhouse floor is a potential source of heat storage. Many floor designs have been researched for active heat storage systems including direct utilization of geothermal heating sources (Lund and Freestone 2001) or recirculating greenhouse air through buried pipes in the greenhouse floor to increase storage of heat (Kurata and Tatakura 1991). The current research was focused on passive heat storage in the greenhouse floor.

The objective of this study was to compare the heat energy stored in gravel, soil, and woodchips inside the greenhouse environment to determine which material stores the most solar energy. The density of woodchips was estimated using the measured bulk density (kg/m^3) value of uncompacted, 80:20 mixture of woodchips with compost from Sadaka et al. (2002), and the specific heat capacity of woodchips was estimated from the range of the specific heat capacity of miscellaneous woods (Perry's Chemical Engineers' Handbook 1997). The specific heat capacity of gravel was obtained from Cheng et al. (2002), and density of gravel was estimated from the data for specific gravity of dry, loose gravel ranged between 1.4-1.7 (Perry's Chemical Engineers' Handbook 1997). Density of soil was predicted from the value of specific gravity of soil in Perry's Chemical Engineers' Handbook (1997), and specific heat capacity of dry soil was estimated from Buol et al. (2003).

3.3 Materials and Methods

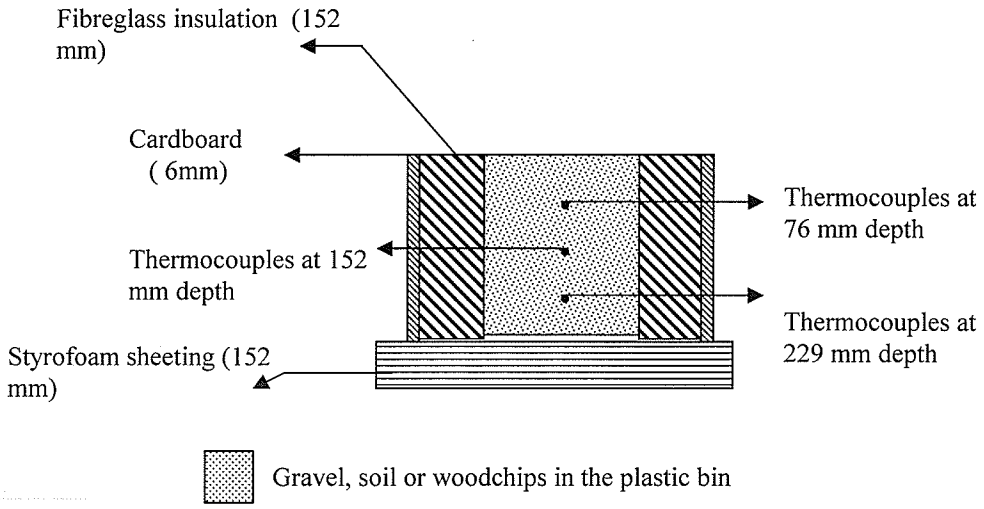
The solar energy greenhouse (SEG) consists of a steel frame, two layers of 6-mil polyethylene plastic cover (kept apart from each other by a layer of air created by a blower), bubble poly insulation, and a solar energy collection (north) wall. The greenhouse was oriented in the east-west direction for the maximum collection of solar energy and to allow the full exposure of the north wall to direct solar radiation. While the north wall and a small section of insulated roof formed the enclosure on the north side, the plastic cover formed the greenhouse enclosure from the south side, which allowed the permittivity of solar radiation into the greenhouse (Beshada et al. 2005).

Three identical plastic bins with an internal diameter of 305 mm and length of 330 mm were used to store gravel, soil, and woodchips inside the solar energy greenhouse

environment (Figure 3.1). Each bin was insulated by 152 mm thick, R-20 fibreglass insulation, protected by 6 mm thick layer of cardboard and placed on 152 mm thick, R-20 styrofoam sheeting.

3.3.1 Temperature monitoring Temperature was recorded at depths of 76, 152, and 229 mm in each bin. Three T-type thermocouples were inserted at each depth to obtain the mean average temperature. Data were recorded every 20 min throughout the day using a stand-alone data acquisition system (OMEGA-LOGBOOK-300^{TM}). A portable weather station (WatchDog™ Model 550, Spectrum Technologies Inc., Plainfield, IL) was used to collect on-site weather information. The average hourly global solar radiation, outdoor temperature, relative humidity, wind speed, and wind direction were recorded.

Figure 3.1 Experimental bin with thermocouples at different depths.



3.3.2 Heat energy calculations The amount of heat energy stored in the gravel, soil, and woodchips was calculated as:

$$Q_{st} = C_i \times \ell_i \times V_b \times \Delta T_i \quad (3.1)$$

Where:

Q_{st} = heat energy stored in the gravel, soil, and woodchips (W),

C_i = specific heat capacity of gravel, soil, and woodchips (J kg^{-1} $°C^{-1}$),

ℓ_i = density of gravel, soil, and woodchips (kg m^{-3}),

V_b = volume of the plastic bin (m^3), and

ΔT_i = rate of change in gravel, soil, and woodchips temperature (°C s^{-1}).

The received solar radiation was determined as follows:

$$Q_{in} = \tau \ S \quad (3.2)$$

Where:

Q_{in} = solar radiation received in greenhouse (W)

τ = transmissivity of the glazed surface (0.57), and

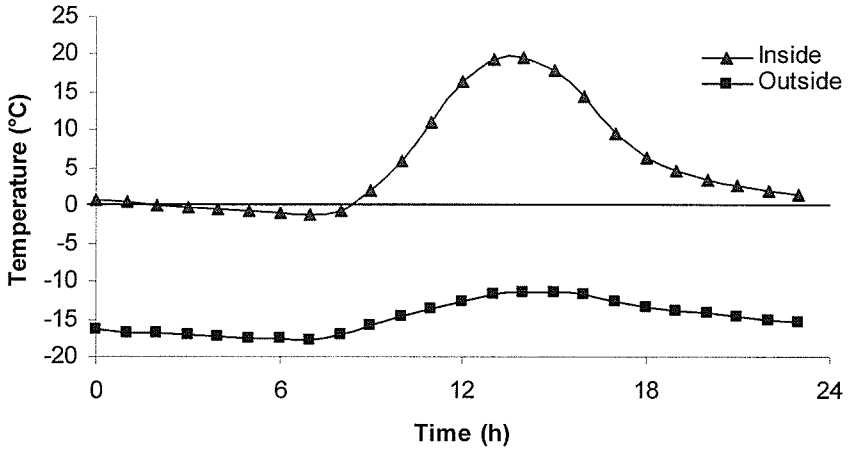
S = solar radiation (W).

3.4 RESULTS and DISCUSSIONS

3.4.1 Greenhouse temperatures The average hourly temperatures for the month of February, inside the greenhouse varied from -1.2 to 19.6°C, while the outdoor average hourly temperature fluctuated between -17.8 and -11.4°C (Figure 3.2). The average hourly temperature of the greenhouse went below 0°C from 03:00 to 08:00 h of the day. The mean indoor and outdoor temperatures were 5.6 and -14.9°C, respectively. The daily average temperature inside the greenhouse varied from -1.7 to 8.0°C, whereas the outdoor daily

average temperature was between -33.1 and -3.8°C (Figure 3.3). On average the daily average indoor temperature was 13°C higher than the outdoor daily average temperature. Typically, the highest temperature inside the greenhouse was recorded between 12:00 and 16:00 h.

Figure 3.2 Hourly average temperatures recorded inside and outside the greenhouse.



3.4.2 Temperature profile of gravel, soil, and woodchips at 76 mm The gravel and soil temperatures started to rise at 08:00 h and continued to rise until 15:00 and 16:00 h, respectively, whereas woodchips gained temperature from 09:00 till 16:00 h. The gravel reached maximum temperature between 14:00 and 15:00 h, while the maximum temperature for soil and woodchips was recorded between 15:00 and 16:00 h. The highest temperatures recorded for gravel, soil, and woodchips were 21.1, 13.3, and 13.1°C, respectively (Figure 3.4).

Figure 3.3 Daily average temperatures recorded inside and outside the greenhouse.

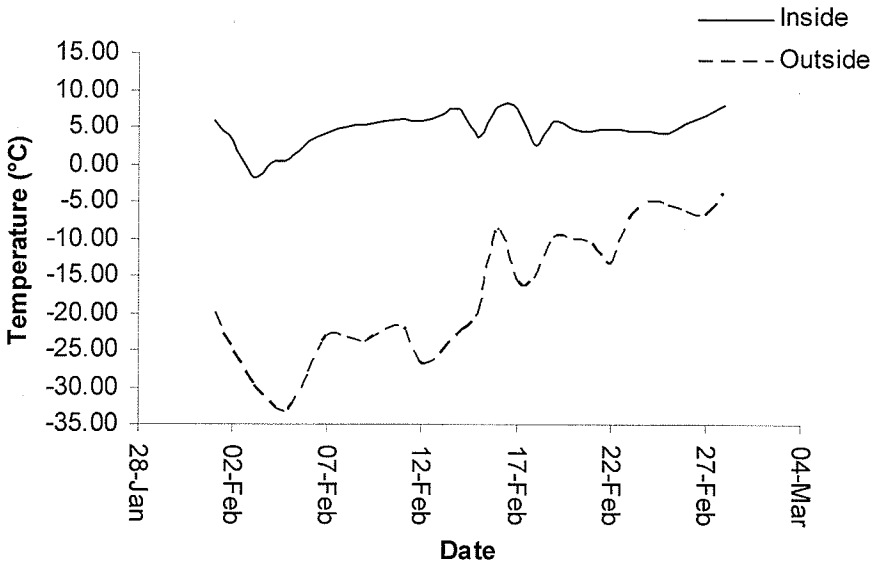
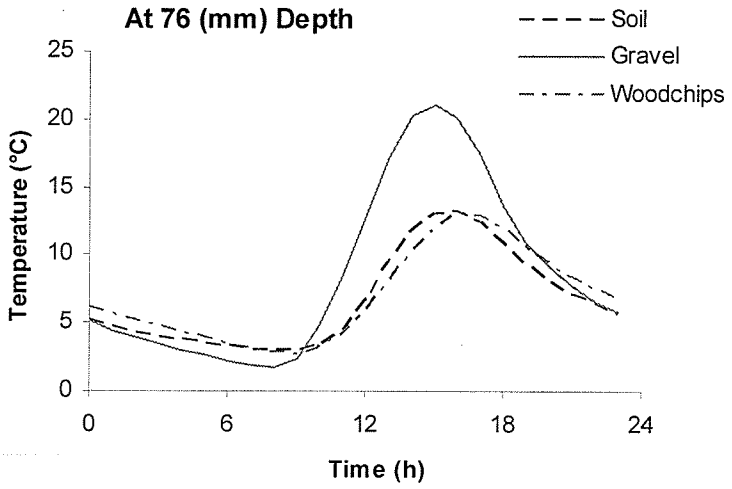


Figure 3.4 Average hourly temperatures of the gravel, soil, and woodchips inside the greenhouse measured at 76 mm depth.

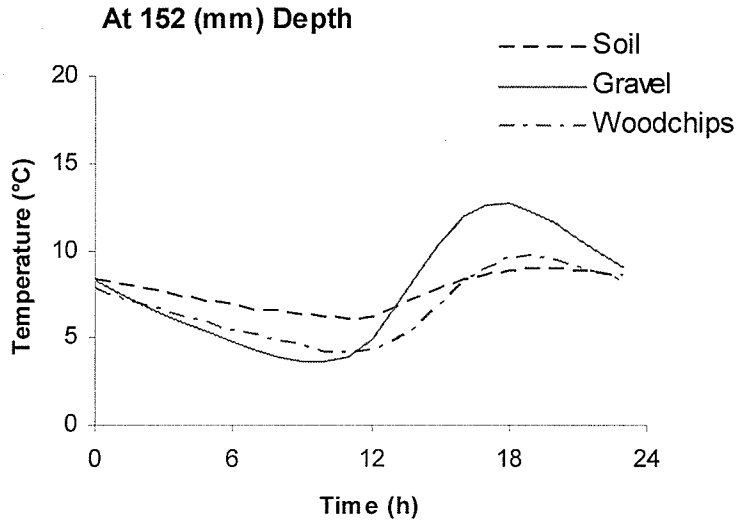


After peaking, all three materials showed gradual decrease in temperature until the next morning. The total increase in temperature of gravel, soil, and woodchips was 19.4 (from 1.7

to 21.1°C), 10.4 (from 2.9 to 13.3°C), and 10.4°C (from 2.7 to 13.1°C), respectively. The significant increase in the temperature of gravel as compared to soil and woodchips was mainly because gravel stored sensible heat energy whereas soil and woodchip stored latent heat energy.

3.4.3 Temperature profile of gravel, soil, and woodchips at 152 mm The temperature of gravel started to rise at 10:00 h, whereas the temperature of soil and woodchips started to increase after 11:00 h. The highest temperatures recorded for gravel, soil, and woodchips were 12.7 (at 18:00 h), 9.0 (at 20:00 h), and 9.7°C (at 19:00 h) (Figure 3.5). The total increase in temperature of gravel, soil, and woodchips was 9.1, 3.0, and 5.6°C, respectively.

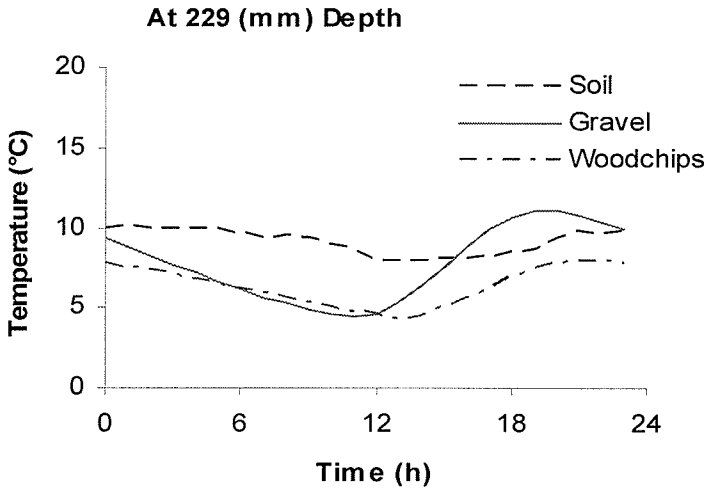
Figure 3.5 Average hourly temperatures of the gravel, soil, and woodchips inside the greenhouse measured at 152 mm depth.



