2011

MOISTURE CONTROL METHODOLOGY FOR GAS PHASE COMPOST BIOFILTERS

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MOISTURE CONTROL METHODOLOGY FOR GAS PHASE COMPOST BIOFILTERS

THESIS

Master of Science in Biosystems and Agricultural Engineering in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2011

ABSTRACT OF THE THESIS

MOISTURE CONTROL METHODOLOGY FOR GAS PHASE COMPOST BIOFILTERS

Gas phase biofilters are used for controlling odors from animal facilities. Some characteristics can affect their performance and moisture content is one very important. A methodology for controlling and measuring moisture content is required to optimize these systems. An experiment was conducted to determine the appropriate placement of a set of soaker hoses 1.2 m in length for water application. It was found that the soaker hose installed in the lower region of the biofilter coupled with appropriate and timely application of water was able to minimize drying of the compost. Thermal conductance proved to be a reliable indicator for measuring the moisture content. Biofilters using the soaker hoses together with the thermal conductance as a media moisture sensor were able to maintain moisture content above 30% w.b. which provided sufficient water for microbial activity and ammonia abatement. A characterization of the ammonia and nitrous oxide concentrations was performed in order to compare the behavior of the gases when water was applied versus no water addition. These analyses revealed that the overall performance was not significantly different between treatments. But a more detailed assessment inside the biofilter media is performed; it is possible to identify different processes taking place.

KEYWORDS: Compost Biofilters, thermal conductance, ammonia removal, nitrous oxide, moisture content.

Lucas Dutra de Melo

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DEDICATION

To my mother Cláudia for the love, support, caring and patience when I wasn't present. To my father José Sergio who always motivated me to be my best and for the inspiration on working hard. To my sister Isis for the support and advice on the hardest decisions. And to God for giving me strength and illumination to walk my path.

DEDICAÇÃO

Para minha mãe Cláudia, pelo amor, suporte, carinho e paciência quando não estive presente. Para o meu pai José Sergio que sempre me motivou a ser o meu melhor e pela inspiração de sempre trabalhar duro. Para minha irmã Isis pelo apoio e conselhos nas mais difíceis decisões. E a Deus por me dar força e iluminação na minha jornada.

ACKNOWLEDGMENTS

First I would like to thanks God for strength, wisdom and illumination to pursue my dreams and to hold on for the opportunities that life putted in my path.

Then I want to thank my family for the love, support and always believing in me. I know that they were with me all the time, in the good and the bad. I am thankful for everything they have done for me, for the education, the inspiration and guidance that helped me to be the person I am today.

I want to thank Dr. George Day who has been more than a mentor for me during my staying in Lexington; he has supported me, believed in me and helped me in the difficult times and not only in the work. He helped me become a better engineer with wise insights and advices. He is and always will be a friend, a member of my chosen family.

Thanks to Dr Taraba for helping me when most needed in my work and for the advices and teaching towards my degree. I know that his professionalism and friendship will be always remembered.

Thanks to the former chairman of the Biosystems and Agricultural Engineering Department Dr. Shearer for supporting my work and for financial support.

I also want to thank the other member of my committee Dr. Gates for giving me the opportunity to come to Unite States and pursue my degree, and for being such a good friend, mentor and for believing in my work. And special thanks for him for travelling 6 hours across 3 states to be present throughout my work and to give so much good advice.

A special thanks for Dr. Del Nero Maia for being of so much help during the whole project, for the tutoring and for putting the hands to work when necessary. And of course for the fun outside the department, for presenting me to the Lexington life, for the political conversations that for many times got some heat coming out of it but always fun.

Thanks to Lloyd Dunn and Burl Fannin for all the help with the biofilters and for putting stuff together, for helping me find tools whenever I needed and for being there when I most needed somebody to give me a hand.

Thanks to Andy Watson, Enrique Alves, Rodrigo Baldo, Williams Ferreira and many others who helped me handle the compost, carry it, mix it with water and of course load the biofilters; I know it was not an easy job and that was really exhausting.

I want to express my appreciation to James Worten at the Waste Water Treatment Plant of Lexington, KY, who received us with arms wide open to get some samples of sludge, which was very important to the accomplishment of this work.

Thanks to Michael Sama for his great help and teaching on the principles of capacitance which was very helpful during the project and for helping me with the electronics in my project.

Also thanks to Tatiana Sales that even from far away was always available to give ideas and solutions for anything I asked.

A very special thanks for these two girls Daniela Sarti and Ester Buiate, I do not think there are enough words to describe how important they are to me, they make my life much easier in Lexington, giving me support when needed and being strong handed when necessary. Thank you very much you are both my adopted sisters, and I will take you in my heart forever.

And thanks to all the friends I made here: Santosh, Igor, Gabi, Shankshank, Quélen, Luis Gustavo, Ricardo, Maíra, Rodrigo, Tatiana, Rogério, Flávio and so many others that were really special to me and that forever will be in my heart.

I know there is a lot of people that are not mentioned here, but I want them to know that I am really thankful to everyone that made part of my life, you are responsible for making me the person I am today.

I want to acknowledge the financial supported provided by USDA/ARS Cooperative State Research, NRI Air Quality Program. Without their support this project could not be accomplished.

Agradecimentos

Primeiro gostaria de agradecer a Deus pela força, sabedoria e iluminação para perseguir meus sonhos e a agarrar as oportunidades que a vida pois no meu caminho.

E também eu quero agradecer a minha família pelo amor, suporte e por sempre acreditar em mim. Eu sei que eles estavam comigo o tempo todo, nos bons e maus. Eu sou muito agradecido por tudo que eles fizeram por mim, pela educação, inspiração e pela orientação que me ajudou a ser a pessoa que sou hoje.

Eu quero agradecer Dr. George Day, quem tem sido mais do que um mentor para mim durante minha estadia em Lexington, ele tem me dado suporte, acreditado em mim e me ajudado nos tempos difíceis e não apenas no trabalho. Ele me ajudou a ser um engenheiro melhor com suas dicas e conselhos. Ele é e sempre será um amigo, um membro da minha família escolhida.

Obrigado ao Dr. Taraba por ter me ajudado quando eu mais precisei no meu trabalho e por todos os conselhos e ensinamentos em prol da minha formação. Eu sei que seu profissionalismo e amizade serão para sempre lembrados.

Obrigado ao ex chefe do Departamento de Engenharia Agrícola e de Biosistemas Dr. Shearer pelo suporte ao meu trabalho e pelo apoio financeiro.

Eu também gostaria de agradecer o outro membro do meu comitê Dr. Gates por ter me dado a oportunidade de vir aos Estados Unidos para prosseguir com minha formação, e por ter sido um bom amigo, tutor e por acreditar no meu trabalho. E um agradecimento especial por ele viajar 6 horas por 3 estados para estar presente durante meu trabalho e dar vários bons conselhos.

Um agradecimento especial para o Dr. Del Nero Maia por ter sido tão prestativo durante todo o projeto, pela tutoria e por ter posto as mãos na obra quando necessário. E claro por toda a diversão fora do departamento, por ter apresentado a vida em Lexington, pelas discussões políticas que várias vezes se tornaram um pouco quentes mas acima de tudo divertidas.

Obrigado ao Lloyd Dunn e Burl Fannin por toda a ajuda com os biofiltros e por juntar as peças do quebra-cabeça, por ajudar a achar as diversas ferramentas sempre que eu precisava e por estarem sempre dispostos a ajudar na hora que eu mais precisei de uma mão.

Obrigado a Andy Watson, Enrique Alves, Rodrigo Baldo, Williams Ferreira e muitos outros que ajudaram a trabalhar com o compost, carregá-lo, misturá-lo com água e claro à carregar os biofiltros. Eu sei que não era um trabalho fácil e sim muito cansativo.

Eu quero expressar minha gratidão à James Worten da Estação de Tratamento de Água Residuária de Lexington, KY, quem nos recebeu de braços abertos para pegar amostras de lodo, que foi muito importante para a conclusão desse trabalho.

Obrigado ao Michael Sama por sua grande ajuda e ensinamentos nos princípios da capacitância, os quais foram de muita ajuda durante o projeto e pela ajuda com as partes eletrônicas do projeto.

Também obrigado a Tatiana Sales que mesmo estando longe sempre se fez disponível para dar idéias e soluções para qualquer coisa que eu perguntasse.

Um obrigado muito especial para essas duas garotas Daniela Sarti e Ester Buiate. Eu não acho que existam palavras suficientes para descrever quão importante elas são para mim, elas fizeram minha vida muito mais fácil em Lexington, me dando suporte quando precisei e puxando minha orelha quando necessário. Muito obrigado, vocês duas são minhas irmãs adotadas e eu vou levá-las para sempre no meu coração.

E obrigado a todos os amigos que fiz aqui: Santosh, Igor, Gabi, Shankshank, Quélen, Luis Gustavo, Ricardo, Maíra, Rodrigo, Tatiana, Rogério, Flávio e vários outros que foram muito especiais para mim e que estarão para sempre no meu coração.

Eu sei que existem muitas pessoas que não foram mencionadas aqui, mas eu quero que elas saibam que eu estou muito agradecido por todos que

fizeram parte da minha vida, vocês são responsáveis por terem feito de mim quem eu sou hoje.

Quero reconhecer o apoio financeiro provido pelo USDA/ARS Cooperative State Research, NRI Air Quality Program. Suporte sem o qual esse projeto não poderia ser concluído

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Chapter 1 Introduction

1.1 Summary

The emission of greenhouse gases (GHG's) by confined animal feeding operations (CAFO's) has become an important issue as governments consider the establishment of stricter limits on GHG emissions. Mitigation strategies are being developed involving new and emerging technologies to reduce these emissions. One technology to treat ventilation air that has been studied is the compost-based biofilter because of its economy, ease of maintenance and sustainability.

Compost-based biofilter performance depends on variables related to the physical characteristics of the media. Considerable work has been accomplished to define these characteristics and their effects on biofilter performance. Research conducted by Sales (2008) identified an optimal media particle size distribution which minimized the pressure drop across the media stack. Further, it has been shown that moisture content is a key variable in maximizing biological conversion of ammonia (NH_3) to nitrate-N and ultimately to nitrogen gas (N_2). However, the importance of optimal media moisture content has only been recently identified. Del Nero Maia (2010) has shown that the media moisture content not only affected microbial activity that oxidizes ammonia, but recognized some moisture content conditions that can work as a trigger for nitrous oxide (N_2O) and methane (CH_4) production. Nitrous oxide (N_2O) and methane are greenhouse gases which exert a significant impact on the radiation heat balance of the planet (Lashof, 1990).

Increased demand for food in the world has resulted in increased need within the agri-business sector to supply more foodstuffs as efficiently as possible. High density food production must necessarily involve increased agriculture activity and often, these enterprises may involve higher production of GHG's. Thus, in order to meet world food demand, new and more efficient techniques for mitigation of these gases are necessary. Previous work has shown that biofilter efficiency is directly related to moisture content. Therefore, to be considered efficient, a biofilter must include effective, reliable instrumentation

for media moisture control. The purpose of this work is to establish a system that will deliver water to the media to maintain certain prescribed levels of moisture content to maximize NH_3 conversion and minimize or prevent N_2O production.

1.2 Justification

1.2.1 Importance

Researchers worldwide are studying the effects of greenhouse gases on climate change and it is known that agriculture contributes significantly to GHG production. Specifically, livestock production generates various harmful gases like methane and carbon dioxide; which have been targeted as chief contributors. Increased food production in this case will lead to increased generation of potentially harmful gases. The generation of GHG and its relation to climate change continues to be an important topic of discussion and this relation has yet to be proven. However solutions for mitigation of these gases have been developed and are being placed on the market as a means to control the increased amount of gas emitted into the atmosphere. Smith (2007) listed various technologies such as cropland management, pasture improvement, management of organic soils, restoration of degraded lands and livestock and manure management which include biofiltration.

Biofiltration is an important mitigation technology which has been proven cost-effective and environmentally friendly. Further, the biomass for the media may be a waste by-product which figures as a sustainable method for waste recycling. Operational strategies for biofilters to effectively mitigate the exhaust gas(es) of concern continue to evolve as the science behind the reactions within the biofilters is developed. Recent findings have shown that various characteristics of the biomedia itself, such as moisture content (Del Nero Maia, 2010) and particle size (Sales, 2008) can affect biofilter performance and even create conditions that can produce higher levels of harmful gases like nitrous oxide. The media particle size can affect the performance through formation of preferential flow pathways (Sales, 2008) and excessive moisture content in the compost can create conditions that favor the transformation of ammonia into

nitrous oxide (Del Nero Maia, 2010) by affecting the particle micro-environment oxygen concentrations and microbial viability on external surfaces and internal pores. This latter consideration is of particular concern to researchers owing to the nature of the gas itself. Nitrous oxide is considered to have the equivalent global warming potential of approximately 180 units of CO_2 in the atmosphere (Lashof, 1990). Thus the need for an adequate moisture measurement and delivery system is demonstrated. Accurate control of moisture will optimize the process of biofiltration for maximum ammonia conversion and minimum nitrous oxide production.

1.3 Benefits

Biofilters operating at optimal moisture levels should provide higher rates of ammonia conversion and minimize nitrous oxide production. This system coupled with its relatively low operating costs and high sustainability will provide society with a tool to reduce the emission of greenhouse gases to the atmosphere. This may in turn, reduce the impact of the animal production system on climate change. In the short term this technology could provide society with a cleaner exhaust air that lowers impacts on those individuals that live or work in the surroundings of agricultural facilities and provide improved animal welfare and a more comfortable place to work.

1.4 Objectives

The scope of this study is to evaluate and test an indirect method for moisture measurement coupled with a method for applying water in gas phase compost biofilters in order to maintain optimal moisture levels. The major objectives of this work are:

- **Objective 1:**

Evaluate the use of commercially available “soaker hoses” as a method for moisture delivery and to determine the effect of vertical position within the biofilter on moisture content uniformity.

- **Objective 2:**

Evaluate the thermal conductance of the biofilter media as an indirect means for moisture measurement.

- **Objective 3:**

Determine the effect of the moisture control methodology on the ammonia and nitrous oxide concentrations across the gas phased biofilter.

1.5 Expected outcomes

- **Objective 1:**

An optimal vertical positioning of a set of commercially available soaker hoses within the media does exist to maintain a set moisture level in the entire biofilter volume.

- **Objective 2:**

The relationship between the moisture content and the thermal conductance, and to use this property as reference in a model for predicting moisture content.

- **Objective 3:**

The effect of the use of a uniform, controlled moisture application system working together with a moisture sensor in the biofilter media is expected to enhance the biofilter performance.

Chapter 2 Literature review

2.1 Biofiltration

Biofiltration is an alternative method for treatment of large air streams with low ammonia concentrations. This method is inexpensive compared to traditional absorption technologies and therefore attractive to animal production farms (Baquerizo, 2005).

Biofiltration technology uses biological processes that happen in nature to remove odorous compounds from the air stream. It achieves high levels of reduction when the concentrations of the compounds are below 2,000 parts per million (ppm) (Boyette, 2008).

The system which creates conditions for these biological processes to happen is called a gas-phased biofilter which has a porous solid media such as compost to work as the support for the microbes to grow. Another element that must be provided to the biofilter is water. The water activity in the media is an indicator of the intensity with which water associates with various entities within the system. Values greater than 0.95, provide conditions for microbes to grow and to create a thin surface layer referred to as a biofilm, where the pollutants are diluted and are transformed into non pollutant compounds (Wani et al, 1997). This technology differs from other biological waste treatments in that the biological mass is static and the waste being treated is moving across the biological mass which acts as the filter (Cohen, 2000).

The concept of using biological technologies as a way of mitigating gases is a new idea. However, the use of biofiltration for odor control has been in the US since 1953 and in Europe and Japan more recently (Ergas et al, 1995). Biofiltration technology has evolved for 20 years from a system for odor removal to a complex system that mitigates specific chemicals (Swanson et al, 1997).

The most common gas that needs to be reduced on animal producing farms is ammonia. Biofiltration applies the nitrogen cycle (Figure 2.1) in a closed and controlled environment. Ammonia is an essential nutrient for various microorganisms that use it for energy and transforms it into nitrogen gas (Sylvia

et al, 1998). It is this process that is used in the biofilters to transform the ammonia into nitrogen gas.

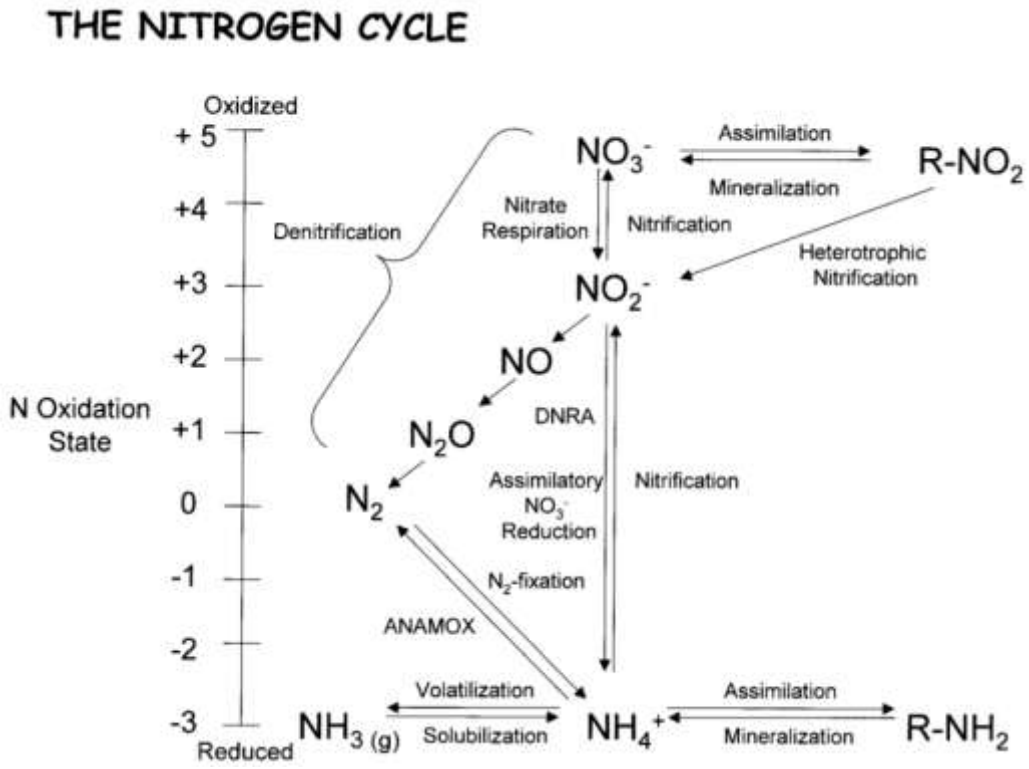

Figure 2.1. Nitrogen Cycle (Sylvia et al, 1998)

2.2 Compost

The biofiltration process is dependent on a porous solid media, which provides a physical support to the microorganisms that are responsible for the metabolization of ammonia adsorbed from the air. Some characteristics must be fulfilled by the compost for the biofilter to work properly: porosity, availability, costs of handling and ability to support the microorganisms' growth requirements.

2.2.1 Porosity

Compost media bed porosity, as compared to internal particle porosity, is a critical property of the media material (Sales, 2008) and the ideal bed porosity is one that provides the greatest microbial surface area at the least resistance to airflow. This is primarily an energy concern because high porosity requires less fan power (Mann, 2002). Also, the size of the pores can affect the formation of

preferential pathways which could lead to anaerobic cores in the biofilter (Sales, 2008).

2.2.2 Water Content

The microbial transformations that occur during the biofiltration process require water. This underscores the importance of media water holding capacity and a determinant of the degradation rates (Bohn, 1999). Water is the basic element to sustain life and is especially important for the biological processes of ammonia transformation.

Water content is an important indicator; however, it is only an indirect index of availability, because water can be found bound to the particles in a way that is not available to the microbes (Bohn, 1999). Microbes need water for two main reasons: formation of the biofilm, an environment which supports microbial growth, and also to provide a medium where the gases can be diluted and diffuse to the microbes for processing (Robert et al, 2005).

Typically, biofilters run in the 55% moisture range (Boyette, 1998). One important step for biofiltration moisture control is to identify a reliable method for continuously monitoring the water content in the media in order to calculate the necessary water to be replaced (Robert et al, 2005). Capacitance based sensors could be an affordable method because they are already a widely used methodology for soil water measurement. Compost is assumed to have similar characteristics as soil. Therefore, it is expected that capacitance would respond to water content similarly to soil. Other technology for water measurement that could be tested is thermal conductance, which is a characteristic of the compost related to moisture content.

2.2.3 Temperature

Temperature affects microorganisms' rate and ability to transform the gases, and also affects the media drying process. A high temperature in the compost can kill the microorganisms while a cold temperature could slow down the metabolism of the microorganisms decreasing biofilter performance. In addition, the temperature of the biofilter incoming air is important. If the gas is

warm, it has a higher water capacity and will dry the biofilter media (Sales, 2008). If exhausted gas to be treated is warm with a high relative humidity, and the biofilter is outside of a building in winter conditions, there may be continual water condensation and saturation of the medium (Devinny et al, 1999)., This may create anaerobic regions inside the media that are more likely to produce nitrous oxide and methane. Microbial activity requires that the temperature should remain above freezing, and optimally between 15.6^{o} and 21.1^{o} C (Goldstein, 1996).

2.2.4 Chemical Properties

The pH of the media affects the efficiency of a biofilter because the microorganisms responsible for the biofiltration processes have an optimal pH range. Fortunately, there are species that are tolerant to neutral pH range (pH = 7) in which the biofilters are designed to operate (Devinny et al, 1999).

Transformation of ammonia to nitrate-N or nitrogen gas is a reaction that yields energy. This is one of the reasons that the biofiltration process happens. The microorganisms need energy to sustain their life so in this case the ammonia works as a nutrient and energy source for the microorganisms (Sylvia et al, 1998). A microorganism also needs carbon and other minerals which are provided by the biological activities of the consortium of microorganisms already present in the media from the sludge used as an inoculum. Some of these nutrients also come from the compost itself that is formed from once-living tissues of plants (Devinny et al, 1999).

Oxygen concentration is another important component for the biofiltration process because of the relatively low concentrations are necessary for the conversion of nitrate to nitrogen. However, the distribution of oxygen in the biofilter is not uniform and is hard to control, which may lead to areas with low oxygen where incomplete denitrification can occur along with methane production (Devinny et al, 1999) and nitrous oxide production (Del Nero Maia, 2010).

2.2.5 Microbial population

Most organic substrates contain their own indigenous population of microbes including: bacteria, actinomycetes and fungi. These microbes generally are present in the material at the beginning of the composting process (Sylvia et al, 1998). There are certain groups of microorganisms that are more important in the compost because of their involvement with the nitrification and denitrification processes. Table 2.1 shows some nitrifying bacteria:

Table 2.1. Nitrifying bacteria (Sylvia et al, 1998).

Class	Genus	Species	Physiological	Habitats
NH3 oxidizers				
Betaproteobacteria	Nitrosomanas	europae	Halotolerant	Sewage treatment, eutrophic freshwater, brackish water
		eutrophus		
		halophila		
		communis		Soil
		nitrosa	Urease	Eutrophic freshwater
		oligotropha	Urease	Oligotrophic freshwater, soil
		ureae		
		aestuarii	Halophilic, urease	Marine environment
		marina		
	Nitrosospira	briensis	Some have urease	Soil, rocks, freshwater
		multiformis		
		tenuis		
Gammaproteobacteria	Nitrosococcus	nitrosus	Halophilic, some have urease	Marine environment
		oceani		

2.3 Pilot Scale gas phase biofilters

Sales (2008) designed and constructed three quarter-scale biofilters at the Biosystems and Agricultural Engineering Department at the University of Kentucky. The pilot scale biofilters were assembled and located in the Agricultural Air Quality Laboratory (Room 179). Sales (2008) results indicate that biofilter number three did not behave similarly compared to the other two units. The cause of this disparate behavior was not identified. Leakage in ducts or tubing was suspected and leakage tests were recommended to be performed on each biofilter as well as all sampling lines, the air supply system, and the gas metering subsystems.

2.4 Irrigation system

Moisture content in a biofilter is a key factor for its performance, thus, an irrigation system may be beneficial in optimizing its operation. Humidification of the airstream alone may not succeed in maintaining the moisture content of the media bed at optimal values as reported by Sales (2008). Hence, an irrigation system that could supply enough water to balance drying is essential for a successful biofilter (Devinny et al, 1999).

Sales (2008) recommended that the application of water onto the media should be improved. Inlet application proved to be insufficient to control media moisture content. Sales suggested a strategy which used a fogging system in the inlet airstream along with irrigation from the top of the media bed. A further alternative would use soaker hoses within the biofilter media to maintain media bed moisture.

2.5 Moisture sensing

2.5.1 Capacitance technology

Capacitance probes are a commonly used technique for measuring water content in soils (Kelleners et al., 2004), and they have improved substantially in the last decade (Polyakov, 2005). These types of sensors have advantages such as low power dissipation, low noise and ease of integration with other sensing devices (Wu, 2004).

Capacitance is not only used for soil moisture measurements, but is also used in other applications for measuring moisture content. Blichmann (1988) used capacitance to measure the water content in the skin. Kandala (1989) used it to measure moisture content in corn kernels. Owing to the similar characteristics between compost and soil, it is assumed that capacitance would also work for moisture measurement in compost.

2.5.2 Thermal conductance technology

Thermal conductance in the literature is referred to as a transport property, which provides an indication of the transfer rate of energy through the

diffusion process. This transport of energy depends on the state of the matter, which is related to physical, atomic and molecular structure (DeWitt, 2006).

Chandrakanthi (2005) stated that thermal conductivity is an important property that governs the behavior of leaf compost biofilters used in treating gaseous pollutants. Thermal conductance depends on several factors, such as texture, organic matter, water content and bulk density. Therefore, the measurement of moisture content through thermal conductance is assumed to be a viable option for use in compost based gas phase biofilters using other forms of material as a microbial substrate.

2.6 Gas sampling

The process of sampling gases from the biofilters is one of the most important steps in conducting this research. It is important to have a significant number of samples to have a more accurate measure of the gas concentrations. Further, the position of the sampling points within the biofilter is a key point to analyze. Multiple sampling points provide the opportunity to characterize the behavior of the gases inside the biofilter, creating a profile of the concentrations for each of the regions. This methodology for gas collection provides the ability to keep track of which regions are actively abating the gases and which conditions within that region are affecting the process. There are two ways to sample gas from the biofilters. One is manually selecting the sampling points to be measured and the other is continuous and automated.

2.6.1 Manual

The manual procedure was performed by Sales (2008) and consisted of measuring each of the six points (inlet and outlet in three biofilters) for ten minutes which provided approximately 20 measurements of the gas concentration at each port. The last ten measurements out of 20 were chosen to represent the actual gas concentration at that port. A manifold was used to switch from one port to the other. Gas samples were taken from the plenum pit (inlet) and from the head space (exhaust) of each biofilter every 12 hours for nine days in each of three runs, for a total of 27 days of data collection.

2.6.2 Automated

Del Nero Maia (2010) designed an automated sampling point selection system (Figure 2.2) for gas sampling that could make continuous measurements of gas concentration during the biofiltration process. This allowed a greater number of measurements over time.

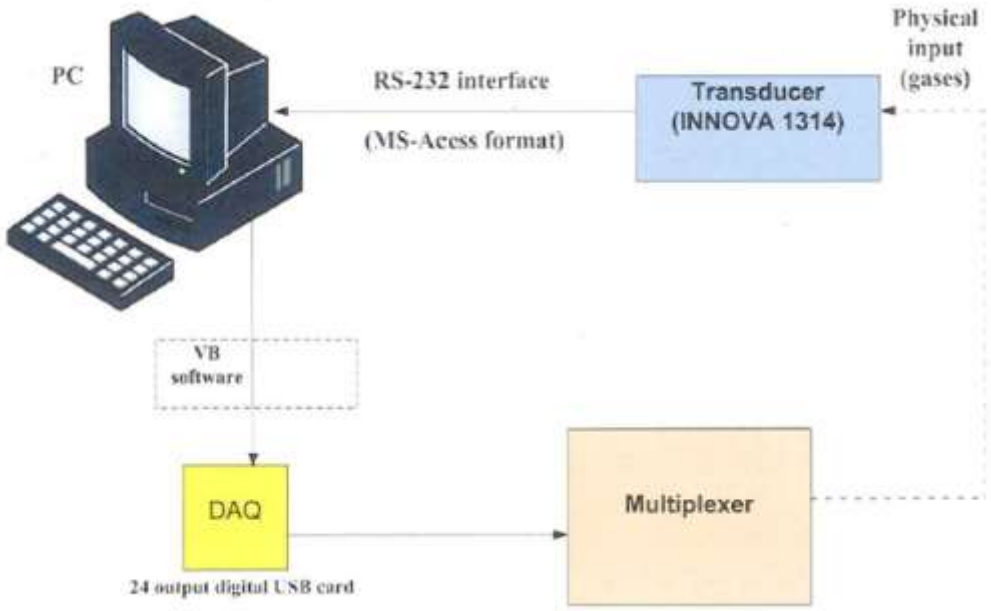

Figure 2.2. From Del Nero Maia (2010), automated sampling system: control diagram.

The automated system features a multiplexer containing multiple solenoid valves individually connected to sampling ports at each biofilter. The output of the multiplexer sends gas samples to an INNOVA 1314 photoacoustic gas analyzer (INNOVA Model 1314, California Analytical, Inc., Orange, CA, USA) for constituent concentration analysis and recording of data. The data is transmitted and stored numerically on a personal computer. Fifteen samples were taken for each location, after which, a custom written sampling program sends a signal to the multiplexer to close the current sampling valve and switch to the next sampling position. The process is repeated until all 15 sampling ports (five positions on three chambers) have been sampled and recorded. The program then directs the entire sequence to begin again providing long term and continuous measurement of multiple ports.

Chapter 3 Material and Methods

3.1 Biofilters chambers

This section of the work will detail the methods and testing undertaken to identify and correct anomalies reported in Sales (2008) in the data obtained from chamber 3 in addition to the materials and methods required by the objectives of the project.

Three pilot scale biofilters were built and installed by Sales (2008) in the Agriculture Air Quality Laboratory at the Biosystems and Agriculture Engineering Department (Figure 3.1). The chambers were made of plywood and coated with water based catalyzed epoxy (Pro Industrial 0 VOC Acrylic, Sherwin Williams Company, USA) to assure the durability of the structure and to avoid the release of any volatile organic compound. The biofilters had a plenum pit (0.40 m x 0.60 m x 0.18 m) with an aeration floor baseplate (BacTee BioAer® Aeration Floor System, Bactee Systems, Inc., Grand Forks, ND, USA) for air distribution. The chambers included a 7.6 cm diameter hole for gas duct connection, four sampling ports on one side wall spaced vertically at every 15.2 cm. A metallic cone was used as the lid for each chamber during the experiment, in which the velocity of the air was measured at its outlet. Internal dimensions, not counting the volume on the cone lid, are 0.60 m x 0.81 m x 0.61 m comprising a total volume of 0.30 m^3. The front wall was made of acrylic sheet for visual inspection of the media column (Sales, 2008).

Figure 3.1. Biofilter chambers in the Agriculture Air Quality Laboratory (Sales, 2008).

Some modifications to the original design were performed on the chambers in order to support the new procedures of the experiments. Three sampling ports in opposing side walls of the biofilter were installed for compost sampling placed 15.2 cm vertically from each other with the lowest one at 7.6 cm from the bottom of the chamber. A hose connection was installed at the top of the back wall with a combination of a ball valve and a pressure gauge for water control using the gauge for flow control. Also the lower 1/3 of the biofilter and the plenum pit were coated with black rubberized undercoating (Rust-Oleum Undercoating Rubberized) for waterproofing as evidenced on Figure 3.2.

Figure 3.2. Modifications of the biofilter chamber.

It was reported during the MS research of Sales (2008) that Chamber 3 presented anomalies in the results. Statistically, it was very important for each of the chambers to provide similar results. Several possible components of the chamber were identified as possibly contributing to the differences found in Chamber 3. To investigate this further, various tests were performed to identify the origin of the anomalies and modify the biofilter components as needed. The tests performed are described as follow.

3.1.1 Flow meter test

One of the first areas for consideration was to determine if flow imbalances were caused by any of the flow meters. The original apparatus used

a set of precision flow meters (FL-220, Omega Engineering, Inc., Stamford, CT, USA) to accurately meter NH_3 into the chambers as a controlled contaminant stream. The flow meters were connected to a diaphragm pump for air supply, and then the vernier valve positions of the 3 flow meters were set to assess the flow marked on the body of the flow meters, assuming the flow from the pump was constant.

Initial testing of the flow meters using the pump as an air source revealed slight oscillations in flow. Thus, owing to the pulsing nature of the pump, the flow meters were then tested with a mass flow controller (MFC) to eliminate any interference in the readings (Figure 3.3). The MFC was installed in the circuit and the flow meters were tested individually and in series, with two different air flow sources: the diaphragm pump and a pressurized air tank.

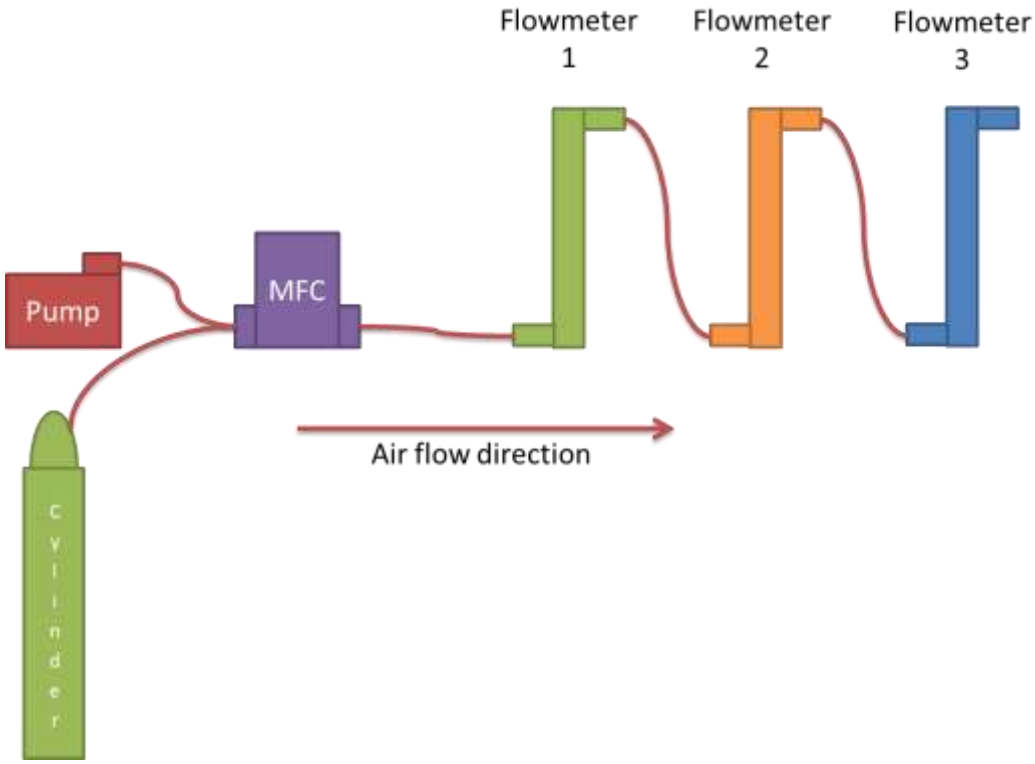

Figure 3.3. Schematic for flow meter connections in series with both: air pump or pressurized air cylinder.

Two flow rates were set by the MFC. The rates were 20 and 25 $mL.min^{-1}$ for tests with the flow meters connected in series (Figure 3.4). The flow meters were assessed for these two flow rates by alternating the order of the flow meters

to eliminate any interference that the order might create. Individually, the MFC was set to supply various flows from 20 to 50 $mL.min^{-1}$ with 5 $mL.min^{-1}$ increments.

Figure 3.4. Setup of the flow meters connected in series with the pump (not shown) or the cylinder through the mass flow controller.

3.1.2 Chamber leakage

Examination of the physical structure of the biofilter chambers was the next area for consideration, because any leakage in this structure could be responsible for errors or differences in previous results. The examination for any leakage in the structure was performed visually using smoke, looking for any sign of leakage coming out of the biofilter in any place other than the exhaust. . A smoke machine (ROSKO Fog Machine, model 1700) was used to produce glycerin smoke (ROSKO, FG07303A). The smoke machine was connected to the plenum pit of the biofilter (Figure 3.5) to push the smoke into the structure of the biofilter (Figure 3.6). This arrangement required the biofilter to be disconnected from the plenum. The test was performed with the exhaust system turned on, in

order to create more realistic conditions for the test. Additional tests were performed with the exhaust system turned off.

Figure 3.5. Smoke machine connected to the biofilter plenum

Each biofilter was examined separately. Smoke was not applied to the intake of the plenum fan to avoid accumulation of glycerin on the duct walls. The compost used in these tests was discarded after the test because of the presence of the glycerin in the media and because of the lack of information about how the potential “glycerin coating” could interfere in the biofiltration process.

Figure 3.6. Smoke passing through the compost.

A test was performed by sealing the outlet of the biofilter to block the smoke from coming out of the top (Figure 3.7) in an attempt to create conditions of positive pressure inside the chamber. This was done in order to identify small leakages which might only occur at higher pressure.

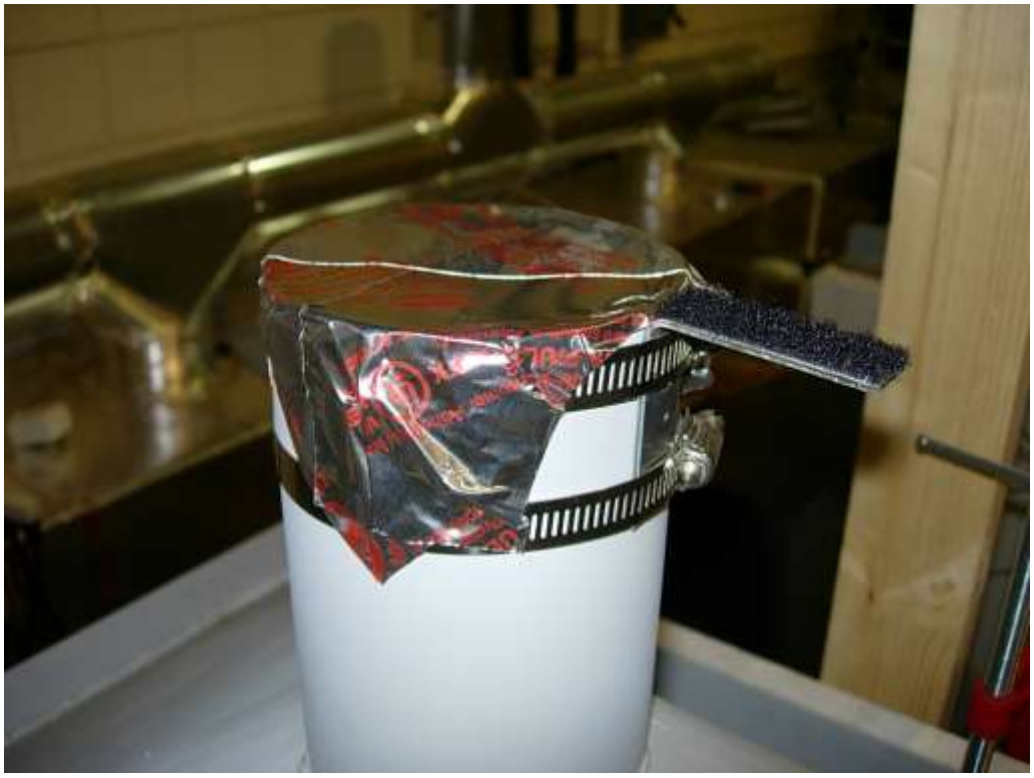

Figure 3.7. Biofilter outlet blocked.

3.1.3 Balancing the system: exhaust side

An exhaust duct with four booster fans (Model AF-6, Aero-Flo Industries Inc., Kingsburg - IN, USA) was installed over the biofilters and connected to the building's exhaust system. This exhaust duct system was evaluated to determine effect on each individual biofilter air flow. A visual evaluation of the behavior of the smoke in the exhaust system made it possible to see the impact of the exhaust system on the biofilter. Smoke was used for evaluating the potential back pressure over the biofilter created by the exhaust system. The exhaust system contained a booster fan installed directly over each biofilter and a fourth booster fan used to overcome backpressure in the line to the building exhaust system. It was hypothesized that any back pressure created by these fans might have resulted in interference in the succeeding biofilter. A black board was positioned behind the outlet of the biofilter to create a contrast for better visual analysis (Figure 3.8).

Figure 3.8. Black board positioned behind the outlet, with smoke coming out.

3.1.4 Balancing the system: supply side

The air delivery system consisted of an axial fan connected to a plenum with three supply ducts connected to the biofilters (Figure 3.9) and one exhaust duct used as an auxiliary air flow regulator (Figure 3.10). It was important for this system to be correctly balanced to deliver a uniform air flow to each of the three biofilters.