3.4.4 Temperature profile of gravel, soil, and woodchips at 229 mm There was minimal temperature variation at the 229 mm depth compared to 76 and 152 mm depth which suggests that fluctuation in temperature decreases as the material depth increases.

The peak values of gravel, soil, and woodchips at 229 mm depth were obtained later in the night as compared to 76 mm depth when the highest values were obtained in the afternoon. The maximum temperatures of gravel, soil, and woodchips were recorded as 11.1 (at 20:00 h), 10.0 (01:00 h), and 7.9°C (at 22:00 h) (Figure 3.6).

Figure 3.6 Average hourly temperatures of the gravel, soil, and woodchips inside the greenhouse measured at 229 mm depth.



3.4.5 Comparison of sensible heat energy storage Equation 3.1 was used to determine the amount of heat energy stored in the gravel, soil, and woodchips at 76, 152, and 229 mm depths; the temperature change rate was calculated as the difference between two consecutive hourly temperatures of gravel, soil, and woodchips divided by the time interval (1h) between the two measurements. Each bin was divided into 3 layers. Each layer ends at the media depth where temperature was recorded (i.e. 1st layer ends at 76mm depth, 2nd layer is from 76 to 152 mm depth, and 3rd layer is from 152 to 229 mm depth). Surface temperature of gravel, soil, and woodchips was obtained by linear extrapolation of the gravel, soil, and woodchips temperatures from 152mm, and 76 mm depth. Temperature within each layer was obtained

by taking the average of the temperatures measured at top and at the bottom of each layer. Volume used for the calculation of energy storage at each layer was equal to the volume of that particular layer only. Table 3.1 shows the estimated values of specific heat capacity and density of gravel, soil, and woodchips used for the calculations.

The daily average rate of sensible heat energy storage by gravel, soil, and woodchips was 11.29, 4.04, and 3.56 W, respectively. On average, gravel stored approximately 7.25, and 7.73 W more heat energy than soil and woodchips, respectively. Gravel stored 107.5 % of the available solar energy whereas soil and woodchips stored about 38.5, and 33.1 % of the available solar energy, respectively. We could not accurately calculate percentage of available solar energy stored by gravel as a sensible heat because the calculations showed that gravel was storing more than 100% available solar energy as a sensible heat which is theoretically not possible. These values present approximate results, and maybe over estimated or underestimated because of estimated density, specific heat capacity values, and extrapolation of the data to obtain surface temperature of gravel, soil, and woodchips.

Table 3.1 Specific heat capacity and density values of gravel, soil, and woodchips.

Materials	Specific heat capacity ($J\ kg^{-1}\ °C^{-1}$)	Density ($kg\ m^{-3}$)
Gravel	840	1400
Soil	837	1120
Woodchips	1880	368

3.5 Conclusions

1. Fluctuation in temperature decreased as the media (gravel, soil or woodchips) depth increased

2. Gravel stored approximately 107.5% of the available solar energy, while soil and woodchips stored about 38.5, and 33.1 % of the available solar energy. Although the value of percentage of heat energy stored by gravel is not accurate these results give a good comparison that gravel stored maximum heat energy and maximum percentage of available solar energy as compared to soil and woodchips.

4 A Perpetual Harvest Greenhouse System: Integrating Barn, Biofilter, and Greenhouse

4.1 Abstract

A prototype was built to evaluate the performance of an integrated barn-biofilter-greenhouse system. The greenhouse floor in the integrated system consisted of a bed of gravel to store maximum solar energy. A vertical airflow biofilter (3.34 x 3.34 m) was constructed inside a solar energy greenhouse (floor area of 15 x 6.7 m); exhaust air from a barn was passed through the biofilter for odour treatment before being released into the greenhouse. A booster fan was used to provide a steady airflow rate of 1.4 m^3/s to the biofilter. Data were collected from October 19 to December 6, 2007. The maximum temperature drop along the 15.5 m long, and insulated (R-20) duct carrying the exhaust air from the hog barn to the biofilter was 7°C. The lowest temperature recorded on top of the biofilter surface was 1.3°C when the biofilter booster fan was not working, while the lowest floor temperature was -3°C. On the coldest day in December, when the biofilter booster fan was not in service, the daily average temperature inside the greenhouse was 4.3°C, whereas the outdoor daily average temperature was -25°C. In order to keep the minimum greenhouse temperature at 10°C, the maximum required volumetric flow rate of barn exhaust air at 15°C was 1.60m^3/s. Maximum hydrogen sulfide (H_2S) removal efficiency was 55%. The weekly average concentration of carbon dioxide (CO_2) inside the greenhouse varied from 841 to 1536 ppm. The system has shown promise at creating an environment suitable for plant growth inside the greenhouse using a waste gas stream from a hog barn to provide both auxiliary heat and enhanced CO_2 levels.

4.2 Introduction

Currently, the air exhausted from a hog barn is an offensive waste-product. It is offensive because of the odour nuisance; it is a waste-product because the heat energy contained in the air is not used for any purpose.

Greenhouse operators need supplemental heating during the winter (Tiwari 2003; Beshada and Zhang 2006). Although solar energy is an attractive substitute for conventional fuels for greenhouse heating (Badescu 2002; Ozturk 2005), previous research on solar energy greenhouses in Manitoba has concluded that solar energy is insufficient to maintain suitable temperatures inside the greenhouse during the night (Beshada et al. 2006). According to the Manitoba Hydro statistics, approximately 6.0×10^6 kW.h energy was provided to the Manitoba's greenhouse sector in 2005(Manitoba Hydro 2005).

Building a greenhouse next to a hog barn provides an excellent opportunity to use the heat energy in the barn exhaust air to heat the greenhouse, potentially eliminating the need for supplemental heating. However, ducting exhaust air into a greenhouse would create an undesirable work environment. To become acceptable, the odour must be removed from the air stream.

The process of biofiltration is known to obtain high levels of odour reduction in livestock facilities (Nicolai and Janni 1998; Burgess et al. 2001; Hartung et al. 2001; Kennes and Viega 2001). It is a biological process that consists of a reactor packed with filter material on which a biolayer containing a suitable microbial population is formed. When a contaminated air stream is diffused in the biofilter, the pollutants (such as CH_3, H_2S, NH_3) in the stream are adsorbed onto the biolayer and biodegraded to simple end-products such as water and carbon dioxide (Janni et al. 1998; Devinny et al. 1999; Chaudhary et al. 2003).

Although biofiltration is a proven technology, cold winter temperatures limit the efficiency that can be obtained with an external biofilter. Mann et al. (2002) concluded that exhaust air from a hog barn contained sufficient heat to prevent an uncovered biofilter bed from freezing during ambient temperatures below -20°C. However, the effectiveness of the biofilter was inconsistent. Placing a biofilter inside a greenhouse should, in theory, provide protection from cold weather conditions.

In addition to heat, plants also require carbon dioxide (CO_2) for the process of photosynthesis. Carbon dioxide is a by-product of the respiration (by pigs) that occurs in the barn, and as mentioned before, CO_2 is also one of the major end-products of the biofiltration process. Consequently, air leaving the barn and passing through a biofilter will have elevated levels of CO_2 when it enters into the greenhouse environment.

Elevated CO_2 concentrations are widely expected to enhance the growth and productivity of many greenhouse crops (Kimball 1986; Hinklenton 1988; Allen 1990; Groninger et al. 1996; Schapendonk et al. 2000; Tisserat 2002; Tisserat and Vaughn 2003; Rodgers et al. 2004; Cermak et al. 2005; Phippen et al. 2006). Flowers and vegetable plants show very robust effects of CO_2 enrichment by increased photosynthesis, dry weight, plant height, and lateral branching under CO_2 enrichment (Mortensen 1987; Campbell et al. 1988). Carbohydrate formed in the leaves is eventually used to sustain the growth of the developing fruits; thus increased yield in crops such as cucumber (Peet and Willits 1987; Willits and Peet 1989), tomato (Slack 1986; Willits and Peet 1989; Reinert et al. 1997), and pepper (Hinklenton 1988) are a common result of CO_2 enrichment. Similarly, production time of lettuce and kohlrabi can be reduced by 15 to 25% under an elevated CO_2 environment (Wittwer and Robb 1964; Hand et al. 1981). Hand and Soffe (1971) recorded 32 to 72%

higher tomato yields after six weeks of harvesting when plants were grown in 1200 ppm CO_2. There was only a slight increase in the total tomato fruit set with CO_2 enrichment, but the fruit weight under CO_2 enrichment was significantly higher (Peet and Willits 1984). Growth and yield responses to enhanced CO_2 concentration might also be influenced by a wide range of environmental factors including light and humidity (Mortensen 1992; Wong 1993), nutrient status (Israel et al. 1990), and temperature (Sionit et al. 1987 a,b; Idso et al. 1988). High CO_2 levels can reduce the minimum temperature required by a plant to grow and complete its life-cycle. For example, Sionit et al. (1981) showed that okra was unable to complete its life-cycle in normal CO_2 at temperatures below 23/17°C (day/night), while okra plants grown in 1000 ppm CO_2 at 20/14°C (day/night), matured and produced fruit.

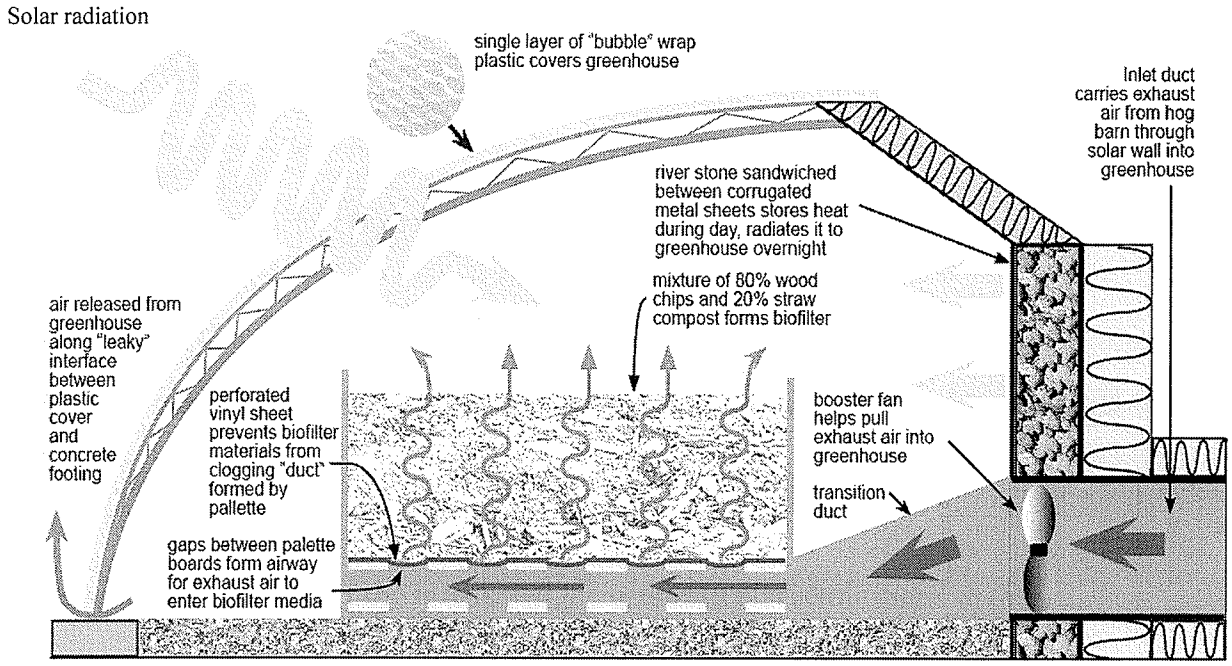
The integration of both a biofilter and a greenhouse to a hog barn creates a synergistic system, in which the exhaust air from a hog barn can be used for both nutrients and energy.

The present research took place at the University of Manitoba's Glenlea Research Station (49°N and 97°W). A solar energy greenhouse was built next to a hog barn. An open bed biofilter was constructed inside the greenhouse and an insulated duct carried exhaust air from the barn to the biofilter for odour treatment before introducing it into the greenhouse (Figure 4.1). The goal was to be able to generate a micro-climate in the headspace above the biofilter that has elevated levels of CO_2 and warm temperatures near the roots of the potted plants (i.e., on the biofilter surface).

The main objectives of this research were: i) to evaluate the thermal profile of the integrated barn-biofilter-greenhouse system; ii) to measure the H_2S reduction as an indicator of biofilter odour removal efficiency; iii) to measure the CO_2 concentrations that can be generated by the integrated system; iv) to quantify the sources of both energy release and

storage in the integrated system; and v) to develop an equation for calculating the required volumetric flow rate of the exhaust air from the hog barn to maintain the interior of a greenhouse at a desired temperature.

Figure 4.1 Schematic of the integrated barn-biofilter-greenhouse system.



4.3 Materials and Methods

4.3.1 Duct A 15.5 m long and 600 mm inner diameter high density polyethylene (HDPE) pipe, with two 90° bends, was used to carry the exhaust air from a hog barn to the biofilter.