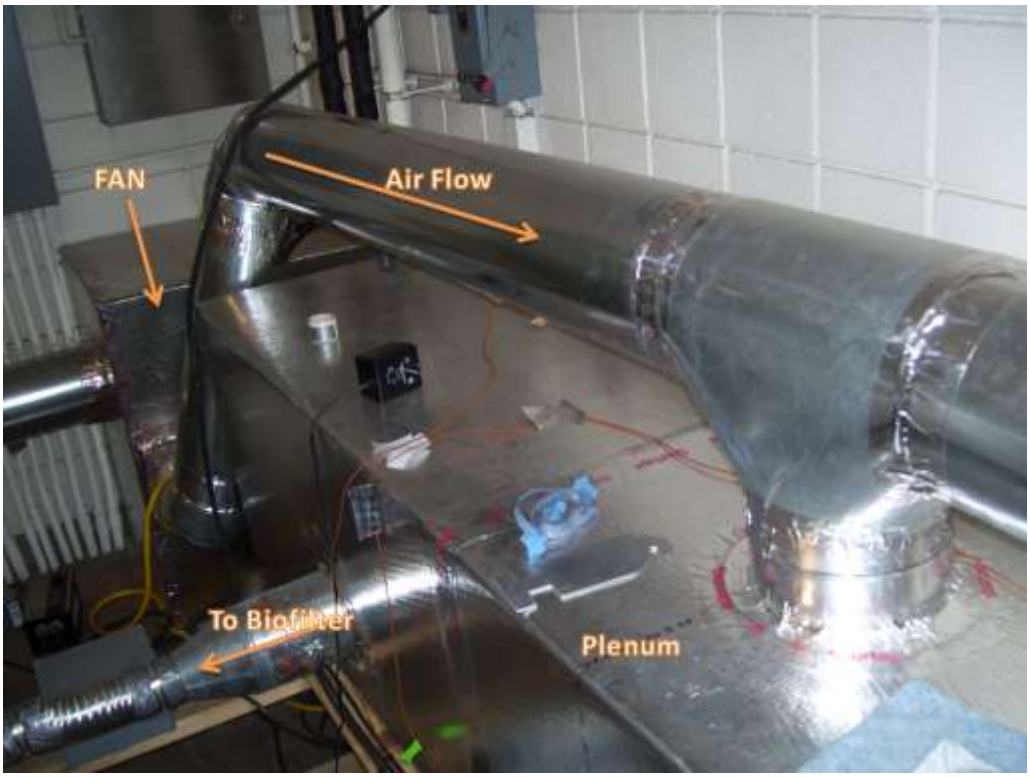

Figure 3.9. System connecting the fan to the plenum and biofilters.

Figure 3.10. Air regulator and air delivery to the plenum.

It was speculated that the anomalies associated with Chamber 3 as reported by Sales (2008) may have been attributable to air flow distribution problems within the supply plenum. Fan tests were performed with the air flow regulator opened and closed to determine any possible imbalances in the air flow rate supplied to Chamber 3. The air flow out of the plenum was measured with a hot wire anemometer (Model 425, Testo, Inc., Sparta, NJ, USA) right at the exit of the plenum pit of the biofilter (Figure 3.11). Six measurements were taken at each opening of the plenum with the air flow regulator opened and closed. The data were analyzed using Analysis of Variance with means separated by the Tukey test.

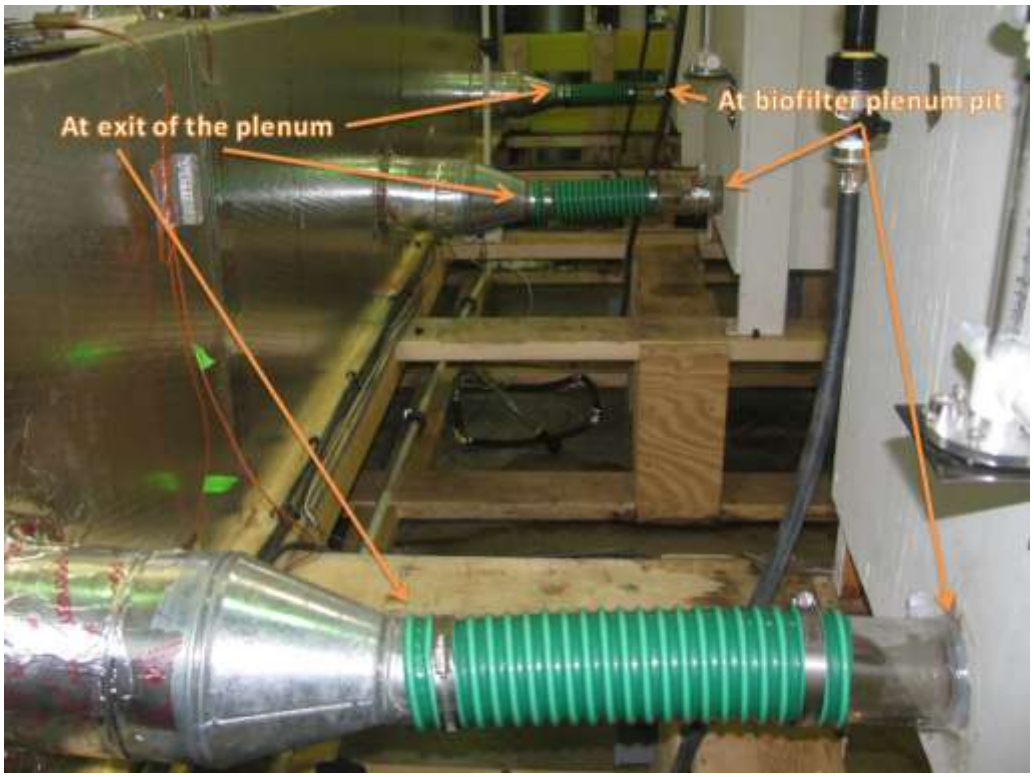

Figure 3.11. Position of the measurements for air flow from the plenum.

3.2 Sieve shaker machine

This study required a large amount of sieved compost to provide sufficient material for the three replicate biofilters. Several large trailer loads of compost were brought to campus from the farm to supply enough material for the experiment. Raw compost was prepared at the Beef Research Unit (BRU) at the

University of Kentucky C. Oran Little Research Center (LRC) located in Woodford County, KY.

The original system (Figure 3.12) designed and developed by Sales (2008) was intended to provide three distinct gradations. The scope of the work for this project required only a single gradation earlier referred to as the “medium particle size” (4.75mm < Medium < 8.0mm), thus, the system was further modified to reduce the amount of time and labor required to produce the necessary material. It was observed that the material was retained on the screens for a long period of time before falling to the next level. Accordingly, an add-on component was designed to increase the slope of the screens without decreasing its sieving functionality. This add-on component was constructed at the Agricultural Machinery Research Laboratory of the Biosystems and Agricultural Engineering Department at the University of Kentucky and attached on top of the shaker (Figure 3.13).

Figure 3.12. Sales (2008) sieving machine.

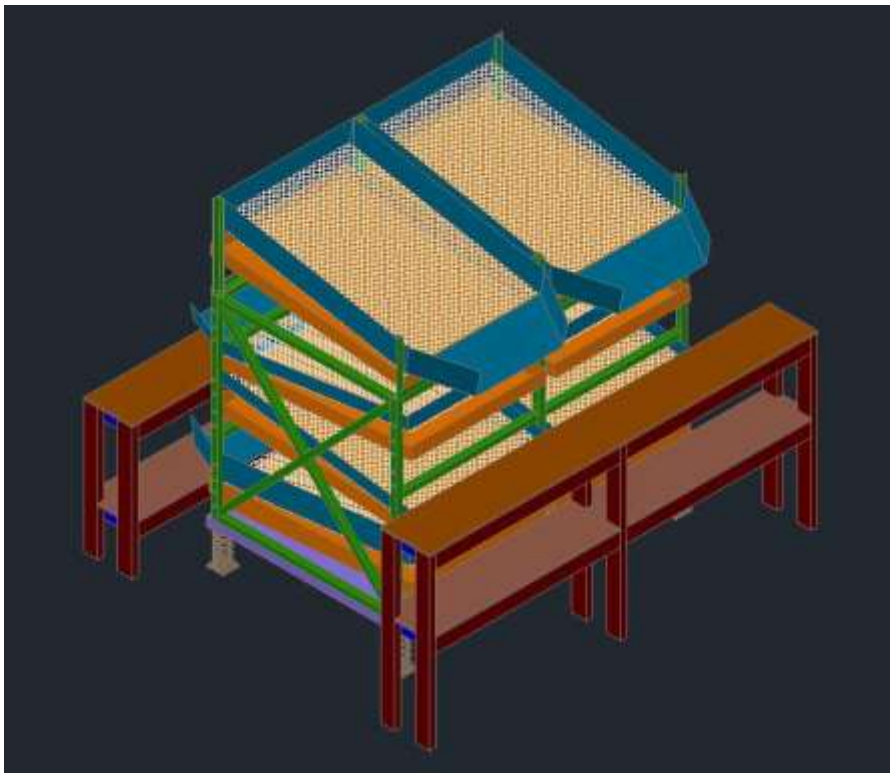

Figure 3.13. 3D model of the improved sieve shaker.

Further, solid side walls were installed to avoid spreading the compost dust to the surrounding environment in the laboratory during sieving (Figure 3.14). Custom wood stands were built to facilitate the procedure of collecting the sieved compost. All of the enhancements to the system greatly improved the tedious process of sieving.

As-received compost was poured onto the top of the sieve shaker machine using a skid steer loader (Bobcat S630) equipped with a 0.76 m^3 bucket, and sieved all the way down to the bottom pan. Each sieve had an opening to either the front or the back of the machine to deliver the sieved material into receiving containers placed at the respective openings. The material retained on the sieves was separated into five particle size ranges as the machine was shaking: Rocks > 12.5mm > Large > 8.0mm > Medium > 4.75mm > Small > 1.35mm > Fines. The “Rocks”, “Large”, “Small” and “Fines” gradations were discarded and the remaining “Medium” gradation was used for testing.

Figure 3.14. Sieve shaker machine with the add-on component.

3.3 Physical properties

3.3.1 Particle size distribution

A total of 1200 grams of as-received compost was sieved in a testing sieve shaker (model Ro-Tap B, W. S. Tyler, Inc., Mentor, OH USA). The compost was divided into four samples that were sieved through four screens (12.5, 8, 4.75 and 1.7 mm). These samples were allowed to vibrate for three minutes and the amount of compost retained on each screen was weighed. This process was carried out in order to determine the relative percentage of each gradation in the as-received material. This information was used to determine approximately how much compost was required to obtain the necessary material for these experiments. In order to remain consistent with Sales (2008) earlier work, each particle size within the compost was classified by name.

3.3.2 Compost water content

The most important parameter to be measured during the experiments is compost water content. This value can be measured directly or indirectly. The

direct method involves taking representative media samples from the biofilters and measuring the amount of water present. This method is both labor intensive and time consuming. Further, it is difficult to automate and is destructive, because the samples taken from the media stack cannot be replaced. This latter consideration is of particular concern owing to the scale of the biofilters used in this project. It is desirable to avoid the development of preferential flow paths within the stack, and it is possible that repeated manual sampling could contribute to the establishment of these pathways. The indirect way uses other physical properties of the matter that may be correlated to moisture content. This project tested a commercially available thermal conductance meter (Decagon KD2 Pro Thermal Properties Analyzer, Decagon Devices) to establish the correlation between thermal conductance and compost moisture content. The indirect method was compared to the direct method and to measurements made using a photoacoustic gas analyzer (INNOVA Model 1314, California Analytical, Inc., Orange, CA, USA), which allows long term, non-invasive measurements of the water content of the air entering the biofilter and coming out of it. The difference of the water content is assumed to be water evaporated from the compost.

3.3.2.1 The direct method

The procedure, referred to as the Standard Oven Drying Procedure (Ahn, 2009) consists of taking a sample of the compost matter for which the water content is desired to be measured and recording its initial weight. The material is then dried in an oven for 24 hours at 103^{o}C. Once the sample is dried, it is weighed and the difference between initial and final weight is the water that was present in the matter. Water content can be determined on a wet basis (M_{wb}) or on a dry basis (M_{db}). The first relates the water weight to the total weight and the second relates water weight to the dry matter weight. Equations for calculating the moisture content are presented below.

For moisture content wet basis:

$$M_{wb} = \frac{M_{H_2O}}{(M_{H_2O} - M_{dm})} \quad 3.1$$

M_{wb} = moisture content (wet basis, decimal)

M_{H_2O}= mass of water, kg

M_{dm}= mass of dry matter, kg

For moisture content dry basis:

$$M_{db} = \frac{M_{H_2O}}{M_{dm}} \quad 3.2$$

M_{db} = moisture content (dry basis, decimal)

M_{H_2O}= mass of water, kg

M_{dm}= mass of dry matter, kg

Earlier work by Sales (2008) established optimum particle size and air flow rates (residence times) to optimize NH_3 conversion. This project's experimental goal required that the drying front inside the biofilter be characterized in order to determine a moisture replacement strategy. The biofilter chamber was divided into three regional layers: Lower, Middle and Upper (Figure 3.15). Samples were extracted from each region twice a day with a grabber tool (Figure 3.16) through a sealable opening on the side wall of the biofilter (Figure 3.17). The grabber tool is a flexible instrument with three spring loaded tweezers in the tip which close automatically when the thumb actuator is retracted. This tool was used owing to its ability to reach a representative area across the region for sampling (Figure 3.18). Multiple small samples (particles) were extracted from each region to ensure that the results would be more representative of the true value of moisture content for that region. Further, it was assumed that the biofilter would have a vertical symmetry with respect to the moisture content.

Three samples of approximately nine grams of compost were extracted from each region of the biofilter for moisture content measurement. The containers were then placed in the oven to dry at 103^{o}C for 24 hours.

Figure 3.15. Biofilter and its regions.

Figure 3.16. Grabber tool.

Figure 3.17. Side wall openings for the grabber tool.

Figure 3.18. Grabbing tool for taking samples.

A water content of 50% w.b. was chosen for this experiment. The amount of water to be added to the compost depends on its actual moisture content and is calculated based on dry basis moisture content with the following equation.

$$\mathrm{Add}_{H_2O} = \mathrm{M}_{dm} \times (\mathrm{M}_{\mathrm{db2}} - \mathrm{M}_{\mathrm{db1}}) \quad 3.3$$

Where:

Add_{H_2O}= water to be added, kg

M_{dm}= dry mass, kg

$\mathrm{M}_{\mathrm{db1}}$= moisture content dry basis initial, decimal

$\mathrm{M}_{\mathrm{db2}}$= moisture content dry basis final, decimal

Figure 3.19 shows the containers used for storage and transportation of compost for processing. The amount of water to be applied to each portion of compost was calculated for each container. The material was placed into a concrete mixer (Model 65CM, Stone Construction Equipment, Inc., Honeoye, NY, USA) (Figure 3.20) for water application. Three containers were assigned to each

biofilter with one container for each region. One container held the volume used in the concrete mixer when adjusting the initial moisture content.

Thorough mixing of the compost with calculated amounts of water is an important process during the experiments because the water in the compost must be evenly distributed to ensure all the compost used had the same initial moisture content. The procedure for applying the water was to put one container in the concrete mixer and add the calculated amount of water, and then mix it until the water is absorbed by the compost.

Once the compost had the water added to it, each container was placed in one region in the biofilters and it was sampled to determine the initial moisture content in order to ensure uniformity among all the regions.

Figure 3.19. Containers used for storage.

Figure 3.20. Concrete mixer used for mixing compost.

3.3.2.2 The indirect method

Initially, an effort was undertaken to evaluate a capacitive sensor board design developed by Robert (2005) as a potential means of moisture measurement within the biofilters. There were two phases for testing the capacitance-based sensor. The first consisted of using the control board built by Robert (2005) to develop a set of small form factor capacitance grids. These grids were essentially two metal planes which acted as the charged surfaces. The second phase involved using a commercially available capacitance meter (BK Precision, model 815) to measure the capacitance through these same metal grids as a function of the media water content. A more descriptive approach to these tests is presented in Appendix A.

The technology chosen for this project involved the evaluation of a commercially available thermal conductivity sensor as a method for indirect measurement of the moisture content in the compost. The Decagon KD2-Pro (Decagon Devices Inc.) was used to evaluate the thermal conductance associated with eight water content levels ranging from 150g of water to 500g in

50g increments (Figure 3.21) This sensor uses a metal probe that heats up the material and then reads the temperature decay as the material dissipates the heat to calculate its thermal properties (Figure 3.22). This range of moisture content was selected to emulate the driest conditions where little or no microbial activity occurs up to conditions simulating the water holding capacity of the material. Three replicates of water content were prepared by mixing 150 g of compost at 10% w.b. initial moisture content with one of the eight different water contents in a small bucket, starting with the lowest amount of water. Measurements were made by placing the sensor probe into the compost and recording the measurement after 1 min, which was the recommended procedure for this sensor.

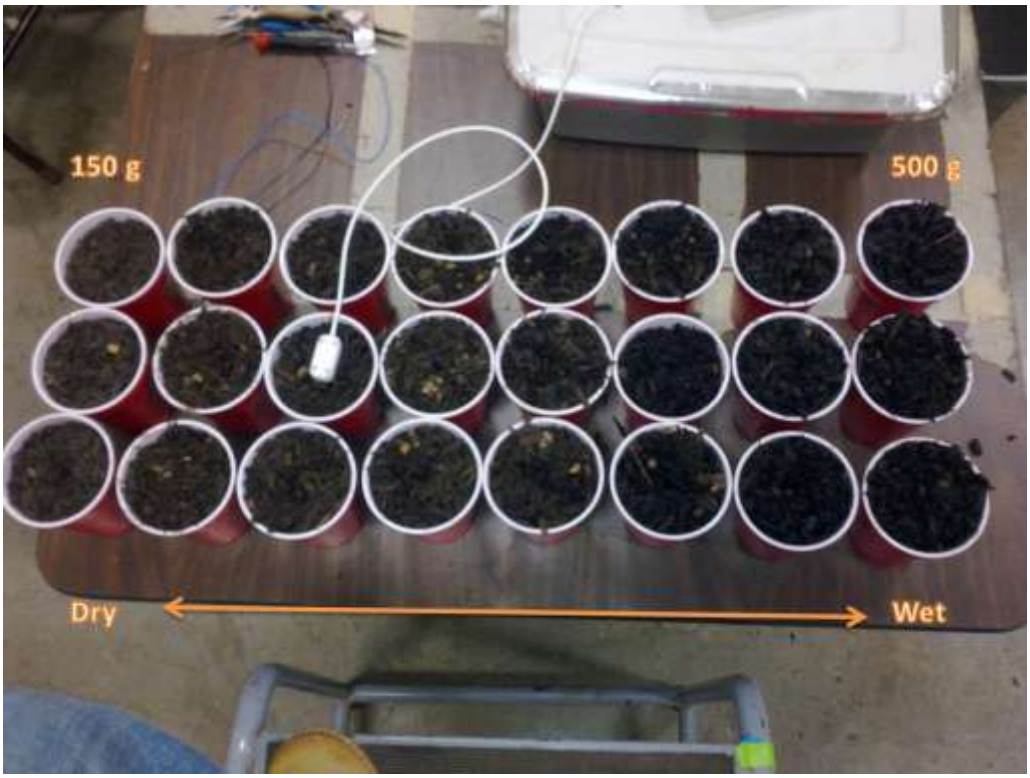

Figure 3.21. Cups filled with compost at different moisture levels

Figure 3.22. Decagon probe inserted into the compost.

Tests were performed with the medium particle size because it was the one used during the experiments. However, additional tests with the large and small gradations were also performed to validate the technology as a viable approach for moisture measurement in different media gradations. The tests with the large and small gradations were performed the same way as the medium particle sizes, with the same initial moisture content and the same water addition.

The thermal conductance versus moisture content was regressed for each particle size to develop a representative relationship.

The probe was used with the entire length of the needle embedded inside the compost. However, it was noted that when used in the biofilter the plywood wall created an additional “layer” which might interfere with the measurement.

Therefore, a test was designed to determine the effect of the plywood wall on the sensor probe readings (Figure 3.23) and the effects that partial insertion of the probe would make on the readings (Figure 3.24).

Figure 3.23. Thermal conductance probe tested for plywood wall effect.

Figure 3.24. Thermal conductance measurement when the probe is inserted 1/3 of the length.

Three compost moisture content levels were used in this test: 35, 45 and 55% w.b. with three repetitions for each moisture content. There were five treatments in this test: three depths of insertion (1/3, 2/3, and 1), and two plywood conditions (wet and dry). The numbers 1/3, 2/3 and 1 represent the fractional length of the needle inserted in the compost, and the plywood used was one dry and the other wet. The wet plywood was submerged in water for 1 hour to absorb water. The idea for using wet plywood was to simulate situations where the plywood in the biofilter might have absorbed water from the compost.

This portion of the work was undertaken to fulfill the requirements of **Objective 2** of this research.

3.4 Irrigation system

Sales (2008) recommended enhancements to the original laboratory setup which included the use of soaker hoses within the biofilter media to maintain moisture. Thus, six meters (20 ft.) of commercially available soaker hose (SWAN

1/2"Dia. Soaker Hose) were obtained and tested for water application in compost biofilters. The tests consisted of the calibration of the flow as affected by the water pressure in the hoses and optimization of hose position within the media stack to create a uniform water distribution and to maintain moisture content. This portion of the work was undertaken to fulfill the requirements of **Objective 1** of the research.

3.4.1 Calibration

The calibration tests were performed in the Agricultural Air Quality Laboratory in the Biosystems and Agricultural Engineering Department (room 179), using a 68 liter plastic container as a reservoir for the water and a stainless steel grid to support the hose. Three meters of soaker hose were positioned on the grid over the container (Figure 3.25) and connected to the water distribution system of the building using a gauge to monitor the pressure in the hoses (Figure 3.26).

Figure 3.25. Hose Calibration device.

Figure 3.26. Pressure gauge.

Water was allowed to flow through the hoses for four minutes. Each run was repeated three times. The amount of water accumulated in the reservoir was weighed. Pressure was adjusted from 28 kPa (4 psi) to 126 kPa (18 psi) in increments of 7 kPa (1 psi).

The water delivered in four minutes was regressed against applied pressure to determine water flow as a function of pressure. A check for linearity of the results and analysis of variance were used to determine goodness of fit for the prediction model. This equation is important to establish the pressure that has to be applied to deliver the desired water flow.

3.4.2 Positioning Experiment

The formation of an inverted conical drying region (Figure 3.27) was noted by Sales (2008) and further described (Figure 3.28) by Dutra de Melo (2010). The soaker hoses were installed in the pilot-scale biofilters and were tested at three different regions, lower, middle and upper. The tests consisted of drying the material in the biofilters by blowing air through the compost media at a rate of

104 $m^{3}.hr^{-1}$ which provided a residence time of 6 seconds, (the average residence time suggested in the literature).

Figure 3.27. Conical drying noted by Sales, 2008

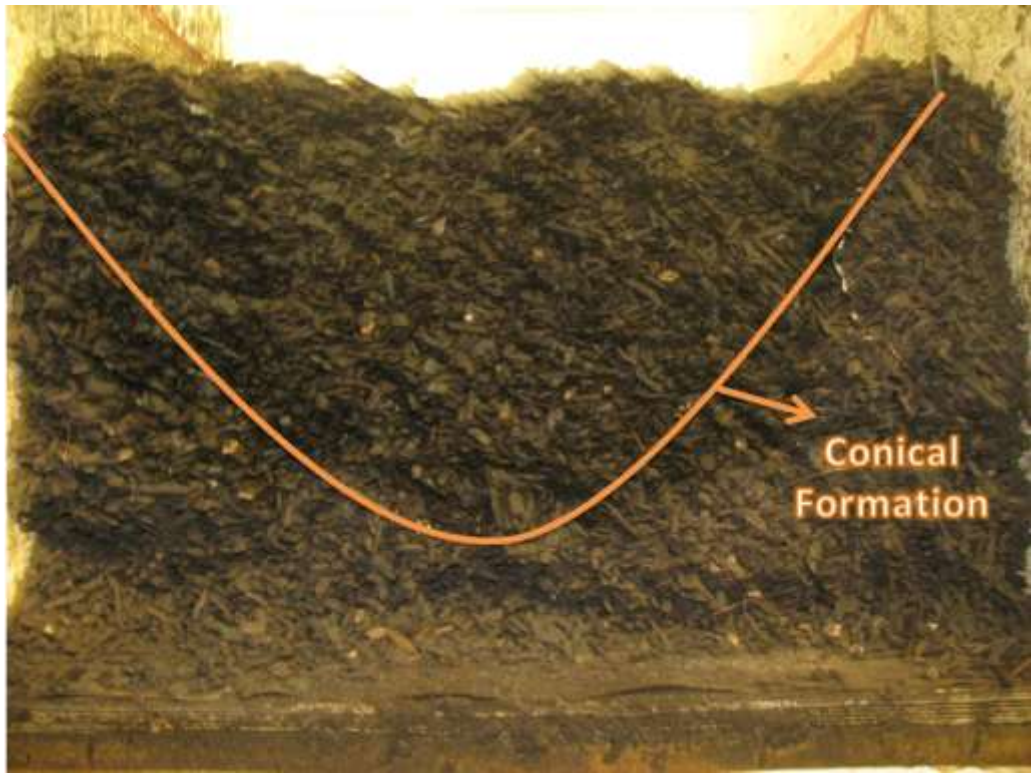

Figure 3.28. Conical drying formation in the biofilters.

The lower position corresponded to an installed height of the hose equal to one third of the height of the compost media, or approximately 12.6 cm (5 in) as shown in Figure 3.29. The middle position corresponded to an installed height of the hose equal to two thirds of the height of the compost media, or approximately 25.3 cm (10 in) as shown in Figure 3.30. The upper position corresponded to laying the hose on the surface of the compost media which was 38.1 cm (15 in.) high as shown in Figure 3.31.

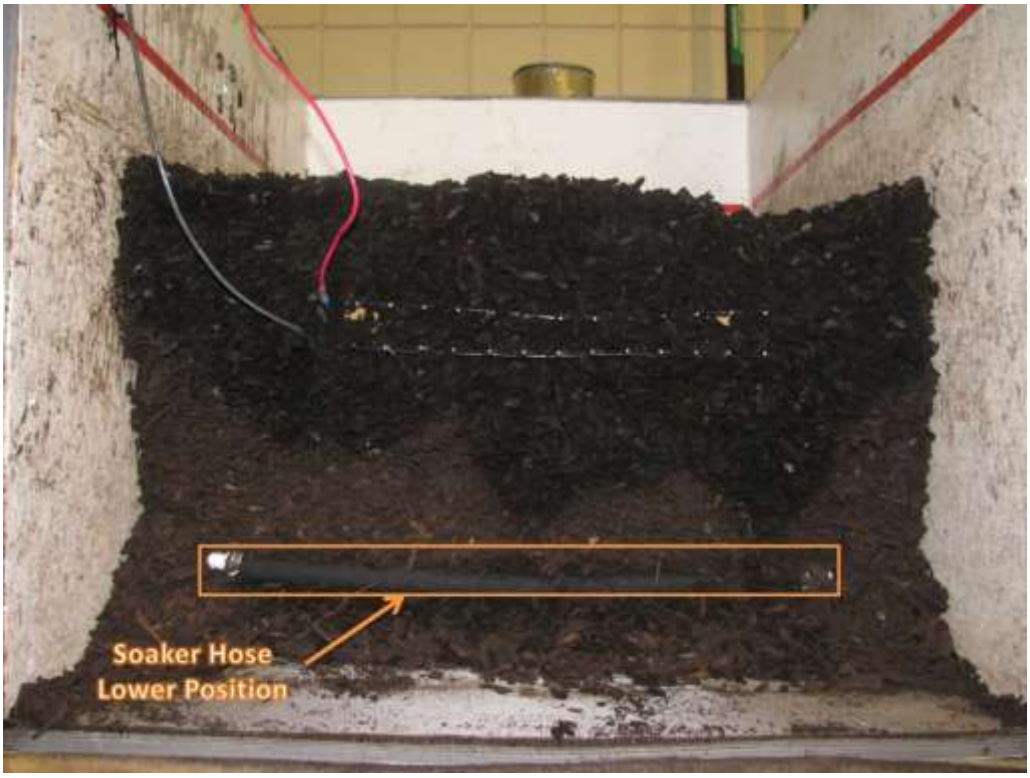

Figure 3.29. Hose located in the lower position.

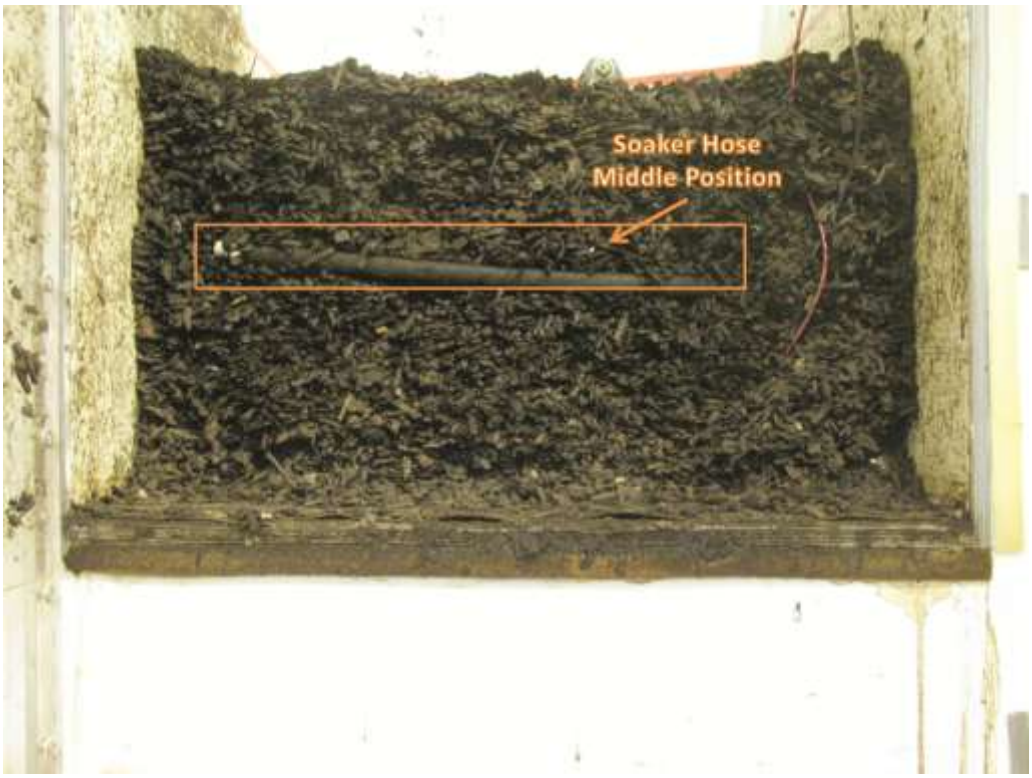

Figure 3.30. Hose located in the middle position.

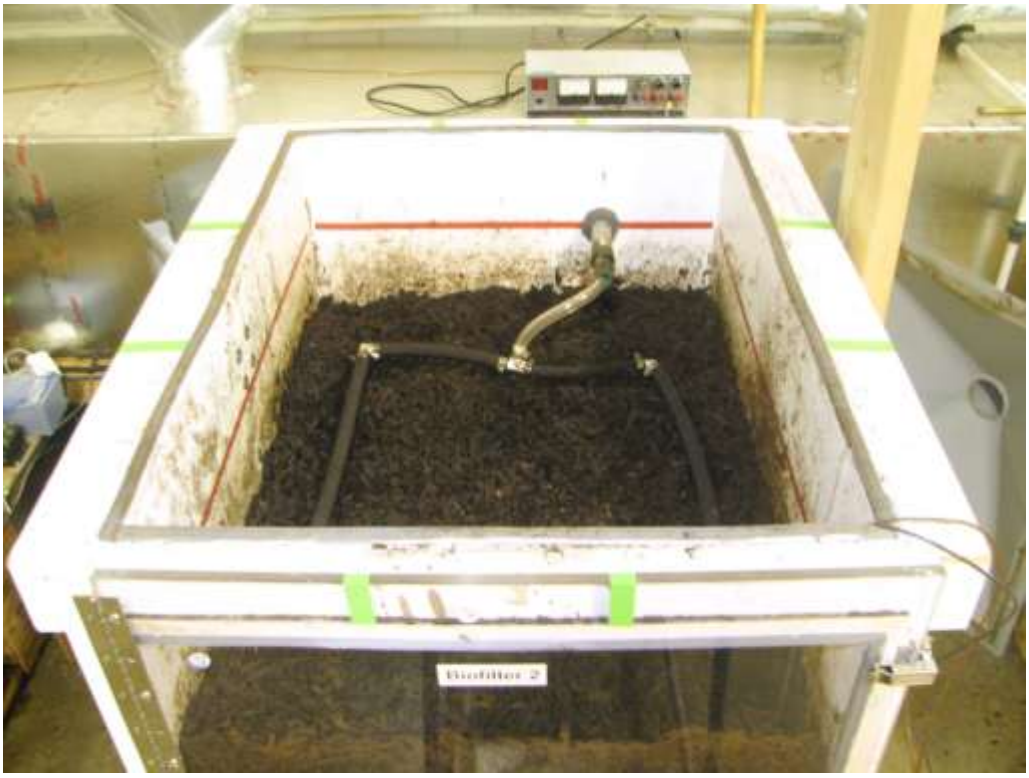

Figure 3.31. Hose located at the upper position in the biofilter.

The dependent variable was moisture content from each level measured twice a day and determined by the oven dry test. This data was used to build a curve of the moisture content over time. The purpose of the experiment was to keep the media moisture content constant with time for each position.

A linear regression has the form of Y = AX + B, in this case the Y represents the moisture content and the X the time. The procedure was to determine if there was a significant difference between the slope constants, A and zeroes, B, for each of the hose positions. A zero slope reflects constant moisture in the media. The standard error of the regression gives information on the variability in moisture content, and the standard errors of the regression coefficients gives insight into the goodness of fit.

The media moisture content was the average of 3 samples at a point in time for each region in the biofilter, lower, middle and upper. The samples were taken through openings on the side walls with a grabbing tool for a representative sample of each layer.

There were four treatments for this experiment: no hose, lower, middle and upper position for the hose. A repeated measures statistical analysis method was used for comparison between the curves produced by these treatments. This method determines whether there is significant difference between the water contents of the regions in the biofilters. This is necessary to determine the appropriate placement of the soaker hose in the compost and to fulfill **Objective 1.**

3.4.3 Water application interval

It was assumed that the water loss due to drying of the media could be balanced by adding water for two minutes at 69 kPa (10 psi) which gives a flow rate of 34 ml/s as determined in the positioning experiment. The experimental design included three water application time durations: 30 seconds of application with 2 minutes interval, 2 minutes straight and 15 seconds with 45 seconds interval; with three biofilters as the replications. The tests were performed sequentially which likely had an effect on the latter two treatments.

The effectiveness of the application strategy depended on the ability of the media to absorb the water before it drained from the media bed. The collected water that drained from the biofilter during the interval tests was the response variable tested for significance of impact of the time interval treatment effects on the application interval of water.

Figure 3.32. Container collecting water from the biofilter.

3.5 Ammonia and Nitrous Oxide observations

Work completed under **Objectives 1** and **2** provided the moisture control methodology necessary to evaluate ammonia abatement within the pilot scale biofilters. During this experiment the water content of the biofilters was monitored using the thermal conductance sensor and the standard oven drying test. Water that was lost due to drying would be replaced by the hoses installed in the position indicated in **Objective 1**.

3.5.1 Experimental set-up

Weighed, sieved compost was mixed with domestic waste water nitrification sludge, used as inoculum obtained from the West Hickman Waste Water Treatment Plant of Lexington, KY in a concrete mixer (Model 65 cm, Stone

Construction Equipment, Inc., Honeoye, NY, USA). Uniformity of moisture distribution was assumed when no free water was present in the drum of the mixer as visually verified by direct inspection of the material in the drum. A total of 204 liters of compost were loaded into the biofilters with a particle size range of 4.75 mm to 8 mm. This particle size range is an optimized particle size for better ammonia removal with minimum pressure drop (Sales, 2008). An initial moisture content of 50% was used since this was considered the optimum for ammonia (NH_3) removal while minimizing nitrous oxide (N_2O) generation (Maia, 2010).

The biofilters were loaded with 120 cm of soaker hose installed in the mass of compost in the position indicated by **Objective 1**. Also thermal conductance was used for moisture content monitoring as described in **Objective 2**.

Flow meters (FL-220, Omega Engineering, Inc., Stamford, CT, USA) were used to adjust the anhydrous ammonia (99.99% concentration) flow to a calculated loading rate of 0.8 g/h. This required the flow meter to deliver 30 ml/min to the inlet of each biofilter where it was diluted with clean room air from the plenum. The airflow from the plenum was adjusted to 108 m^3/h which provided a loading rate of 10 ppmv.

The automated gas sampling system developed by Del Nero Maia (2010) was used to collect the data for ammonia (NH_3) and nitrous oxide (N_2O) at five sampling points in each biofilter. The automated system included a multiplexer running 16 solenoids valves (Figure 3.33 and Figure 3.34) used to select different sampling points across the three chambers. The software selects the ports and records the readings of ammonia, nitrous oxide and water vapor from a photoacoustic gas analyzer (INNOVA Model 1314, California Analytical, Inc., Orange, CA, USA) shown in Figure 3.35.

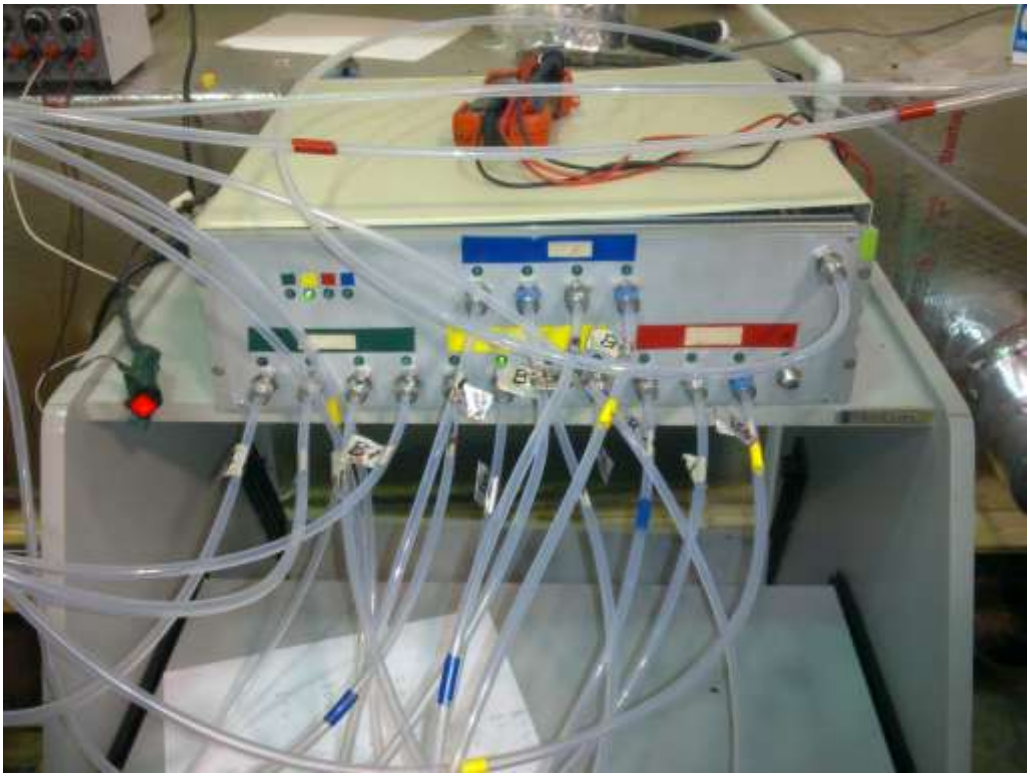

Figure 3.33. Multiplexer connecting the sampling points of the INNOVA.