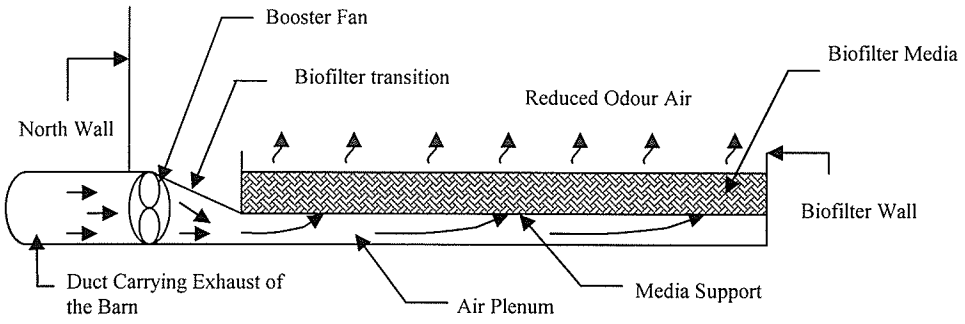
The pipe was placed on cinder blocks at a height of about 0.5 m from the ground. Adjustable iron legs were attached to the pipe at different points to provide stable and permanent support. The pipe was wrapped by R-20 fibreglass insulation to minimize heat loss from the air before it reached the biofilter. Chicken wire was used to hold the insulation around the pipe. To protect the fibreglass insulation, it was covered by a double layer of

6-mil polyethylene plastic sheet.

4.3.2 Biofilter An open bed, vertical airflow biofilter (Figure 4.2) covering an area of 11 m^2 and having a media depth of 610 mm, was fabricated inside the greenhouse using pressure treated plywood. An air plenum was built to provide appropriate airflow to the biofilter. Vinyl mesh netting was placed on top of the air plenum to prevent the biofilter media from falling into the plenum. The biofilter media consisted of woodchips mixed with straw based compost in an 80:20 ratio. Woodchips and compost were obtained from a local supplier (Remier Soils).

Airflow rate is an important factor in the design of a biofilter because it determines the length of time that an air stream will be in contact with the biofilter medium (Nicolai and Janni 1998). This is generally referred to as residence time. The true residence time is obtained by multiplying total filter bed volume by the porosity of the filter medium, divided by the airflow rate (Devinny et al. 1999). Because the porosity of the biofilter medium changes over time due to compaction, residence time is often estimated by the empty bed residence time (EBRT) (DeBruyn et al. 2001). The EBRT is defined as the ratio of biofilter volume to airflow rate (Devinny et al. 1999). It has been concluded that a residence time of 5 s is sufficient to achieve 80% odour reduction from swine facilities (Nicolai and Janni 1998). In this study, the biofilter was designed for an EBRT of 3 s to minimize the surface area covered by woodchips because Mahmood and Mann (2008) had previously determined that gravel stored more solar energy than woodchips, which can be used as passive heat storage material.

Figure 4.2 Schematic of vertical airflow open-bed biofilter in the integrated system.

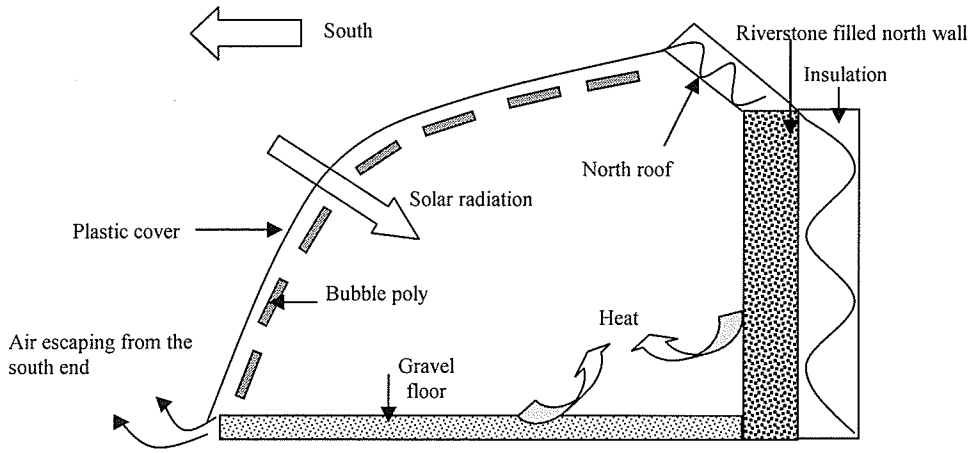


This biofilter was designed for vertical airflow because vertical airflow suits the current configuration in which potted plants can be placed onto the biofilter surface so that the heat energy being harvested from the exhaust air is used to heat the roots of the plants. A booster fan, located at the end of the duct before transition to the biofilter, was used to supply a constant airflow rate of 1.4 m^3/s to the biofilter. The air flow rate was measured by using a hotwire anemometer and a cone like hood (240mm x 240mm) (Garlinski 2004), placed at the end of the biofilter transition before it was connected to the biofilter plenum. The hotwire anemometer was placed at the end of the cone to measure the flow rate. The airflow rate readings were taken for three times at the center and sides of the biofilter transition. The speed of the booster fan was adjusted such that the average of these replications at each point was measured to be 1.4m^3/s. Irrigation of the biofilter occurred only three times per week at a rate of approximately 0.3 L/s for a period of 20 min. A sprinkler was used to spray water on top of the biofilter media and an irrigation hose was placed at a depth of 0.3 m inside the biofilter media. At the time of data collection, no permanent supply of water was available in the greenhouse. Moisture content of the biofilter media (wet basis) was determined during the course of the experiment using the oven dry method (ASAE 2003). Without a permanent

supply of water to the greenhouse, moisture content fluctuated from day to day (13 to 38% wb). This fluctuation in moisture contents was mainly because the irrigation of the biofilter was not done on a daily basis.

4.3.3 Solar energy greenhouse A 15 m long and 6.7 m wide solar energy greenhouse with a gravel floor was built adjacent to a hog barn. The main components of the solar energy greenhouse consisted of steel framing, a plastic cover, bubble insulation (25.4 mm diameter and 6.4 mm deep), a vent, and a solar energy storage north wall (Figure 4.3). The greenhouse was oriented in the east-west direction to maximize the collection of solar energy.

Figure 4.3 Schematic of the side view of the solar energy greenhouse.



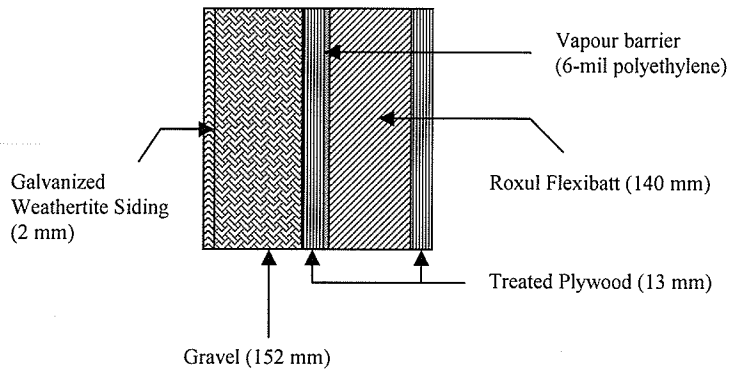
The plastic cover acts as a solar window and enclosed the south side of the greenhouse, while the north wall and a small section of insulated roof formed an enclosure from the north side. The bottom edge of the south side was not sealed to provide a means of escape for the air entering the greenhouse from the barn (Figure 4.1). The plastic cover was a layer of 6-mil thick polyethylene. Bubble insulation with thermal resistance of $R \leq 2$ was

placed under the plastic cover to reduce the heat loss during the night. This translucent bubble insulation transmits evenly diffused light throughout the greenhouse.

The greenhouse floor was a bed of gravel which acted as thermal heat storage to retain solar energy during the day and radiate it back at night. The north wall, which was filled with riverstone, also acted as a passive heat storage system. The north wall was painted black so that it absorbed maximum solar radiation during the day. The north wall consisted of a 2 mm thick galvanized weathertite siding from the inside, 152 mm of riverstone, 13 mm pressure treated plywood, a 6-mil vapour barrier followed by 152 mm roxul flexibatt® insulation, and 13 mm pressure treated plywood at the outside (Figure 4.4). The roxul flexibatt® (Roxul Inc., Grand Forks, British Columbia) insulation in the roof and north and side walls provided a thermal resistance of approximately R-22.

A vent was installed on the east wall of the greenhouse. The thermostat of the vent had a set point of 30°C throughout the experiment. The vent opened automatically when the air temperature inside the greenhouse reached 30°C.

Figure 4.4 Cross-section of the north wall of the solar energy greenhouse.



4.3.4 Data recording The duct temperature, biofilter plenum temperature, room temperature, greenhouse floor temperature and north wall surface temperature were recorded every 20 min using T-type thermocouples and a computer-controlled data acquisition system. The outside air temperature, solar radiation, relative humidity, and wind speed were recorded every 30 min by a weather station (Dr. Mario Tenuta, University of Manitoba) located at the Glenlea Research Station.

Three thermocouples were installed inside the pipe to study the heat loss along the length of the duct. One thermocouple was placed near the exhaust of the barn and the other two thermocouples were installed at distances of 6.4 and 11 m from the barn exhaust fan.

The temperature inside the plenum of the biofilter was monitored at different points to examine the temperature difference between the odorous stream coming out from the barn and just before it is diffused to the biofilter media for odour treatment. Biofilter surface temperature was also monitored to investigate the possibility of placing potted plants on the biofilter surface to heat the root zone of the plants.

The greenhouse floor temperature was recorded near the side walls, north wall, south end, and in the middle of the greenhouse around the biofilter. The inside air temperature was monitored at different locations, specifically, on top of the biofilter at a height of 2.5 m above the ground. Temperature of the north wall was also recorded at three different heights on the inside surface of the wall.

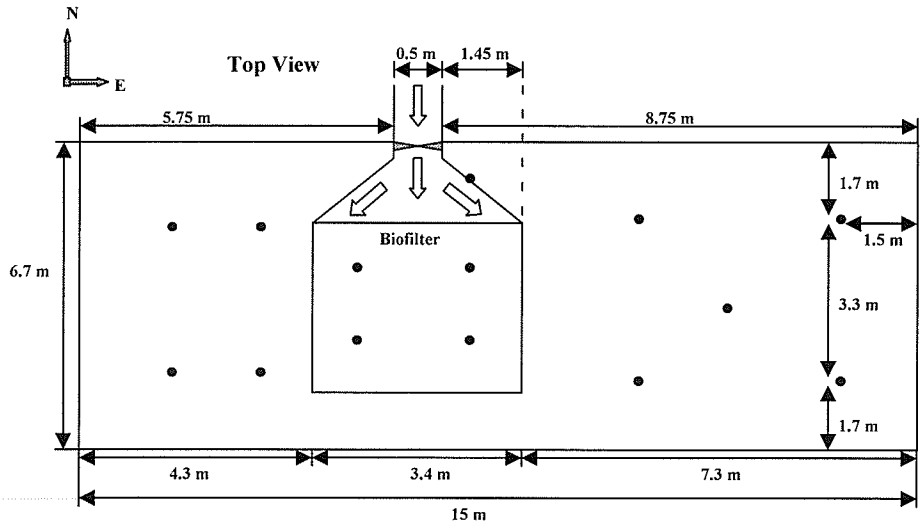
4.3.5 H_2S and CO_2 Measurements

Hydrogen sulfide is one of the major odorous components in the exhaust from a hog barn. For this research, H_2S concentration was used as an indicator of odour treatment of the

air stream by the biofilter, and odour level reduction was measured by comparing the hydrogen sulfide (H_2S) concentration of the air entering and leaving the biofilter. Hydrogen sulfide (H_2S) and carbon dioxide (CO_2) concentrations were obtained at different locations inside the solar energy greenhouse (Figure 4.5). A Jerome Meter (Jerome 631-X Hydrogen Sulfide Analyzer, Arizona Instrument Corporation, Phoenix, AZ) was used to monitor the concentrations of H_2S and a VAISALA CO_2 probe (VAISALA GMP222 Carbon dioxide probe, Vaisala Oyj, Finland) was used to record the CO_2 concentrations.

The first set of H_2S and CO_2 samples was collected four weeks after the biofilter became operational. It was expected that this was sufficient time to ensure the development of the microbial community within the biofilter medium (Nicolai and Janni 1998). Samples of H_2S and CO_2 were measured three times a week for six weeks.

Figure 4.5 H_2S and CO_2 sampling points ("•") inside the solar energy greenhouse.



4.3.6 Energy balance calculations The energy balance of the integrated barn-biofilter-greenhouse system included the energy gained from the barn, the solar energy received by the greenhouse, energy lost due to conduction and convection, and energy stored in the

greenhouse. Mathematical presentation of the energy balance equation is:

$$Q_b + Q_{in} = Q_{cd} + Q_{cv} + Q_{st} \quad (4.1)$$

Where:

Q_b = heat gain from the barn (W),

Q_{in} = solar radiation received in greenhouse (W),

Q_{cd} = heat loss due to conduction through the greenhouse envelope (W),

Q_{cv} = heat loss through infiltration (W), and

Q_{st} = heat stored in greenhouse (W).

This calculation was made for the coldest day (November 17) in the data set, when the biofilter booster fan was running, and the air flow rate of barn exhaust air entering in the greenhouse after biofiltration was 1.4m^3/s.

The heat gain from the barn was calculated as:

$$Q_b = V \ell_a C_a (t_b - t_o) \quad (4.2)$$

Where:

V = volumetric flow rate of barn exhaust air leaving the biofilter surface (m^3/s),

ℓ_a = air density (kg/m^3),

C_a = specific heat capacity of air (J/kg °C),

t_b = temperature at biofilter surface (°C), and

t_o = outside temperature (°C).

The received solar radiation is determined as follows:

$$Q_{in} = \tau \ S \quad (4.3)$$

Where:

τ = transmissivity of the glazed surface (0.7), and

S = solar radiation (W).

The heat loss due to conduction through the greenhouse envelope, which included the north wall, west wall, east wall, north roof, door, and plastic cover with bubble poly (Table 4.3, Thermal resistance of North wall, east wall, side wall, and north roof was estimated based on R-22 roxul flexibatt® insulation) was calculated by:

$$Q_{cd} = \frac{A}{R}\Delta T \tag{4.4}$$

Where:

R = overall thermal resistance (m^2 °C /W),

A = total surface area of greenhouse envelope (m^2), and

ΔT = temperature difference of inside and outside air (°C)

The overall thermal resistance of the greenhouse was calculated as:

$$\frac{A}{R} = \frac{A_{nw}}{R_{nw}} + \frac{A_{ww}}{R_{ww}} + \frac{A_{sw}}{R_{sw}} + \frac{A_{nr}}{R_{nr}} + \frac{A_d}{R_d} + \frac{A_c}{R_c} \tag{4.5}$$

Where:

$A_{nw}, A_{ww}, A_{sw}, A_{nr}, A_d, A_c$ = areas of north wall, west wall, south wall, north roof, door, and plastic/bubble poly, respectively (m^2), and

$R_{nw}, R_{ww}, R_{sw}, R_{nr}, R_d, R_c$ = thermal resistance of north wall, west wall, south wall, north roof, door, and plastic with bubble poly, respectively (m^2 °C /W).

Table 4.3 Thermal resistance of greenhouse envelope components

Section	Area (m^2)	Resistance (m^2 °C /W)
North wall	37	3.87
West wall	20	3.87
East wall	17	3.87
North roof	33	3.87
Door	1.9	0.176
Plastic with bubble poly	118	0.285

The heat loss due to air infiltration was calculated as:

$$Q_{cv} = V\ell_a C_a (t_i - t_o) \quad (4.6)$$

Where:

V = volumetric air exchange rate by infiltration (m^3/s), and

t_i = inside temperature (°C).

The amount of heat stored in the greenhouse (north wall and gravel floor) was determined as:

$$Q_{st} = Q_{wall} + Q_{floor} \quad (4.7)$$

$$Q_{wall} = V_{wall}\ell_{wall}C_{wall}\ \Delta T_{wall} \quad (4.7a)$$

$$Q_{gravel} = V_{gravel}\ell_{gravel}C_{gravel}\ \Delta T_{gravel} \quad (4.7b)$$

Where:

Q_{wall}, Q_{gravel} = heat stored in north wall and gravel floor, respectively (W)

V_{wall}, V_{gravel} = volume of wall and floor, respectively (m^3),

ℓ_{wall}, ℓ_{gravel} = density of wall and floor, respectively (kg/m^3),

C_{wall}, C_{gravel} = specific heat capacity of wall and floor, respectively (J/kg °C), and

ΔT_{wall}, ΔT_{gravel} = rate of change in wall and floor temperature, respectively (°C /s).

Equation (4.1) can be rearranged as:

$$Q_b - Q_{cv} = Q_{cd} + Q_{st} - Q_{in} \tag{4.8}$$

Substituting the values of Q_b and Q_{cv} from equations 4.2 and 4.6 into equation 4.8

$$V\ell_a C_a(t_b - t_o) - V\ell_a C_a(t_i - t_o) = Q_{cd} + Q_{st} - Q_{in} \tag{4.9}$$

Since the volumetric flow rate of air entering the greenhouse is equal to the volumetric flow rate of air leaving the greenhouse, equation 4.9 will become:

$$V\ell_a C_a(t_b - t_i) = Q_{cd} + Q_{st} - Q_{in} \tag{4.10}$$

Rearranging equation 4.10

$$V = \frac{Q_{cd} + Q_{st} - Q_{in}}{\ell_a C_a(t_b - t_i)} \tag{4.11}$$

Equation 4.11 is used to determine the volumetric flow rate of barn exhaust air entering the greenhouse to maintain the minimum (10°C) inside temperature.

4.4 Results and Discussion

4.4.1 Temperature gradient along the length of the duct The maximum temperature drop before the shutdown of the biofilter booster fan was 1°C. The coldest days (Nov. 24 – Dec. 5) and time (07:00 h) were selected as a worst case scenario to determine the temperature gradient along the length of the duct after the biofilter booster fan was stopped. The temperature decrease along the length of the duct varied between 1 and 7°C. The maximum temperature decrease was recorded on November 29 when the barn exhaust air temperature was measured as 18°C and the air temperature inside the biofilter plenum was recorded as

11°C (Figure 4.6).

The outside air temperature on the same day and time was observed as -23°C. However, on the coldest day (Dec. 5) when the outside air temperature was -28°C, the temperature decrease along the length of the duct was only 3°C. More heat was lost on November 29 than December 5 due to convective cooling. The wind speed on November 29 was approximately three times higher than the wind speed observed on December 5.

4.4.2 Greenhouse temperature profile The temperature inside the greenhouse varied from -3.2°C to 40°C, while the outdoor temperature ranged between -29.9 and 13.4°C. The daily average temperature inside the greenhouse varied from 1.5 to 20.9°C, whereas the outdoor daily average temperature was between -25.0 and 10.4°C (Figure 4.7).

Figure 4.6 Temperature profile along the length of the duct at 7:00h of the days.

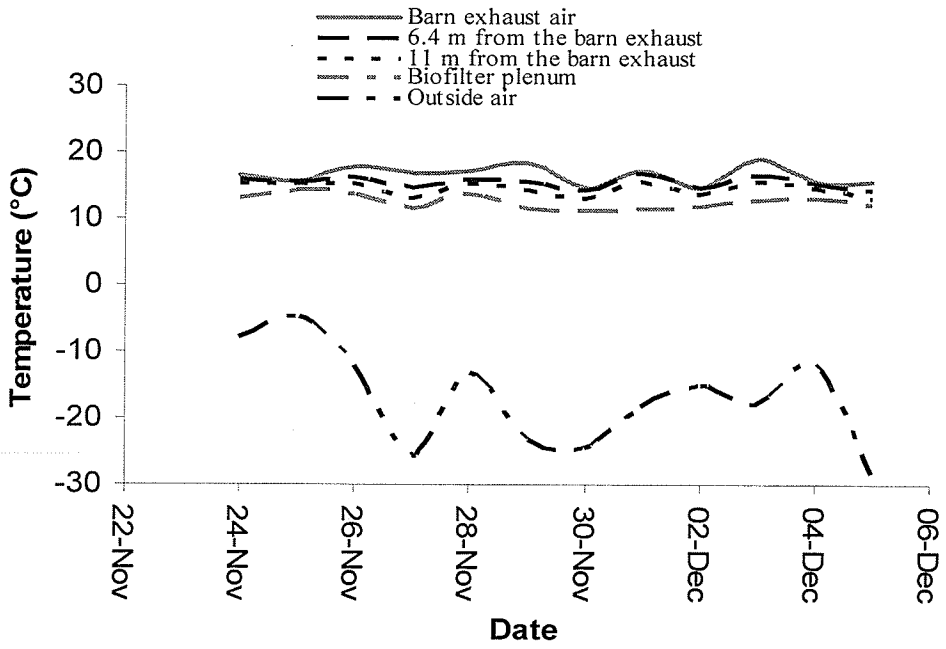
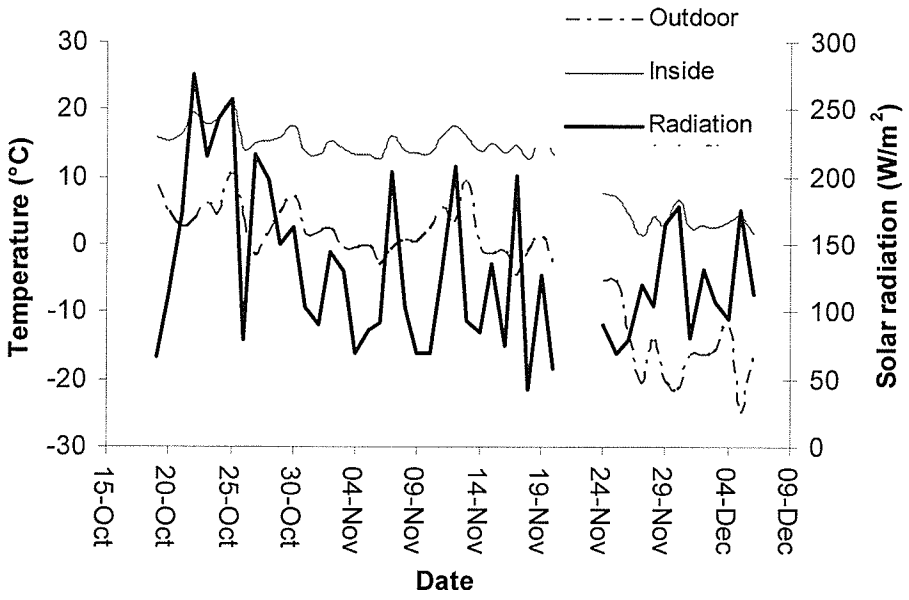


Figure 4.7 Daily average inside, and outdoor temperatures and solar radiation.

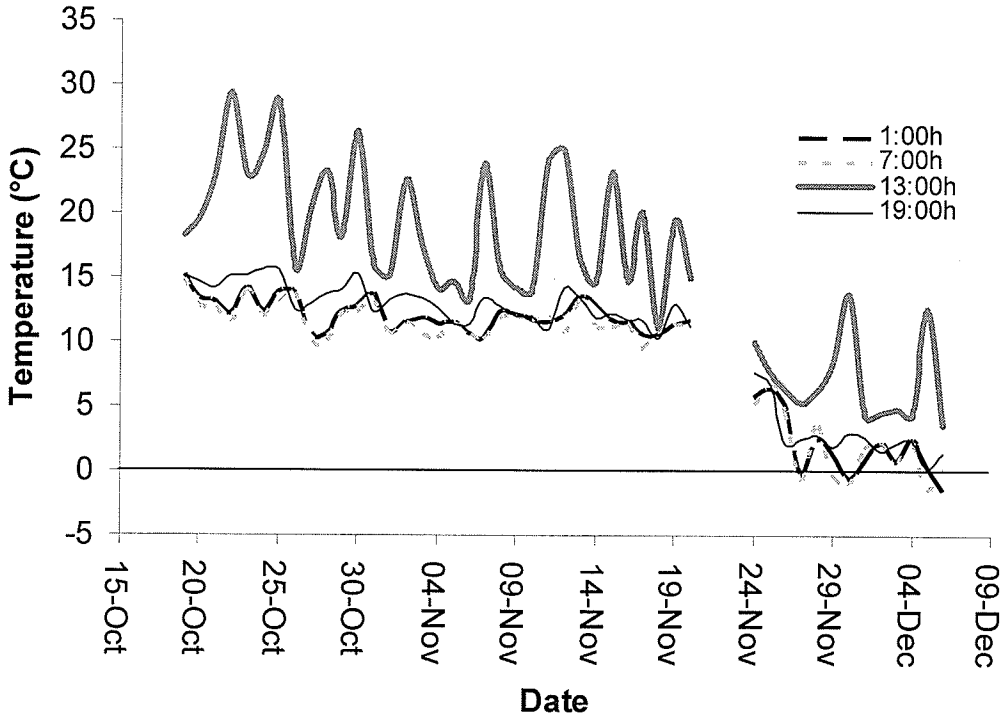


Indoor temperature was influenced by solar radiation as the lowest daily average indoor temperature occurred on a cloudy day (daily average solar radiation of 120W/m^2), not on the day with the lowest daily average outdoor temperature of -25°C with daily average solar radiation of 176 W/m^2. The mean indoor and outdoor temperatures were 11.9 and -3.3°C, respectively. On average, the daily average indoor temperature was 15°C higher than the outdoor daily average temperature.

Figures 4.8 and 4.9 represent the temperature profiles of the greenhouse air and floor at four different times of the day. These times reflect the maximum and minimum recorded temperatures with a possible variation of ±2°C. The minimum and maximum greenhouse floor temperature was recorded as -1.9 and 29.3°C, respectively (Figure 4.8), whereas the minimum and maximum greenhouse air temperature was measured as -2.0 and 38.4°C, respectively (Figure 4.9). The sudden drop in greenhouse air and floor temperature from November 21 to November 24 occurred when the biofilter booster fan was turned off. It was

necessary to stop the booster fan because it was extracting too much heat from the partially-filled room (< 20 pigs in a room designed for 130 pigs). As a consequence of stopping the booster fan, there was very little air entering the greenhouse through the duct. Air flow rate was not measured, and would have fluctuated throughout the day. The system was designed on the expectation that booster fan would be running constantly. In the absence of positive pressure inside the greenhouse, it is possible that cold air was entering the greenhouse from the south edge.

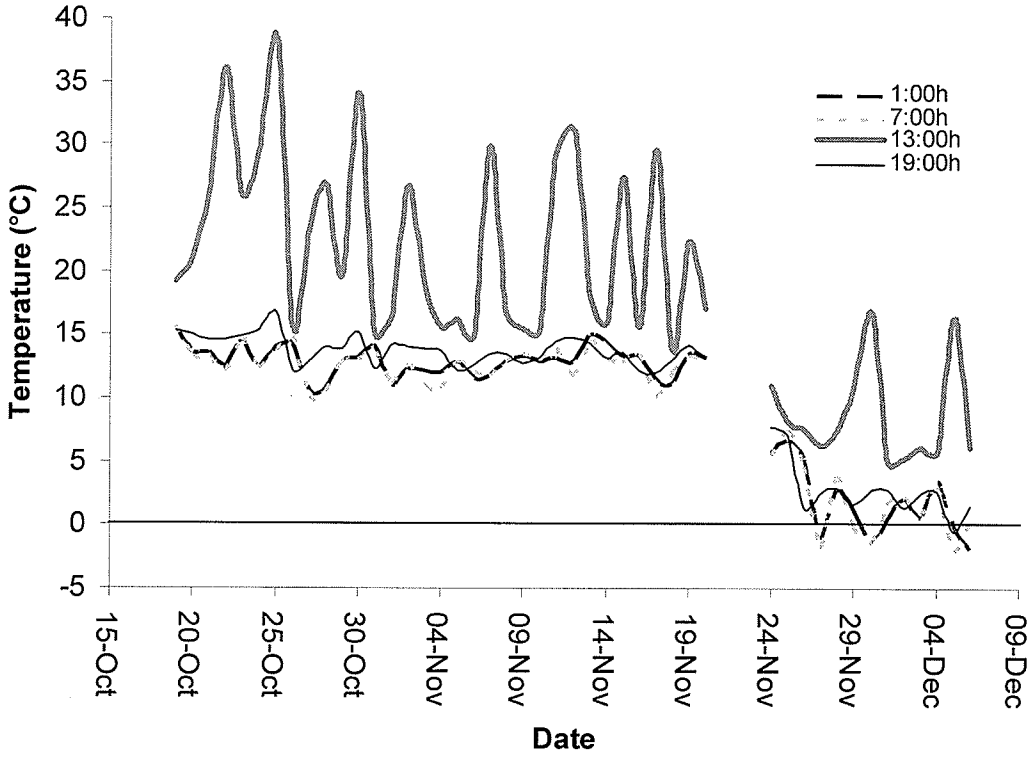
Figure 4.8 Temperature profile of greenhouse floor at different times of the day.