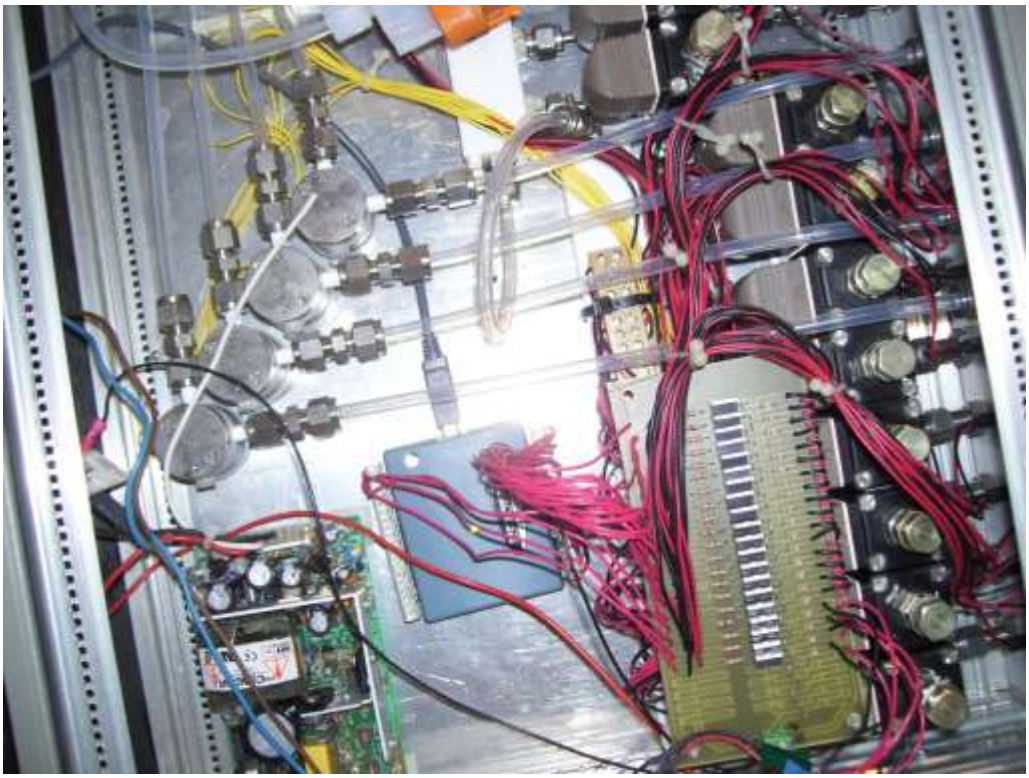

Figure 3.34. Solenoid valves within the multiplexer box.

Figure 3.35. INNOVA photoacoustic gas analyzer.

3.5.2 Water balance

The water vapor concentration was read and analyzed during the analysis of ammonia and nitrous oxide in order to develop a water balance. Three methods were compared: the direct method where compost samples were taken from the media for standard oven drying, the thermal conductance method performed during the period of the experiment and the water loss calculated using the water vapor concentration data collected with the photoacoustic gas analyzer (INNOVA).

The thermal conductance method was used as the reference. Thermal conductance was measured four times a day on each of the three regions of the three biofilters. The data were entered into an EXCEL® spreadsheet that calculated the moisture content using the regression from the thermal conductance calibration test. The spreadsheet took the moisture content and transformed it into dry basis which was a more accurate way to measure the difference of water content for application of makeup water to the mass.

3.5.3 Concentration analysis

Gases were sampled in the plenum pit of the biofilter (inlet), lower, middle, upper position and in the headspace (outlet), for a total of 15 points of gas sampling. The process of analyzing the gases was continuous with the use of the software that connects the multiplexer with the INNOVA gas analyzer. It was programmed to make 15 readings at each sampling point. Subsequent readings were taken when the computer closed one solenoid valve and opened the next point to be analyzed. Ammonia, nitrous oxide, methane, carbon dioxide and water vapor were the gases sampled by the INNOVA. Gas profiles were developed for this analysis by calculating the removal efficiency of the treatment using equation 3.4.

$$Y = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) \times 100 \qquad 3.4$$

Y = removal efficiency

C_{in} = inlet concentration of the gases

C_{out} = outlet concentration of the gases

This removal efficiency was calculated in two ways. The first method calculated the removal which occurred region by region in order to create a profile of removal efficiencies for the gases across the media. The second method considered the removal efficiency of the biofilter as a whole by taking into consideration of the concentration at the inlet and outlet of the biofilter.

The trend curves for these removal efficiencies were compared with the moisture content in each of the regions and also with the air flow rates applied to the biofilters. These comparisons were performed visually in order to find any link between the behavior of the gases in the biofilter and the conditions that the biofilter was subjected too.

An important observation during these comparisons was the behavior of the biofilter as whole in contrast with each individual region. This consideration provided additional insight to the processes which occurred in the system and had a significant impact on the conclusions regarding behavior and efficiency.

The conclusions drawn would have been noticeably different had this not be taken into consideration.

Chapter 4 Results and discussion

A significant effort was put forth to evaluate the biofilter chambers and all of the auxiliary systems in order to identify measurement anomalies associated with chamber 3. Characterization of the compost with respect to the moisture content was undertaken by evaluating the thermal properties of the compost as a reference for moisture content. The use of a soaker hose as a way to apply water into the compost was evaluated and tested to determine the effect of its vertical position in the biofilter. The effects of applying the moisture measurement method with the water application system were investigated by direct observation of the gas concentrations within the biofilters.

4.1 The biofilter chambers

In order to identify and correct the anomaly in chamber number 3 reported by Sales (2008) the overall system beginning with the flow meters, including the chambers, the exhaust system, and the supply system were analyzed for possible sources of leakage or infiltration. The results of those analyses are presented in the following sections.

4.1.1 Flow meter test

Two different tests were formulated to evaluate the meters in order to determine if any flow imbalances had occurred. The first test compared flow rates of the meters connected to a small diaphragm pump, which was the flow supply. A second series of tests were performed using a mass flow controller (MFC) to control the flow rates. The test was performed with the air pump as a supply source for the MFC and subsequently repeated using a compressed air cylinder in order to alleviate any pulsing from the pressure source which may have affected the results.

4.1.1.1 Pump control

The flow meters were connected to the pump as a source for the flow and the verniers were set to three different positions to assess the flow that was marked. The results presented in Table 4.1 show the individual readings from the flow meters connected to the pump.

Table 4.1 Results of the flow meters individually connected to the pump.

Flow meter	Vernier Setting	Flow(ml/min)
3	0.000	30
	0.500	6
	1.000	1.7
2	0.000	25
	0.500	17
	1.000	3.5
1	0.000	10
	0.500	7.5
	1.000	2.3

These values are approximations because during the test the ball that marks the flow in the flow meter was not stable at one value, it was varying across many values because of the non-steady nature of the diaphragm pump. Because of this behavior the following tests were performed with the inclusion of a mass flow controller.

4.1.1.2 Mass flow controller

The conditions for these tests called for the flow to be controlled by a mass flow controller using different flow sources: one is the diaphragm pump and the other uses a pressurized air tank. Table 4.2 shows the results for the flow meters when they were connected individually to the pump through the mass flow controller and presented a more steady measure with lower variation of the measurements in the flow meter.

Table 4.2. Results for the flow meters individually connected to the pump through the mass flow controller.

Mass Flow Controller (ml/min)	**FM3 (ml/min)**	**FM2 (ml/min)**	**FM1 (ml/min)**
20	6	6	6
25	13	13	12
30	22	20	20
35	32	30	30
40	40	38	38
45	50	48	40
50	60	60	40

An important observation that can be seen in Figure 4.1 is the relatively poor performance of the flow meters when measuring flow at their upper and lower limits, measuring 5 $mL.min^{-1}$ when the actual flow was 20 $mL.min^{-1}$ and 60 $mL.min^{-1}$ when the actual flow was 50 $mL.min^{-1}$. This information shows the importance of the calibration of this equipment before using it to avoid discrepancies during operation. The flow for this research will be in the range of 35 $mL.min^{-1}$ in which presented an R^2 of 0.99 and a P-value of 0.84 when the three flow meters were compared with each other. This indicates that there is not a significant difference between the three flow meters (Appendix B).

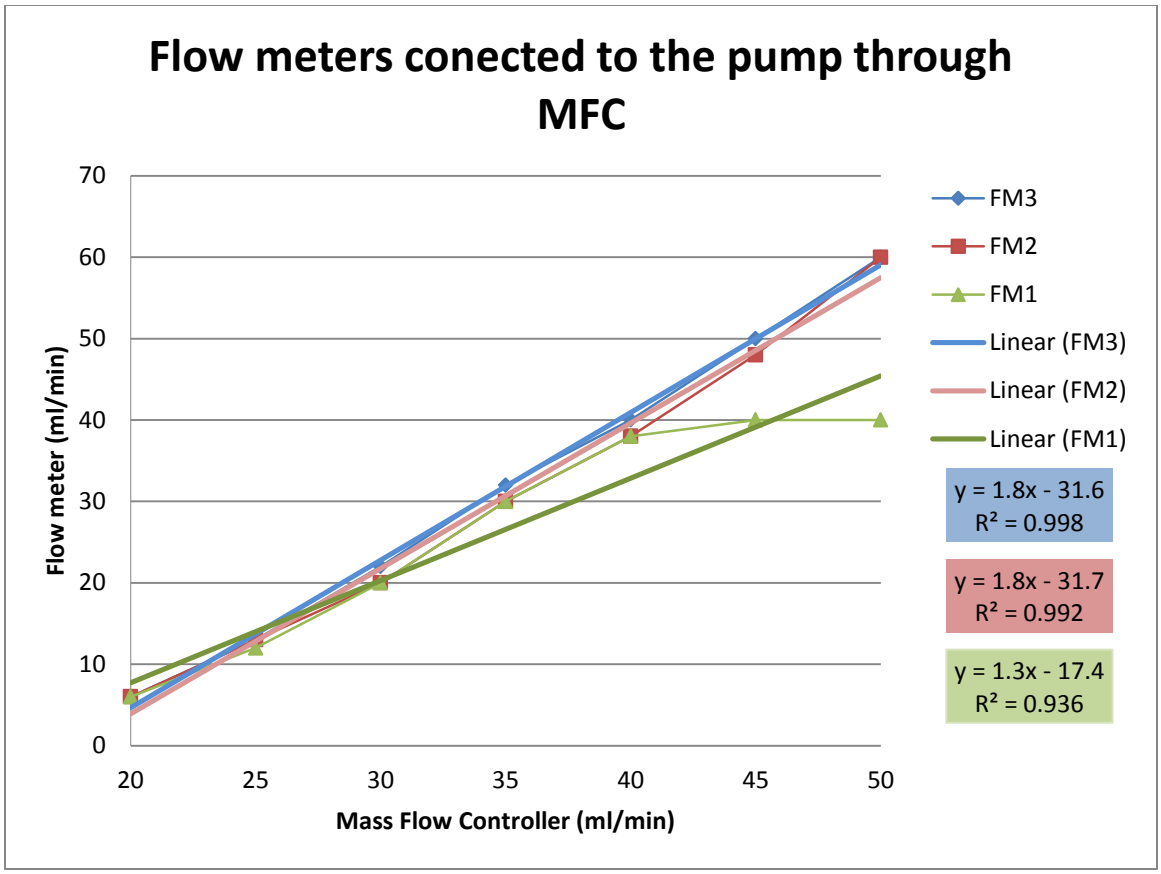

Figure 4.1. Graph representing the flow meters connected individually with the pump through the mass flow controller.

The data were analyzed over a smaller range of operation and the results indicated the three flow meters were in close agreement. Figure 4.2 shows the linear regressions for the three biofilters. Flow meter 1 showed a better agreement with the remaining meters and in this case all showed equation coefficients very close one to another with a P-value of 0.90 (Appendix B). Further this range is the most representative for the range that the flow meters will be operating during this experiment.

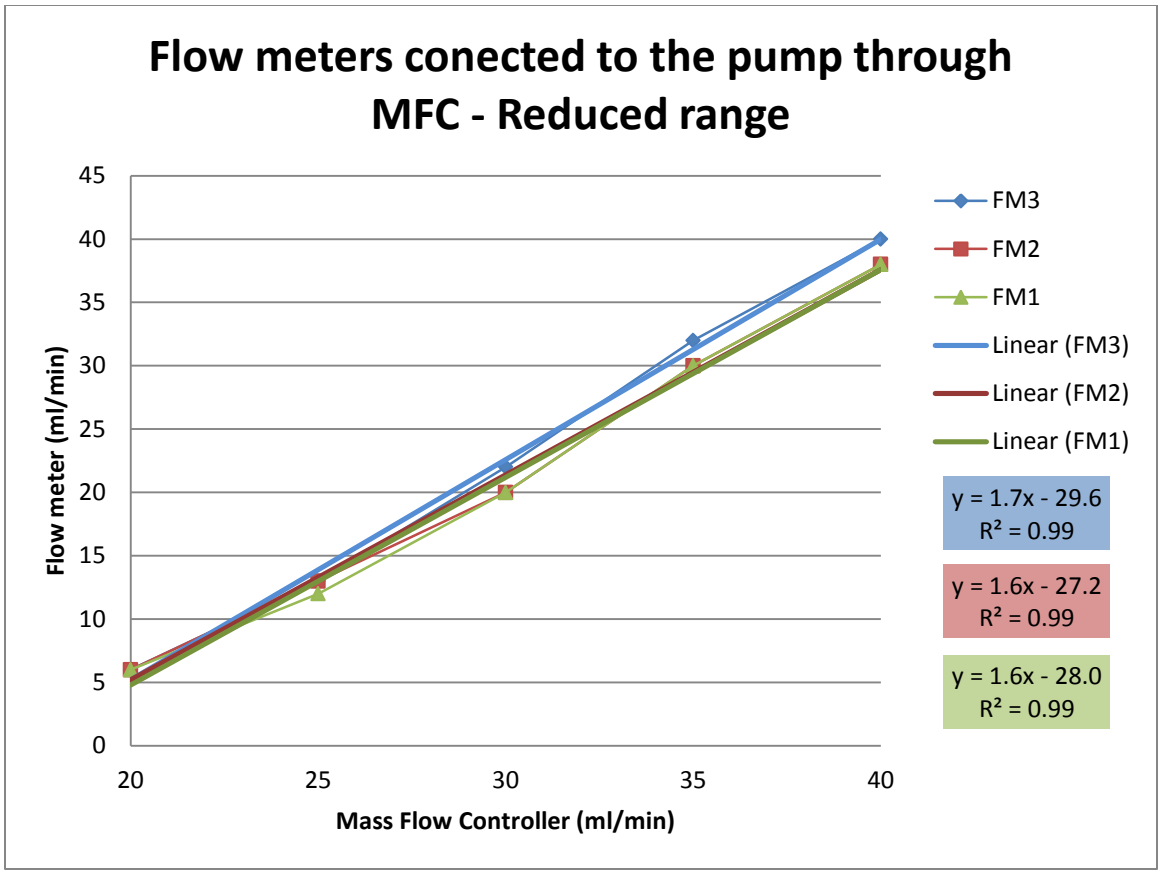

Figure 4.2. Graph representing the flow meters connected individually with the pump through the mass flow controller in the range between 20 and 40 ml/min.

The flow meters were connected in series with each other and connected to the pump operating through the MFC. Table 4.3 shows the results for the connection in series with the pump through the mass flow controller. The order of the flow meters was changed in order to avoid any interference that might occur.

Table 4.3. Results for flow meters connected in series with the pump through the mass flow controller.

Order	Flow meter	MFC (20 mL.min^{-1})	MFC (25 mL.min^{-1})
	1	3	8
1-2-3	*2*	3	8
	3	4	9
	1	2.5	5.5
2-3-1	*2*	4.5	10
	3	3.5	7.5
	1	1.8	4.5
3-1-2	*2*	2	5.5
	3	2.5	8

An important observation from Table 4.3 which first suggested the idea of the unbalanced nature of these flow meters at lower flows was made when one realized the mass flow controller was set to 20 and 25 mL.min^{-1}. The flow meters showed a maximum reading of 10 mL.min^{-1}. Here the order of the flow meters did not show significant difference with P-values of 0.48 and 0.32 for 20 and 25 mL.min^{-1} respectively (Appendix B).

Concern regarding the pulsing nature of the diaphragm pump as a flow source resulted in a set of companion tests using a compressed air tank as the source. The results presented in Table 4.4 correspond to the use of the tank connected with the flow meters individually.

Table 4.4. Results of the flow meters individually connected to the tank and the mass flow controller.

MCF (mL.min^{-1})	**FM3 (mL.min^{-1})**	**FM2 (mL.min^{-1})**	**FM1 (mL.min^{-1})**
20	25	28	25
25	32.5	30	30
30	37.5	37.5	35
35	42.5	43	40
40	49	45	45
45	50	50	50
50	52.5	52.5	53

The data in this experiment (Figure 4.3) suggest that the range of good agreement for the flow meters is larger, ranging from 20 to 50 ml/min. That can be observed through the R^2 of the linear regressions that are all above 0.95 and with very similar coefficients for regressions through an ANNOVA with the P-value of 0.95 (Appendix B). This may be attributable to having sufficient pressure at the tank to overcome the pressure drop imposed by the MFC.

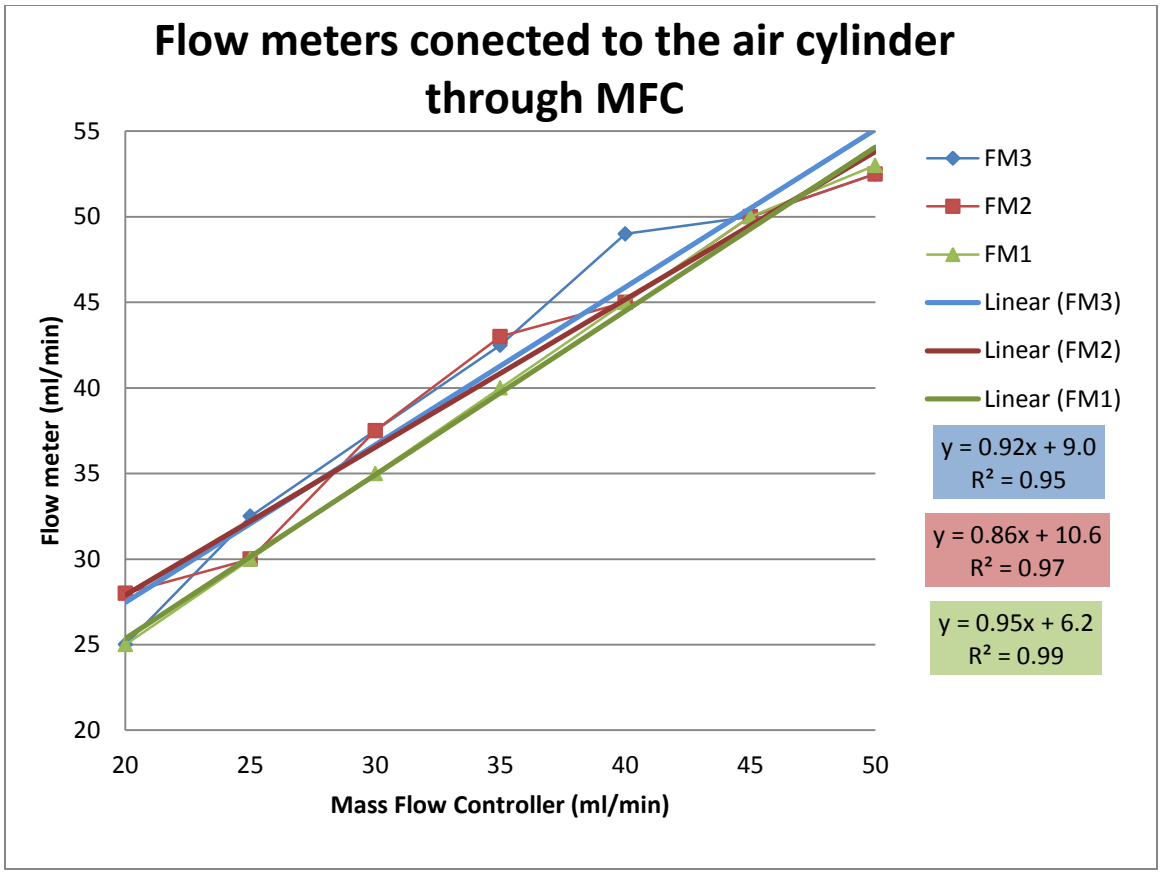

Figure 4.3. Graphic representing the flow meters connected to the tank individually through the mass flow controller.

The flow meters were then connected in series with the tank through the mass flow controller. The results are presented in Table 4.5, where the flow meters had their order changed similar to the test when connected to the pump in order to avoid any error that might occur as a consequence of the order. The results presented high P-values which indicate that there were no significant differences when the order was changed (Appendix B).

Table 4.5. Results for the flow meters connected in series with the air tank through the mass flow controller.

	Flow meter	MFC (20 mL.min^{-1})	MFC (25 mL.min^{-1})
	1	17.5	22.5
1-2-3	*2*	25	30
	3	25	30
	1	12.5	15
2-3-1	*2*	25	32.5
	3	17.5	28
	1	10	15
3-1-2	*2*	18	22.5
	3	15	20

The tests with flow meters indicated that all three of them were working properly and in agreement with each other eliminating the hypothesis of flow imbalances from the flow meters.

4.1.2 Chamber leakage

Tests were conducted to find leakage within the biofilter chambers that could have compromised their operation by creating different pressure conditions within the chambers. Various points in the structure were evaluated for leakage, with special attention given to the joints where the wood was glued together.

The analyses using smoke tests were made visually. Wherever there was smoke coming out of the biofilter other than the exhaust, a leakage point was identified. During the test the smoke was flowing uniformly across the media, with a linear front rising from the bottom to the top of the media (Figure 4.4).

Figure 4.4. Smoke rising to the media surface.

This behavior of the smoke was an indication that no preferential pathways were forming in the media while the tests were being performed. Preferential pathways are a problem for the biofilters because the airflow can pass faster which in turn, can reduce the percentage of the biofilter bacterial population exposed to the ammonia in the air for metabolization.

No major leaks were found in the chambers. However, a very small leak was noticed between the chamber and the cone at one corner on biofilter #3 and also under biofilter #1 through a crack at the bottom of the plenum. After some discussion it was decided that this leakage was not significant to the biofilter performance and also did not have an effect on the performance of the other biofilters.

A smoke test was performed in biofilter #1 with the outlet plugged expecting that some pressure would build up within the biofilter. This was done to simulate the pressure caused by the air coming from the blower and therefore some smoke would escape from any possible leaking points. Unfortunately, the smoke machine was not able to produce sufficient pressure and the smoke

merely exiting from the hose supplying the smoke. Hence, this test was not able to conclude anything about possible leaks when the biofilter is pressurized. Therefore it was not repeated for the other two biofilters.

4.1.3 Balancing the system: exhaust side

An important observation made during the smoke test happened when the exhaust system was turned on. It could be seen in biofilter 1 that the exhaust system was drawing the smoke thoroughly in a well-defined shape (Figure 4.5). The exhaust stream was less well-defined over biofilter number 2, which indicated the possibility of slight back pressure at the exhaust hood (Figure 4.6). This pattern was even more noticeable over biofilter number 3 (Figure 4.7). These differences may have been indictors of non-uniform conditions within the test chambers which could mean a higher gas flow in a biofilter. After some consideration it was concluded that was not the reason for the unexpected values for biofilter number 3. It was reasoned that the potential back pressure created by the exhaust fan above biofilter 3 was not responsible for the behavior reported in Sales (2008) because the chaotic formation of the smoke during the test was outside the biofilter. There was insufficient pressure in the biofilter from the smoke machine to create positive pressure in the biofilter; still the smoke was coming out the biofilter. This suggests that during the actual tests when the biofilter is under pressure, this back pressure from the exhaust fan is small enough to be considered negligible or does not exist and therefore would not constitute a source of error.

Figure 4.5. No back pressure over biofilter 1.

Figure 4.6. Slight back pressure over biofilter 2.

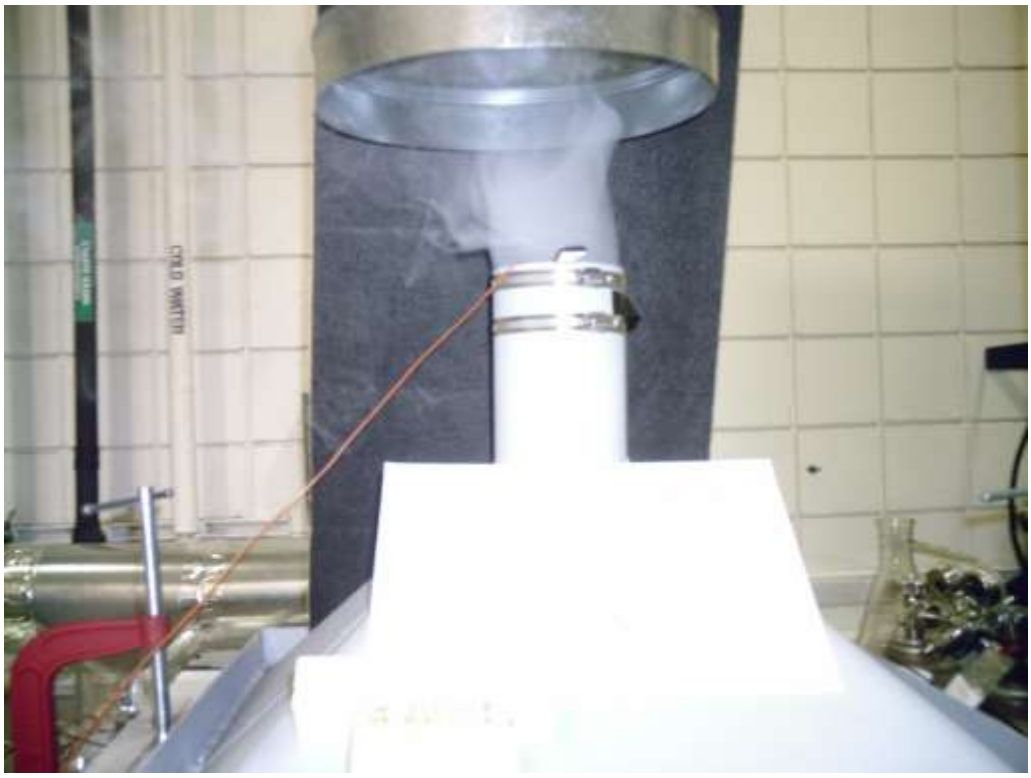

Figure 4.7. Showing back pressure over biofilter 3.

4.1.4 Balancing the system: supply system side

The supply system was tested to check if the three biofilters were operating under the same conditions during the tests. It was important to determine whether the air flow supplied to them was the same. Two treatments were performed while testing the supply system. One treatment operated the system with the balancing damper over the plenum open and the other with the damper closed.

The p-value of the averages of the air speed coming out of the plenum was calculated for comparison. The results of that analysis show that there was a significant difference between the biofilters when the damper was opened (Table 4.6). The Tukey analysis for means difference shows that biofilter 2 and 3 are not significantly different, but that both are different from biofilter 1 (Table 4.7).

Table 4.6. Anova test for the air supply system with the damper open.

Source	**DF**	**Type III SS**	**Mean Square ($(m.sec^{-1})^2$)**	**F-Value**	**Pr > F**
Biofilter	2	0.503	0.25167	66.62	<0.0001

Table 4.7. Tukey grouping for the air supply system with the damper open.

Tukey Grouping	Mean ($m.sec^{-1}$)	N	Biofilter
A	6.5	6	3
A	6.5	6	2
B	6.2	6	1
Error mean square	0.0038		

Table 4.8 shows the p-values for the treatment where the damper was closed and sealed. The results show the p-value is high which means no significant difference exists between biofilters. The equilibrium among the biofilters is further proven with the Tukey analysis in Table 4.9, where the test classifies all biofilters as being in the same group.

Table 4.8. Anova test for the air supply system with the exhaust duct closed.

Source	DF	Type III SS	Mean Square ($(m.sec^{-1})^2$)	F-Value	Pr > F
Biofilter	2	0.191875	0.0959375	0.02	0.9814

Table 4.9. Tukey grouping for the air supply system with the exhaust duct closed.

Tukey Grouping	Mean ($m.sec^{-1}$)	N	Biofilter
A	6.3	6	2
A	6.3	6	1
A	6.2	6	3
Error mean square	5.0943		

4.2 Sieve shaker machine

The new add-on component increased the performance of sieving significantly. The compost was sieved at a rate of 0.272 $m^3.h^{-1}$ for the medium gradation. This rate represented a total throughput of 2.092 cubic meters per hour, which represents about 2.75 trips of a skid steer loader per hour.

4.3 Physical properties

4.3.1 Particle size distribution

As-received compost was sieved in order to measure the different portions of particles sizes that are present in the media. After the measurement the total of the particle sizes, used on this experiment comprised 48% (140 g) of the total amount of compost measured. Material with a particle size bigger than 12.5 mm represents 3% (9.325 g), large material 8% (22.975 g), medium material 13% (37.55 g), small material 27% (79.35 g) and the finer material with diameter smaller than 1.35 mm represents 49% (146.55 g) of the total (Figure 4.8).

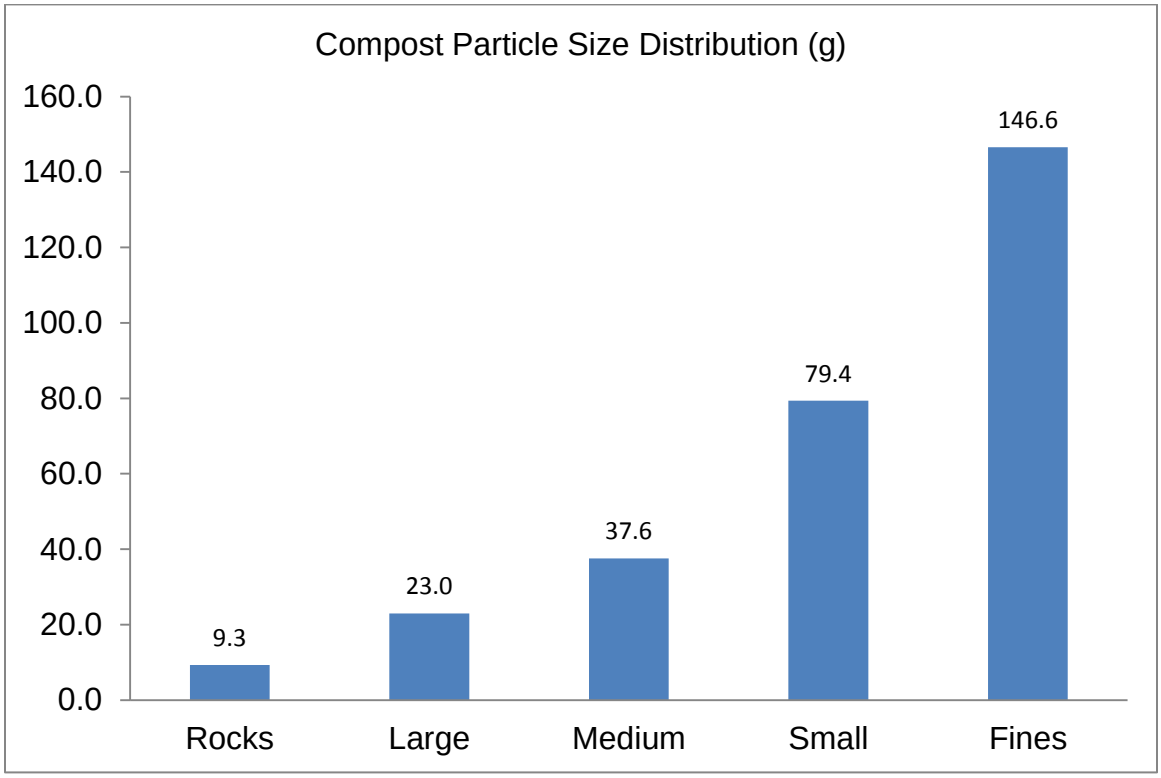

Figure 4.8. As received compost particle size distribution.

Previous research has shown that the presence of fines in the as-received compost, such as that used in the field, can contribute to the formation of preferential air ways and also significant pressure drops which are problematic for airflow (Sales, 2008). The material used for this experiment was comprised of 49% fines which further underscore the importance of sieving material for improved biofilter efficiency. These results are comparable with Sales, 2008,

where the fines material comprised 46.3%. The other particle sizes were also similar to within a +/- 5% range. This suggests that the compost produced at the farm for this experiment was physically very similar to that used by Sales (2008) in the earlier work and therefore an additional basis for comparison was established.

This project used the medium particle size (between 4.75 and 8 mm), which represented 13% (539 g) of the total amount of as received material. The tests outlined for the biofilters required a total of 612 liters of sieved, medium particle size material. This required a total of 4707 liters of as received compost to be sieved. A total of 7700 liters of as received compost was sieved in order to provide additional enough material for the supporting experiments. Compost material ranging between 1.35 to 4.75 mm and 8 to 12.5 mm comprised a total of 4095 liters and was saved.

4.3.2 Compost water content

4.3.2.1 Moisture measurement - Direct method

A preliminary drying test was performed to characterize the drying front curves for the different regions of the biofilters. Table 4.10 shows the movement of the drying front through the media, with the lower part of the biofilter drying faster than the regions above it.

Table 4.10. Moisture content wet basis representing the movement of the drying front in the media.

Time (hours)	**B1**			**B2**			**B3**		
	Lower	***Middle***	***Upper***	***Lower***	***Middle***	***Upper***	***Lower***	***Middle***	***Upper***
0	0.45	0.51	0.51	0.48	0.45	0.46	0.51	0.50	0.49
12	0.26	0.50	0.46	0.35	0.46	0.47	0.40	0.53	0.49
24	0.19	0.48	0.48	0.18	0.50	0.47	0.20	0.50	0.45
36	0.13	0.42	0.48	0.18	0.44	0.45	0.15	0.46	0.48
48	0.07	0.43	0.40	0.10	0.42	0.42	0.09	0.42	0.43
60	0.10	0.33	0.34	0.11	0.27	0.36	0.10	0.36	0.40
72	0.09	0.29	0.38	0.07	0.17	0.40	0.10	0.21	0.33
84	0.10	0.12	0.28	0.08	0.17	0.36	0.08	0.19	0.34
96	0.04	0.15	0.27	0.09	0.10	0.19	0.10	0.10	0.33
108	0.14	0.08	0.08	0.24	0.09	0.09	0.11	0.08	0.09

These data are presented graphically in Figure 4.9 to better represent the drying front movement. It can be seen that the middle part just starts to dry after the lower part reaches equilibrium in the moisture content, after about 50 hours and the upper region starts to dry after about 70 hours.

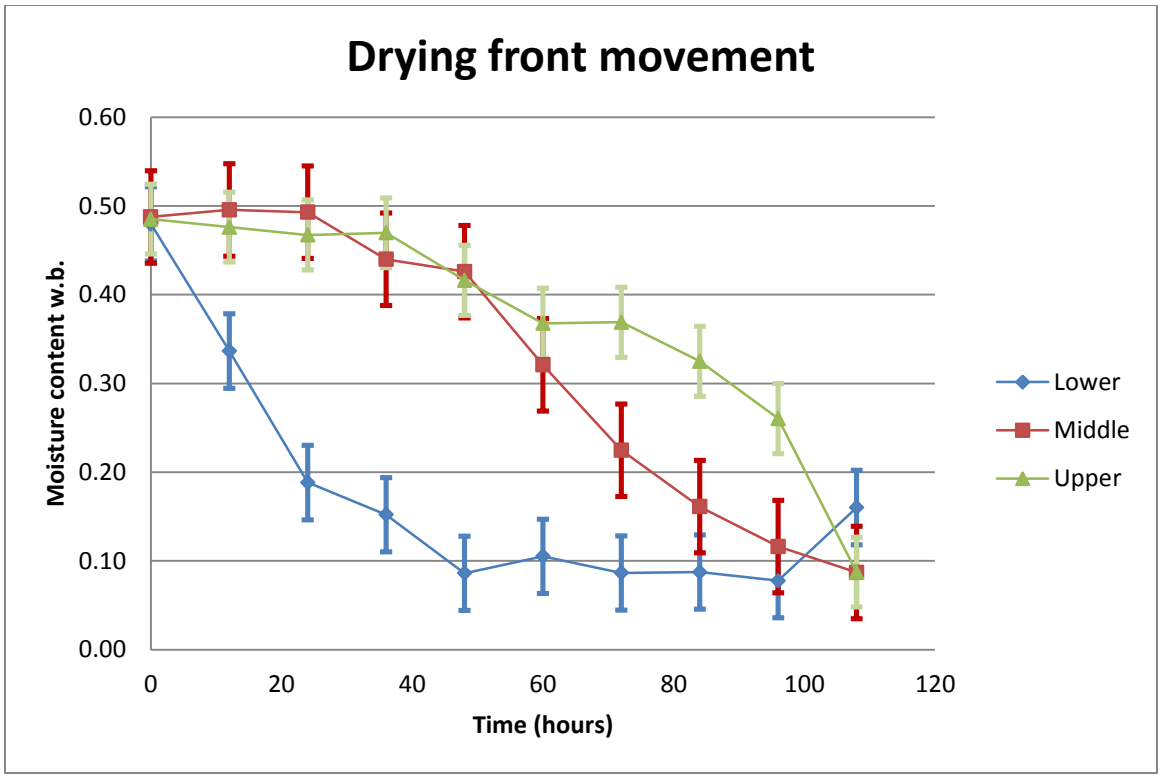

Figure 4.9. Characterization of the drying front movement in the biofilter.

The individual biofilters were compared to determine if all three of them were subjected to the same pattern of drying front movement. Figure 4.10 shows the drying front in the lower region for the three biofilters, and indicates a drying period in the firsts 52 hours of experiment and after this time the moisture content reaches equilibrium with the supply air at approximately 10% wet basis. Table 4.11 shows that the P-Value for the equilibrium period is high which indicates that the slopes are not significant different from zero and the drying period have a significantly different slope from zero.

Table 4.11. P-values for the hose positioned in the lower position.

Lower Region	P-Value
Equilibrium Period	0.0115
Drying Period	<0.0001

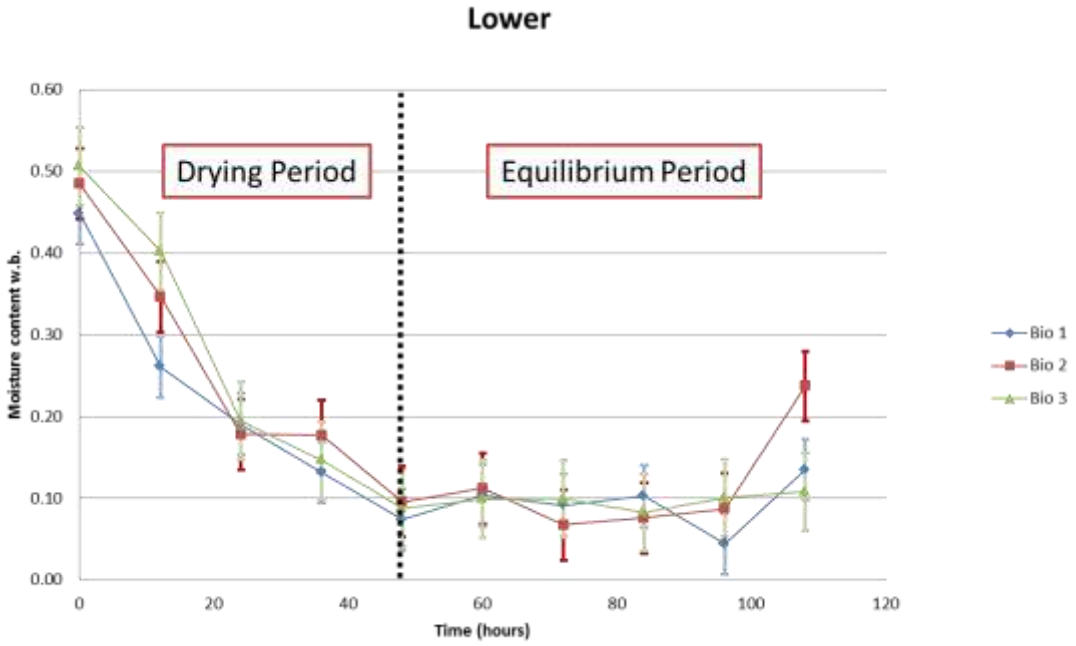

Figure 4.10. Drying pattern for lower region.

Results for drying in the middle position are presented in Figure 4.11 where the data shows a drying front that started after 52 hours, when the lower region reaches an equilibrium at 10% w.b.. This is important information because it is possible to assume that the lower region worked as a buffer for the regions above it allowing them to dry after the lower region have reached equilibrium. This equilibrium period and drying period are described by the Table 4.12 and the statistical analyses are in the Appendix C, where it is possible to see that the three biofilters are working similarly.

Table 4.12. P-values for the hose positioned in the middle position.