Typically the lowest temperature inside the greenhouse was recorded between 01:00 and 07:00 h which shows that bubble insulation was not sufficient to hold the heat inside the greenhouse during the night time. It was also observed that the greenhouse temperature never

went below 10°C even when the outside temperature was -10°C before the booster fan shutdown.

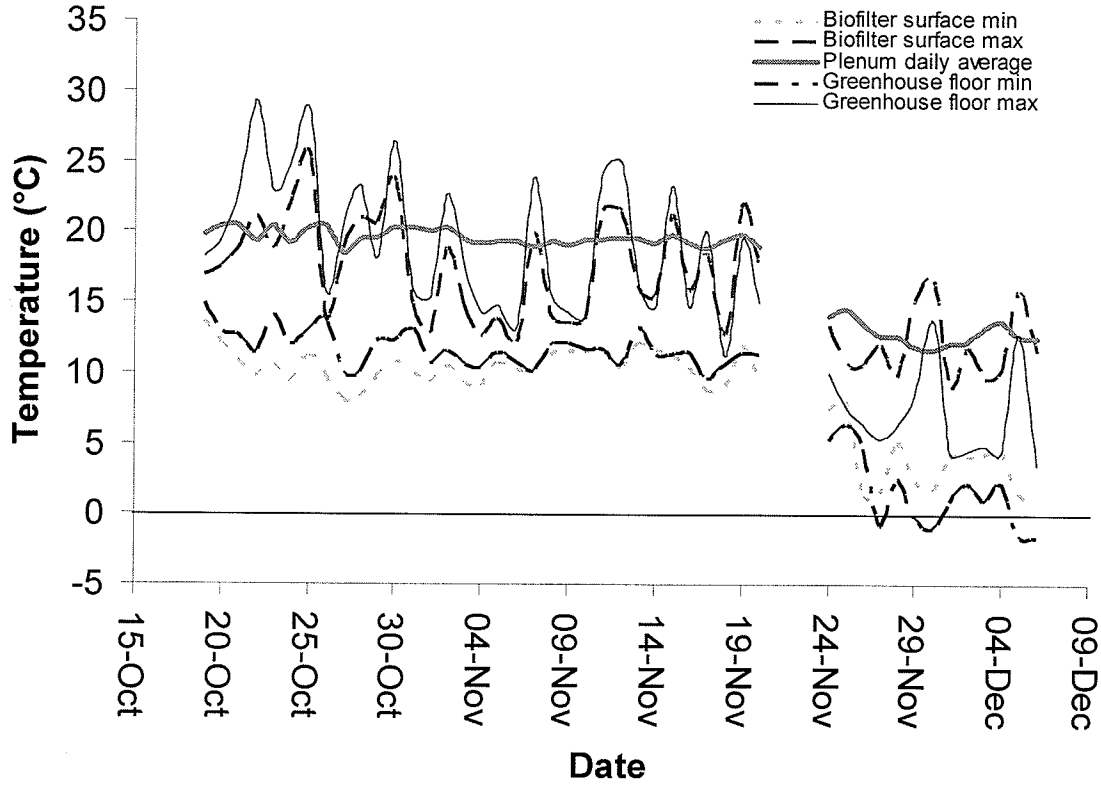
Figure 4.9 Temperature profile of the air inside the greenhouse at different times of the day.



4.4.3 Temperature comparison of biofilter surface and greenhouse floor The minimum and maximum greenhouse floor temperatures shown in Figure 4.10 were based on greenhouse floor readings at 07:00 and 13:00 h, respectively. The daily average temperature of the biofilter plenum fluctuated between 11.7 and 20.4°C. The minimum and maximum temperatures of the greenhouse floor were a little bit higher than the minimum and maximum temperatures of the biofilter surface when the weather was not too cold. However, the temperature of the biofilter surface never went below 1°C throughout the experiment even when the biofilter booster fan was shut down, suggesting that the biofilter was still getting

some heat from the barn.

Figure 4.10 Temperature profile of biofilter surface and greenhouse floor.



The greenhouse floor temperature varied between -1.9 and 29.3°C. The lowest temperature on the biofilter surface was recorded as 1.3°C. It is considered that the biofilter surface would have higher temperatures if the booster fan had remained in service, as the minimum temperature of the biofilter surface before the shutdown of booster fan was measured as 8°C. Figure 4.10 shows that minimum and maximum floor temperatures were slightly higher than minimum and maximum temperatures of the biofilter surface when the outside temperature was above -10°C. However, a reversal occured when the outside temperature went below -10°C. This supports the hypothesis of putting the potted plants on

top of the biofilter surface for the direct gain of heat energy and CO_2 when the outside temperature gets cold ($<-10°C$).

4.4.4 Hydrogen sulfide reduction The mean hydrogen sulfide (H_2S) concentration in the plenum of the biofilter was 0.56 ppm with a standard deviation of 0.2 ppm over the six sampling periods, these values are an average of three replicates at different sampling points (Table 4.2). The H_2S concentration in the barn exhaust can be as high as 0.93 ppm (Zhou 2001). After passing through the biofilter, the mean H_2S concentration ranged between 0.15 and 0.39 ppm. Based on the inlet and outlet H_2S concentrations, the H_2S reduction ranged between 35 and 55% (Table 4.2). The main reasons for lower H_2S removal rates are: i) lower EBRT time (3 s) of biofilter operation (Janni et al. 1998), and ii) inadequate biofilter moisture content (13-38%, wb) necessary for favourable microbial environment and bacterial growth (Devinny et al. 1998).

Table 4.2 Hydrogen sulfide (H_2S) concentrations inside the greenhouse.

Sampling week	H_2S concentration (ppm)			Mean H_2S reduction (%)
	Inlet	Biofilter surface	Solar energy greenhouse	
5	0.33	0.15	0.2	55
6	0.7	0.39	0.42	44
7	0.36	0.21	0.22	42
8	0.6	0.39	0.41	35
9	0.68	0.38	0.38	44
10	0.71	0.37	0.38	48
MEAN	**0.56**	**0.32**	**0.34**	**45**
STDEV	**0.2**	**0.11**	**0.11**	

4.4.5 Carbon dioxide environment The mean carbon dioxide (CO_2) concentration on the biofilter surface was 1146 ppm with a standard deviation of 304 ppm over the six sampling

periods, whereas the mean CO_2 concentration in other locations of the solar energy greenhouse was 1151 ppm with a standard deviation of 285 ppm over the six sampling periods, these values are an average of three replicates at different sampling points (Table 4.3). The main reasons for gradual increase in CO_2 concentration in the greenhouse are:

i) As the hogs were growing up, they were producing more CO_2, which was adding into the greenhouse environment through biofilter

ii) CO_2 is one of the end products of biofiltration. After the biofilter booster fan was shut down, the biofilter was still getting some exhaust air from the hog barn. It is anticipated that flow rate of the exhaust air was less than biofilter booster fan flow rate (1.4 m^3/s). This reduced airflow rate had higher proportion of CO_2 concentrations in the volume of air as compared to higher air flow rate. The reduced airflow rate also allowed more time for a parcel of air to remain in the biofilter bed which allowed extra time for the microbial environment in the biofilter to complete biooxidation reactions to produce more CO_2 concentration.

iii) South end of the greenhouse was not effectively sealed to let the air coming in from the hog barn to escape. But as snow fell, layers of snow piled up at the south end. This reduced the escape of air from the greenhouse and helped in accumulating the CO_2 concentration inside the greenhouse.

The carbon dioxide concentration in fresh air varies between 300 and 600 ppm. The current threshold limit value (TLV), or maximum level that is considered safe for healthy adults for

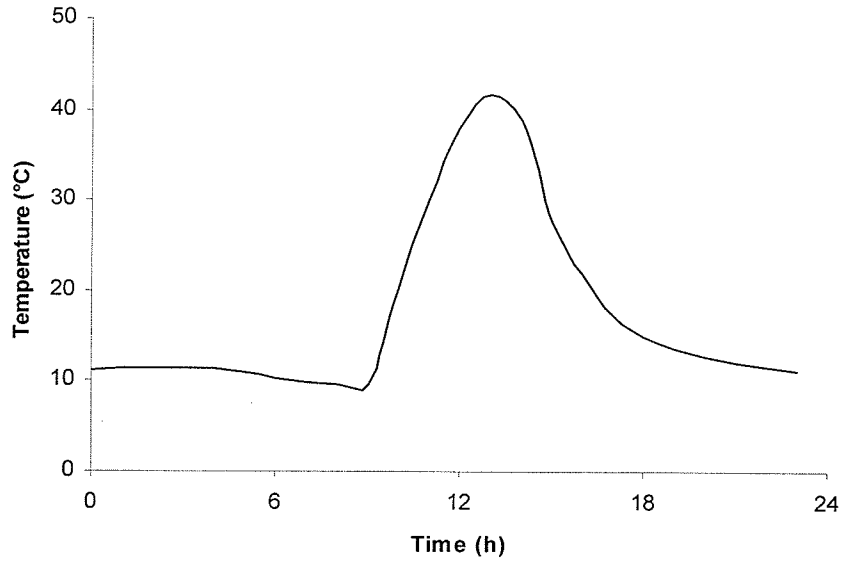
an eight-hour work day, is 5000 ppm (Robertson 2006).

Table 4.3 Carbon dioxide (CO_2) concentrations inside the greenhouse.

Sampling week	CO_2 concentration (ppm)	
	Biofilter surface	Solar energy greenhouse
5	877	941
6	841	841
7	940	953
8	1456	1446
9	1536	1521
10	1223	1201
MEAN	**1146**	**1151**
STDEV	**304**	**285**

4.4.6 Solar wall temperature and stored energy The wall surface temperature started to rise at 9:00h and reached the maximum value of 42°C at 13:00h, whereas solar radiation and indoor air temperature peaked at 12:00h, and 13:00h, respectively (Figure 4.11). The wall surface temperature started to decrease gradually thereafter, and reached the minimum value of 9.6°C just before the sun set. Beshada et al. (2006) concluded that the temperature distribution across a north wall filled with sand at 10, 60, and 100 mm depths was approximately linear. Since the specific heat capacity of riverstone is almost the same as the specific heat capacity of sand, it was assumed that the temperature distribution of a north wall filled with gravel would be the same as the temperature distribution of a north wall filled with sand in Beshada et al.'s study. The temperatures of gravel filled wall for this experiment were calculated based on the graphical presentation of the north wall temperature profile in Beshada et al. (2006).

Figure 4.11 Hourly temperatures recorded at the surface of north wall on November 17, 2008

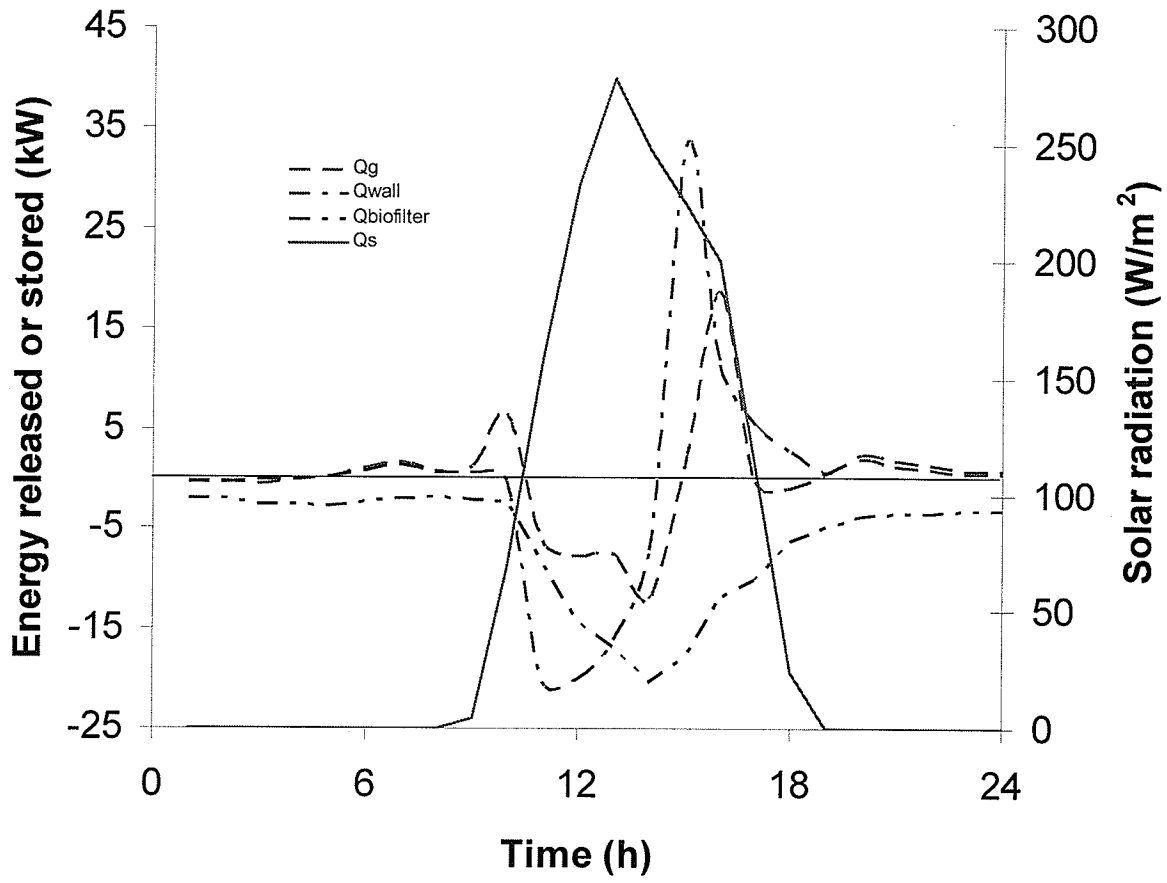


Equation 4.7a was used to estimate the amount of energy stored in or released from the north wall. The rate of change in wall temperature was calculated as the difference between two consecutive measurements of wall temperature divided by the time interval between the two measurements. Increased wall temperature indicated that energy was stored, whereas a decrease in wall temperature meant that energy was released from the wall to the greenhouse. The values of specific heat capacity and density of riverstone used for the calculations were estimated as 0.840 kJ/kg °C (Cheng et al. 2002), and 1522 kg/m^3, respectively (Perry's Chemical Engineers' Hand Book 2007).

The largest difference of 10.1°C occurred at 11:00h. The wall started to store solar energy as soon as the sun was out at 8:00h (Figure 4.12). The peak rate of 20.2 kW occurred at 11:00h. This peak rate at 11:00h suggests that the temperature distribution of riverstone at different depths may not be the same as the temperature distribution of sand at different depths in Beshada at al.'s (2005) study. The daily cumulative energy stored in the wall was

65.1 kWh, and the daily energy release was 64.7 kWh. This indicated that almost all the energy stored by the wall during the day was released to the greenhouse in the night (Figure 4.12).

Figure 4.12 Energy stored (-) in and released (+) by the north wall and gravel, and energy available from barn, based on the November 17, 2007 readings.



Gravel temperature and stored energy The research data from Mahmood and Mann (2008) was used to determine the gravel temperature as a function of solar radiation, and inside temperature. A regression model (R^2 = 0.667) was developed to determine the gravel temperature:

$$T_g = 6.34 + 0.499T_i - 0.01965Q_s \qquad (4.12)$$

Where:

T_g = gravel temperature (°C),

T_i = inside temperature (°C), and

Q_s = solar radiation (W/m^2).

The total area of the greenhouse envelope was calculated to be 100.5 m^2. Equation 4.7b was used to calculate the heat stored or released by the gravel floor. The highest temperature of gravel was obtained at 13:00h. The largest difference of 3.46°C occurred at 15:00h. A peak rate of 18.8 kW occurred at 15:00h. According to the regression model, almost all the energy stored by gravel was released at night.

4.4.8 Energy available from the barn Available barn energy was calculated based on the biofilter airflow rate (1.4 m^3/s) and biofilter surface temperature. The barn room connected to the greenhouse was only partially-filled (< 20 pigs in a room designed for 130 pigs). As a consequence, the heat content of the exhaust air was quite low and the biofilter surface temperature was less than the greenhouse temperature throughout the day. Figure 4.12 shows that no heat energy was available from the barn on November 17, 2007 to maintain the minimum (10°C) greenhouse temperature. In order to obtain heat energy from the barn, the biofilter surface temperature should always be higher than the greenhouse temperature. It was also noted that barn energy would be wasted during the peak sunny hours (1100- 1500h). During that time, solar energy was sufficient to maintain the required temperature inside the greenhouse. Wasted barn energy could be stored as geothermal energy during the daytime, and introduced into the greenhouse during the night hours.

4.4.9 Required Volumetric Flow Rate of the Barn

The main purpose of this calculation was to determine the maximum required volume of barn exhaust leaving the biofilter surface at 15°C to maintain the minimum temperature (10°C) inside the greenhouse.

After substituting the values of Q_{cd}, Q_{in}, Q_{st}, ℓ_a, C_a, t_b, and t_i in equation 4.11, the maximum volumetric flow rate of barn exhaust air required to maintain the minimum greenhouse temperature (10°C) at night time was calculated to be 1.60 m^3/s.

4.5 Conclusions

1.1. The maximum temperature drop along 15.5 m long high density polyethylene pipe (HDPE), insulated by R-20 fibreglass insulation, fluctuated between 1 and 7°C. Wind speed had more influence on the temperature drop than did the outdoor temperature.

1.2. The daily average temperature inside the greenhouse was always above 1.5°C even when the daily average outside temperature went below -25°C. When the biofilter booster fan was in service, the greenhouse temperature never went below 10°C, even though the outside temperature was -10°C.

1.3. Under cold weather conditions, the biofilter surface temperature was higher than the greenhouse floor temperature. Hence, it would be good to put the potted plants on the biofilter surface for maximum heat gain.

1.4. In order to obtain heat energy from the barn, the biofilter surface temperature should be higher than the greenhouse temperature. Sufficient amounts of heat energy from the barn could be stored as active heat energy storage in the floor of the greenhouse

during the day time, and can be re circulated to the greenhouse environment during the night hours.

2. The biofilter hydrogen sulfide (H_2S) reduction efficiency ranged between 35 and 55%.
3. The mean CO_2 concentration inside the greenhouse varied between 877 and 1536 ppm over the six sampling periods.

4.1. Almost all the energy stored by the north wall during the daytime was released to the greenhouse in the night time

4.2. According to the regression model, nearly all of the energy absorbed in the gravel during the daytime was released during the night hours.

5. In order to keep the minimum greenhouse (15m x 6.7m) temperature at 10°C on November 17, 2007, the maximum required volumetric flow rate of barn exhaust air at a temperature of 15°C is 1.60m^3/s.

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5 General Conclusions and Recommendations

With the data collected from the prototype of this integrated barn-biofilter-greenhouse system, it was determined that heat energy from the barn could be used as auxiliary heat to maintain the required (10°C) greenhouse temperature. However, in order to accomplish that, biofilter surface temperature should be higher than the greenhouse temperature. Biofilter surface temperature in the current research was generally low because the barn room connected to the greenhouse was only partially-filled (< 20 pigs in a room designed for 130 pigs). Without a permanent supply of water to the greenhouse, it was hard to maintain the biofilter media moisture content necessary for the microbial population to treat the odorous compounds. Therefore, biofilter hydrogen sulfide removal efficiency was less than 60%. Following are the results of the objectives of this research:

1.1 Gravel stored 107.5% of the available solar energy as a sensible heat, while soil and woodchips stored about 38.6, and 34.2 % of the available solar energy as a sensible heat. These values present approximate results, and maybe over estimated or underestimated because of the estimated density, and specific heat capacity values, and extrapolation of the data to the measured surface temperature of gravel, soil, and woodchips.

2.1 The maximum temperature drop along the 15.5 m long duct insulated by R-20 fibreglass insulation fluctuated between 1 and 7°C. Wind speed had more influence on the temperature drop than did the outdoor temperature.

2.2 The daily average temperature inside the greenhouse was always above 1.5°C even when the daily average outside temperature went below -25°C. When the biofilter booster fan was in service, the greenhouse temperature never went below 10°C even though the outside temperature was -10°C.

2.3 Under cold weather (< -10°C) conditions, the biofilter surface temperature was higher than the greenhouse floor temperature. Hence, it may be good to put potted plants on the biofilter surface for maximum heat gain.

3.1. The energy storage in the north wall on the coldest day (November 17, 2007) when the biofilter booster fan was in operation was recorded as 65.1 kW and energy release was 64.7 kW. This means almost all the energy stored by north wall during the daytime was released to the greenhouse in the night time.

3.2. According to the regression model nearly all of the energy stored in the gravel during the daytime on November 17, 2008 was released to the greenhouse as sensible heat in the nighttime.

4. In order to keep the minimum greenhouse (15m x 6.7m) temperature at 10°C, the maximum required volumetric flow rate of barn exhaust air at 15°C is 1.60m^3/s.

5. Hydrogen sulfide (H_2S) reduction between 35 and 55% was achieved. Adequate moisture content and an increase in EBCT are recommended to increase the biofilter hydrogen sulfide removal efficiency.

6. The mean CO_2 concentration inside the greenhouse varied between 877 and 1536 ppm over the six sampling periods. This enriched CO_2 environment should be good for enhanced plant growth rate and yield.

Following are some recommendations for the future work on this research project

1) The present research showed that barn heat energy was available to the greenhouse at night time, if the biofilter surface temperature was higher than the greenhouse temperature. A better way of achieving this would be to connect the central exhaust fan of a hog barn to the greenhouse so that instead of pulling the air from only one room of the barn, exhaust air would be collected from all the rooms.
2) In the current design, during the peak sunny hours when solar energy was sufficient to maintain the required greenhouse temperature (10°C) on November 17, 2007; the heat energy from the barn was being wasted. An active heat energy storage system can be used to store this heat in the floor of the greenhouse during the day time, and re-circulate it to the greenhouse environment during the night hours.
3) An electrical heating system should be installed in the greenhouse to supply supplemental heat in case of any emergency when heat energy from the barn is not sufficient to maintain minimum temperature inside the greenhouse.
4) A cooling system would be required in order to make this integrated system work year round. Because greenhouse temperature can be as high as 40°C during the summer time, this high temperature environment would not be suitable for plants.

5) Temperature distribution of north wall filled with riverstone should be evaluated to determine the accurate values of the heat energy storage in the north wall.

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Q = Airflow rate = 1.4 m^3/s

τ = True residence time = 3 s

θ = Porosity = 60%

$$\tau = \frac{V_f \times \theta}{Q}$$

V_f = volume of the biofilter medium = 7 m^3

A = Area of the biofilter = 3.35m x 3.35m = 11.24 m^2

$$A = \frac{V_f}{D}$$

D = Media depth = 0.62 m

SL = Q / A

SL = surface loading = 0.125 m/s

For vertical airflow (Sadaka et al. 2002):