Middle Region	P-Value
Equilibrium Period	0.0269
Drying Period	<0.0001

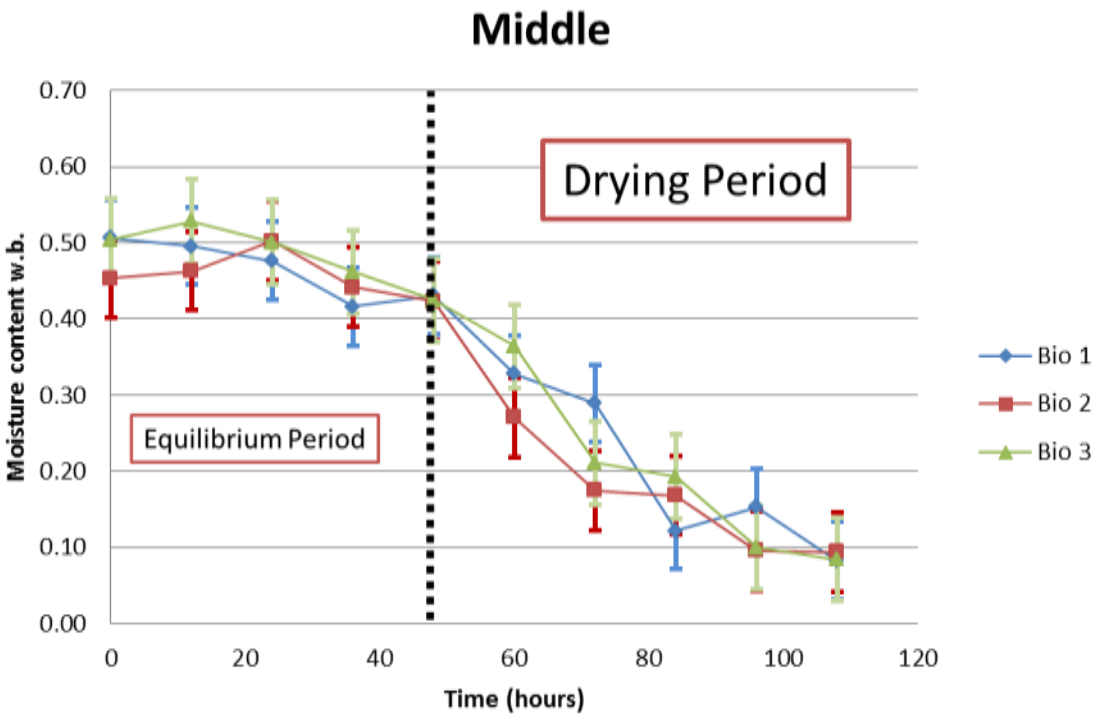

Figure 4.11. Drying pattern for middle region.

Figure 4.12 is the graphical representation of the drying front in the upper position of the three biofilters. It is possible to see that there are two distinctive periods of drying: the first period is the equilibrium period when the moisture content is kept constant. This is the period where the biofilter media is in moisture equilibrium with the air exiting the middle region. The second period is the drying period that starts at 60 hours just few hours after the middle region starts to dry and the lower reaches equilibrium, Table 4.13 shows the p-values for these periods during the experiment and the statistical analysis are in the Appendix C.

Table 4.13. P-values for the hose positioned in the upper position.

Upper Region	P-Value
Equilibrium Period	0.0014
Drying Period	<0.0001

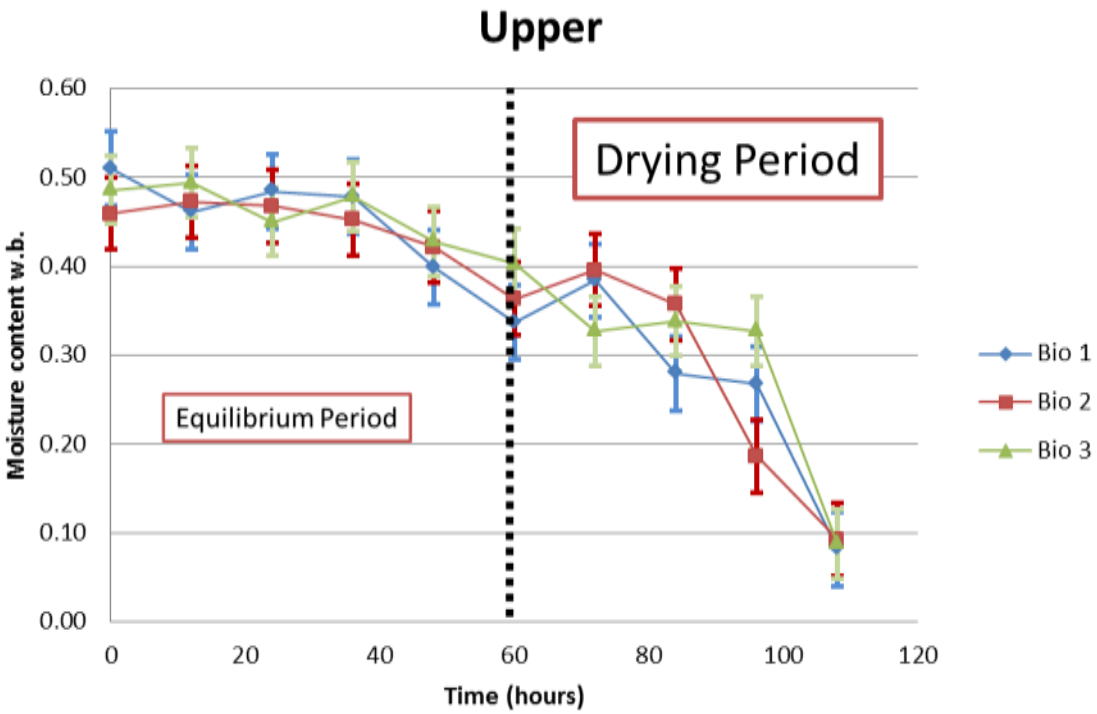

Figure 4.12. Drying pattern for upper region.

With all this information it can be concluded that the medium and upper region dries out after the lower region reaches equilibrium moisture content. The lower region is a moisture buffer zone for the biofilter which indicates the critical need for moisture content control in this region. It could be assumed once the moisture is maintained in equilibrium at the designed level in the lower region the other regions would be protected.

Table 4.14 shows the P-values for the contrasts between the biofilters where they are all high values which means that the three biofilters are working similarly as replicates. Appendix C shows the statistical analysis for these contrasts.

Table 4.14. P-values for the contrasts between the biofilters.

		1 vs 2	1 vs 3	2 vs 3
Dry Period	Lower	0,89	0,41	0,34
	Middle	0,54	0,75	0,35
	Upper	0,47	0,94	0,51
Equilibrium	Lower	0,22	0,52	0,06
	Middle	0,04	0,46	0,16
	Upper	0,31	0,53	0,7

4.3.2.2 Moisture measurement - Indirect method

A curve for thermal conductance and moisture content was developed using three replicates of eight media moisture content for the medium size range. This measurement resulted in the graphical representation shown in Figure 4.13 and presented an R^2 of 0.925 for an exponential regression.

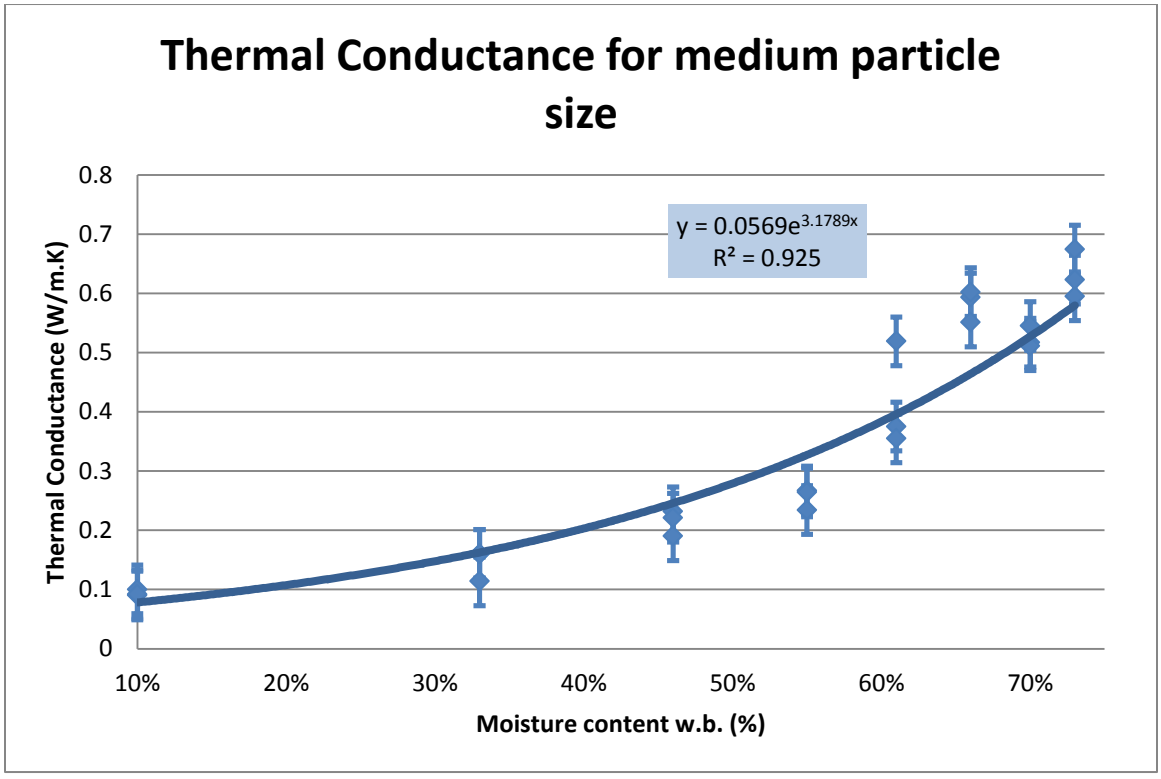

Figure 4.13. Thermal conductance exponential regression for compost medium particle sizes.

A second regression analysis was performed on the range between 30 and 50% because this was the range of moisture content in which a biofilter

would normally operate. In this case the data presented a different pattern as presented in Figure 4.14 where a linear regression with a R^2 of 0.85 was fitted to the data. The standard error for the operational range regression is presented in Table 4.15 with a value of 0.02.

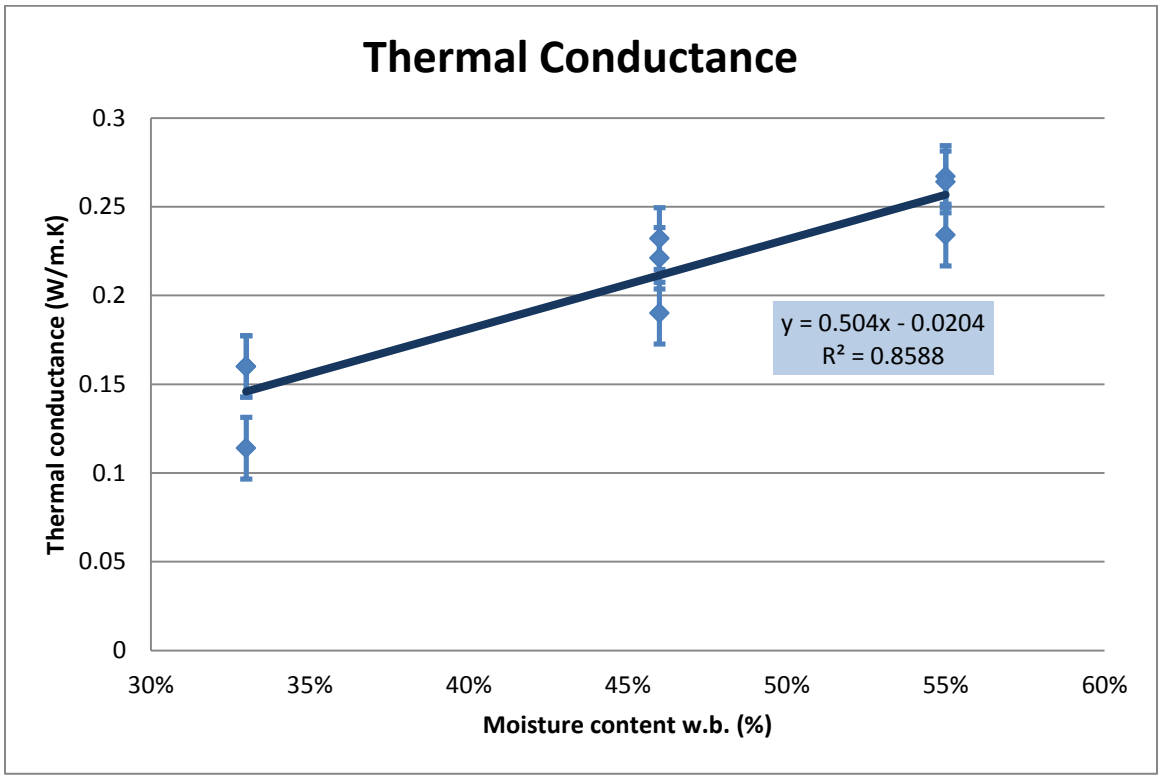

Figure 4.14. Thermal conductance linear regression for compost medium particle sizes.

Table 4.15. Regression analysis for thermal conductance on the operational range of the biofilter.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93
R Square	0.86
Adjusted R Square	0.84
Standard Error	0.02
Observations	9.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1.00	0.02	0.02	42.58	0.00
Residual	7.00	0.00	0.00		
Total	8.00	0.02			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.02	0.04	-0.58	0.58	-0.10	0.06	-0.10	0.06
Moisture	0.50	0.08	6.52	0.00	0.32	0.69	0.32	0.69

The medium particle size presented an R^2 equal to 0.859 relating moisture content to thermal conductivity. The moisture content of the biofilters is intended to fall within this narrower range because of it encompasses the limits of microbial activity on the lower end and reasonable levels of ammonia conversion without the danger of nitrous oxide production on the upper end. Based on the exponential regression equation 4.1 was be used during the performance tests to measure the water present in the compost and estimate the amount of water to be applied to maintain the target media moisture content.

$$M_W = 0.291\ln(\mathrm{K}) + 0.8727 \qquad 4.1$$

M_W = Moisture content (wet basis)

K = Thermal conductance read in the sensor (W/m.k)

The use of this sensor presented the possibility of error in the measurement from partial insertion of the probe into the compost. The initial calibration experiments were performed with the probe entirely inserted into the compost mass. However, when the system was used in the biofilter there would be a difference in the inserted depth owing to the thickness of the biofilter plywood wall.

A test was conducted to measure the effect of the depth of the probe in the compost mass. Five treatments were chosen, entirely inside the mass, 2/3 and 1/3 of the needle inserted into the media and also with plywood covering a portion of the probe. The plywood itself had two treatments: wet and dry, in order to consider the water absorption of the biofilter wall. Three replicates and three moisture contents were used for this experiment with the results presented in Table 4.16.

Table 4.16 Thermal conductance (W/m.K) for different depths of the metal probe in the compost mass.

	35%	**45%**	**55%**
1	0.210	0.212	0.315
	0.234	0.179	0.249
	0.203	0.214	0.556
2/3	0.173	0.172	0.176
	0.161	0.180	0.144
	0.176	0.173	0.175
1/3	0.144	0.096	0.104
	0.107	0.108	0.125
	0.111	0.099	0.091
Plywood dry	0.160	0.205	0.159
	0.227	0.180	0.209
	0.188	0.186	0.243
Plywood wet	0.195	0.181	0.190
	0.181	0.227	0.207
	0.156	0.187	0.225

A statistical comparison between the depths was performed in order to determine any difference among the results of thermal conductance and the condition of the treatment. The results of that analysis are presented in Table 4.17.

Table 4.17. Statistical output for the different probe depths test.

Moisture (% w.b.)	**Depth**	**Depth**	**Estimate (W/m.K)**	**StdErr**	**tValue**	**P-value**
35	1	1/3	0.09	0.02	4.05	0.0003
		2/3	0.04	0.02	1.71	0.0974
		Plywood	0.02	0.02	0.91	0.3704
		Plywood wet	0.03	0.02	1.43	0.1624
	1/3	2/3	-0.05	0.02	-2.34	0.0261
		Plywood	-0.07	0.02	-3.14	0.0038
		Plywood wet	-0.06	0.02	-2.62	0.0137
	2/3	Plywood	-0.02	0.02	-0.8	0.4291
		Plywood wet	-0.01	0.02	-0.28	0.7823
	Plywood	Plywood wet	0.01	0.02	0.52	0.605
45	1	1/3	0.11	0.02	4.63	<.0001
		2/3	0.02	0.02	1	0.3244
		Plywood	0.01	0.02	0.41	0.6846
		Plywood wet	0.00	0.02	0.13	0.8962
	1/3	2/3	-0.08	0.02	-3.63	0.001
		Plywood	-0.10	0.02	-4.22	0.0002

Table 4.17, continued

		Plywood wet	**-0.10**	**0.02**	**-4.5**	**<.0001**
	2/3	Plywood	-0.01	0.02	-0.59	0.5585
		Plywood wet	-0.02	0.02	-0.87	0.391
	Plywood	Plywood wet	-0.01	0.02	-0.28	0.7824
55	1	1/3	0.20	0.02	8.84	<.0001
		2/3	0.14	0.02	5.94	<.0001
		Plywood	0.10	0.02	4.5	<.0001
		Plywood wet	0.10	0.02	4.3	0.0002
	1/3	2/3	-0.07	0.02	-2.89	0.0071
		Plywood	-0.10	0.02	-4.33	0.0002
		Plywood wet	-0.10	0.02	-4.53	<.0001
	2/3	Plywood	-0.03	0.02	-1.44	0.1593
		Plywood wet	-0.04	0.02	-1.64	0.1108
	Plywood	Plywood wet	0.00	0.02	-0.2	0.8428

The results presented in Table 4.17 suggest that when the moisture content is lower (in this case, at 35%) there was not much difference between the readings when the probe was totally inserted as compared to the other conditions, except when the probe was only 1/3 inserted. There were significant differences in the readings for the 45% moisture content samples when the probe was inserted only 1/3 of the probe as compared to all the other conditions. For

55% samples there is significant difference of the readings for any condition other than entirely inserted.

These results suggest that for any moisture condition it is important that the probe stays more than 1/3 inserted into the compost to get a better measurement. Further, with increased moisture content it was more important to get the probe fully inserted into the compost. These analyses also indicated embedment of the probe into the compost for a more accurate and reliable measurement, instead of inserting it in the media through the biofilter wall.

4.4 Irrigation system

4.4.1 Preliminary test and calibration

The preliminary test for drying the compost was the no hose treatment used when analyzing the effects of vertical positions of the hoses. It was performed in order to determine the amount of water that should be applied in the biofilter to maintain given moisture content during operation. These results also reinforce the movement of the drying front through the media pattern, with the lower part of the biofilter drying faster than the upper part as shown in section 4.3.2.1 when the drying front's curves were characterized.

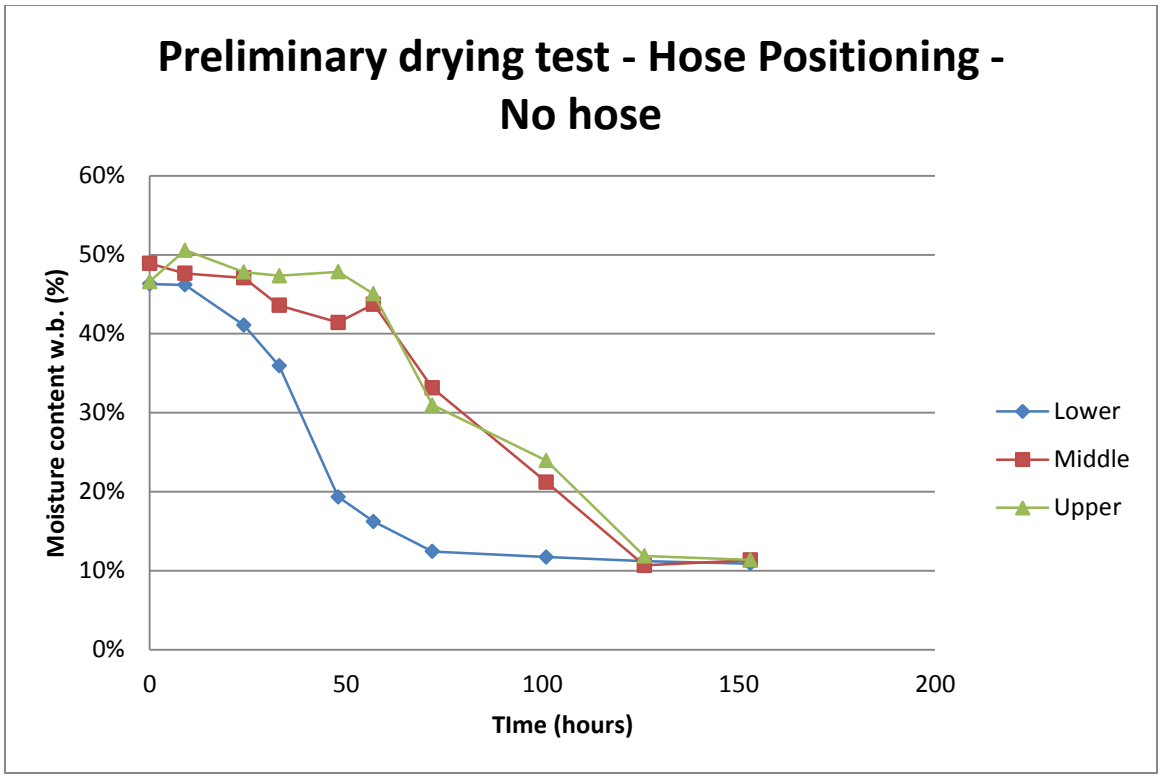

Figure 4.15. Preliminary test for water demand calculation.

An average of 111 kg of wet compost was loaded into the three biofilters with an initial moisture content of 47%, which translated to 58.6 kg of dry matter and 52.5 kg of water.

Table 4.18 was used as the reference for calculating the most severe drying rate during the test which occurred between 72 and 101 hours at the upper region. However, based on the preliminary tests when the middle and upper regions did not start to dry before the lower region reached equilibrium, it was determined that the most severe drying rate occurred in the lower region where the water loss reached 6.28 kg between 48 and 57 hours. This constituted a water loss rate of 0.42 kg/h as show in Table 4.19. Details for water application and calculation are shown in the Appendix E.

Table 4.18. Moisture content wet and dry basis for the preliminary tests.

	Wet Basis			Dry Basis		
Time (hours)	***Lower***	***Middle***	***Upper***	***Lower***	***Middle***	***Upper***
0	46%	49%	47%	86%	96%	87%
9	46%	48%	51%	86%	91%	102%
24	41%	47%	48%	70%	89%	92%
33	36%	44%	47%	56%	77%	90%
48	19%	41%	48%	24%	71%	92%
57	16%	44%	45%	19%	78%	82%
72	12%	33%	31%	14%	50%	45%
101	12%	21%	24%	13%	27%	31%
126	11%	11%	12%	13%	12%	13%
153	11%	11%	11%	12%	13%	13%

Table 4.19. Water Loss rate for the three regions of the biofilter.

	Water Loss Rate (kg/h)		
Time	***Lower***	***Middle***	***Upper***
0	0.00	0.00	0.00
9	0.01	0.10	-0.33
24	0.21	0.03	0.14
33	0.30	0.25	0.04
48	0.42	0.09	-0.02
57	0.10	-0.15	0.21
72	0.07	0.37	0.48
101	0.01	0.15	0.09
126	0.01	0.12	0.14
153	0.00	-0.01	0.00

The highest drying rate for this process was used to calculate the necessary water to be applied into the biofilter media. It was assumed that if the system could supply enough water for this rate, then all the drying rates would exceeded and the media would maintain its moisture content.

4.4.2 Soaker hose test

The soaker hoses were calibrated to determine the flow as a function of pressure before being used in the biofilters. There were two steps involved in the calibration. First, three meters of soaker hose were calibrated in order to find the rate of flow per meter of hose. This information helped to determine the appropriate length of hose to be placed in the media in order to supply enough water to the biofilter. The hose was subjected to a series of pressures where the amount of water collected and recorded are presented in Table 4.20. This analysis was repeated three times. The results of the analysis along with a prediction curve are presented in Figure 4.16.

Table 4.20. Calibration of soaker hoses

Pressure (kPa)	Flow (ml/s)
27.6	30.1
41.4	33.1
55.2	37.1
68.9	40.7
82.7	43.3
96.5	43.3
110.3	48.8
124.1	51.1

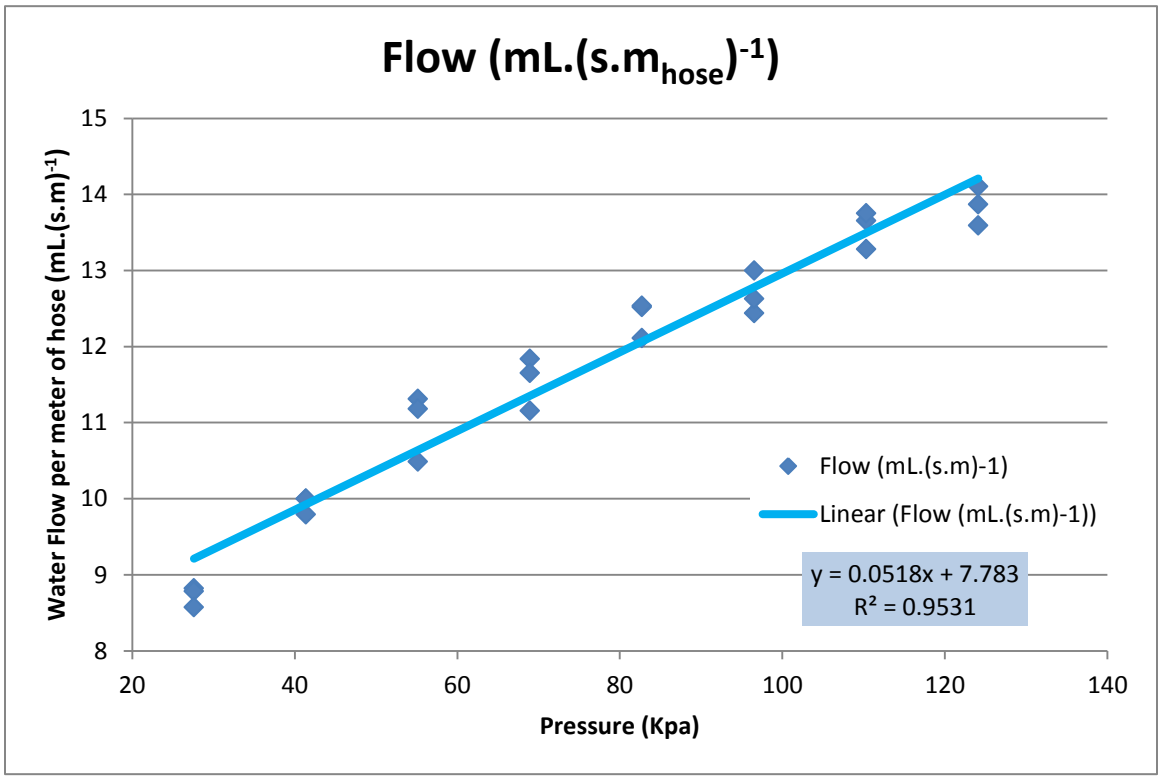

Figure 4.16. Linear regression of the soaker hose flow with the pressure.

The prediction model showed excellent agreement with the data resulting in an R^2 of 0.95. The model was used with the water requirements calculated in

the drying tests to define a length for the soaker hose to be installed in the biofilter. The drying tests data indicated that the highest rate of water removal from the biofilters was 420 grams of water per hour.

The equation for the hoses was created with three meters of hose, so the equation can be transformed into a linear equation showing the flow results as a function of the length. The equation then is transformed into the following.

$$Q = 0.05 \times P + 7.8 \qquad 4.2$$

Q = water flow (mL.(s.m)$^{-1}$)

P = pressure (kPa)

The flow is given in mL.(s.m)$^{-1}$ of soaker hose and the pressure in kPa. It was stipulated that the hose would work at a 68.95 kPa (10 psi) controlled by ball valve and monitored by a pressure gauge. This is half of the maximum pressure allowed in the soaker hose. The flow resulting from this pressure was 14.5 ml/s over 1.2 m of soaker hose which required 5 minutes to apply all the water necessary for the 12 hour period between readings.

4.4.3 Hose positioning (water added)

The hose positioning tests evaluated the performance of the soaker hoses placed at three different positions in the biofilter which constituted the treatments of this experiment. Compost samples were taken twice a day to monitor the moisture content of the biofilters and water was applied to the biofilter right after the sample was taken in order to avoid interference with the measurements.

Figure 4.17 shows the profile of moisture content in the biofilter when the hose was positioned at the lower region. Figure 4.18 and Figure 4.19 shows the SAS output for the moisture slopes in the lower and middle region and the p-value calculated demonstrated that these slopes are not different from zero which means constant moisture content. The upper region dried throughout the extent of the experiment at a very low rate, but still the slope is not zero (Figure 4.20).

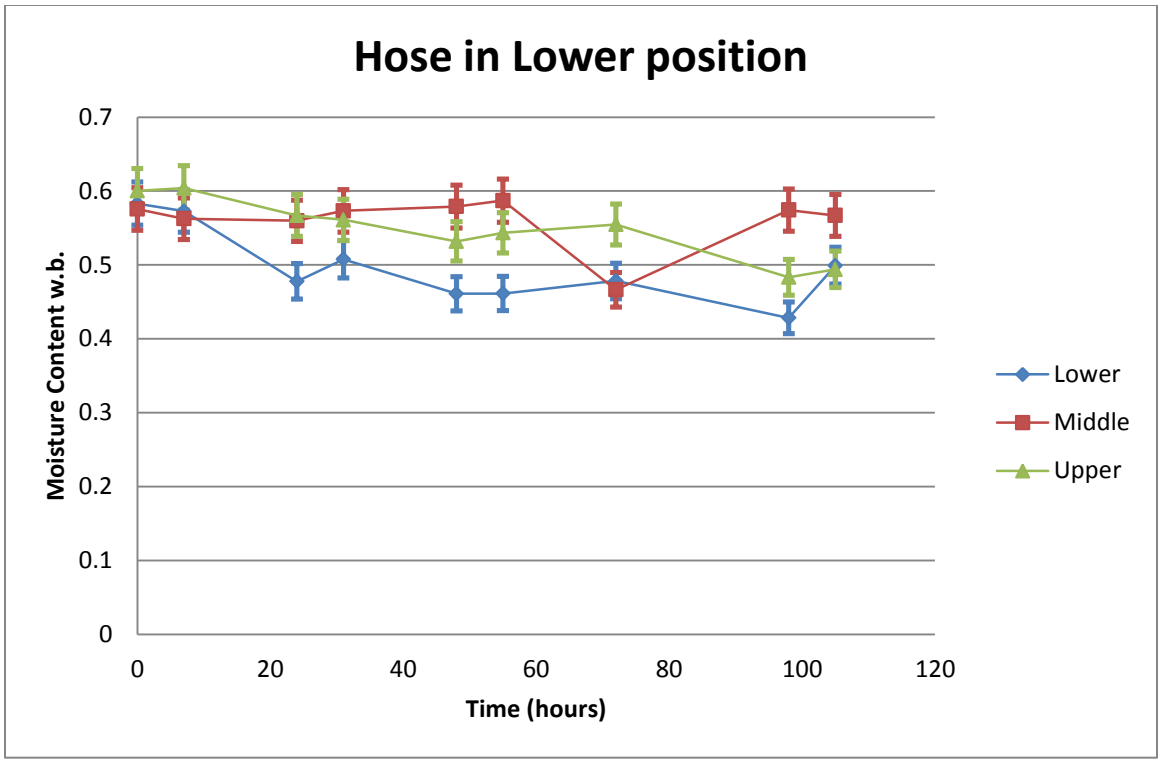

Figure 4.17. Chart showing the moisture content of the regions of biofilters with the hose installed in the lower position.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5209	0.02180	75	23.90	<.0001
biofilter	1	0.03494	0.03083	75	1.13	0.2607
biofilter	2	0.03557	0.03083	75	1.15	0.2523
biofilter	3	0	.	.	.	.
time		-0.00006	0.000361	75	-0.15	0.8792
time*biofilter	1	-0.00125	0.000511	75	-2.44	0.0171
time*biofilter	2	-0.00152	0.000511	75	-2.98	0.0039
time*biofilter	3	0	.	.	.	.

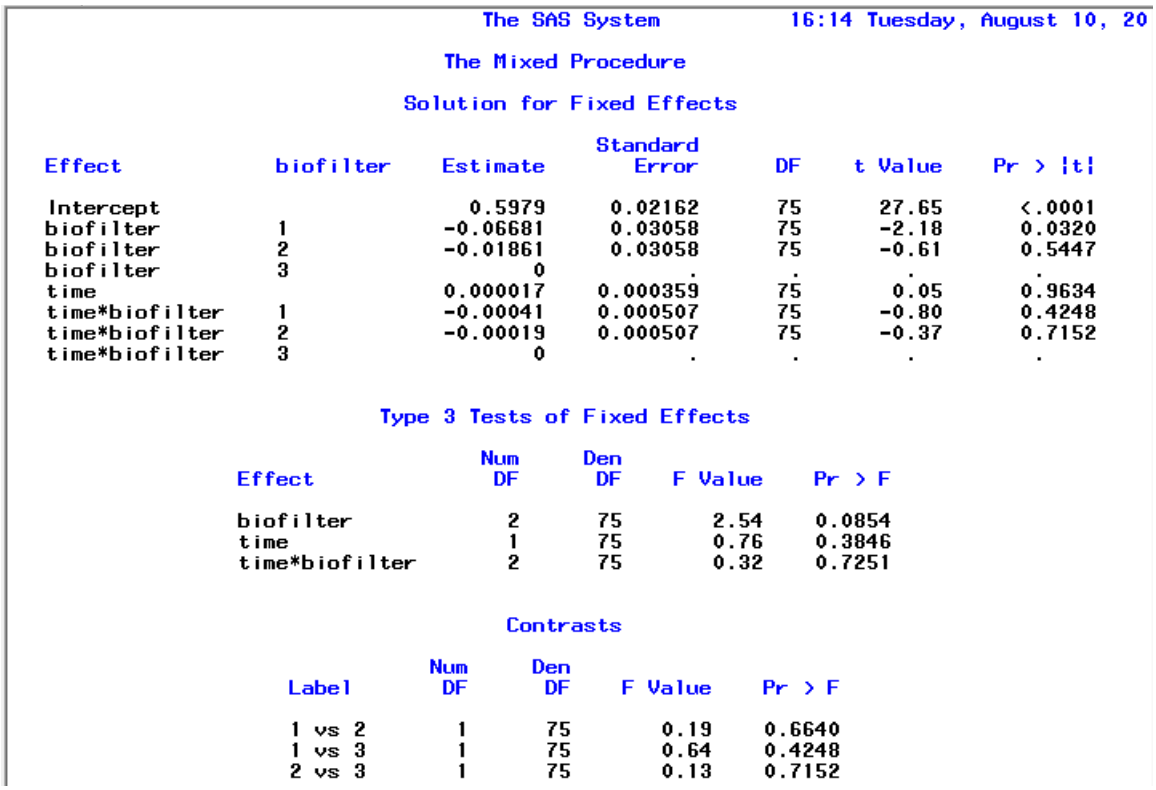
Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	75	0.87	0.4223
time	1	75	21.99	<.0001
time*biofilter	2	75	5.04	0.0088

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	75	0.29	0.5911
1 vs 3	1	75	5.95	0.0171
2 vs 3	1	75	8.88	0.0039

Figure 4.18. SAS output to the lower region when the hose is positioned in the lower region.



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Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5979	0.02162	75	27.65	<.0001
biofilter	1	-0.06681	0.03058	75	-2.18	0.0320
biofilter	2	-0.01861	0.03058	75	-0.61	0.5447
biofilter	3	0	.	.	.	.
time		0.000017	0.000359	75	0.05	0.9634
time*biofilter	1	-0.00041	0.000507	75	-0.80	0.4248
time*biofilter	2	-0.00019	0.000507	75	-0.37	0.7152
time*biofilter	3	0	.	.	.	.

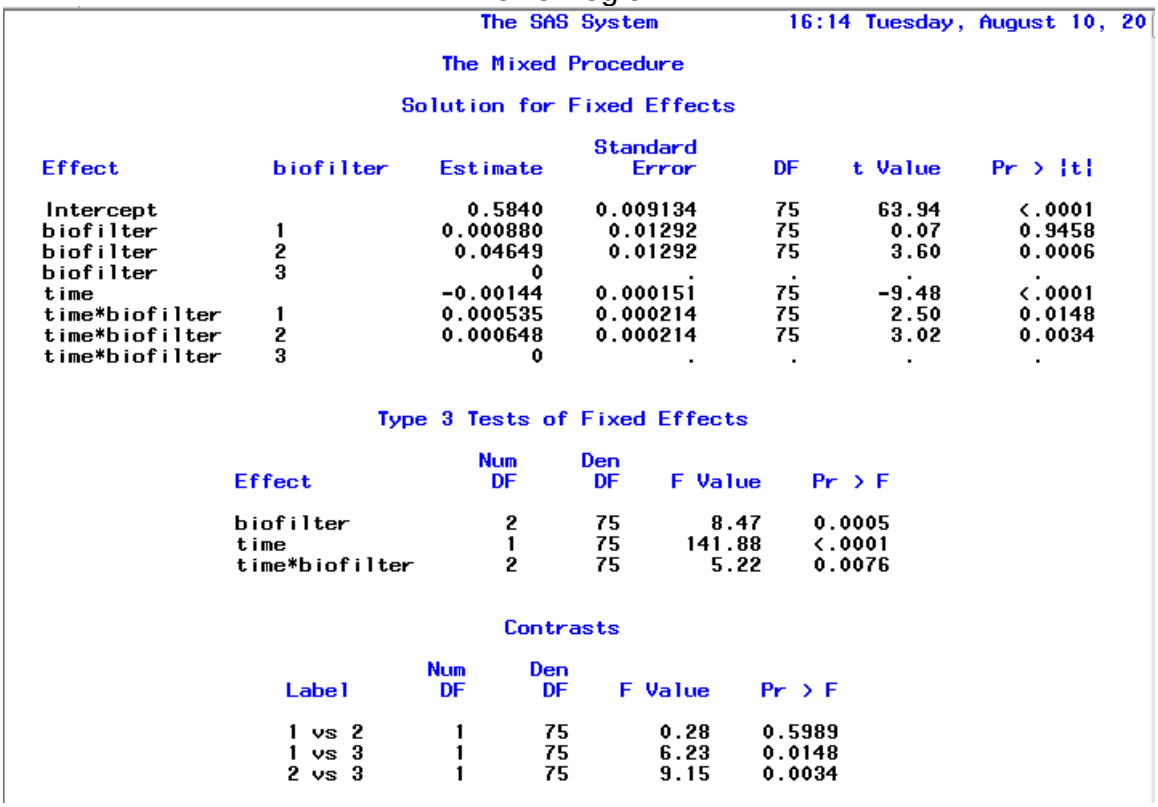
Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	75	2.54	0.0854
time	1	75	0.76	0.3846
time*biofilter	2	75	0.32	0.7251

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	75	0.19	0.6640
1 vs 3	1	75	0.64	0.4248
2 vs 3	1	75	0.13	0.7152

Figure 4.19. SAS output to the middle region when the hose is positioned in the lower region.



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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5840	0.009134	75	63.94	<.0001
biofilter	1	0.000880	0.01292	75	0.07	0.9458
biofilter	2	0.04649	0.01292	75	3.60	0.0006
biofilter	3	0	.	.	.	.
time		-0.00144	0.000151	75	-9.48	<.0001
time*biofilter	1	0.000535	0.000214	75	2.50	0.0148
time*biofilter	2	0.000648	0.000214	75	3.02	0.0034
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	75	8.47	0.0005
time	1	75	141.88	<.0001
time*biofilter	2	75	5.22	0.0076

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	75	0.28	0.5989
1 vs 3	1	75	6.23	0.0148
2 vs 3	1	75	9.15	0.0034

Figure 4.20. SAS output to the upper region when the hose is positioned in the lower region.

The hose when placed in the middle region allowed media drying (Figure 4.21), because its slopes were significantly different from zero as shown in Figure 4.22, Figure 4.23 and Figure 4.24 in the SAS output with high p-value for the slopes.

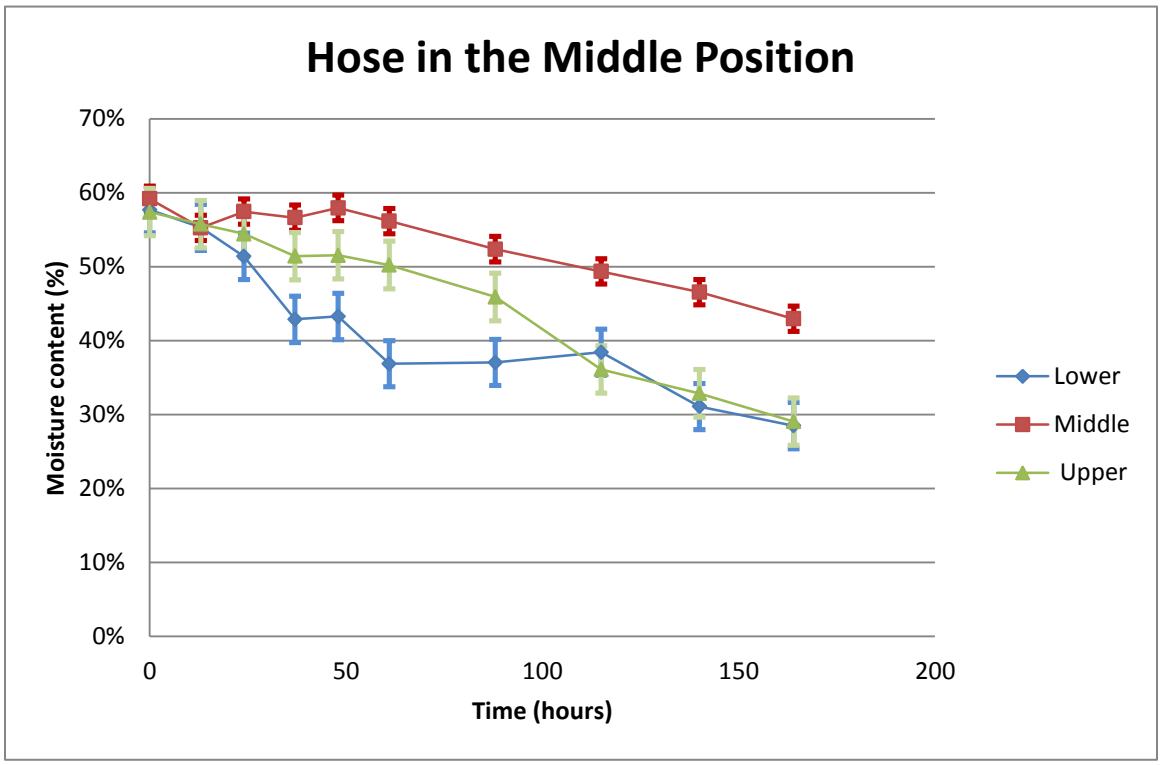

Figure 4.21. Chart showing the moisture content of the regions of biofilters with the hose installed in the middle position.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5566	0.02226	84	25.01	<.0001
biofilter	1	-0.04908	0.03147	84	-1.56	0.1227
biofilter	2	-0.00732	0.03147	84	-0.23	0.8167
biofilter	3	0	.	.	.	.
time		-0.00320	0.000264	84	-12.15	<.0001
time*biofilter	1	0.000958	0.000373	84	2.57	0.0119
time*biofilter	2	0.003513	0.000373	84	9.42	<.0001
time*biofilter	3	0	.	.	.	.

Figure 4.22. SAS output to the lower region when the hose is positioned in the middle region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5838	0.01599	84	36.52	<.0001
biofilter	1	0.05240	0.02261	84	2.32	0.0229
biofilter	2	-0.00854	0.02261	84	-0.38	0.7066
biofilter	3	0	.	.	.	.
time		-0.00235	0.000189	84	-12.43	<.0001
time*biofilter	1	0.001252	0.000268	84	4.67	<.0001
time*biofilter	2	0.002933	0.000268	84	10.95	<.0001
time*biofilter	3	0	.	.	.	.

Figure 4.23. SAS output to the middle region when the hose is positioned in the middle region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.6333	0.01990	84	31.82	<.0001
biofilter	1	-0.1151	0.02814	84	-4.09	<.0001
biofilter	2	-0.01362	0.02814	84	-0.48	0.6297
biofilter	3	0	.	.	.	.
time		-0.00268	0.000236	84	-11.36	<.0001
time*biofilter	1	0.001356	0.000333	84	4.07	0.0001
time*biofilter	2	0.001085	0.000333	84	3.26	0.0016
time*biofilter	3	0	.	.	.	.

Figure 4.24. SAS output to the upper region when the hose is positioned in the middle region.

The hose in the upper position (Figure 4.25) was able to bring the lower region into an equilibrium moisture content of 30% w.b. after 20 hours as can be seen in Figure 4.26 where the p value for the slope in the lower region after 20 hours is not significantly different from zero. The upper and middle regions were drying (Figure 4.27 and Figure 4.28). One possible explanation for this could be that the water was only passing through the media and not being absorbed by the compost.

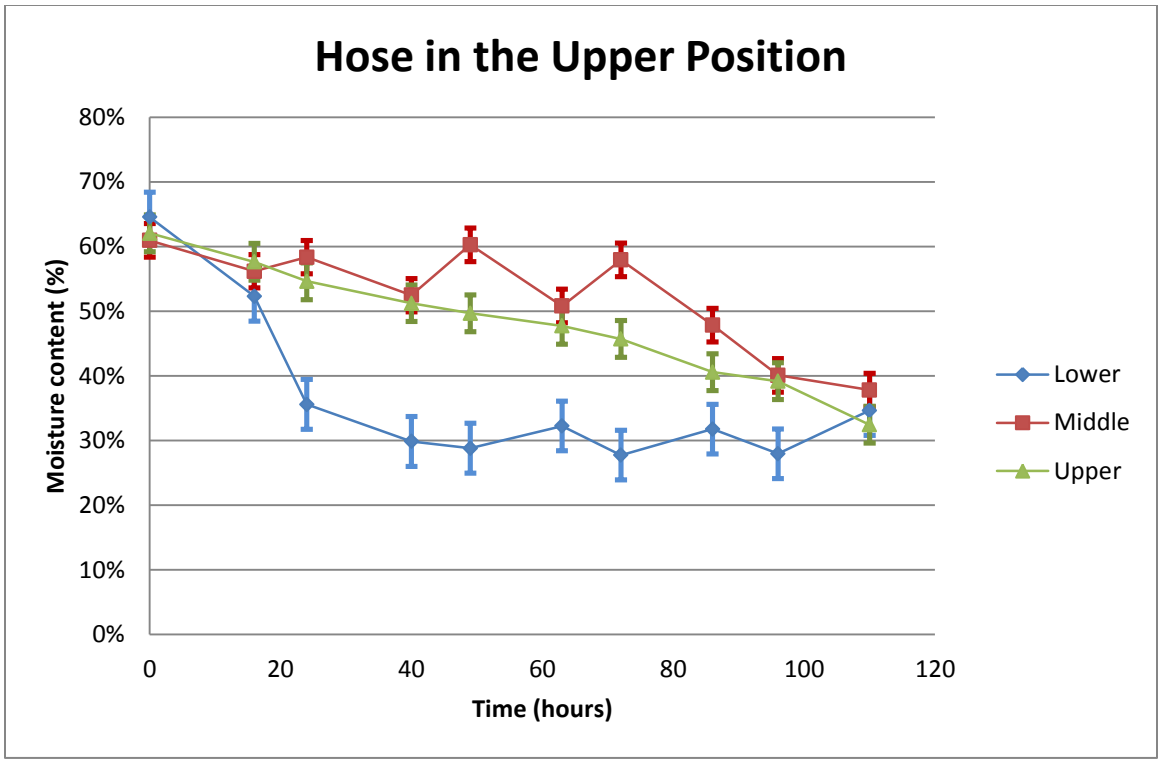

Figure 4.25. Chart showing the moisture content of the regions of biofilters with the hose installed in the middle position.

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Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.1193	0.03025	66	3.94	0.0002
biofilter	1	0.3471	0.04278	66	8.11	<.0001
biofilter	2	0.2580	0.04278	66	6.03	<.0001
biofilter	3	0	.	.	.	.
time		0.000233	0.000321	66	0.73	0.4697
time*biofilter	1	-0.00107	0.000454	66	-2.36	0.0212
time*biofilter	2	0.000018	0.000454	66	0.04	0.9692
time*biofilter	3	0	.	.	.	.

Figure 4.26. SAS output of the equilibrium period of the lower region when the hose is positioned in the upper region.

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Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.6289	0.03722	84	16.90	<.0001
biofilter	1	0.01070	0.05264	84	0.20	0.8395
biofilter	2	-0.04857	0.05264	84	-0.92	0.3587
biofilter	3	0	.	.	.	.
time		-0.00202	0.000441	84	-4.58	<.0001
time*biofilter	1	0.000161	0.000623	84	0.26	0.7969
time*biofilter	2	0.001929	0.000623	84	3.10	0.0027
time*biofilter	3	0	.	.	.	.

Figure 4.27. SAS output of the middle region when the hose is positioned in the upper region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.6843	0.02452	84	27.91	<.0001
biofilter	1	-0.1672	0.03467	84	-4.82	<.0001
biofilter	2	-0.06153	0.03467	84	-1.77	0.0796
biofilter	3	0	.	.	.	.
time		-0.00232	0.000290	84	-7.99	<.0001
time*biofilter	1	0.000459	0.000410	84	1.12	0.2664
time*biofilter	2	0.001105	0.000410	84	2.69	0.0086
time*biofilter	3	0	.	.	.	.

Figure 4.28. SAS output of the upper region when the hose is positioned in the upper region.

The installation of the soaker hose was a viable concept for delivering water to the compost media, especially in the lower region where the hose was able to keep the moisture at a level that sustains microbial activity throughout the media over the extent of this experiment. Some drying was observed during the process when the hose was placed in the middle and upper position. This could be an indication of insufficient hose in the media, or that the shape of the hose was not able to deliver the water accurately in the media or even that the water was not being absorbed by the media.

The slopes of each region were contrasted among four treatments: no hose, hose in lower, hose in middle and hose in upper. These contrasts were constructed to find the treatment that was most different from the “no hose” treatment when no water was applied.

Table 4.21. Contrasts of the moisture content slopes.

Contrasts				
Label	***Num DF***	***Den DF***	***F Value***	***Pr > F***
No hose vs Lower	1	332	15.07	0.0001
Lower vs Middle	1	332	3.49	0.0625
No hose vs Middle	1	332	8.96	0.0030
No hose vs Upper	1	332	0.00	0.9727
Lower vs Upper	1	332	14.79	0.0001
Middle vs Upper	1	332	8.67	0.0035

The ANOVA results for this analysis are presented in Table 4.21. It is possible to see that the moisture content slope in “lower” treatment is significantly different from the “no hose” treatment. This is reasonable because the lower position of the hose was able to maintain the moisture content. The hose in the “middle” treatment was also significantly different from zero, but the reason is that the drying rate was much lower than when “no hose” was applied. The “upper” treatment did not show any difference from the “no hose” treatment because of the drying of the upper and middle regions.

4.4.4 Water application interval

Water was applied for two minutes to the biofilter at different time intervals in order to evaluate if there was any difference in the applied water draining from the biofilter over different application times (Table 4.22).

Table 4.22. Water interval evaluation.

Time	Biofilter	Water (kg)
30 sec	1	0.85
	2	1.1
	3	1.35
120 sec	1	1.5
	2	1.55
	3	1.5
15 sec	1	1.55
	2	1.5
	3	1.55

A Tukey analysis was performed to test the differences between the treatments (Table 4.23). The treatment with water being applied for 30 seconds with two minutes interval is significantly different from others treatments with the lower mean for water drainage.

Table 4.23. Tukey grouping for water interval tests.

Tukey Grouping	Mean (kg of H_2O)	N	Time (sec)
A	1.5333	3	15
A	1.5167	3	120
B	1.1000	3	30
Error mean square	0.0214		

Water applied for a total of two minutes during four applications of 30 seconds at two minute intervals presented the lowest mean for applied water draining from the filter.

4.5 Ammonia and Nitrous Oxide Observations

4.5.1 Water balance

4.5.1.1 Direct Method

The Direct Method consisted of taking compost samples from the three regions of the biofilter with a grabbing tool in a way that was representative of that region. First, samples were taken once a day, but after the first week the samples were taken every two days. The time interval was increased because taking samples diminished the amount of compost and the process of taking samples every day during the whole time of the experiment would be damaging for the compost mass.

The moisture content for each of the three regions of the biofilters is represented in Figure 4.29 and Figure 4.30. When no water was applied to the compost, it was possible to see a fast drying rate for the lower region which reaches 10% w.b. moisture content after approximately 100 hours. The middle region began to dry right after this region gets to 20% w.b. The upper region of the biofilter was the region with the slowest drying rate reaching 20% moisture content after 350 hours.

The treatments where water was applied to the compost were characterized by higher levels of moisture content which maintained microbial activity for the whole extent of the experiment. The lower region started to dry, but it was maintained above levels required that support microbial activity.

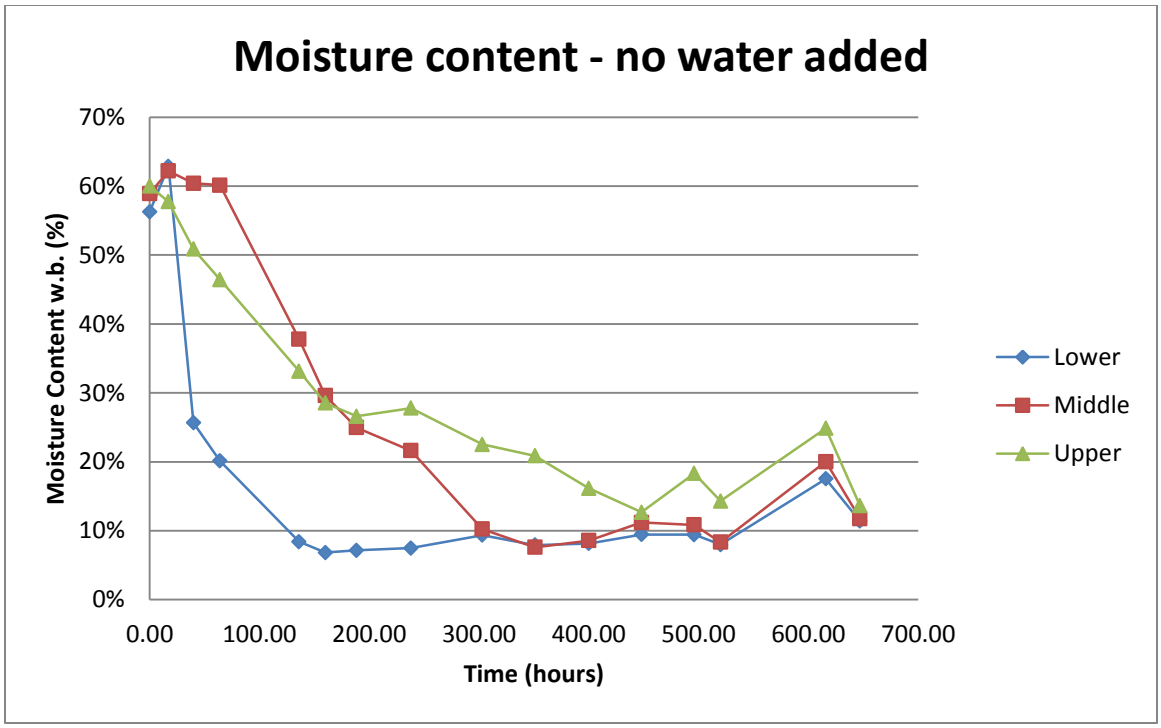

Figure 4.29. Moisture content in the three regions of the biofilter during the run when no water was applied.

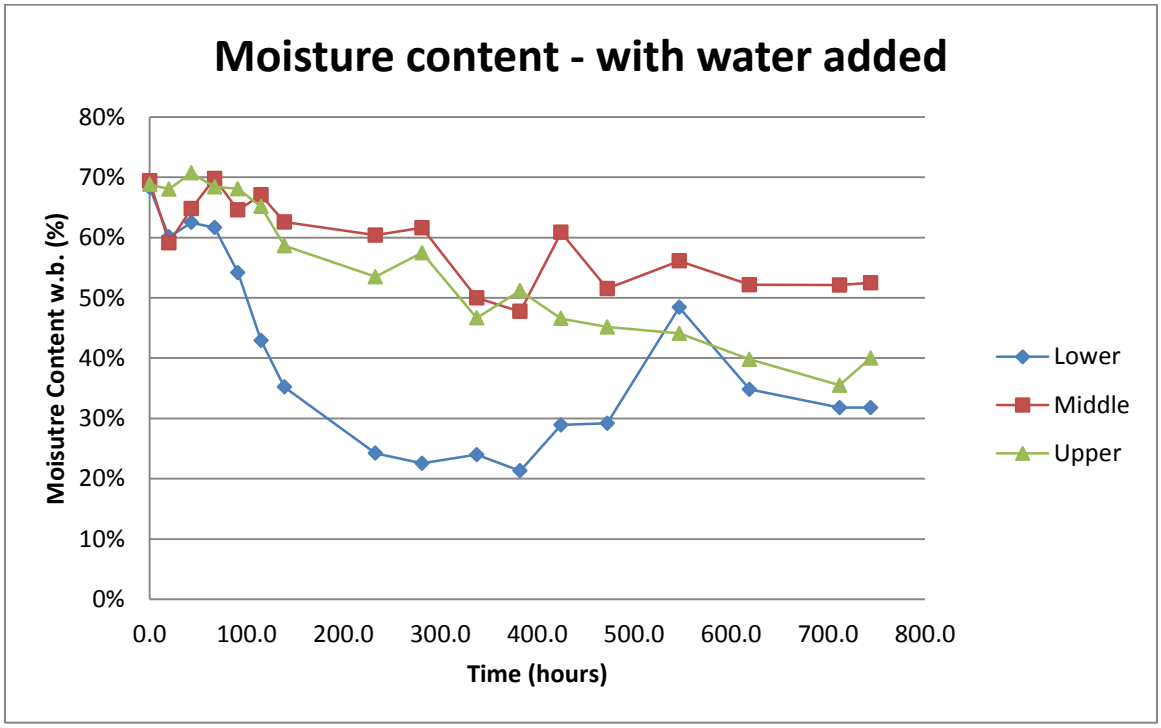

Figure 4.30. Moisture content in the three regions of the biofilter during the run when water was applied according to the thermal conductance sensor.

Water was applied to the compost based on moisture content readings taken four times a day with the thermal capacitance meter. Figure 4.31 shows the drying front in the lower region for the two treatments. The data for the two treatments presented the same pattern but in the treatment with water the lower region may have worked as buffer for the regions above, as can be seen in Figure 4.32. This likely occurred when the soaker hoses kept the minimum moisture content of the middle region above 50% w.b. The upper region presented the same pattern of drying as the lower region but at higher moisture content (Figure 4.33).

These shifts in the drying curves are important because it elevates the overall moisture content of the biofilters. This is important because biological activity ceases at moisture content lower than 17% w.b.(water activity < 0.95) for this media (Del Nero Maia, 2010).

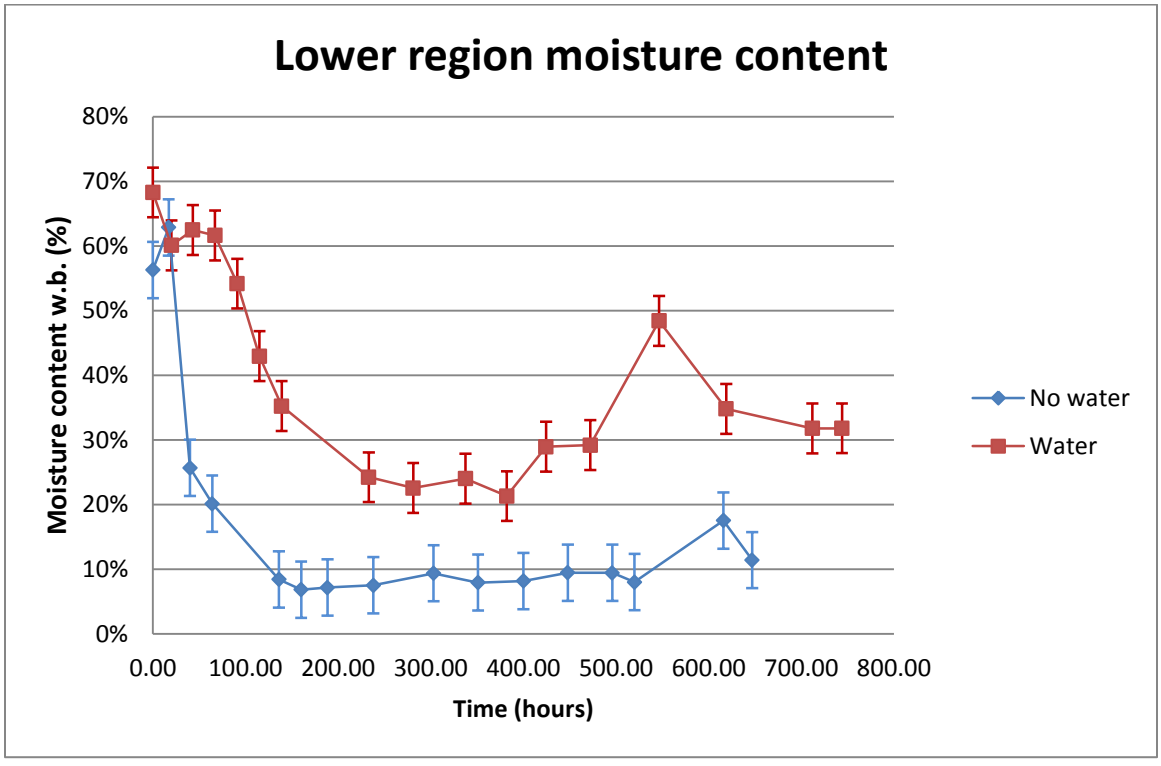

Figure 4.31. Lower region drying fronts comparison between the treatments with no water and water applied.

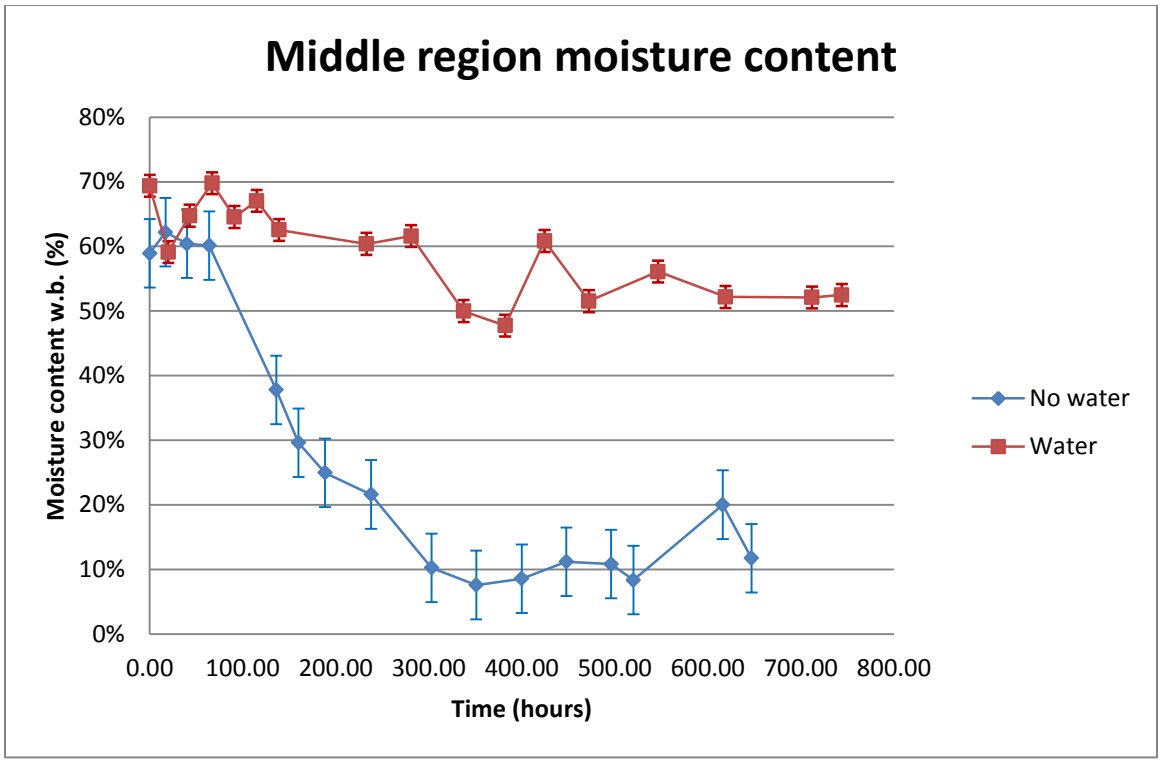

Figure 4.32. Middle region drying fronts comparison between the treatments with no water and water applied.

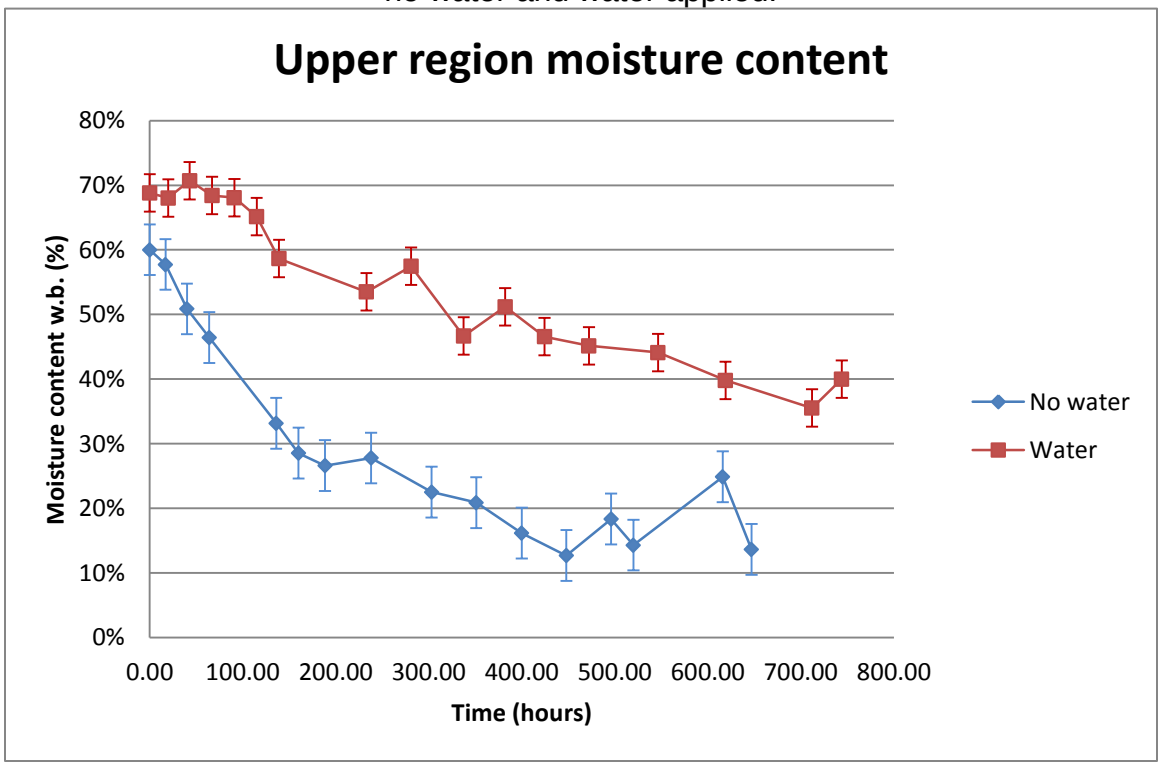

Figure 4.33. Upper region drying fronts comparison between the treatments with no water and water applied.

Without the water application the biofilters reached a moisture content threshold that does not support biological activity after 100 hours in the lower region, 300 hours in the middle and 450 hours in the upper region. Conversely, with the water being applied the biofilters did not reach this limit for the extent of the experiment.

Calculation of the water loss rate in this experiment allowed a better understanding of the water behavior in the biofilters when comparing measurement methods, because the water content values were all in Kg.

Table 4.24 shows the biofilter loses a total of 77.2 kg of water during the entire time of the experiment (647 hours of operation).This is a considerable amount of water taking into consideration that the initial amount of water in the biofilter was 88 kg. Drying removed about 87% of the initial water, taking into consideration that this treatment represented no water replacement.

Table 4.24. Mass of water lost in the biofilter when no water is applied into the media.

	No Water		
Time (hours)	***Lower (kg)***	***Middle (kg)***	***Upper (kg)***
0	22.4	25	26.2
17	29.5	28.7	23.8
40	6	26.6	18
64	4.4	26.3	15.1
136	1.6	10.6	8.7
160	1.3	7.3	7
189	1.3	5.8	6.3
238	1.4	4.8	6.7
303	1.8	2	5.1
351	1.5	1.4	4.6
400	1.5	1.6	3.4
448	1.8	2.2	2.5
496	1.8	2.1	3.9
520	1.5	1.6	2.9
616	3.7	4.4	5.8
647	2.2	2.3	2.7
Total Loss (kg)	27.3	26.4	23.5

Table 4.25 shows the final water loss which corresponded to the difference between the initial and the final water content of the experiment for the treatment when water was being applied to the compost to compensate for the drying. It is possible to see that drying occurred but at a lower rate than the no water treatment. Table 4.26 presents the total water lost which is the amount of water lost throughout the experiment and accounting for the water that was applied by the hoses. This represents the actual amount of water removed from the compost.

Table 4.25. Water loss for the biofilter when water is applied into the media.

	Water		
Time (h)	***Lower (kg)***	***Middle (kg)***	***Upper (kg)***
0	30.2	31.8	31
20	21.2	20.3	29.9
43	23.4	25.8	33.9
67	22.6	32.4	30.4
91	16.6	25.6	30
115	10.6	28.6	26.2
139	7.6	23.5	19.9
233	4.5	21.4	16.2
281	4.1	22.5	19
338	4.4	14	12.3
382	3.8	12.8	14.7
425	5.7	21.8	12.2
472	5.8	14.9	11.6
547	13.2	18	11.1
619	7.5	15.3	9.3
712	6.5	15.3	7.7
713	6.5	15.5	9.4
Total Loss (kg)	23.7	16.9	24.5

Table 4.26. Water loss for the biofilter treatment for water applied into the media, taking into consideration the water added during the process.

	Water		
Time (h)	***Lower (kg)***	***Middle (kg)***	***Upper (kg)***
0	9.1	11.5	1.1
20	0	0	0
43	0.8	0	3.5
67	6	6.9	0.4
91	6	0	3.7
115	2.9	5.1	6.3
139	3.1	2.1	3.8
233	0.4	0	0
281	0	8.5	6.7
338	0.6	1.2	0
382	0	0	2.5
425	0	6.9	0.7
472	0	0	0.5
546	5.7	2.6	1.8
619	1	0	1.5
712	0	0	0
713	0	0	0
Total Loss (kg)	35.7	44.8	32.5

Table 4.21 shows that drying represented 70% of the total initial water amount in the biofilter. Based on this data, it is inferred that there was a 17% reduction in the moisture loss by the media.

4.5.1.2 Photoacoustic gas analyzer

The INNOVA 1412 is a photoacoustic gas analyzer that measures the amount of water vapor as well as other gases present in a sample. It was used during the experiment to track the water vapor in the gas stream across all the regions of the biofilter by determining the increase in water content of the gas phase.

Sampling ports were installed in five regions in the biofilter: plenum, lower, middle, upper and headspace. This was necessary to create a profile of the water loss across the media. The INNOVA gives the amount of water in the air as mgh2o/m3air. Figure 4.34 is a graphic representation of the amount of water in the gas phase in the five regions of the biofilters during the treatment of water being applied.

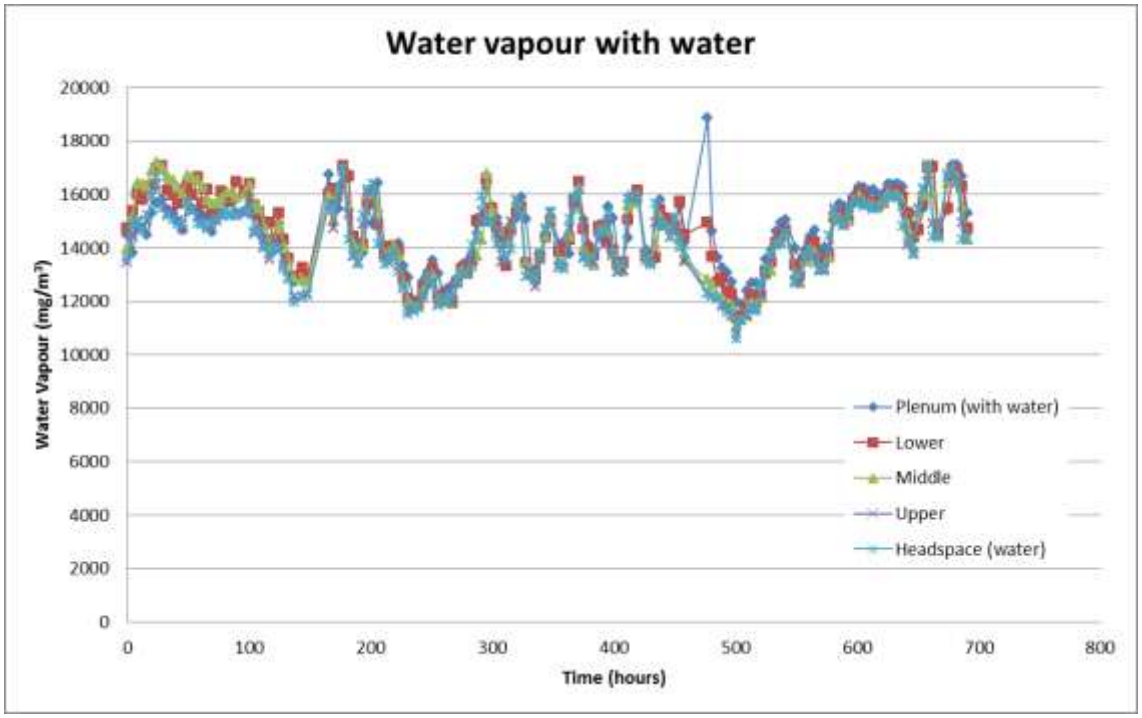

Figure 4.34. Water vapor profile in the biofilter.

The water loss in the biofilter as measured by the INNOVA was calculated in kg of water to generate a comparison to the oven tests. The airflow was used to calculate the amount of water that was removed from the compost. To calculate the water removed from the biofilter, the difference between the headspace water vapor content and the laboratory air water vapor contents was calculated.

The laboratory air had an average of 25^{o}C and 57% relative humidity which gave an average of 9,500 mg/m^3 of water vapor. The average air flow was 95 m^3/h. The water removed from the biofilter was determined by calculating the difference of water content of the air coming out of the headspace from the water content of the laboratory air with equation 4.3.

$$WR = HS - LA \qquad 4.3$$

WR = Water removal (mg/m^3)

HS = Headspace air water content (mg/m^3)

LA = Laboratory air water content (mg/m^3)

This water removal (Figure 4.35) was then multiplied by the air flow to find the mass of water being removed from the compost which gave the rate of water loss in g/h of water removed.

The water loss rate can be multiplied the time interval between readings to find the water mass removed. The total amount of water lost based on the Innova measurements is 308 kg of water during 691 hours of experiment.

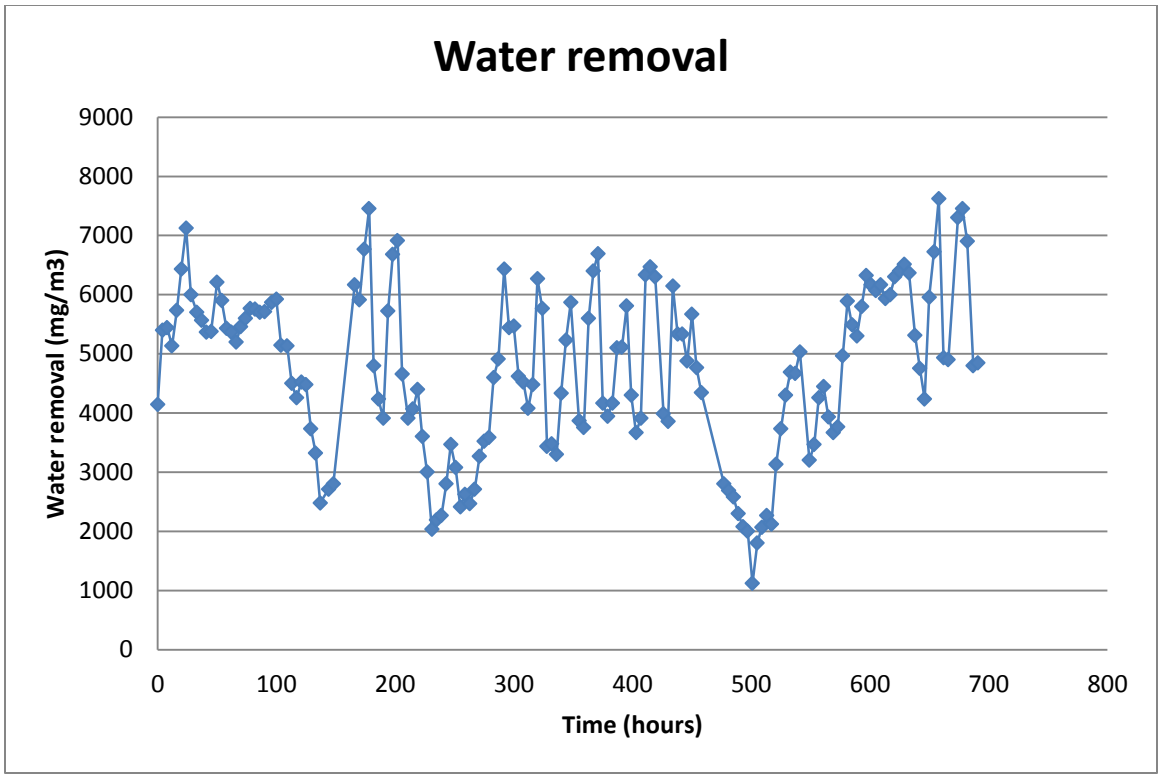

Figure 4.35. Water removed from the biofilter.

4.5.1.3 Thermal conductance

The values for thermal conductance vs. time in the compost biofilter are presented in Figure 4.36. Three measuring points were used on the wall of the biofilter to measure the thermal conductance of the compost during the abatement test.

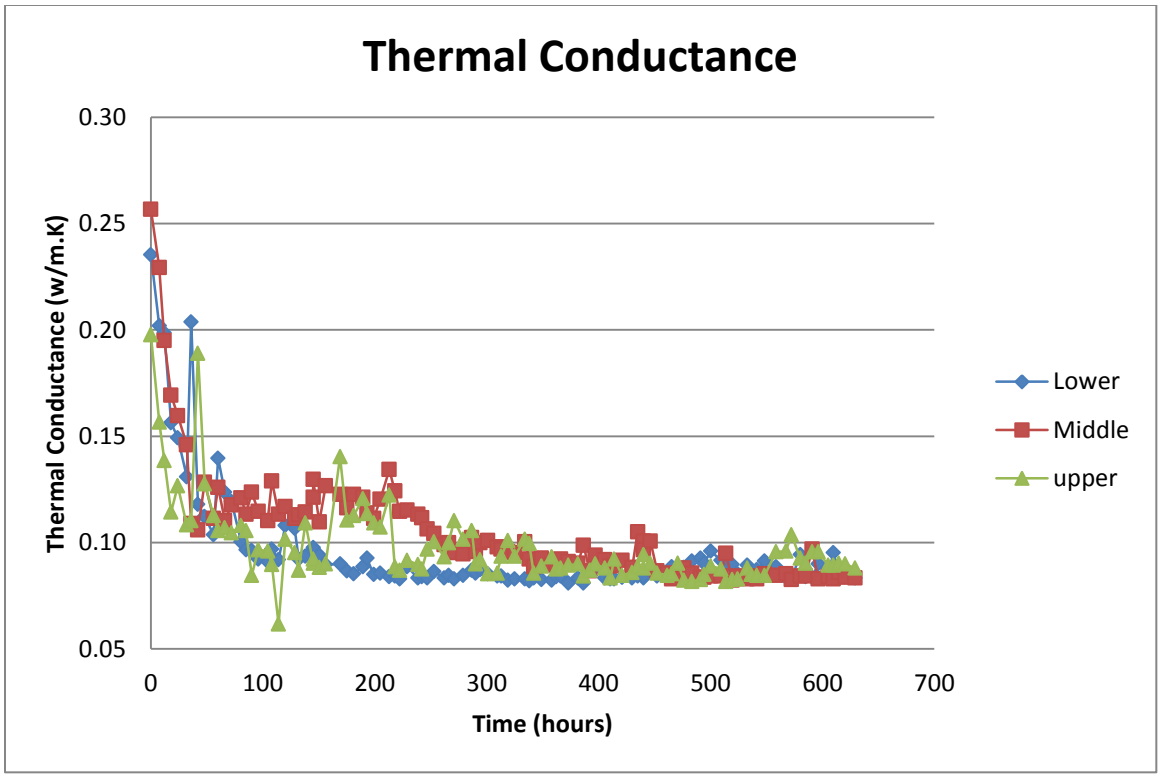

Figure 4.36. Thermal conductance in the biofilter compost in the three regions.

The values for thermal conductivity were transformed into equivalent moisture contents using the calibration equation 4.1. The results are presented in Figure 4.38. The data indicate that this material reached equilibrium after 250 hours for all three regions. As indicated by the SAS output in the Figure 4.37 because of the high p-value which means no significant difference with a zero slope.

The SAS System 16:14 Tuesday, August 10, 2

The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		3.3865	0.03458	570	97.92	<.0001
biofilter	1	-0.2120	0.04891	570	-4.34	<.0001
biofilter	2	0.1299	0.04891	570	2.66	0.0081
biofilter	3	0	.	.	.	.
time		-0.00022	0.000077	570	-2.86	0.0044
time*biofilter	1	0.000368	0.000109	570	3.38	0.0008
time*biofilter	2	-0.00029	0.000109	570	-2.66	0.0081
time*biofilter	3	0	.	.	.	.

Figure 4.37. SAS output for the thermal conductance readings after 250 hours.