a = ASAE pressure formula (80:20 W) = 13506

b = ASAE pressure formula (80:20 W) = 256

$$\frac{\Delta P}{D} = \frac{a \times (SL)^2}{\ln(1 + b \times SL)}$$

ΔP = 37.2 pa

Figure B.1 Arrangement of thermocouples inside the duct

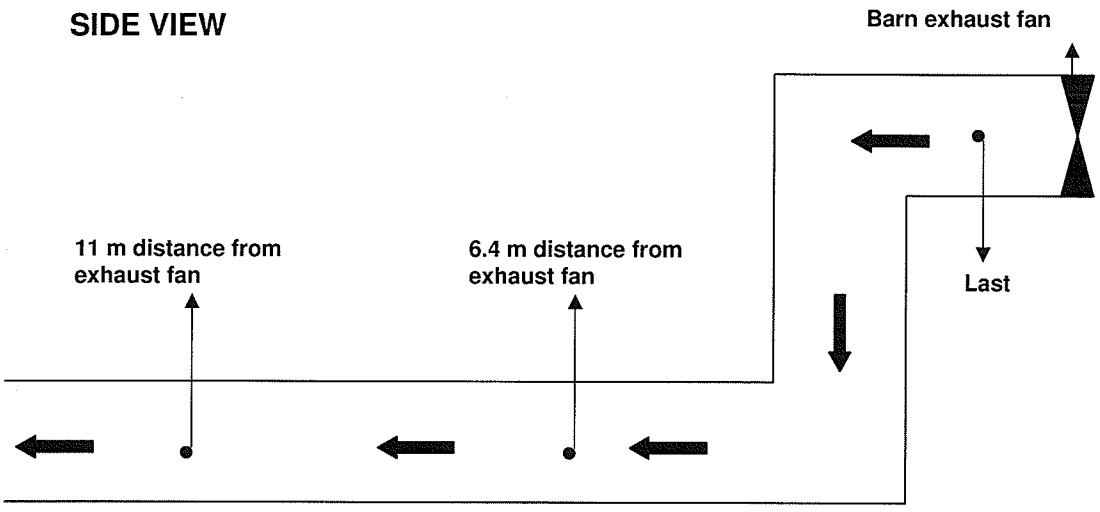

Figure B.2 Arrangement of thermocouples on greenhouse floor

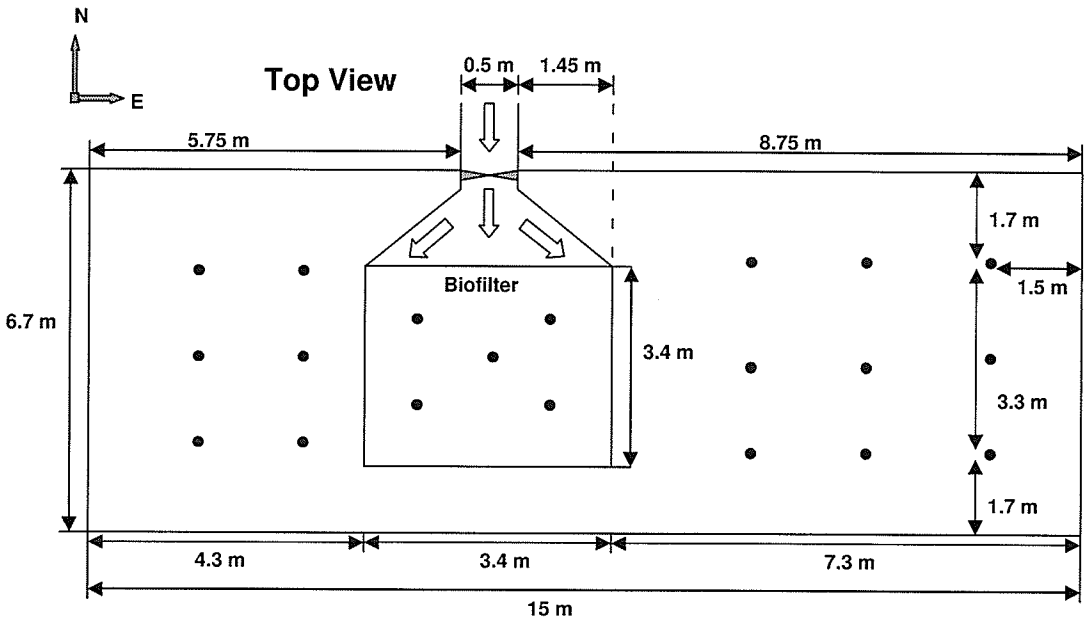

Figure B.3 Arrangement of thermocouples on top of biofilter

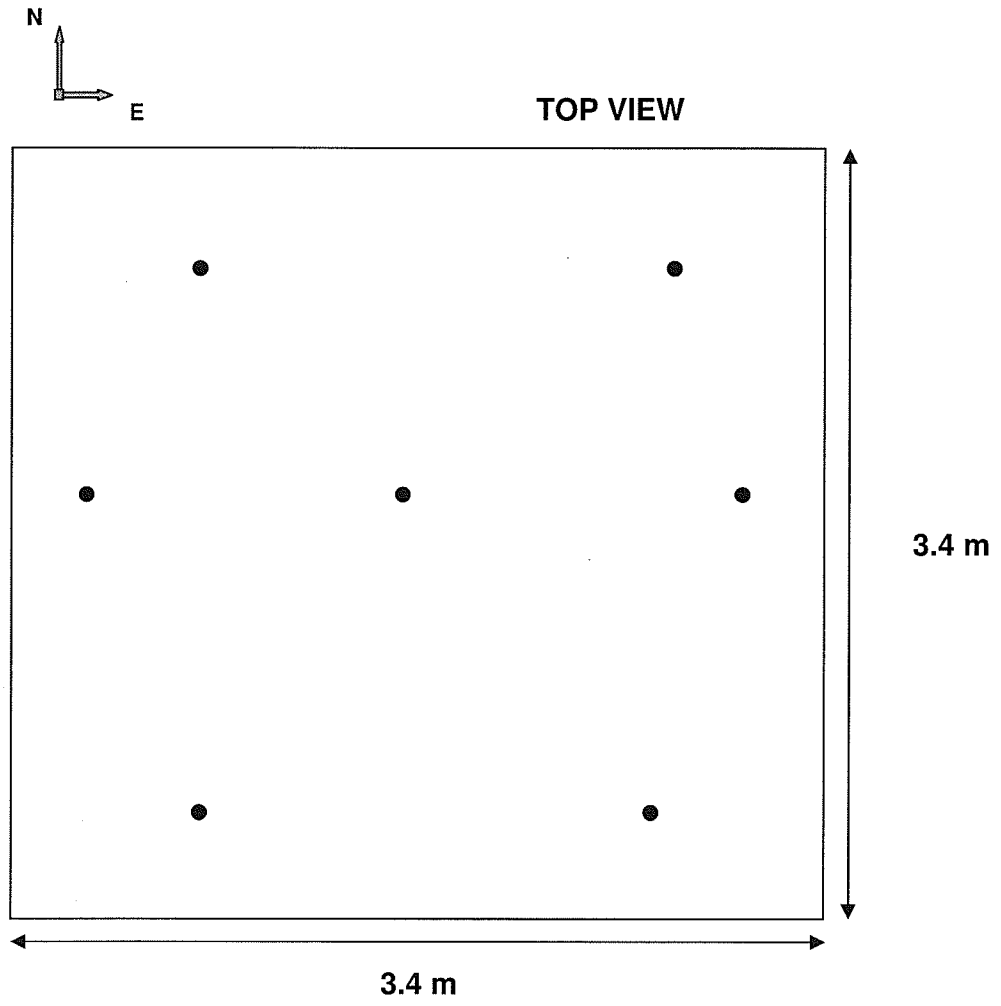

Figure B.4 Arrangement of thermocouples inside the biofilter plenum

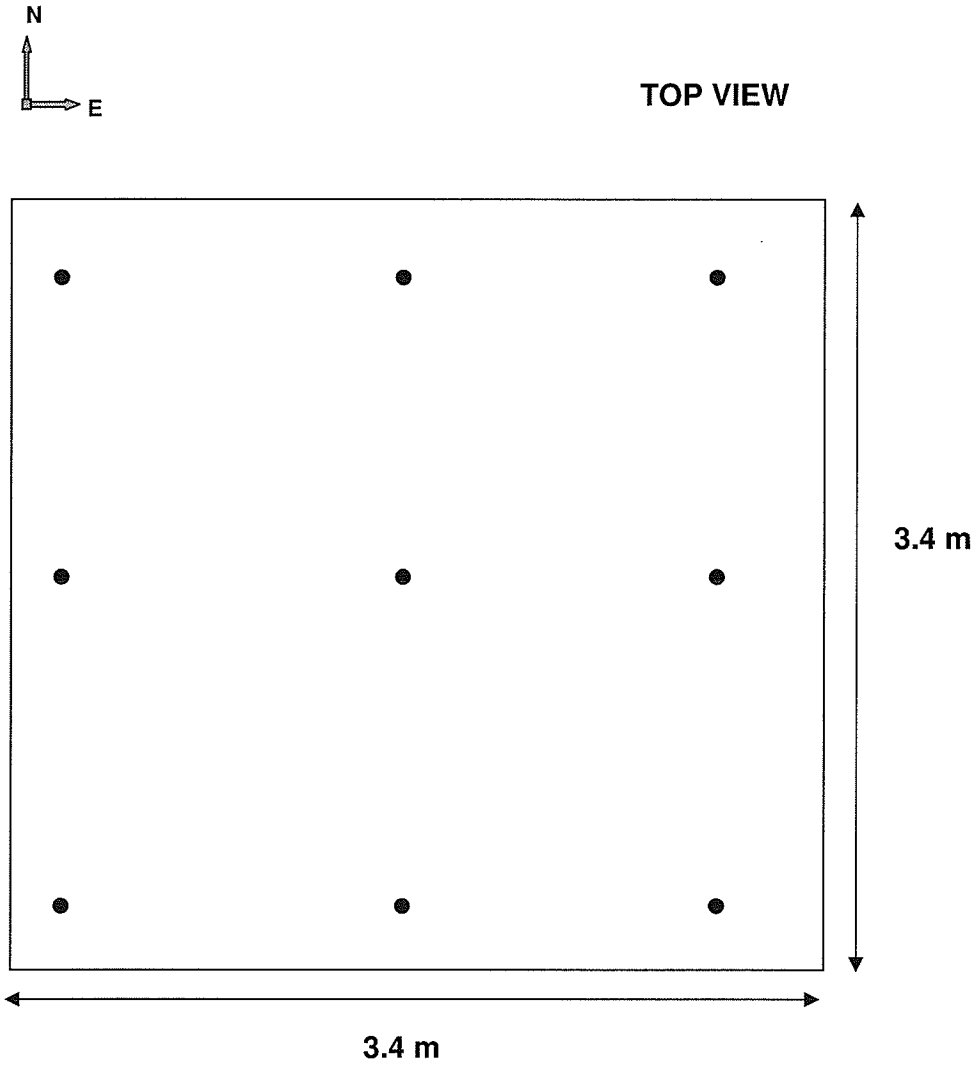

Table C.1 Temperature profile along the length of the duct during the coldest days

	Temperature (°C)					
Date	Barn exhaust air	6.4 m from the barn exhaust	11 m from the barn exhaust	Biofilter plenum	Loss in Temperature	Outside air
24/11/2007	16.52	15.80	15.22	13.18	3.34	-7.83
25/11/2007	15.62	15.75	15.40	14.33	1.29	-4.72
26/11/2007	17.89	16.13	15.40	13.83	4.06	-12.07
27/11/2007	16.81	14.69	13.26	11.59	5.22	-25.68
28/11/2007	17.06	15.87	15.18	13.90	3.16	-12.97
29/11/2007	18.33	15.73	14.46	11.49	6.84	-23.00
30/11/2007	14.76	14.27	13.12	11.29	3.47	-24.36
01/12/2007	17.22	16.76	15.72	11.62	5.60	-18.12
02/12/2007	14.70	14.66	13.84	11.93	2.77	-14.96
03/12/2007	19.06	16.61	15.60	12.69	6.37	-17.86
04/12/2007	15.63	15.32	14.63	13.17	2.46	-11.96
05/12/2007	15.62	14.42	13.18	12.15	3.47	-28.30

Table C.2 Daily average temperature and solar radiation

Date	Temperature (℃)		Radiation (w/m^2)
	Outdoor	Inside	
19/10/2007	8.89	15.86	65.96
20/10/2007	4.92	15.41	112.35
21/10/2007	2.54	16.37	172.91
22/10/2007	3.48	19.40	275.24
23/10/2007	5.94	17.83	215.33
24/10/2007	4.66	18.56	242.80
25/10/2007	10.36	20.92	257.15
26/10/2007	3.77	14.14	78.74
27/10/2007	-1.62	15.10	215.93
28/10/2007	1.47	15.37	198.18
29/10/2007	4.55	15.71	150.24
30/10/2007	7.00	17.55	163.17
31/10/2007	1.36	13.72	103.71
01/11/2007	1.56	13.27	91.25
02/11/2007	2.32	15.37	143.93
03/11/2007	-0.60	14.18	130.68
04/11/2007	-0.68	13.40	68.99
05/11/2007	-0.38	13.30	86.50
06/11/2007	-3.22	12.80	92.50
07/11/2007	-0.92	16.25	203.88
08/11/2007	0.48	14.00	103.57
09/11/2007	0.31	13.58	69.20
10/11/2007	2.21	13.70	69.07
11/11/2007	5.40	16.19	129.65
12/11/2007	3.53	17.62	207.45
13/11/2007	9.45	15.74	93.15
14/11/2007	-0.51	13.87	84.30
15/11/2007	-1.36	14.89	135.68
16/11/2007	-1.25	13.45	74.43
17/11/2007	-4.45	14.59	201.32
18/11/2007	-1.01	12.64	42.72
19/11/2007	1.19	15.40	127.29
20/11/2007	-3.76	13.38	57.47
24/11/2007	-5.35	7.55	90.89
25/11/2007	-5.65	7.17	69.76
26/11/2007	-13.58	4.42	78.74
27/11/2007	-20.79	1.54	120.01
28/11/2007	-14.18	4.22	104.04
29/11/2007	-20.35	2.95	165.34
30/11/2007	-21.56	6.78	178.57
01/12/2007	-16.43	2.58	80.44
02/12/2007	-16.46	2.79	131.83
03/12/2007	-15.93	2.55	108.22
04/12/2007	-12.20	3.37	95.39
05/12/2007	-25.01	4.30	175.65
06/12/2007	-16.62	1.74	113.45

Table C.3 Temperature profile of greenhouse floor at different times of the day

Date	Temperature at different times of the day (℃)			
	1:00h	7:00h	13:00h	19:00h
19/10/2007	15.08	14.84	18.25	15.13
20/10/2007	13.37	12.81	19.54	14.68
21/10/2007	13.08	12.61	23.01	14.28
22/10/2007	12.16	11.39	29.31	15.17
23/10/2007	14.27	14.02	22.90	15.12
24/10/2007	12.41	12.06	24.69	15.63
25/10/2007	13.86	12.98	28.66	15.69
26/10/2007	13.79	13.78	15.71	12.42
27/10/2007	10.66	10.00	20.40	13.01
28/10/2007	10.70	10.02	23.31	13.71
29/10/2007	12.35	12.26	18.14	13.99
30/10/2007	12.85	12.27	26.35	15.26
31/10/2007	13.70	13.05	15.89	12.33
01/11/2007	10.74	10.63	15.23	13.27
02/11/2007	11.53	11.59	22.70	13.77
03/11/2007	11.82	10.55	17.62	13.41
04/11/2007	11.40	10.31	14.28	12.61
05/11/2007	11.63	11.45	14.75	11.35
06/11/2007	10.56	10.64	13.21	11.35
07/11/2007	10.37	10.15	23.91	13.37
08/11/2007	12.33	11.88	15.56	12.74
09/11/2007	12.15	12.09	14.26	12.00
10/11/2007	11.78	11.66	13.94	12.03
11/11/2007	11.62	12.01	24.26	10.98
12/11/2007	11.97	10.62	24.93	14.19
13/11/2007	13.56	13.26	16.38	13.46
14/11/2007	12.74	11.28	14.66	11.93
15/11/2007	11.73	11.32	23.30	12.25
16/11/2007	11.64	11.41	14.61	11.65
17/11/2007	10.67	9.59	20.09	11.68
18/11/2007	10.58	10.83	11.11	10.25
19/11/2007	11.40	11.36	19.51	13.02
20/11/2007	11.71	11.26	15.00	11.29
24/11/2007	5.73	5.14	9.98	7.59
25/11/2007	6.40	6.74	7.59	6.71
26/11/2007	5.14	4.66	6.39	2.17
27/11/2007	-0.13	-0.84	5.25	2.51
28/11/2007	2.56	3.57	6.27	2.85
29/11/2007	1.28	-0.25	8.42	1.81
30/11/2007	-0.55	-1.02	13.71	2.98
01/12/2007	0.84	1.65	4.37	2.60
02/12/2007	2.19	2.16	4.52	1.58
03/12/2007	0.84	0.86	4.87	2.15
04/12/2007	2.50	2.23	4.37	2.39
05/12/2007	0.24	-1.48	12.73	0.34
06/12/2007	-1.59	0.34	3.54	1.48

Table C.4 Temperature profile of greenhouse at different times of the day

Date	Temperature at different times of the day (°C)			
	1:00h	7:00h	13:00h	19:00h
19/10/2007	15.68	15.66	19.24	15.40
20/10/2007	13.62	13.27	21.13	15.09
21/10/2007	13.56	13.12	26.23	14.58
22/10/2007	12.46	11.97	36.06	14.68
23/10/2007	14.41	14.55	26.07	14.92
24/10/2007	12.46	12.50	29.40	15.27
25/10/2007	14.07	13.62	38.37	16.80
26/10/2007	14.11	14.73	15.68	12.20
27/10/2007	10.61	10.06	23.22	12.85
28/10/2007	10.79	10.47	26.90	13.97
29/10/2007	12.94	12.94	19.72	13.95
30/10/2007	13.21	12.97	34.02	15.24
31/10/2007	14.08	13.67	14.99	12.26
01/11/2007	10.97	11.12	16.40	14.15
02/11/2007	12.24	12.64	26.79	14.10
03/11/2007	12.15	11.05	19.05	13.91
04/11/2007	12.04	10.79	15.62	13.82
05/11/2007	12.87	12.94	16.23	12.10
06/11/2007	11.54	11.97	14.71	12.64
07/11/2007	11.77	11.72	29.96	13.47
08/11/2007	12.86	12.84	16.70	13.53
09/11/2007	13.30	13.40	15.52	12.72
10/11/2007	12.90	12.99	15.20	13.17
11/11/2007	13.23	13.87	29.36	14.50
12/11/2007	12.89	11.78	31.19	14.70
13/11/2007	15.01	14.56	17.90	14.35
14/11/2007	14.29	13.23	15.93	13.20
15/11/2007	13.29	12.95	27.48	13.64
16/11/2007	13.36	13.53	15.58	12.11
17/11/2007	11.37	10.19	29.61	12.06
18/11/2007	11.17	11.98	13.73	12.99
19/11/2007	13.40	13.25	22.47	14.16
20/11/2007	13.12	12.95	17.02	13.15
24/11/2007	5.67	5.46	11.07	7.68
25/11/2007	6.62	7.38	8.15	7.16
26/11/2007	5.24	4.67	7.50	1.35
27/11/2007	-0.93	-1.72	6.23	2.54
28/11/2007	2.83	3.79	7.33	2.96
29/11/2007	1.16	-0.10	10.87	1.58
30/11/2007	-1.27	-1.35	16.84	2.79
01/12/2007	0.43	1.58	4.98	2.73
02/12/2007	2.07	2.22	5.30	1.33
03/12/2007	0.56	0.80	6.15	2.53
04/12/2007	3.46	2.98	5.62	2.58
05/12/2007	-0.09	-1.96	16.29	-0.50
06/12/2007	-1.95	0.17	6.12	1.55