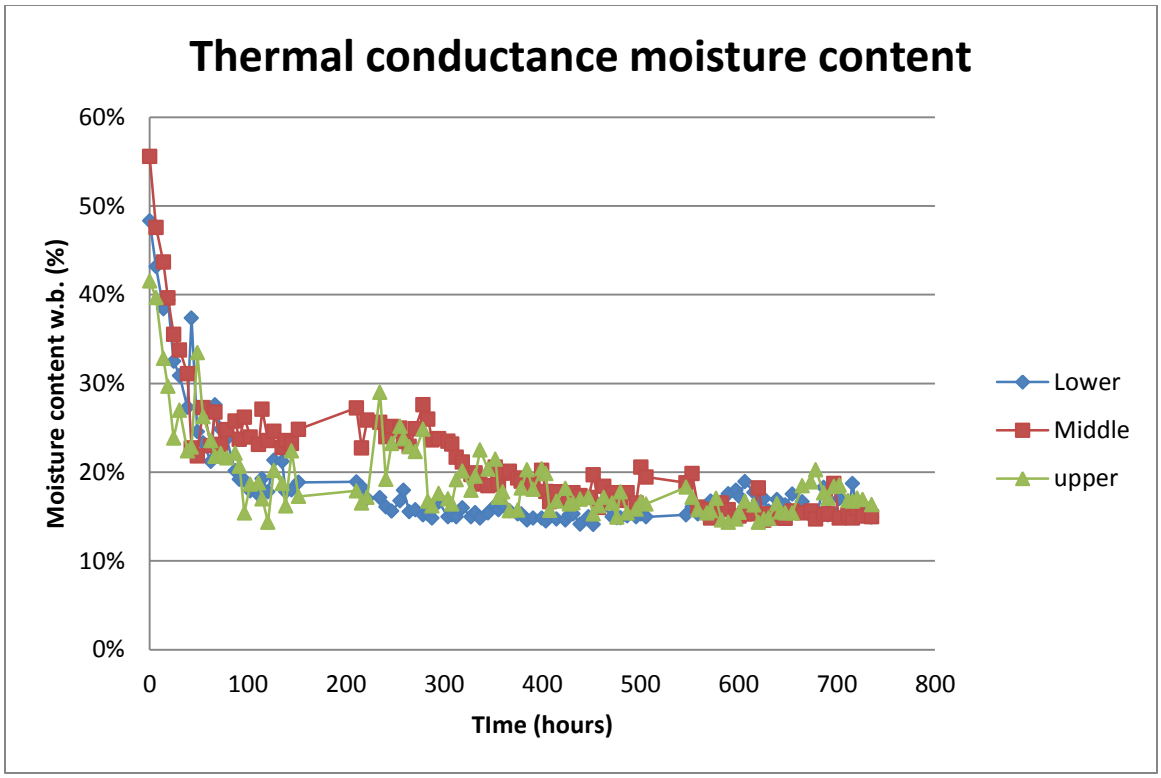

Figure 4.38. Calculated moisture content based on the equation 4.1 calibrated for thermal conductance.

The discrepancy between moisture content as compared to the direct moisture content was first attributed to the fact that the thermal conductivity probe was not entirely inserted into the compost. However, as reported in Section 4.2.2.3, this hypothesis was discarded.

Thermal conductance did not show good performance for a reason not yet defined.

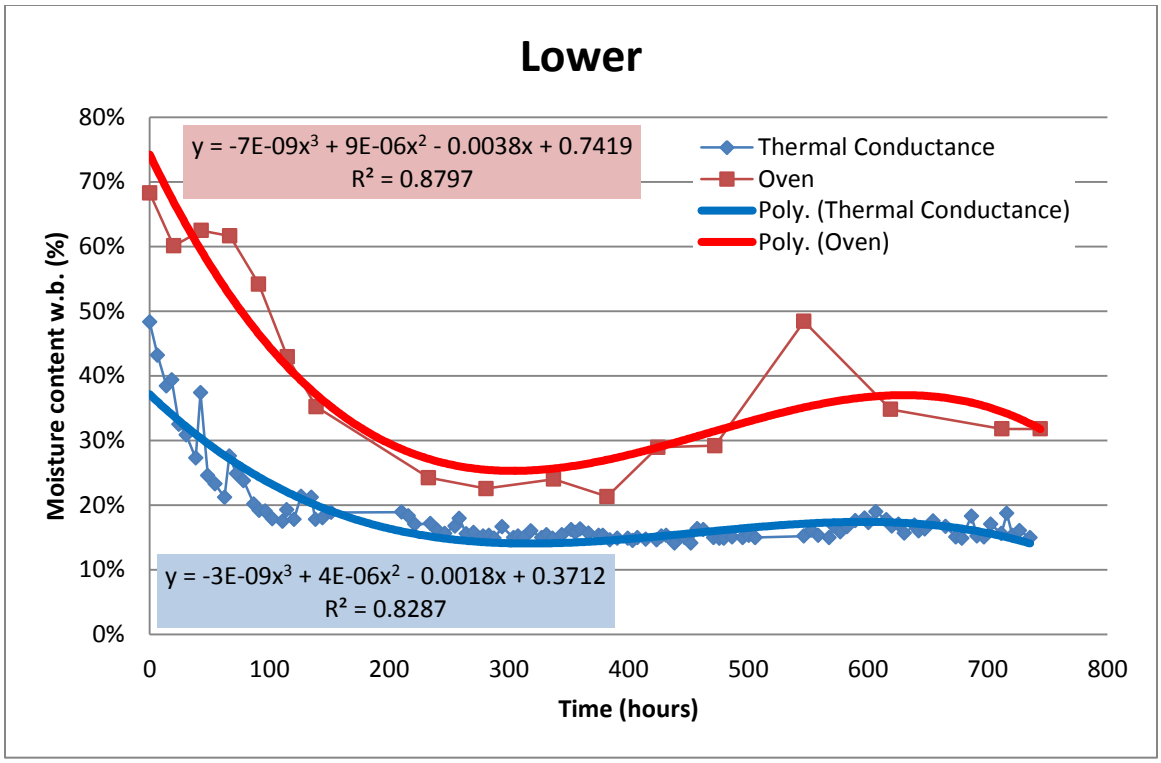

Figure 4.39. Comparison of the moisture content calculated by the thermal conductance method with the oven method at the lower position of the biofilters.

The lower position showed that for both methods of measurements the regression has high R^2, and that the thermal conductance method presented an offset of the actual data.

Comparisons on the middle and upper regions are presented in Figure 4.40 and Figure 4.41 respectively. In these two regions the thermal conductance measurements also indicated an offset of the actual moisture content.

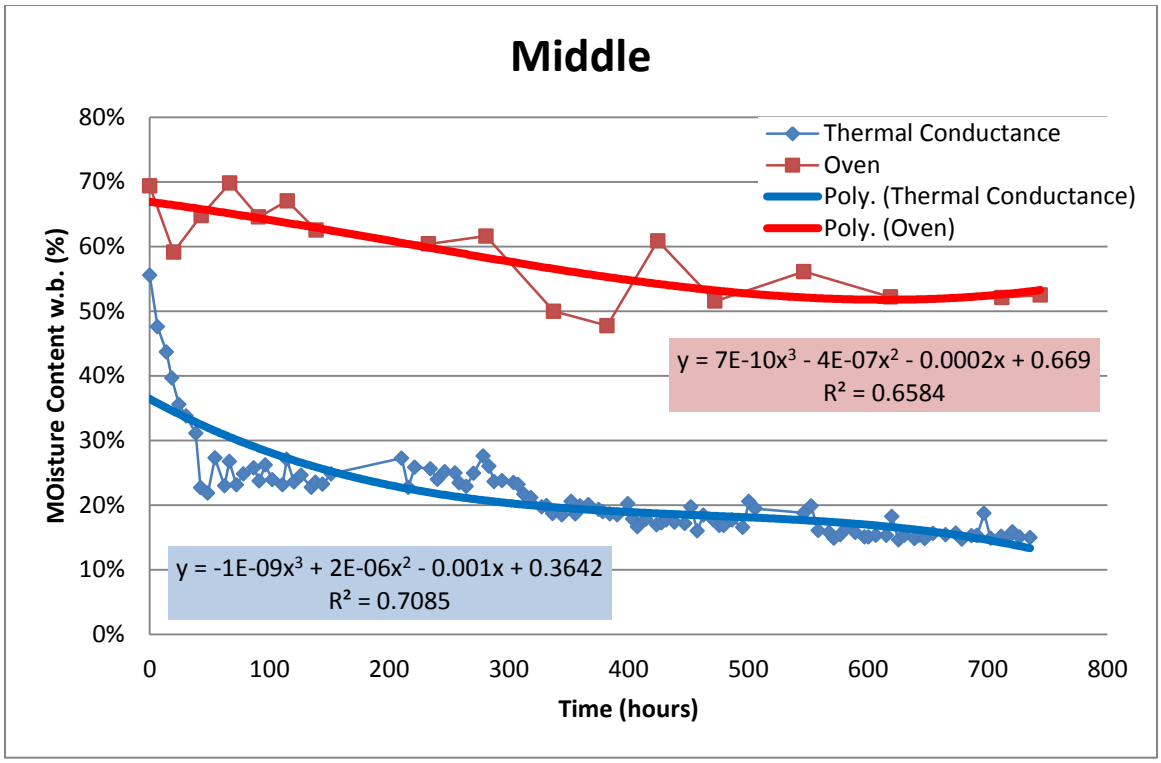

Figure 4.40. Comparison of the moisture content calculated by the thermal conductance method with the oven method at the middle position of the biofilters.

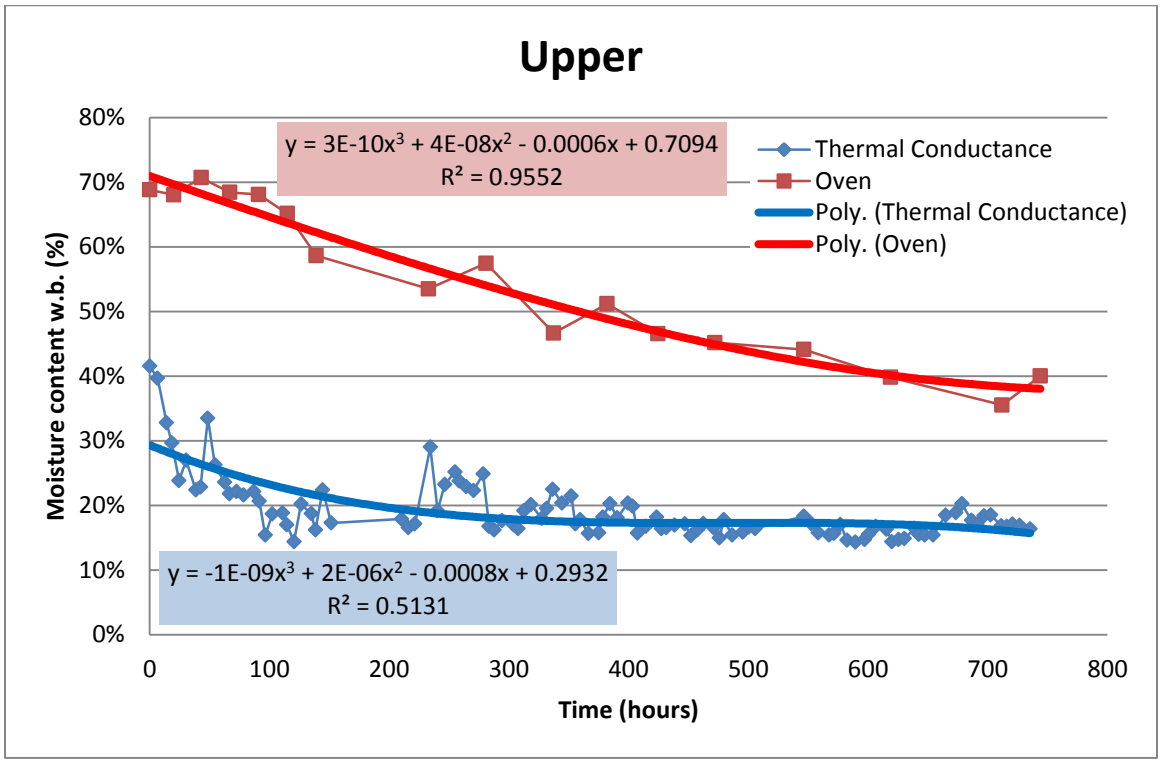

Figure 4.41. Comparison of the moisture content calculated by the thermal conductance method with the oven method at the middle position of the biofilters.

4.5.2 Ammonia Removal

Ammonia concentrations were measured using a photoacoustic gas analyzer at five points in the biofilter in order to develop a profile of the ammonia conversion. The removal efficiency of each region is graphically represented in Figure 4.42, Figure 4.43, Figure 4.44 and Figure 4.45, where a negative number means ammonia production and a positive number means ammonia reduction.

4.5.2.1 No moisture control

The lower biofilter region had high removal efficiency that rose to 90% in biofilter 1 and approximately 60% in biofilters 2 and 3 as can be seen in Figure 4.42 while biofilters 2 and 3 leveled out at around 60%. The removal efficiency remained relatively constant for the three biofilters after 50 hours of the experiment.

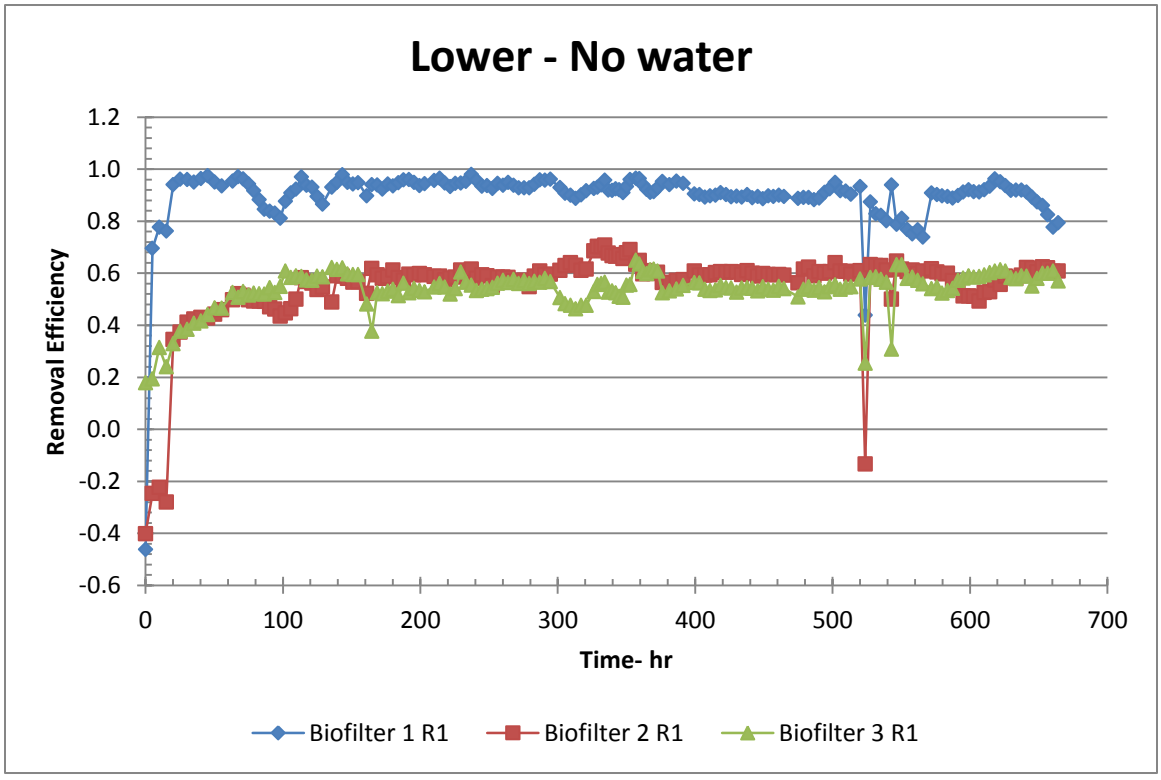

Figure 4.42. Ammonia removal efficiency for the lower region with no water.

The ammonia removal efficiency in the middle biofilter position when no water was applied is found in Figure 4.43. The removal efficiency remained in the zero to 20% range for biofilters 2 and 3. Biofilter 1 indicated that ammonia was

generated. With the moisture content of the media at 10% (Figure 4.32), there was no microbial activity to support ammonia generation. The position of the gas sampling tube for this region may have been located in an area where there was short circuiting the gas through a media section where there was low conversion or adsorption due to no uniformity of media moisture as seen in Figure 4.38 and Figure 4.55.

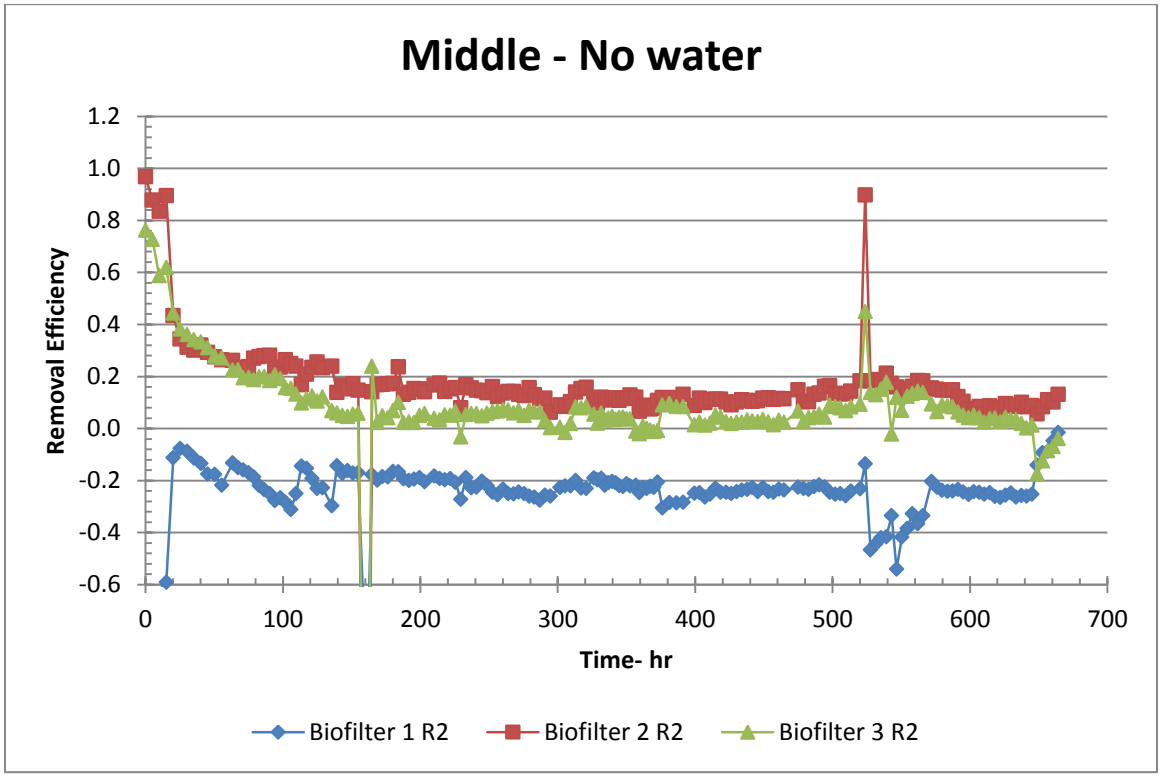

Figure 4.43. Ammonia removal efficiency for the middle region with no water.

The upper biofilter region (Figure 4.44) indicated that biofilter 2 was generating some ammonia. Again, Figure 4.33 indicates that the media moisture content was less than 20% which does not support microbial activity and indicates short circuiting as discussed in the previous paragraph. Biofilter 1 had low removal efficiency and biofilter 3 had removal efficiency around 20%.

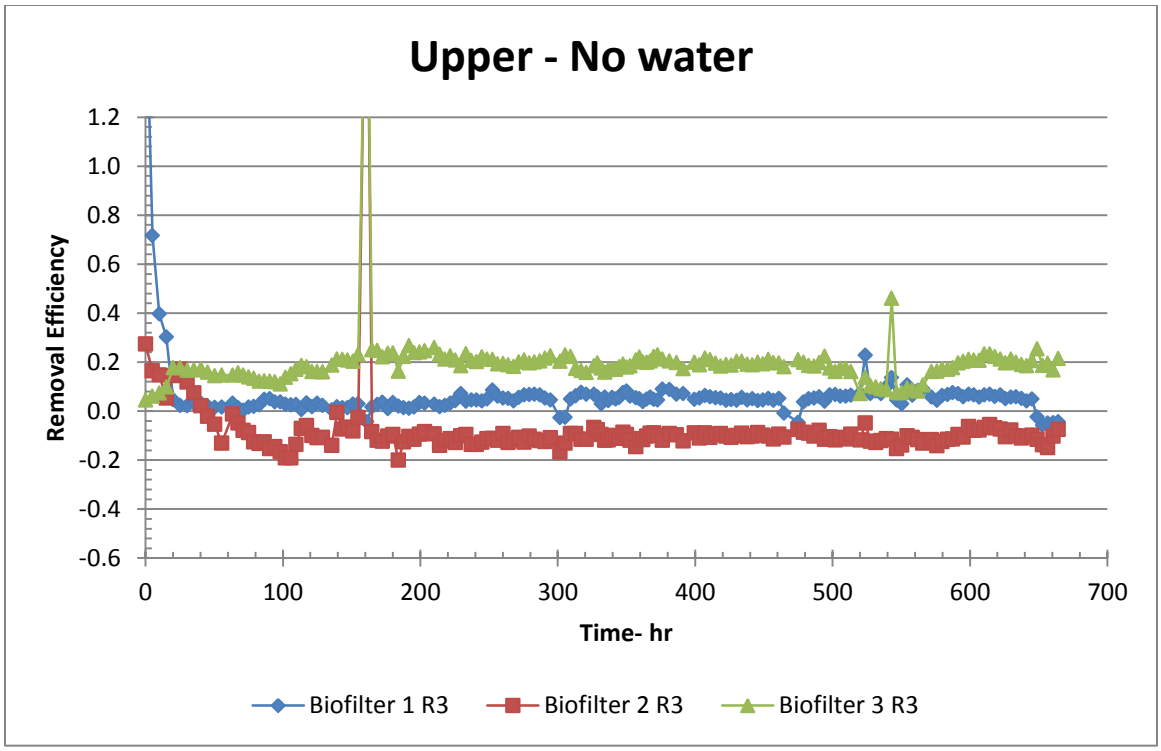

Figure 4.44. Ammonia removal efficiency for the upper region with no water.

There was some removal in the layer of media between the upper region sampling port and the headspace sampling port but at a very low rate (Figure 4.45). When the biofilter was analyzed as a whole the overall ammonia removal efficiency was calculated by the difference between the inlet and outlet concentrations (Figure 4.46) and in this case biofilter 3 had the higher ammonia removal rate.

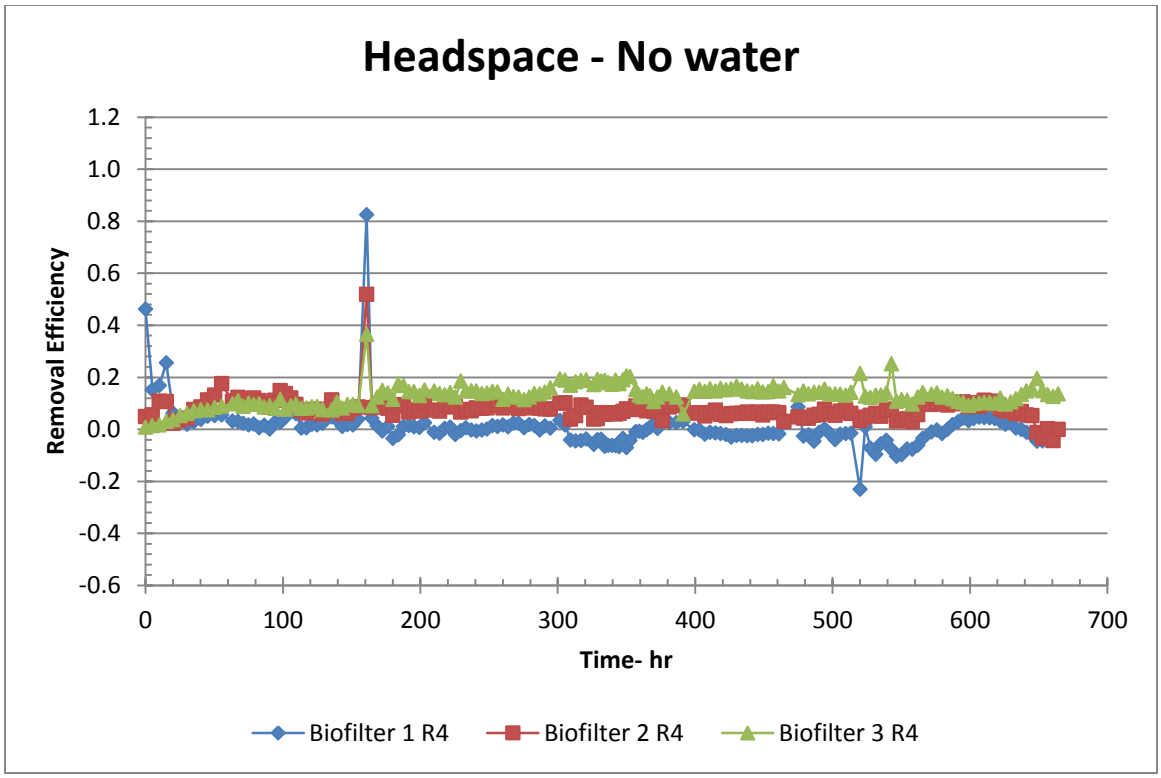

Figure 4.45. Ammonia removal efficiency for the headspace region with no water.

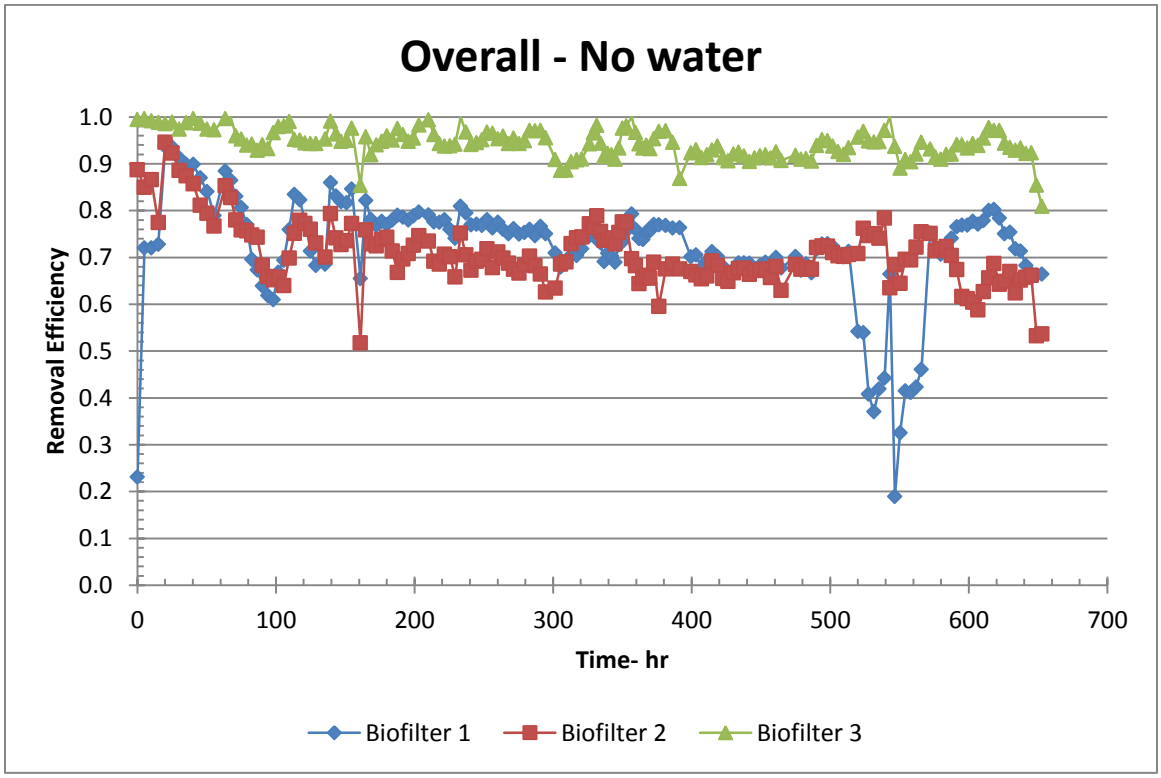

Figure 4.46. Ammonia removal efficiency for the overall biofilter with no water.

Low moisture content biofilters (no microbial activity) that still have ammonia removal, especially in the lower region (Figure 4.47) exhibit ammonia adsorption to the solid media by hydrogen bonding (Liberty, 2001). Liberty (2001) reported that compost can hold up to 1.6 gmol of ammonia per kilo of dry matter of compost for media moisture content near zero. Therefore, the biofilters filled with 51 kg of dry mass would potentially hold up to 81.6 gmol of ammonia. A nitrogen balance on the biofilters with no moisture control can account for the removal efficiency of ammonia when moisture no longer supported microbial activity. This can explain the ammonia removal efficiencies in the lower region.

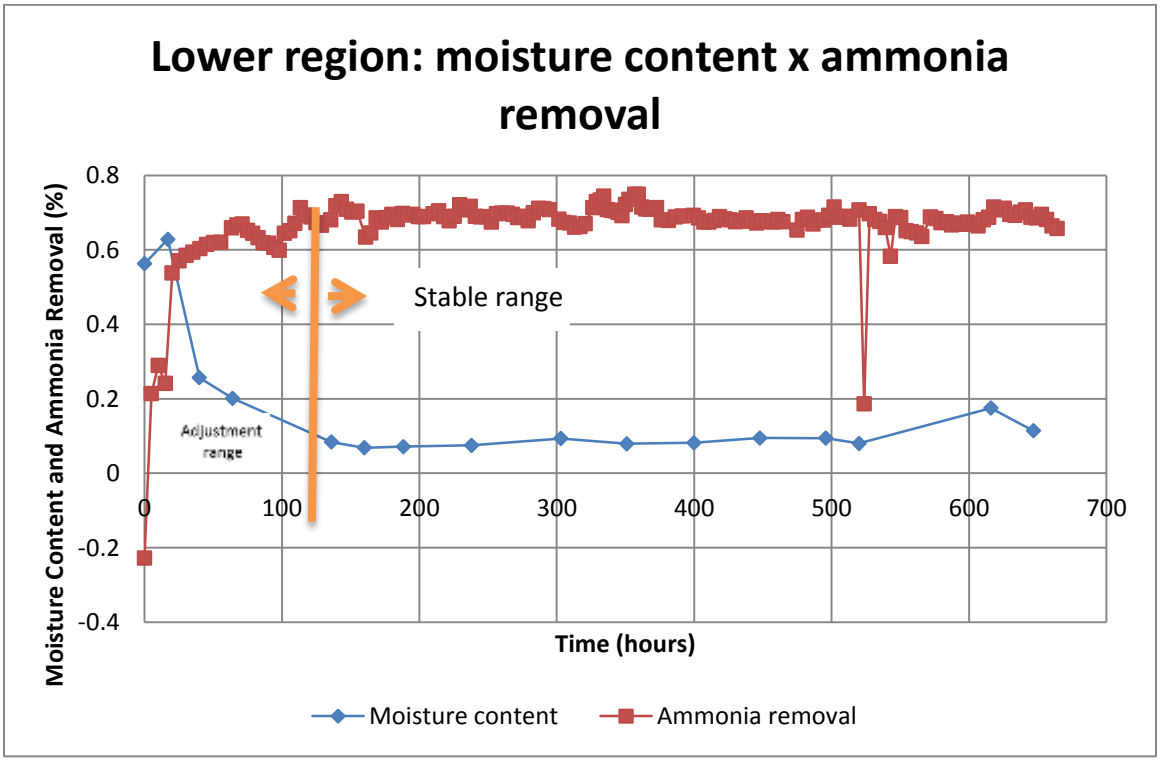

Figure 4.47. Graphical representation of the moisture content and the ammonia removal of the lower region during the treatment when no water is being added.

Ammonia removal efficiency in the middle region had two distinctive phases (Figure 4.48). The first phase had sufficient moisture content in the compost until around 250 hours to sustain biological activity and therefore ammonia removal. After 250 hours, the moisture decreased to below 10% w.b. and biological activity ceased. There was some ammonia generation after 250

hours but at a low rate, as previous paragraphs have reported suggesting that short-circuiting may have contributed to this ammonia reading.

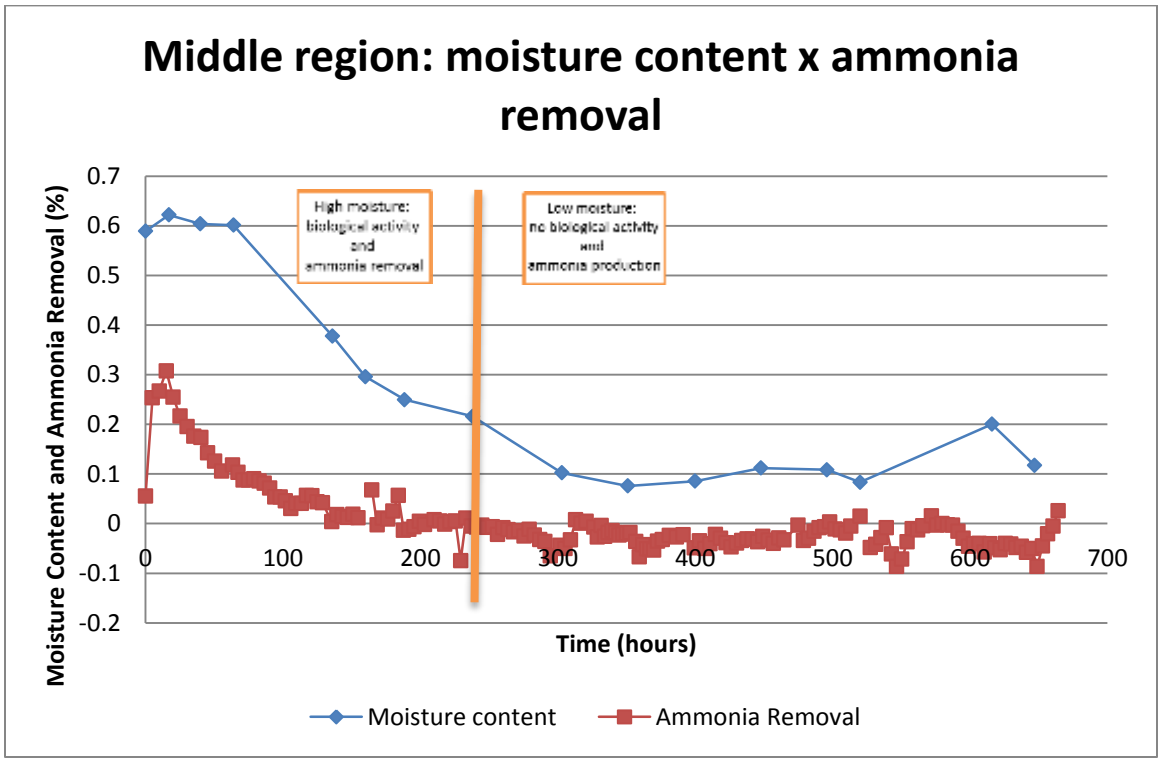

Figure 4.48. Graphical representation of the moisture content and the ammonia removal of the lower region during the treatment when no water is being added.

Figure 4.49 shows the same comparison between moisture content and ammonia removal for the upper region of the biofilter. Before 350 hours there was enough media moisture to maintain the biological activity for ammonia removal. After this period removal still continued at the same rate that the middle region was generating. The interesting point is that after this period the moisture content was close to what was reported by Del Nero Maia (2010) as the limit for microbial activity, which means that the level of moisture content was able to sustain a small microbial activity to transform ammonia entering from the middle region.

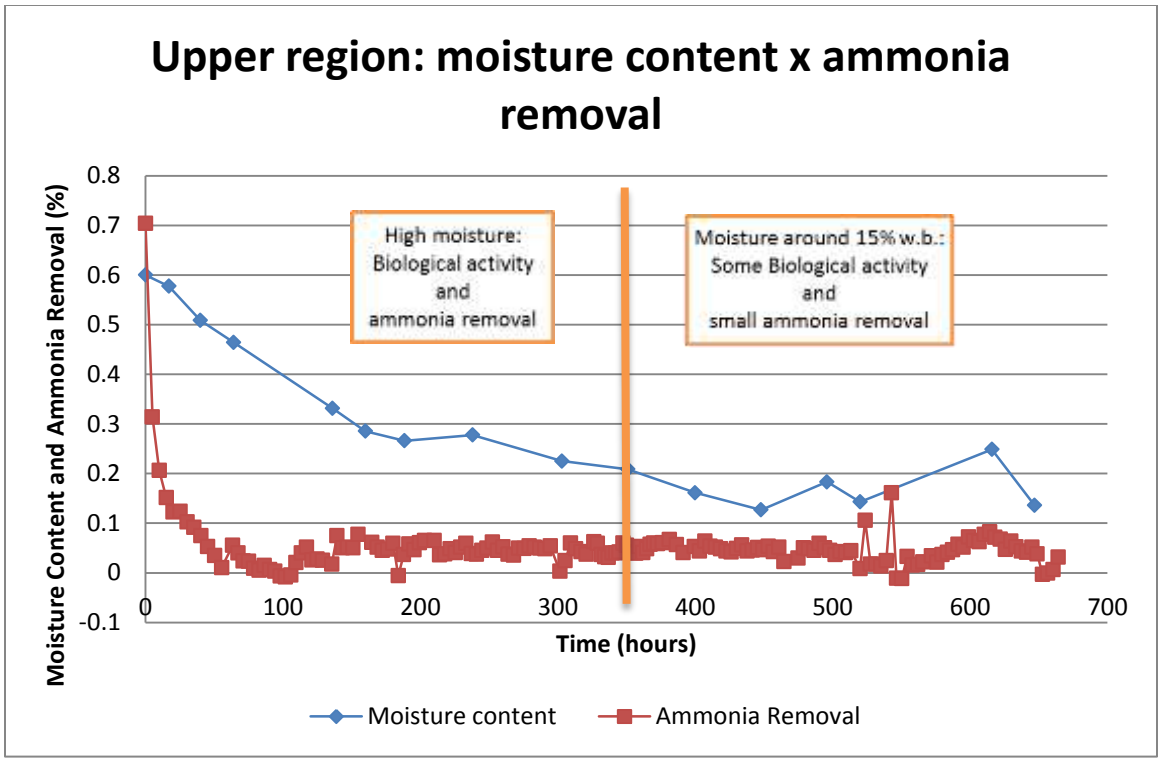

Figure 4.49. Graphical representation of the moisture content and the ammonia removal of the lower region during the treatment when no water is being added.

The removal of ammonia during the no water added test could have resulted from three factors: bacterial activity until 400 hours would have had sufficient moisture to support biological activity, absorption of ammonia by the compost mass and the rest was accounted for in the inefficiency of the system, because the biofilters were not 100% efficient for ammonia removal.

4.5.2.2 Moisture control

Figure 4.50 showed that the lower regions of biofilters 2 and 3 generated ammonia until about 150 hours while biofilter 1 presented the higher ammonia removal efficiency. The initial production was from the re-equilibrium of the initial inoculums species die-off that generated ammonia.

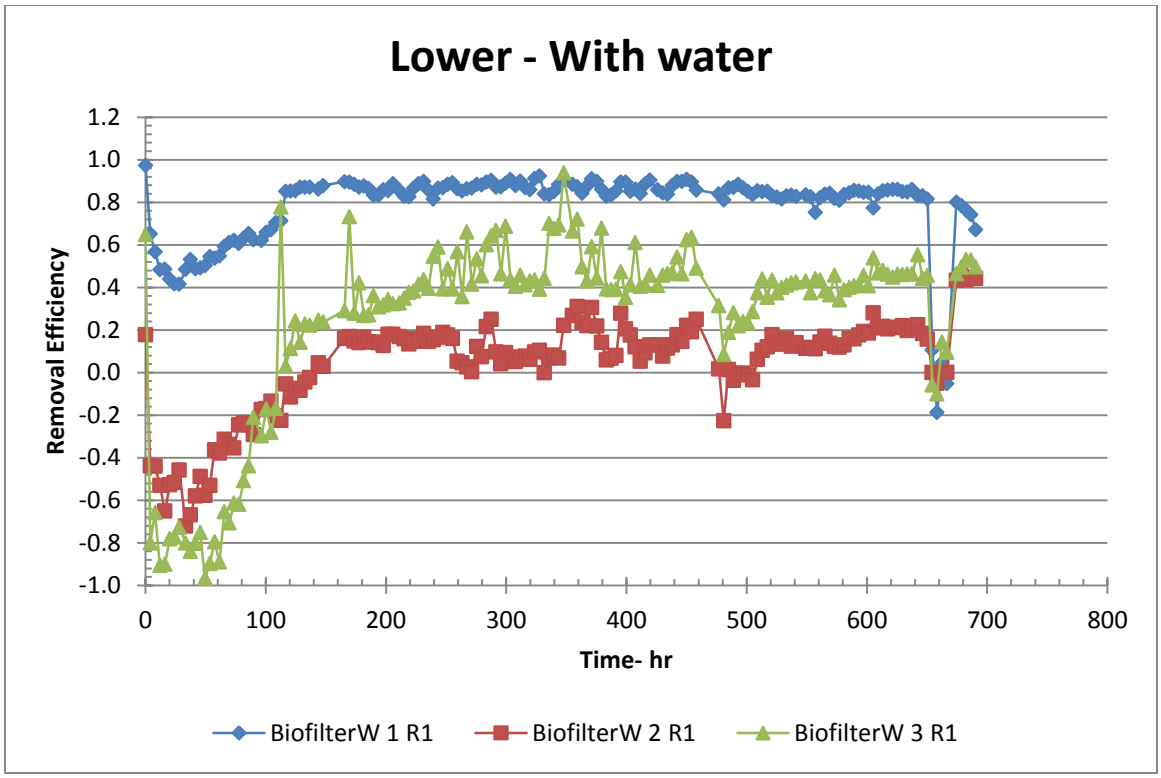

Figure 4.50. Ammonia removal efficiency for the lower region with water.

The middle biofilter region had the most unusual behavior for ammonia removal (Figure 4.51). In this region biofilter 1 had a peak of ammonia generation and settled at a 30% generation level while biofilter 2 had a peak of removal and settled at 80% removal.

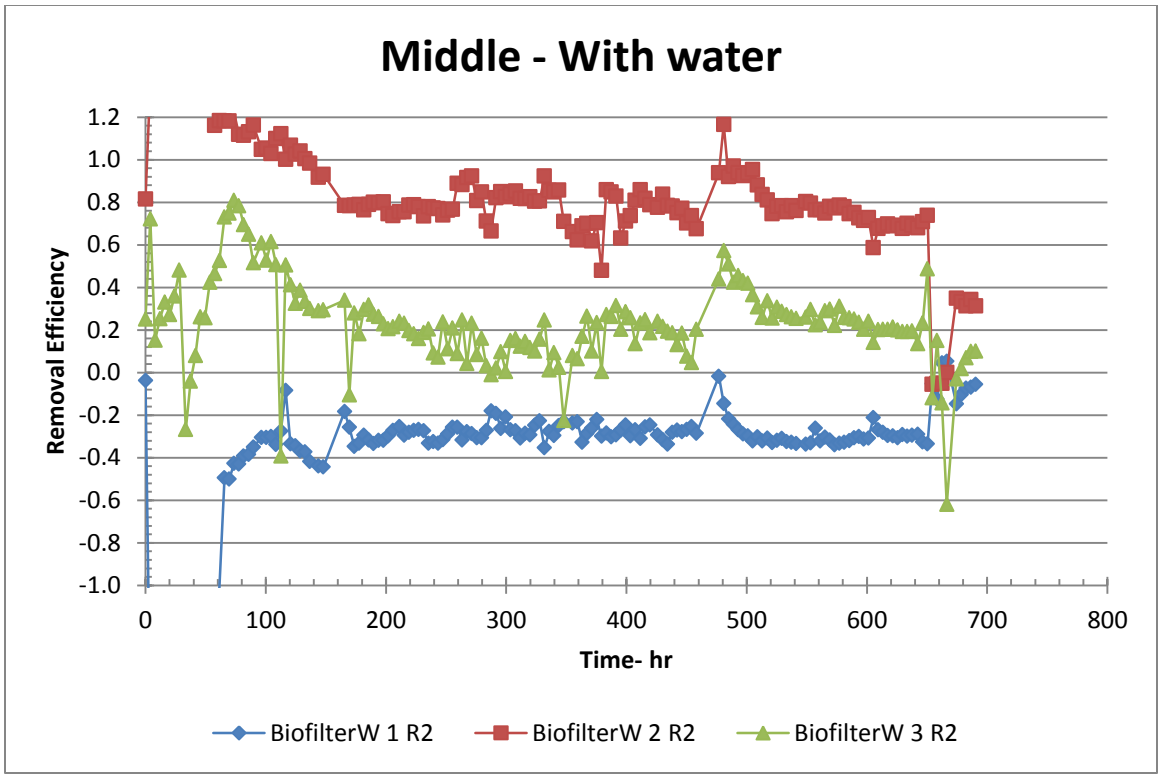

Figure 4.51. Ammonia removal efficiency for the middle region with water.

Figure 4.52 indicates biofilter 1 showed no activity for ammonia removal, while biofilter 2 and 3 had peak of removal initially then, after 200 hours stabilized at 20 % removal efficiency.

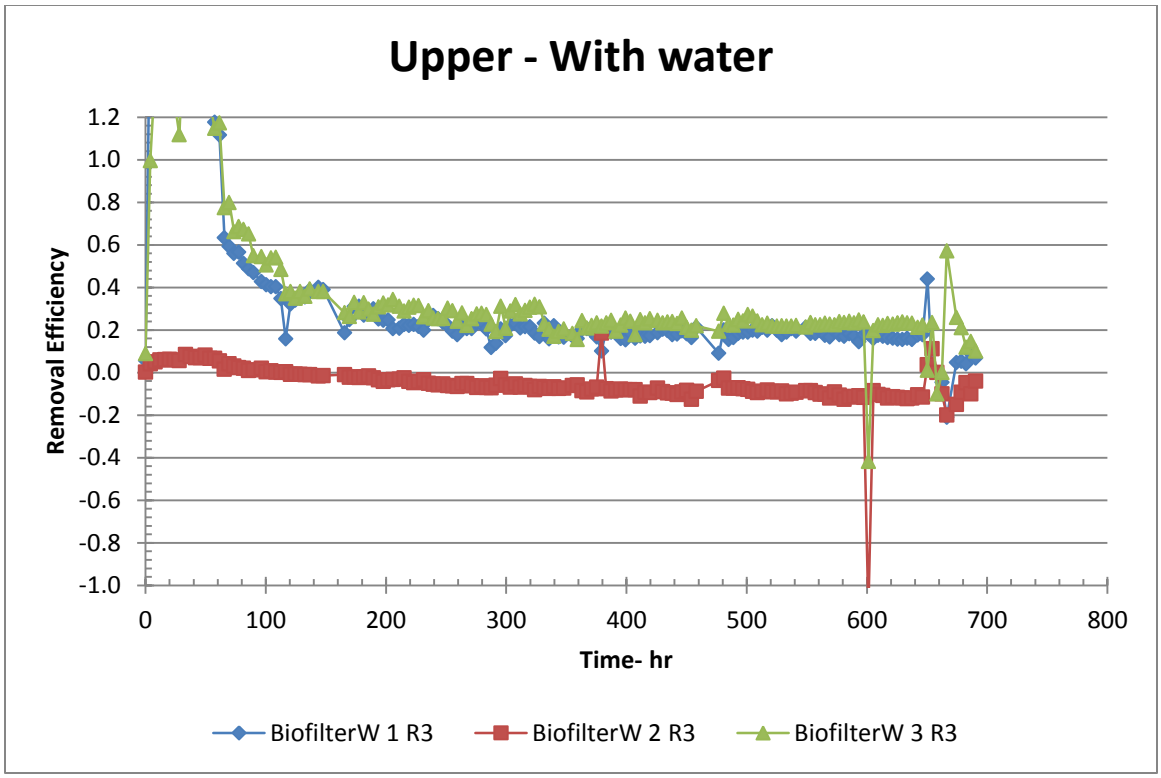

Figure 4.52. Ammonia removal efficiency for the upper region with water.

Figure 4.53 illustrates the removal efficiency of the biofilter media layer between the upper region sample port and the headspace sample port indicating that there was no ammonia removal with the efficiency at zero.

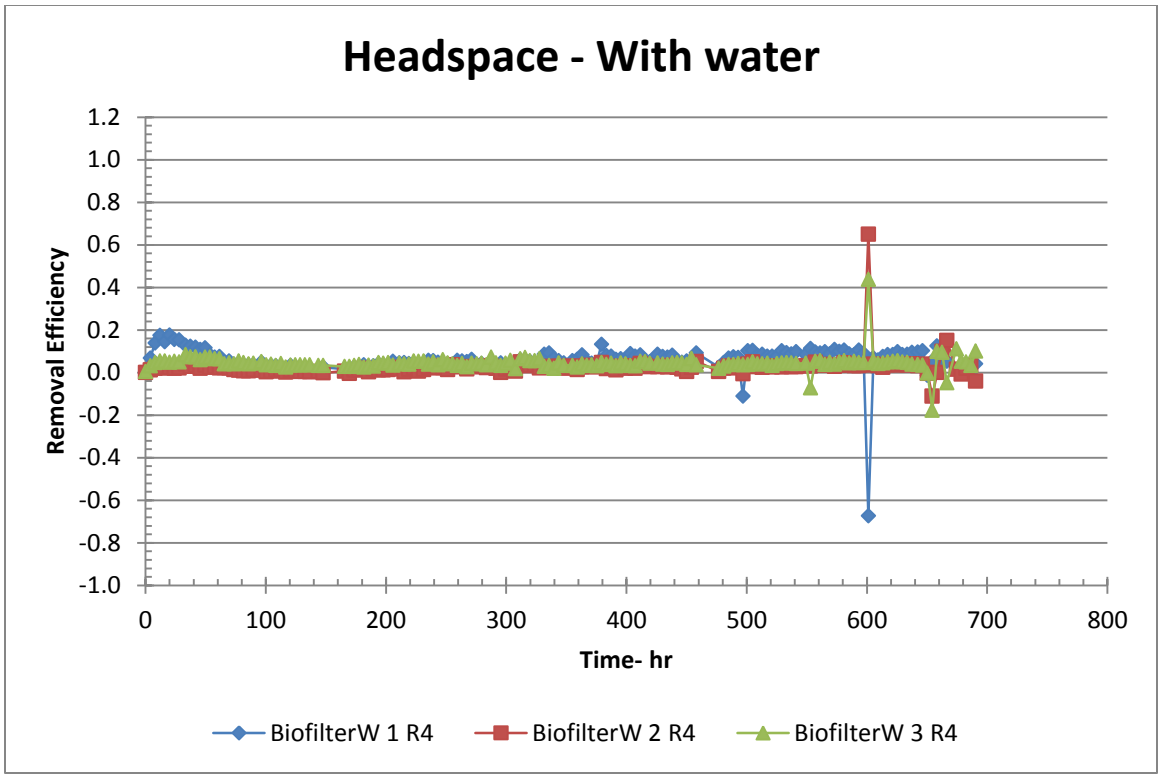

Figure 4.53. Ammonia removal efficiency for the headspace region with water.

The overall performance of ammonia removal when water was applied remained above 80% for the three biofilters (Figure 4.54). This is similar to the test with no water where the ammonia removal efficiencies were between 70% and 90%.

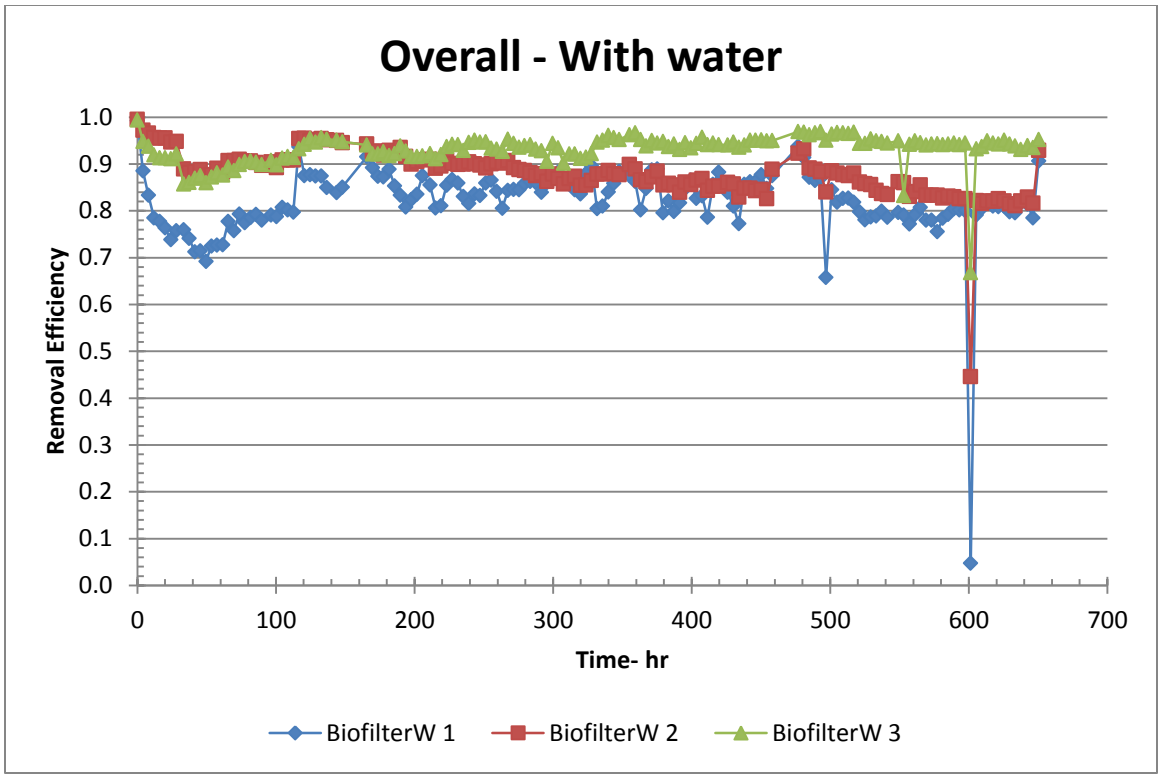

Figure 4.54. Ammonia removal efficiency for the overall biofilter with water.

Figure 4.55 is a basis for understanding the behavior of the ammonia removal in each region. A drying zone developed in the lower region near the center with moist zones around the soaker hose. Water was replenished by the soaker hose and the lower region removed ammonia. More uneven moisture content was visible in the middle region justifying the differences of the ammonia removal in the middle region among the three biofilters. The upper region can be seen to be wet and uniform. It reflected a removal efficiency that has a more stable pattern.

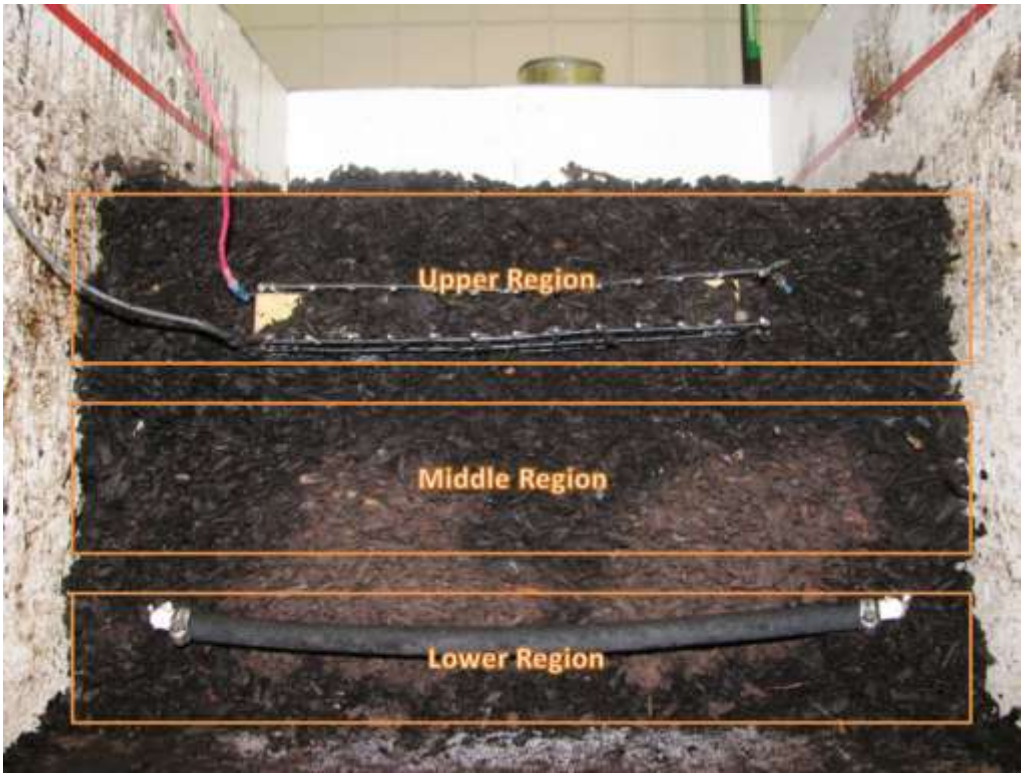

Figure 4.55. Profile of moisture content during the test with water being applied.

The response of the biofilter was illustrated when comparing the time series of the moisture contents with the ammonia removal efficiency. Figure 4.56 presents the moisture content with ammonia removal in the lower biofilter region with the water addition treatment. There was ammonia generation through 100 hours which reached its maximum removal efficiency of about 50% at 150 hours. It was maintained at that level until the end of the experiment. The moisture content did not drop below 20% w.b. which ensured continuing microbial activity.

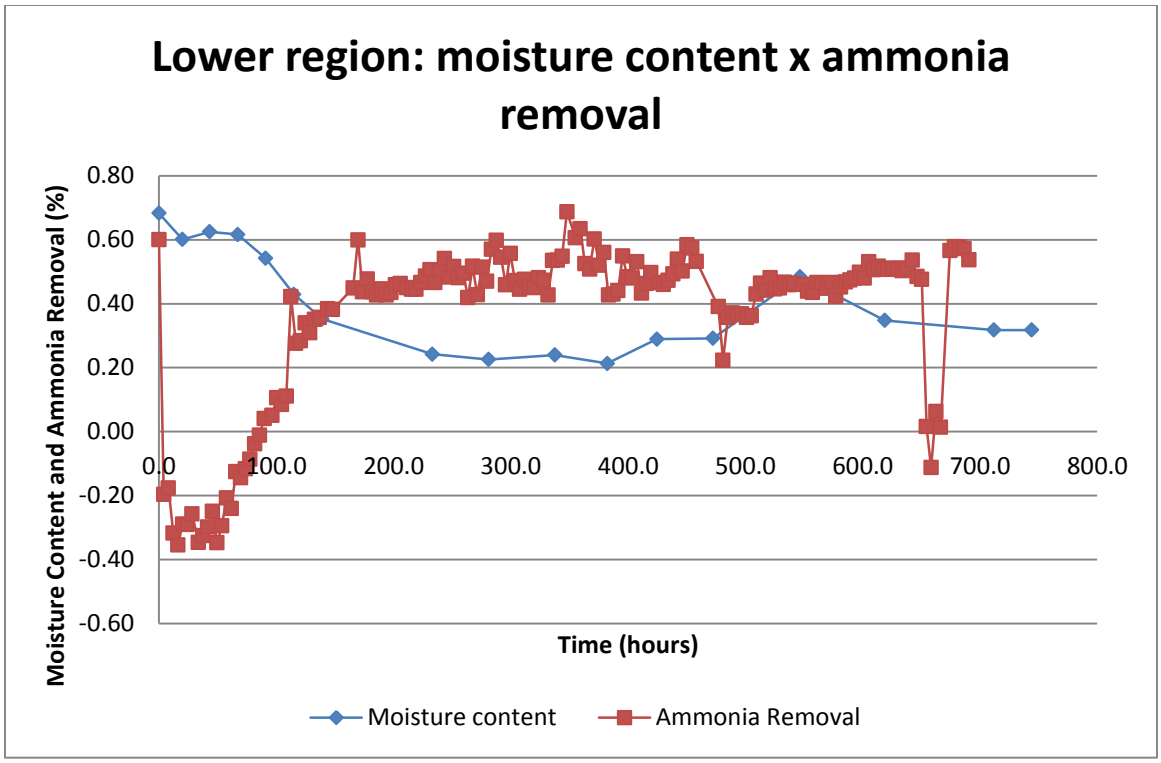

Figure 4.56. Graphical representation of the moisture content and the ammonia removal of the lower region during the treatment with water being added.

The moisture content was more stable in the middle biofilter region (Figure 4.57) throughout the duration of the experiment. The ammonia removal efficiency shows a pattern similar to the ones reported by Sales (2008) and Del Nero Maia (2010) where the removal efficiency reaches a peak in the beginning and then settles to a stable removal.

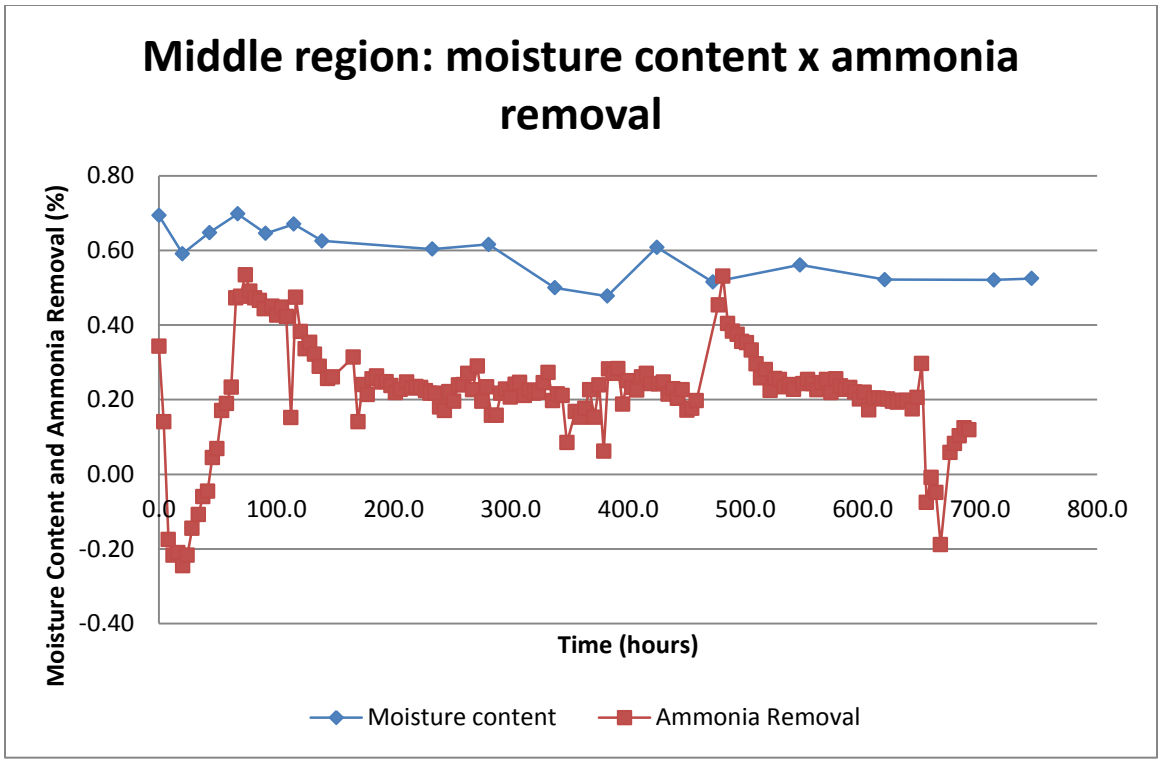

Figure 4.57. Graphical representation of the moisture content and the ammonia removal of the middle region during the treatment with water being added.

The moisture content in the upper biofilter region (Figure 4.58) continuously decreased from the initial value of 70% to 40%, This level of moisture maintained the biological activity for ammonia removal through the whole experiment. The same dynamics were reported by Sales (2008) and Del Nero Maia (2010) where the removal efficiency peaked during the first 100 hours. This occurred in the same time period when the lower and middle biofilter regions were generating ammonia from inoculums degradation, justifying the approximately 140% removal efficiency in the upper region.

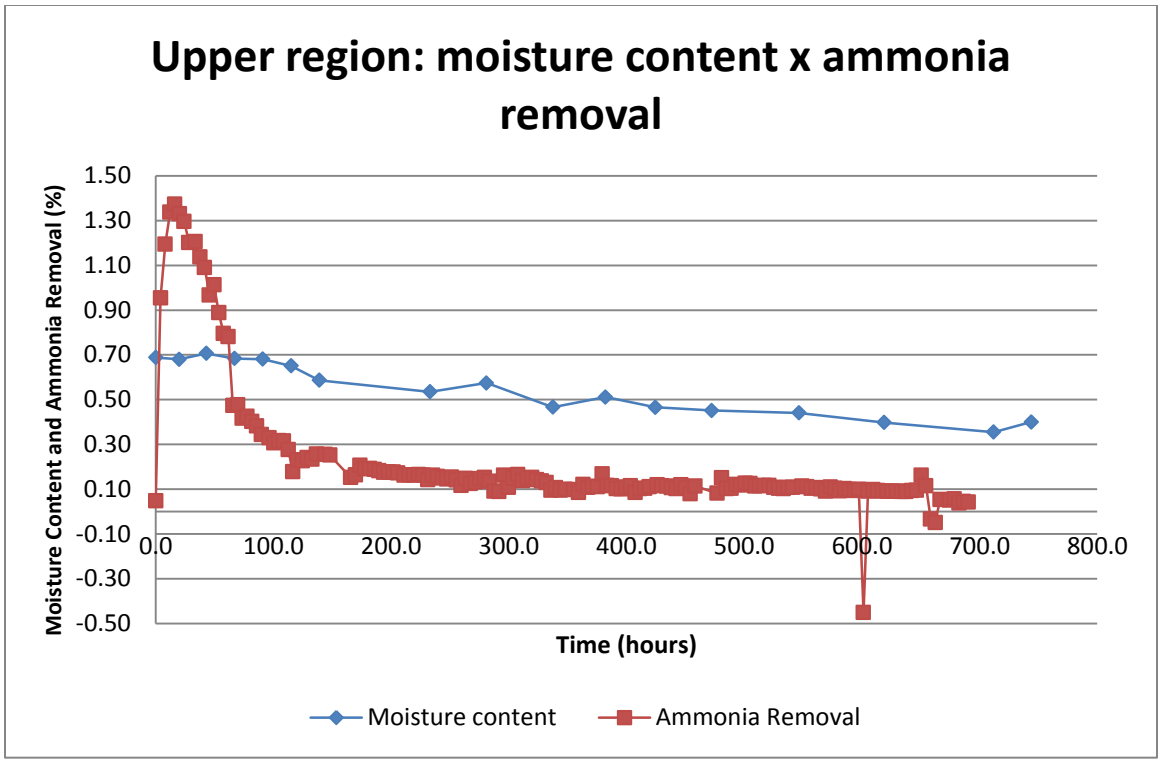

Figure 4.58. Graphical representation of the moisture content and the ammonia removal of the upper region during the treatment with water being added.

It is important to point out that the hose system coupled with a novel moisture measurement technology were generally successful in keeping the moisture at levels which supported microbial activity. This was evidenced by the fact that over the course of this work the ammonia removal efficiencies were kept positive. The system requires further development to achieve its original goal of maintaining “set-point” moisture levels, however, this work proved the viability of the concept.

4.5.3 Nitrous oxide

Generation of nitrous oxide is a big concern when operating biofilters. It is closely related to moisture content control even when operating at the optimal moisture content range of 38-43% for ammonia removal. This range was identified for the biofilter media tested that minimized nitrous oxide generation (Maia, 2010).

Nitrous oxide is formed when nitrate-N is present. Nitrate is formed during ammonia oxidation under microenvironment moisture conditions around or

internal to media particles that limits oxygen. It was expected that during the test with no water being applied to the compost that no nitrous oxide would be formed because of the absence of or low biological activity. Graphical representations of N_2O removal are presented below in Figure 4.59 to Figure 4.62.

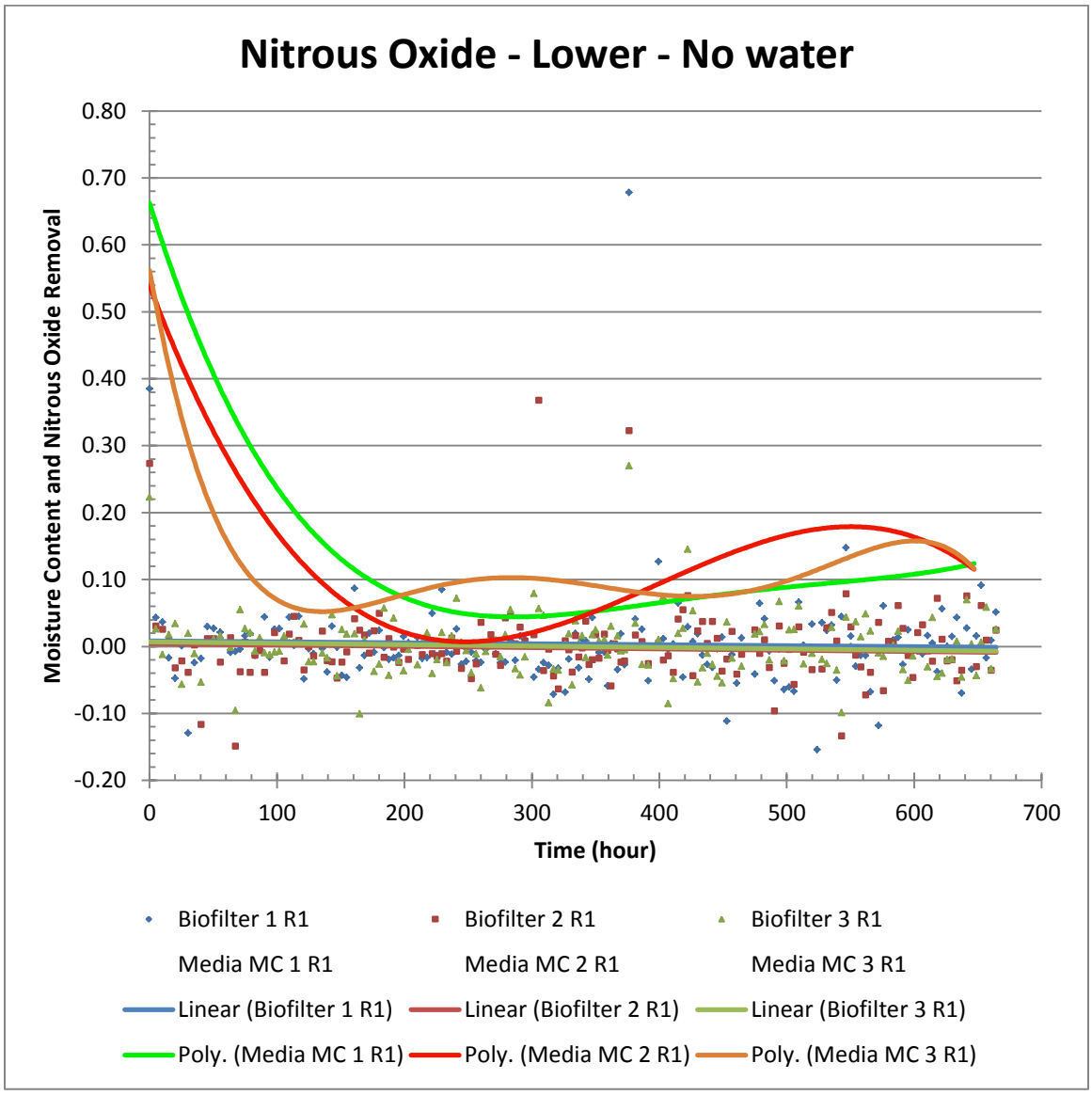

Figure 4.59. Nitrous oxide progression in the lower region with no water.

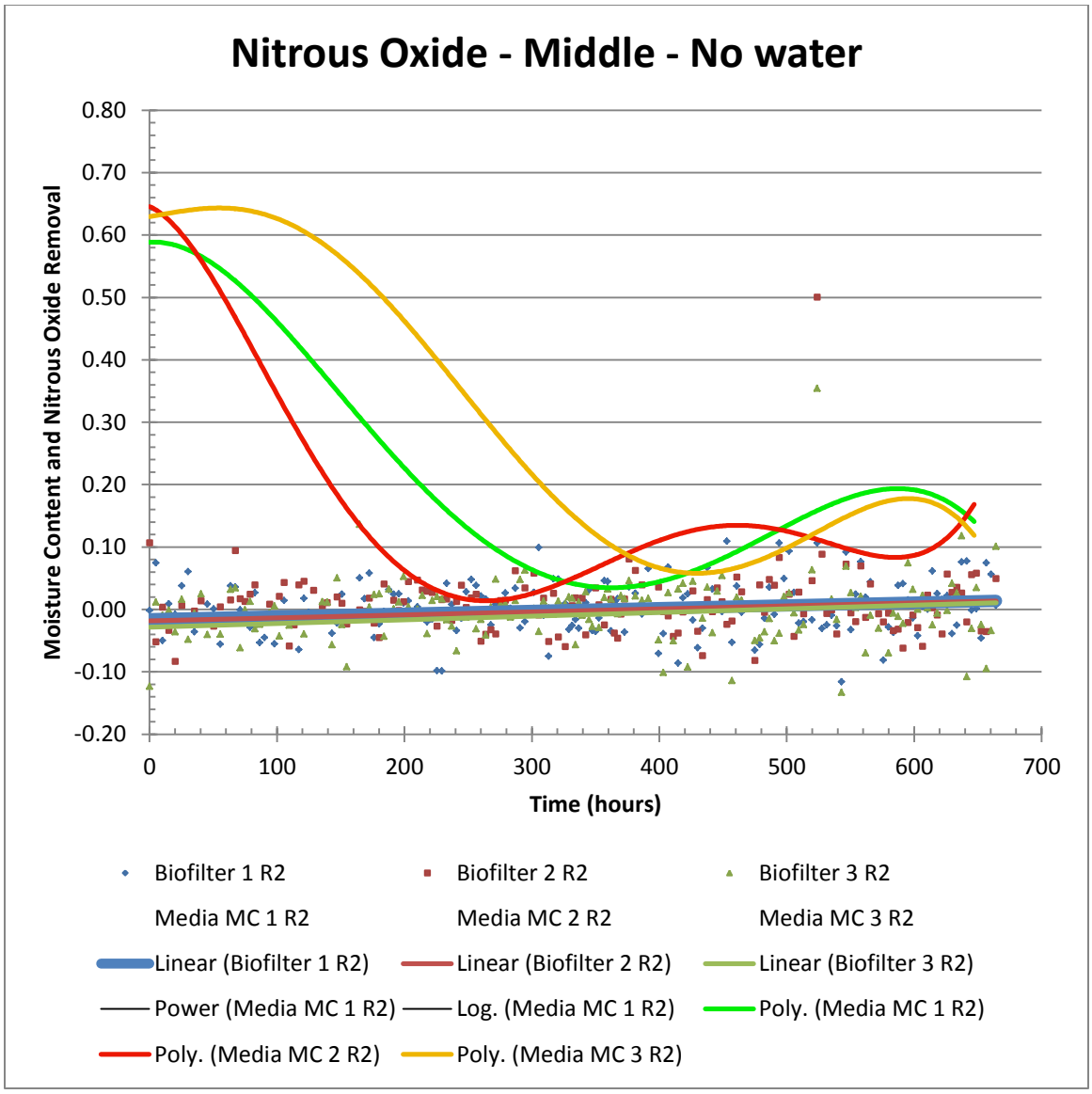

Figure 4.60. Nitrous oxide progression in the lower region with no water.

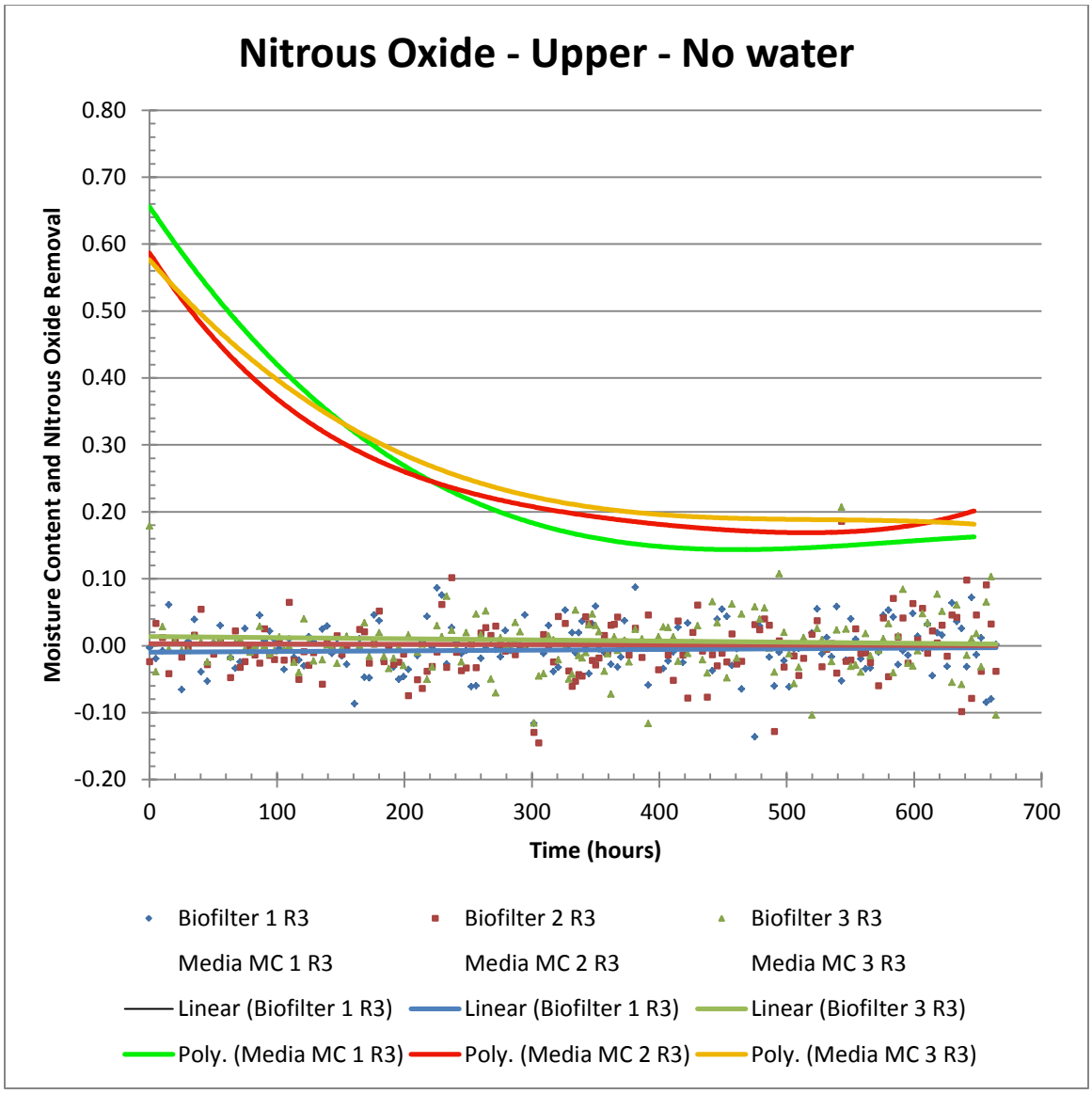

Figure 4.61. Nitrous oxide progression in the lower region with no water.

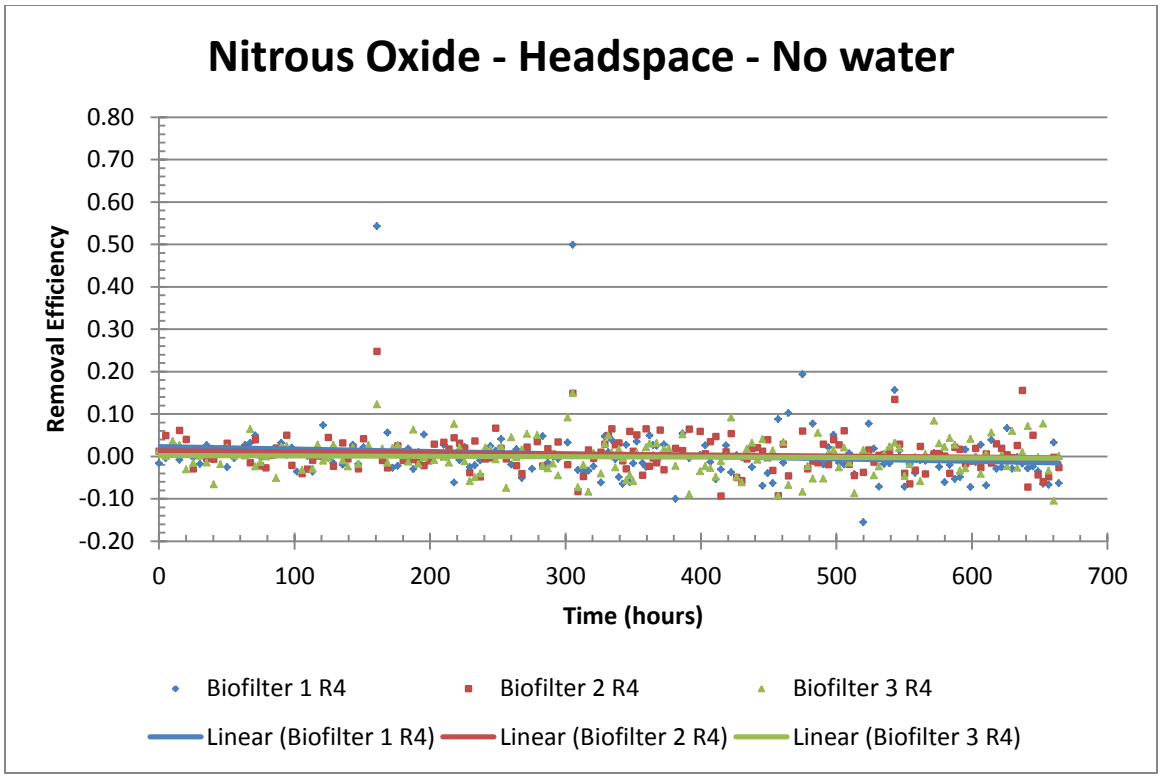

Figure 4.62. Nitrous oxide progression in the headspace region with no water.