Table C.5 Min and max temperatures of biofilter surface and greenhouse floor

Date	Temperature (°C)				
	Biofilter surface min	Biofilter surface max	Plenum daily average	Greenhouse floor min	Greenhouse floor max
19/10/2007	13.51	16.86	19.82	14.84	18.25
20/10/2007	12.03	17.51	20.37	12.81	19.54
21/10/2007	10.69	18.78	20.33	12.61	23.01
22/10/2007	9.68	21.13	19.28	11.39	29.31
23/10/2007	10.56	18.73	20.34	14.02	22.90
24/10/2007	9.41	21.90	19.23	12.06	24.69
25/10/2007	11.20	25.50	20.26	12.98	28.66
26/10/2007	9.76	13.87	20.44	13.78	15.71
27/10/2007	8.03	18.70	18.49	10.00	20.40
28/10/2007	8.18	21.00	19.42	10.02	23.31
29/10/2007	9.69	20.59	19.56	12.26	18.14
30/10/2007	10.81	23.69	20.30	12.27	26.35
31/10/2007	9.93	14.87	20.31	13.05	15.89
01/11/2007	9.24	12.75	19.98	10.63	15.23
02/11/2007	10.50	18.82	20.30	11.53	22.70
03/11/2007	9.24	14.76	19.46	10.55	17.62
04/11/2007	8.96	12.58	19.19	10.31	14.28
05/11/2007	10.72	13.77	19.30	11.45	14.75
06/11/2007	10.21	12.17	19.37	10.64	13.21
07/11/2007	10.10	19.97	18.90	10.15	23.91
08/11/2007	11.24	14.00	19.27	11.88	15.56
09/11/2007	11.55	13.61	19.11	12.09	14.26
10/11/2007	11.58	13.78	19.39	11.66	13.94
11/11/2007	11.64	21.41	19.46	11.62	24.26
12/11/2007	10.42	21.50	19.57	10.62	24.93
13/11/2007	12.07	16.10	19.55	13.26	16.38
14/11/2007	11.66	15.53	19.22	11.28	14.66
15/11/2007	11.18	21.19	19.81	11.32	23.30
16/11/2007	10.30	15.83	19.19	11.41	14.61
17/11/2007	8.82	18.50	18.78	9.59	20.09
18/11/2007	9.03	12.67	19.40	10.58	11.11
19/11/2007	11.91	22.00	19.74	11.36	19.51
20/11/2007	9.74	17.55	18.93	11.26	15.00
24/11/2007	7.30	13.33	14.07	5.14	9.98
25/11/2007	8.02	10.69	14.52	6.40	7.59
26/11/2007	1.38	10.53	13.40	4.66	6.39
27/11/2007	1.42	11.97	12.66	-0.84	5.25
28/11/2007	5.10	9.78	12.55	2.56	6.27
29/11/2007	2.30	15.11	11.86	-0.25	8.42
30/11/2007	1.75	16.50	11.68	-1.02	13.71
01/12/2007	4.07	9.05	12.14	0.84	4.37
02/12/2007	4.05	11.78	12.27	2.16	4.52
03/12/2007	4.17	9.57	13.16	0.86	4.87
04/12/2007	4.49	10.17	13.70	2.23	4.37
05/12/2007	1.42	15.88	12.61	-1.48	12.73
06/12/2007	1.26	11.57	12.53	-1.59	3.54

Table D.1 Gravel energy storage calculations using regression model

Tg calculations using JMP Model			
Tg(℃)	Tdg=t2-t1(℃)	Qg (kW)	Time (h)
11.91		Tdg*5.425	
11.96	0.06	0.32	0
12.02	0.05	0.28	1
12.11	0.10	0.53	2
12.12	0.01	0.05	3
12.09	-0.03	-0.18	4
11.88	-0.20	-1.11	5
11.58	-0.31	-1.67	6
11.42	-0.15	-0.83	7
11.19	-0.23	-1.27	8
10.01	-1.18	-6.38	9
11.17	1.16	6.29	10
12.61	1.44	7.80	11
14.02	1.41	7.64	12
16.26	2.24	12.16	13
16.01	-0.24	-1.32	14
12.56	-3.46	-18.76	15
12.62	0.07	0.36	16
12.80	0.18	0.95	17
12.72	-0.08	-0.44	18
12.36	-0.36	-1.95	19
12.12	-0.24	-1.29	20
11.94	-0.18	-0.97	21
11.85	-0.10	-0.52	22
11.75	-0.10	-0.53	23

Specific heat capacity of gravel = 0.840 kJ/kg-℃

Density of gravel = 1522kg/m^3

Volume of gravel floor = 15.27 m^3

Rate of change of temperature between two readings = ℃/3600s

0.840*1522*15.27/3600 = 5.425

Regression Equation

$$Tg = 6.34 + 0.499Ti - 0.01965Qs$$

Table D.2 North wall energy storage calculations

Twall(°C)	Time (h)	Tw-adjusted (°C)	Tdw=t2-t1 (°C)	Qwall (kW) Tdw*2
11.05		11.05		
11.15	0	11.15	0.10	0.20
11.33	1	11.33	0.17	0.35
11.40	2	11.40	0.08	0.15
11.41	3	11.41	0.01	0.03
11.32	4	11.32	-0.09	-0.18
10.93	5	10.93	-0.39	-0.78
10.24	6	10.24	-0.69	-1.38
9.90	7	9.90	-0.34	-0.67
9.56	8	9.56	-0.35	-0.70
9.71	9	9.71	0.15	0.31
19.89	10	19.89	10.18	20.37
29.98	11	29.98	10.09	20.17
38.13	12	38.13	8.15	16.30
41.76	13	41.76	3.63	7.25
38.89	14	25.02	-16.74	-33.47
27.41	15	19.28	-5.74	-11.48
21.98	16	16.57	-2.71	-5.43
17.22	17	15.20	-1.37	-2.73
14.89	18	14.89	-0.31	-0.62
13.64	19	13.64	-1.25	-2.50
12.75	20	12.75	-0.89	-1.78
12.08	21	12.08	-0.67	-1.34
11.68	22	11.68	-0.40	-0.80
11.26	23	11.26	-0.42	-0.84

Specific heat capacity of gravel = 0.840 kJ/kg-°C
Density of gravel = 1522kg/m^3
Volume of gravel bed = 5.64m^3
Rate of change of temperature between two readings = °C/3600s
0.840*1522*5.64/3600 = 2

Table D.3 Calculation for required flow rate of the barn to maintain the minimum (10°C) temperature

F= density of air (1.3 kg/m^3)*specific heat of air (1.005 kJ/kg-°C) = 1.31					
Time (h)	Temperature (°C)				Qb (kW)
	Ti	Tb	Tdb = Tb-Ti	F	F*Tdb
	11.15				
0	11.27	15.00	3.73	1.31	4.87
1	11.37	15.00	3.63	1.31	4.74
2	11.57	15.00	3.43	1.31	4.48
3	11.59	15.00	3.41	1.31	4.46
4	11.52	15.00	3.48	1.31	4.55
5	11.11	15.00	3.89	1.31	5.08
6	10.49	15.00	4.51	1.31	5.89
7	10.19	15.00	4.81	1.31	6.29
8	10.00	15.00	5.00	1.31	6.53
9	10.06	15.00	4.94	1.31	6.46
10	15.89	15.00	-0.89	1.31	-1.17
11	21.70	15.00	-6.70	1.31	-8.75
12	26.32	15.00	-11.32	1.31	-14.78
13	29.61	15.00	-14.61	1.31	-19.08
14	28.19	15.00	-13.19	1.31	-17.23
15	20.33	15.00	-5.33	1.31	-6.97
16	16.99	15.00	-1.99	1.31	-2.61
17	13.88	15.00	1.12	1.31	1.46
18	12.78	15.00	2.22	1.31	2.89
19	12.06	15.00	2.94	1.31	3.84
20	11.58	15.00	3.42	1.31	4.47
21	11.22	15.00	3.78	1.31	4.93
22	11.03	15.00	3.97	1.31	5.18
23	10.84	15.00	4.16	1.31	5.44

Table D.3 Calculation for required flow rate of the barn to maintain the minimum (10°C) temperature

				JMP Model			
Time (h)	Qb (kW)	Qs (kW)	Qcd (kW)	Qst. (kW)		R	Flowrate m^3/s
				Qw-adjusted	Qgr. jmp	Qcd+Qst.-Qs	R/Qb
0	4.87	0.00	6.62	0.20	0.32	7.13	1.46
1	4.74	0.00	6.43	0.35	0.28	7.05	1.49
2	4.48	0.00	6.48	0.15	0.53	7.16	1.60
3	4.46	0.00	6.58	0.03	0.05	6.66	1.49
4	4.55	0.00	6.88	-0.18	-0.18	6.51	1.43
5	5.08	0.00	7.43	-0.78	-1.11	5.54	1.09
6	5.89	0.00	7.78	-1.38	-1.67	4.73	0.80
7	6.29	0.00	8.12	-0.67	-0.83	6.62	1.05
8	6.53	0.43	8.09	-0.70	-1.27	5.69	0.87
9	6.46	6.90	7.86	0.31	-6.38	-5.12	-0.79
10	-1.17	15.89	9.68	20.37	6.29	20.44	-17.53
11	-8.75	23.36	11.34	20.17	7.80	15.95	-1.82
12	-14.78	27.96	12.86	16.30	7.64	8.84	-0.60
13	-19.08	24.90	14.14	7.25	12.16	8.65	-0.45
14	-17.23	22.53	13.45	-2.87	-1.32	-13.26	0.77
15	-6.97	20.14	9.70	-11.48	-18.76	-40.67	5.84
16	-2.61	11.26	8.29	-5.43	0.36	-8.04	3.09
17	1.46	2.40	7.53	-2.73	0.95	3.35	2.30
18	2.89	0.01	8.28	-0.62	-0.44	7.21	2.49
19	3.84	0.00	8.15	-2.50	-1.95	3.70	0.96
20	4.47	0.00	7.80	-1.78	-1.29	4.73	1.06
21	4.93	0.00	7.86	-1.34	-0.97	5.55	1.13
22	5.18	0.00	7.98	-0.80	-0.52	6.66	1.29
23	5.44	0.00	8.03	-0.84	-0.53	6.66	1.23

Table D.4 Energy stored and released from the gravel and the north wall, and available energy from the barn

Time	Ti (℃)	Tb(℃)	Tb-Ti(℃)	Energy (kW)			
				Qg	Qwall	Qs	Qbarn
0	11.27	10.21	-1.07	-0.32	-0.20	0.00	-1.95
1	11.37	10.24	-1.14	-0.28	-0.35	0.00	-2.08
2	11.57	10.16	-1.41	-0.53	-0.15	0.00	-2.58
3	11.59	10.15	-1.44	-0.05	-0.03	0.00	-2.65
4	11.52	10.03	-1.49	0.18	0.18	0.00	-2.74
5	11.11	9.87	-1.24	1.11	0.78	0.00	-2.28
6	10.49	9.40	-1.09	1.67	1.38	0.00	-2.01
7	10.19	9.18	-1.01	0.83	0.67	0.00	-1.85
8	10.00	8.84	-1.16	1.27	0.70	4.25	-2.13
9	10.06	8.82	-1.23	6.38	-0.31	68.67	-2.26
10	15.89	11.12	-4.78	-6.29	-20.37	158.13	-8.76
11	21.70	13.78	-7.92	-7.80	-20.17	232.47	-14.52
12	26.32	17.01	-9.30	-7.64	-16.30	278.25	-17.06
13	29.61	18.50	-11.11	-12.16	-7.25	247.73	-20.37
14	28.19	18.47	-9.72	1.32	33.47	224.14	-17.83
15	20.33	13.82	-6.51	18.76	11.48	200.41	-11.93
16	16.99	11.44	-5.56	-0.36	5.43	112.07	-10.19
17	13.88	10.47	-3.42	-0.95	2.73	23.92	-6.27
18	12.78	10.18	-2.61	0.44	0.62	0.10	-4.78
19	12.06	9.98	-2.07	1.95	2.50	0.00	-3.81
20	11.58	9.68	-1.91	1.29	1.78	0.00	-3.50
21	11.22	9.35	-1.88	0.97	1.34	0.00	-3.44
22	11.03	9.33	-1.71	0.52	0.80	0.00	-3.13
23	10.84	9.12	-1.72	0.53	0.84	0.00	-3.16

E. Appendix-An Integrated Barn-Biofilter-Greenhouse System

This Appendix is the title of the paper that is accepted for publication in the conference proceedings of "2008 International Conference on Agricultural Engineering"

Details are as follows:

Mahmood, K., D.D. Mann and Q. Zhang. 2008. An integrated barn-biofilter-greenhouse system. International Conference on Agricultural Engineering. Crete, Greece.