Figure 4.59 to Figure 4.62 indicate the nitrous oxide removal efficiency during the test with no water applied. The removal efficiency of nitrous oxide in all regions was not significantly different from zero (Appendix D) which was the consequence of low bacterial activity attributable to low moisture contents.

When water is applied into the compost, in comparison to the no water test, there is enough water in the media to keep biological activity that could be seen in the following graphs (Figure 4.63 to Figure 4.66). The lower biofilter region had minimum removal efficiency or production as shown in the Figure 4.63 where the efficiencies stayed around the 0%.

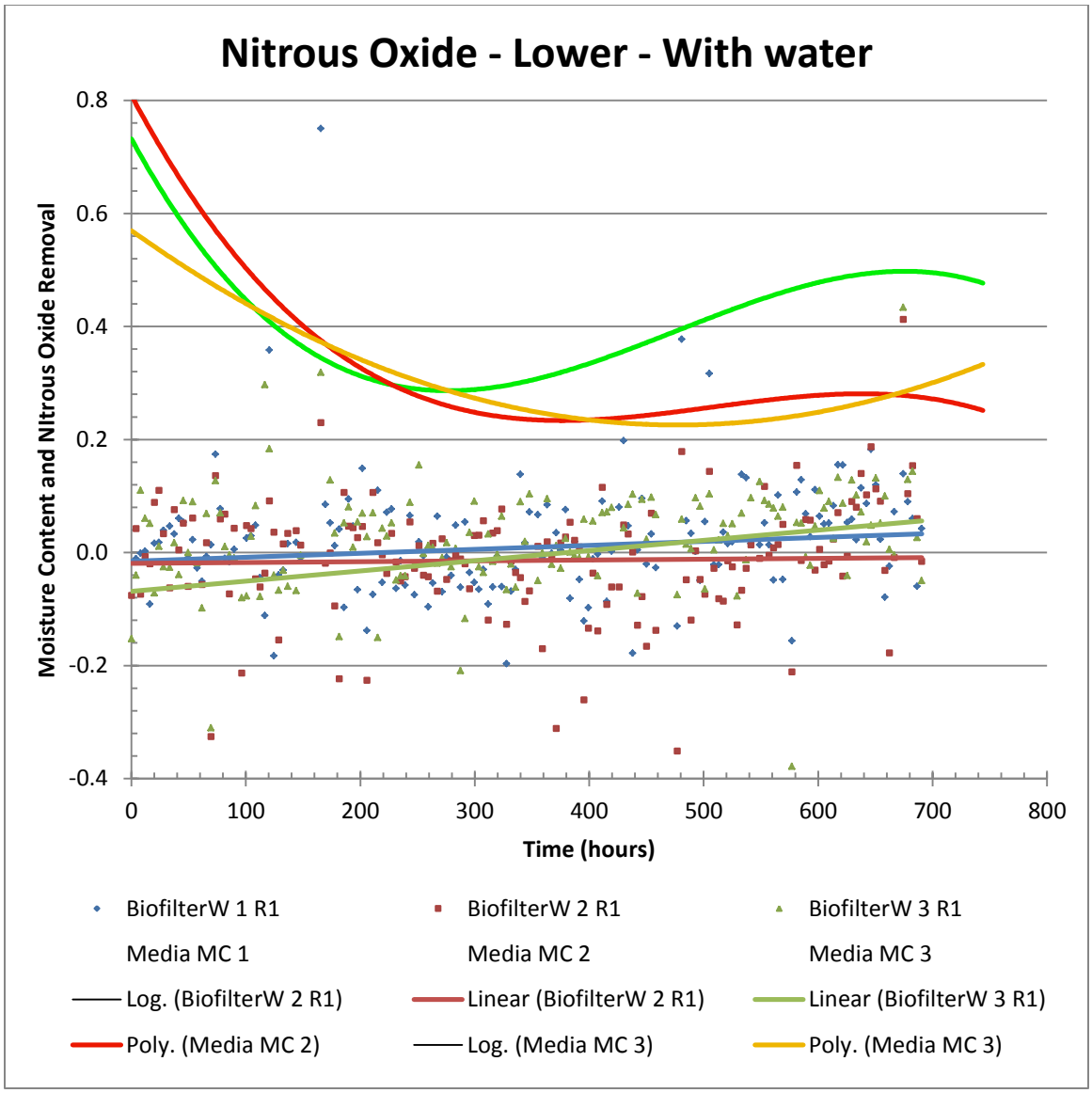

Figure 4.63. Nitrous oxide removal efficiency in the lower region with water.

As in the ammonia analysis, negative values of nitrous oxide means generation of nitrous oxide and positive values means removal. In the middle biofilter region (Figure 4.64) nitrous oxide was generated. Some nitrous oxide generation occurred in biofilter 2 with further removal after around 100 hours. Biofilters 1 and 3 indicated little or no activity.

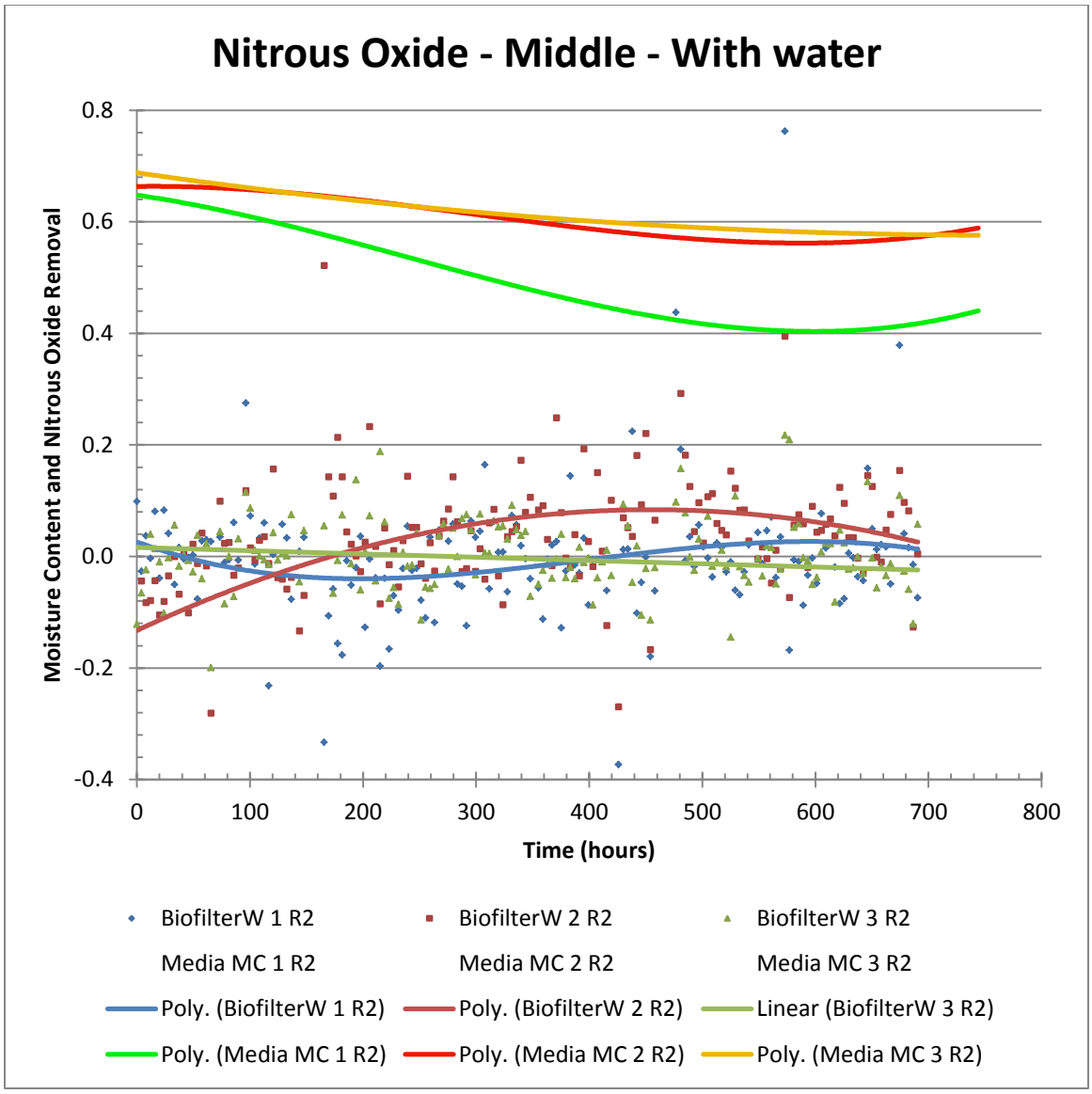

Figure 4.64. Nitrous oxide removal efficiency in the middle region with water.

Figure 4.65 shows that in the upper biofilter region, some nitrous oxide was generated. This likely occurred because its moisture content was maintained at levels above 43% for a sufficient time for the denitrifying bacteria population to grow.

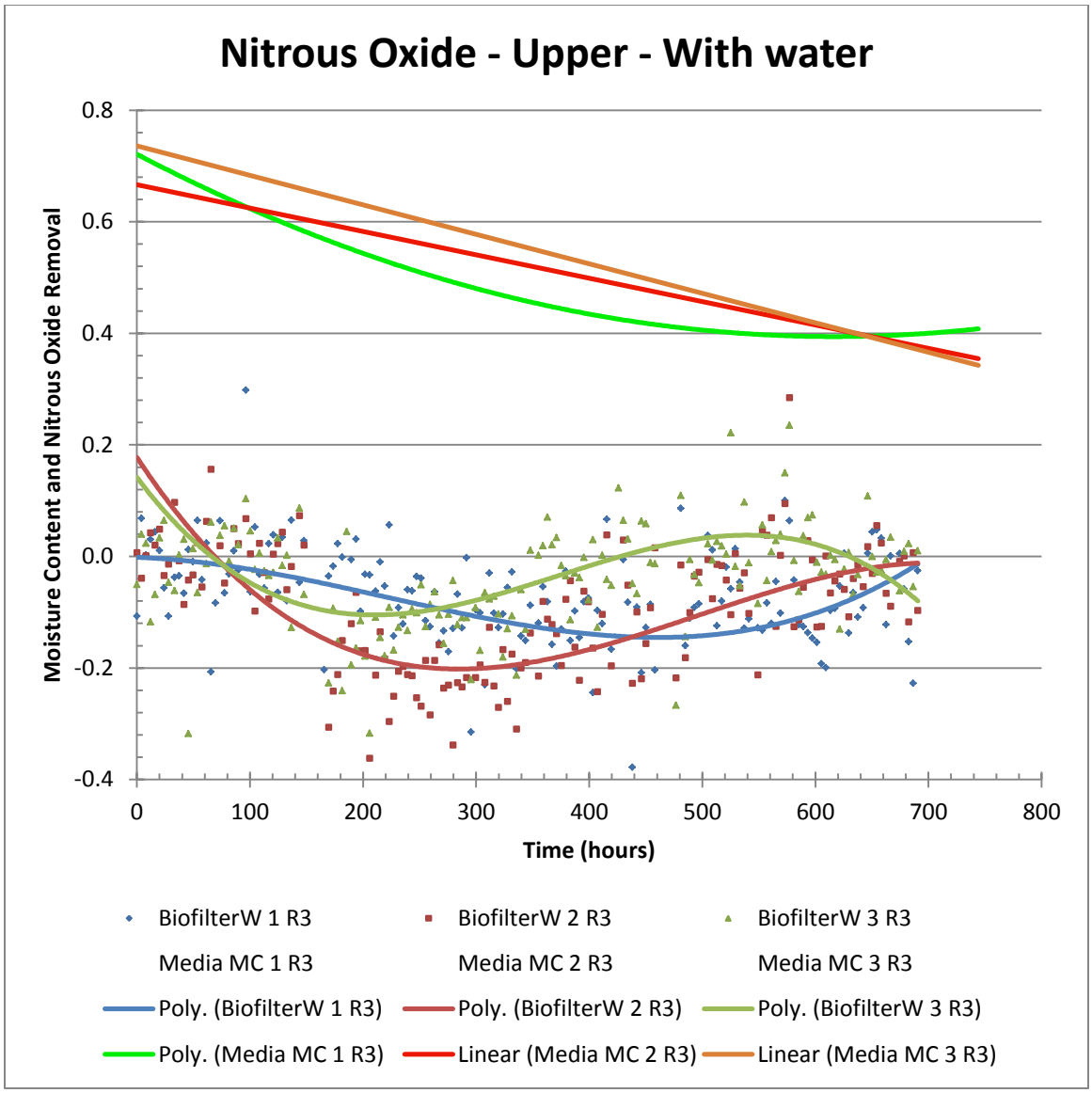

Figure 4.65. Nitrous oxide removal efficiency in the upper region with water.

The biofilter media between the upper sampling port and the headspace port indicated removal of nitrous oxide that was formed in the upper region (Figure 4.66).

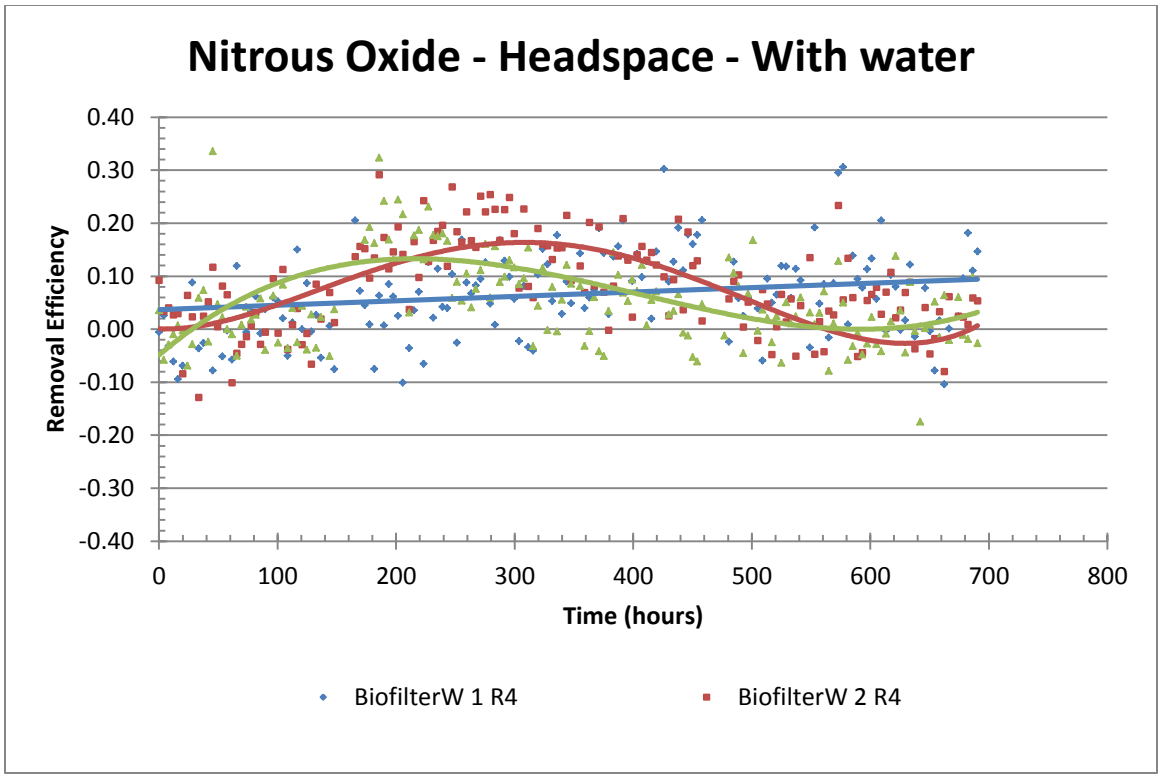

Figure 4.66. Nitrous oxide removal efficiency in the upper region with water.

One very important observation can be made by considering that the overall nitrous oxide removal efficiency remained close to 0% (Figure 4.67). If only the overall efficiency were taken into consideration, it would have masked all the activity which occurred in the middle of the biofilter, thus leading to an incorrect conclusion that no nitrous oxide was generated. It was generated and consumed (Appendix D).

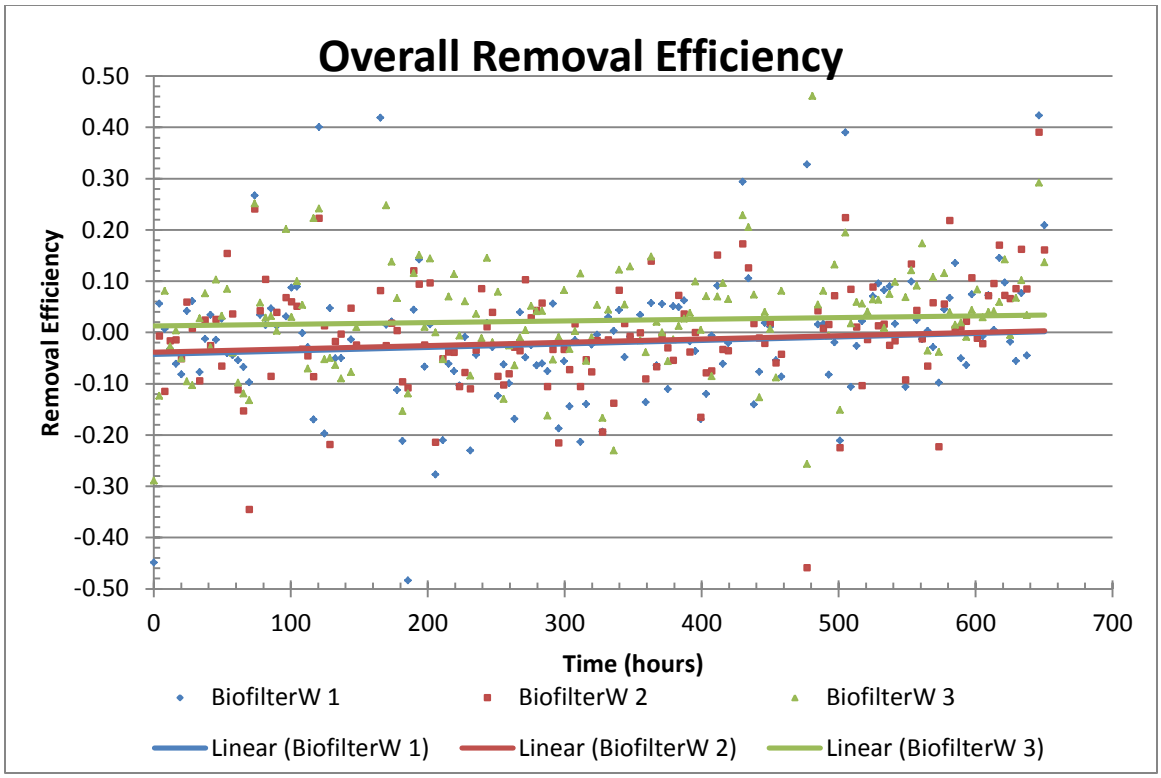

Figure 4.67. Nitrous oxide removal efficiency in the overall biofilter with water.

Chapter 5 Conclusions

Three compost biofilter chambers located in the Air Quality Laboratory at the Biosystems and Agricultural Engineering Department were evaluated for structural integrity and uniformity. These analyses were performed to verify the unusual behavior of biofilter number 3.

The flow meters located in the back of the biofilters were tested individually. They were found to have a linear relation between 20 and 40 ml/min when they were connected to a pump. The linear relation was extended from 20 to 50 ml/min when they were connected to a pressurized tank. This range included the flow that was used during the experiments.

No major leakage in the structure of any of the biofilters was found during the evaluation, and thus, this hypothesis was eliminated as the source of the anomaly associated with any biofilter chamber. A small leak was identified in between the box and the cone at one corner on biofilter #3 and also under biofilter #1, but it could not be identified as the reason for the disparate behavior of biofilter 3.

Evaluation of the exhaust system for any interference revealed that the exhaust in biofilter 3 exhibited a small back pressure which caused chaotic behavior of the smoke coming out of the biofilter. But after consideration it was concluded that this had no effect on the contradictory values for biofilter number 3 because the back pressure and the chaotic behavior of the smoke occurred outside of the chamber.

The air supply system was also evaluated by testing the exhaust duct located above the plenum. It was concluded that this exhaust duct was responsible for an unbalanced air delivery to the biofilters. When the balancing damper was opened biofilter 1 was significantly different from the other two, and when it was closed all three biofilters were subjected to an air flow with no significant difference between each other.

The add-on component to the sieve shaker machine resulted in a much better performance both in quantity of compost sieved and labor demand. It was possible to sieve more compost with less manual labor at a faster throughput.

The original design demanded 25 hours of work to sieve 0.75 m^3 and with the add-on this time was reduced to 2.75 hours of work.

Compost from the Animal Research Center at the University of Kentucky was characterized according to its physical properties and was sieved to obtain a medium particle size ranging from 4.75 to 8 mm. This particle size represented 13% of the as received compost, and the rest of the compost was characterized as rocks (>12.5 mm) with 3% of the total, large particle size (between 12.5 and 8 mm) with 8%, small particle size (between 4.75 and 1.35 mm) with 27% and the fines (<1.35 mm) that represented 49% of the as received compost.

An alternative indirect method of moisture sensing was incorporated which relied on the thermal conductivity of the compost. A relationship with an R2 of 0.925 was found for moisture content and thermal conductivity. An equation for calculating the moisture content of compost with the thermal readings was calculated and used during the experiment. The downside of this technology is the need for better performance of the sensor. The probe should be completely inserted into the mass of compost or even embedded within it. Another significant factor is the relatively high price of the sensor.

Commercially available soaker hoses were calibrated to determine flow as a function of pressure in order to determine the amount of water being applied to the biofilter. A linear regression was created, to calculate the amount of water to be applied to the compost. The water was turned on at constant pressure for a controlled water application. The optimized position of soaker hose for water application was the lower region of the biofilter. This was concluded because the hose in the lower position maintained constant moisture content in the biofilter media.

A water application interval was tested to verify if the interval that the water was turned on and off affected the capacity of the biofilter to hold water or drain before being adsorbed. The Tukey means grouping showed that there was no significant difference between the intervals tested. However, the interval where the water was allowed to run for 30 seconds with a two minute interval between applications was different from the other two. This is an important

consideration for a control system design where the software controls how many 30 seconds applications will be necessary and automatically adjusting the interval between them as may be required to maintain given moisture content. The results of the procedures conducted during these tests indicated that further testing was required in order to make a determination of the application interval.

The water balance conducted during the experiment showed that the no water treatment resulted in the compost moisture content behaving as expected where the lower region dried faster than the others reaching an equilibrium moisture content of 10% wb at 100 hours. The middle region reached this level at 300 hours and the upper region reached a level below 20% w.b. after 400 hours. This level of moisture content is important because it determines when the biological activity ceases. With no water being applied to the media, the biofilter loses its biological activity after 400 hours.

The installation of the soaker hose prevented the biofilter from dropping to moisture content levels below 20% w.b.. The average moisture content throughout the entire biofilter stayed above 30% w.b. Therefore, the water being applied to the lower region of the biofilter resulted in all regions maintaining sufficient moisture content to support biological activity.

The results reported above are based on the direct method for measuring water content. Some measurement discrepancies with the direct method occurred when the INNOVA was used for estimating the water in the biofilter. Using the INNOVA measurements of the water content of the exhaust air, the total amount of water lost was 91 kg of water when no water was applied and 308 kg of water when water was being applied. The difference in these values demonstrates that maintaining the biofilter media moisture content requires significant application of water.

Thermal conductance was used to track the moisture in the compost during the experiment. The results of the analysis did not show a close correlation between the predicted replacement volume of water and what was actually leaving the system. The water calculated to be added into the biofilter was lower than what was actually being lost through drying. The reason for this

phenomenon is still unknown and requires further study. The effect of depths of the probe in the compost did not show any major effect in the reading that would cause this much offset in the moisture readings. Thermal conductance for moisture measurement was a viable indirect method for a second/control system for water application. An alternative is to use the probes totally embedded into the mass of compost on each of the regions of the biofilter connected with a multiplexer for a complete moisture profile of the media.

Gas removal analysis should be performed on a region by region basis instead of only at the inlet and outlet of the entire biofilter. The results showed that it was possible to draw different conclusions based on these two different analyses. In this research effort, the two treatments (no water being applied and water being applied) had the same results when the gases were analyzed over the entire biofilter, but when the region by region analysis was performed the results presented different patterns.

Chapter 6 Recommendations for future work

Pilot scale biofilters need an impermeable finish to deal with the amount of water that would be present during a long term experiment, or perhaps be constructed of a different material such as a stainless-steel that would be inert to the ammonia and standing water.

An improved, real-time water balance is important for validation of media bed moisture content and the true effect of water application measurements and the effects of applied water. A collector system for drainage water below the biofilter is recommended for accounting all water losses.

Simplify the design of the air delivery system, eliminating any exhaust duct or balancing damper for airflow regulation. This balance damper was found to be the cause of chamber performance anomalies in earlier work.

The drying tests showed that the middle and upper regions began to dry after the lower region was in equilibrium with the incoming gas stream. This suggests that the lower region works as a moisture buffer for the rest of the biofilter stacks. This characteristic function, other experiments could evaluate using materials with different water holding capacities for the buffer region and determine the effect on the water content in the biofilter. This modification could also be applied to the upper region which still dries even with the middle region being kept constant. It may be beneficial to place a buffer material over the surface of the biofilter in order to decrease upper region drying.

Moisture sensing systems will likely require the thermal conductor to be totally embedded in the mass of compost. Further, a multiplexer system similar to that developed by Del Nero Maia (2010) can be adapted for the continuous monitoring of the moisture content.

Appendices

Appendix A. Evaluation of capacitance as moisture measure method

A.1 Introduction

To fulfill the objective of finding an indirect nondestructive method for moisture measurement of the compost, capacitance was evaluated as matter for indirect measurement method for moisture content. This electrical property is already used in different fields to this end, like in soil which have similar characteristics to compost. And these similarities lead to the experimentation of capacitance.

A.2 Literature Review

Capacitance is the measurement of the stored electrical charge between parallel bodies, when there is an electrical potential and infinite resistance between them (Kelleners et al., 2004). The technique of using capacitance for moisture content measurement in soil have been improved substantially (Polyakov, 2005), and present some advantages for this kind of use because is a fast and nondestructive method for moisture measurement, also is easily automated (Kelleners et al., 2004).

Typically to measure the moisture content in soil the probes used to measure the capacitance operates at a wide frequency range from 10 MHz to several hundred megahertz (Eller, 1995), these probes are a safe, fast and inexpensive part of the capacitance method and initially they used empirical calibrations where the probe response is directly related to the moisture content in soil which means that the calibration is instrument dependent, to avoid this disadvantage a twofold calibration strategy is developed and described by Robinson et al, 1998. Because of time restraints this kind of experimentation was not performed during this experiment.

In these tests it was used 3 control boards built by Robert et al, 2005 which were designed to work with a large area capacitive plate sensor at media moisture content of 10 to 70% wet basis. The frequencies used were between 300 kHz to 15 MHz, with a new compost media with various particle sizes, resulting in porosity of 57%; this media is similar to the ones used in newly

contracted biofilter. The experimented consisted in air drying the compost and adding water in seven incremental steps in order to have seven different moisture contents, for which samples were taken for drying in the microwave to measure the moisture content by weight difference and at the same time the capacitance in the plates were recorded.

A.3 Material and Methods

This portion of the work involved evaluation of a sensor board design developed by Robert (2005) and was intended to satisfy a portion of the requirements for Objective 2 but due some lack of details in the testing could not be used. There were two phases for testing the capacitance based sensor. The first consisted of using the control board built by Robert (2005) to develop a set of small form factor capacitance grids which were essentially two metal grids which acted as the capacitive surfaces. The second phase was accomplished using a commercially available capacitance meter (BK 815, BK Precision Corp.) to measure the capacitance through the metal grids as a function of the media water content. The grids had a surface area of 0.133 m^2 and two different wire spacing: 1.25 cm (0.5 in) and 0.625 cm (0.25 in).

A.3.1 Chicken wire test

Robert et al (2005) described capacitance plates formed from large galvanized fence panels approximately 91.4 cm by 76.2 cm which were much too large for use in pilot scale biofilter studies. Thus, it was necessary to develop small form factor grids for evaluation of the sensor boards in the present laboratory setup. A preliminary test used a 0.625 cm (0.25 in) spacing galvanized wire grid, commonly known as chicken wire, as the capacitance grids replacing the large capacitive grids used by Robert et al (2005). Three airtight, plastic boxes (with 27 liters) were filled with compost of known moisture content. Each box contained two chicken wire grids with an area of 0.133 m^2 and was filled with sieved compost (Figure A.3.1.1 and Figure A.3.1.2). A layer of compost approximately 2.5 cm thick was placed in the bottom of the container with the first chicken wire grid placed above it. An additional layer of compost 2.5 cm thick

was placed over the first grid followed by the remaining chicken wire grid to create the capacitance volume.

Figure A.3.1.1 Installation of the grids inside the boxes.

Figure A.3.1.2 Boxes with the chicken wire in the compost.

The chicken wire grids were supplied with a +/- 9 volts DC current. A prototype “breadboard” (Figure A.3.1.3) was constructed to serve as a hardwire switch allowing selective connection of all three boards to a multimeter (Equus 3320 Auto-Ranging Digital Multimeter). During this procedure the frequency used was no adjusted or recorded, because the boards were tested as they were received assuming they were in adjusted in accordance with each other.

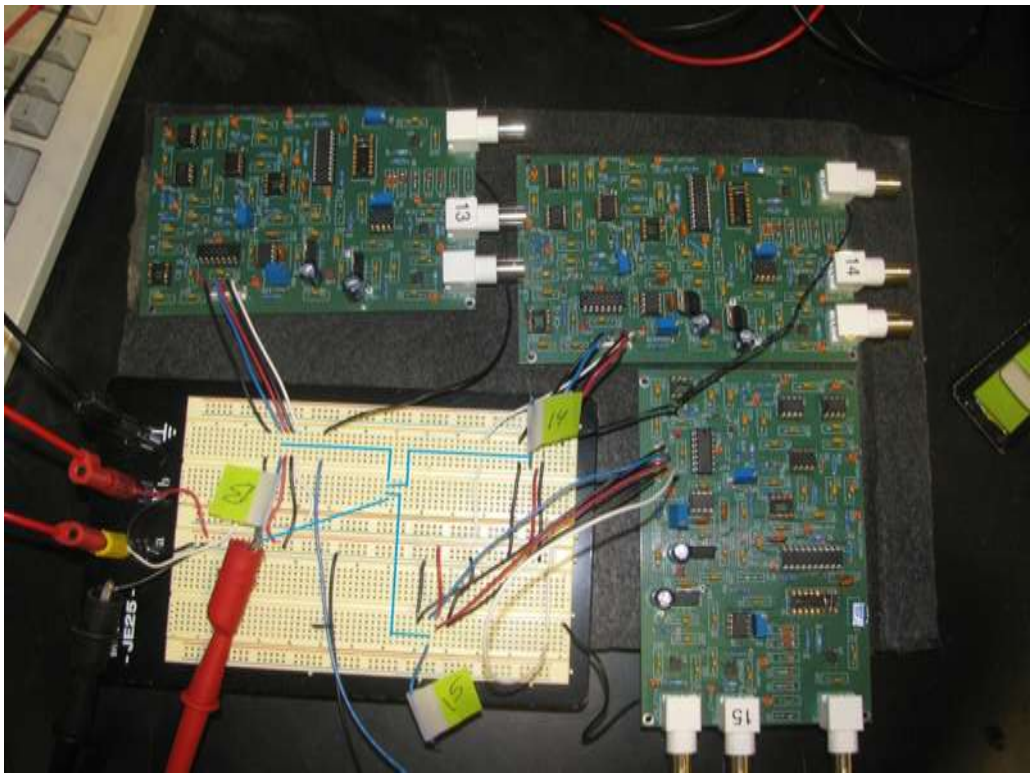

Figure A.3.1.3 Prototype board connected to the control boards.

Twice a day samples of compost were removed from the boxes and dried in an oven for 24 hours at 105^{o}C to determine the moisture content. The multimeter voltage across the grids was recorded for comparison to the oven-dried values.

A.3.2 Insulated grids

Analysis of the preliminary data gathered using the chicken wire grids indicated that the bare wire grids may have actually been short circuited through the compost media owing to its relatively high moisture content. It was decided to construct insulated grids and repeat the tests to determine if short circuiting did, in fact, take place in the media. Coated wire grids made of galvanized wires and coated with vinyl were obtained from McNichols CO. (Vinylmesh, galvanized-PVC coated, 0.2 cm wire). Two different grid spacing (1.25 cm and 0.625 cm) were investigated as possible replacements for the chicken wire grids. The grids used in the experiment are smaller than what is sold by the manufacturer which required the material to be cut. The cutting process leaves the cut points exposed affecting its insulation properties. Thus, a tray was fabricated (Figure

A.3.2.1) to re-coat the tips (Figure A.3.2.2) with a plastic coating (PlastDip® by Performix Inc.).

Figure A.3.2.1 Process of coating the tips of the grids for insulation with PlastDip®.

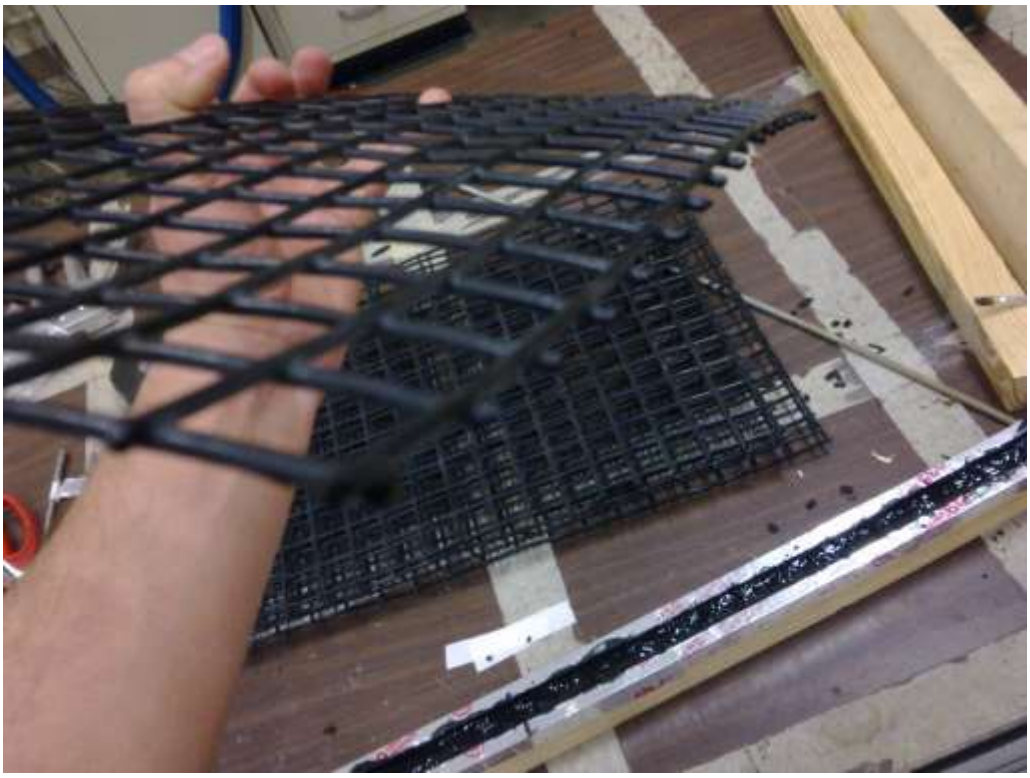

Figure A.3.2.2 Tips of the grids insulated with PlastDip®.

The insulated grids were evaluated using two processes, dynamic and static. Details of these processes are presented in the following sections.

A.3.2.1 Dynamic test

The grids were placed inside the biofilters (Figure A.3.2.1.1) with 68 liters of compost at initial moisture content of 50% (w.b.). The chambers were subjected to an airflow rate of 104 m^3/h to dry the compost. The grids were connected to separate controller boards (one for each chamber) at the same voltage described earlier (Figure A.3.2.1.2).

Figure A.3.2.1.1 Grids installed in the lower position of the biofilter.

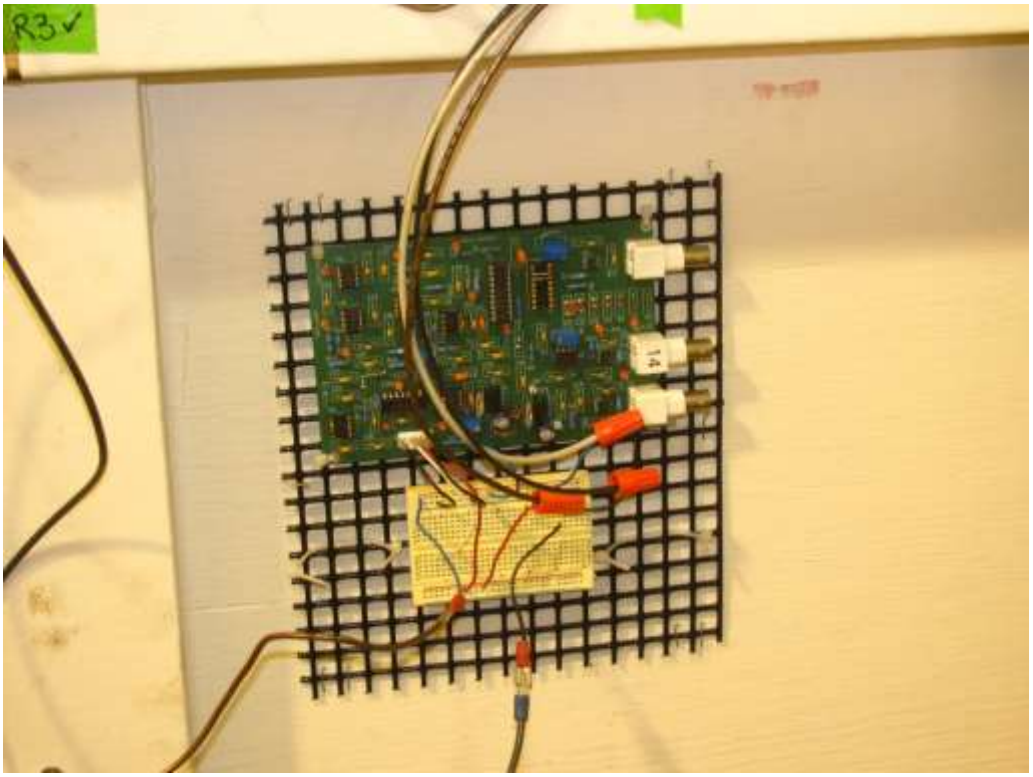

Figure A.3.2.1.2 Control board installed on the side of the biofilter.

The compost was allowed to dry for 12 hours. Media samples were collected every hour for determination of the water content, along with the voltage across the control board for later comparison. A single spacing size grid was used in all three biofilters for each test in order to exclude the effect of pressure drop on the drying rate. The test was repeated for both grid sizes.

The data were analyzed to determine if a relationship between moisture content and voltage at the meter (i.e., capacitance across the grids) exists. Linear regression was used to check for linearity of the results and analysis of variance will be used to determine goodness of fit for the prediction model.

A.3.2.2 Static tests

The dynamic tests were designed to evaluate the sensor's ability to track varying moisture content over time. A subsequent set of tests referred to in this case as static tests were designed to evaluate the sensor's stability in measuring relatively constant moisture content.

The static tests utilized the same plastic, airtight containers used for the earlier chicken wire tests. Six boxes were filled with compost at known moisture contents (40, 50 and 60% w.b.) with two grids placed 2.54 cm (1 in) apart (Figure A.3.2.2.1). Three boxes contained the 1.27 cm (0.5 in) grid spacing and three contained the 0.635 cm (0.25 in) grid spacing. The boxes were sealed so the compost would not loose water with time.

Figure A.3.2.2.1 Boxes with the grids used for the static tests.

The static tests were performed using a commercially available capacitance meter (BK 815, BK Precision Corp.), because the control boards were suspected to be unstable. The readings were taken every hour for 12 hours, after which, the boxes were emptied and filled with the next moisture content. The tests were replicated three times in order to allow every box be filled with each of the three moisture contents.

The data were analyzed for three replicates of three moisture contents and two grid spacing to determine if a relationship between moisture content and capacitance at the meter exists. Linear regression was used to check for linearity of the results and analysis of variance will be used to determine goodness of fit for the prediction model.

A.4 Results and discussion

A.4.1 Chicken wire test

The development of a good set of small form factor capacitance plates was undertaken as part of the requirements of objective 2 and was a fundamental requirement to make the control boards built at the University of

Illinois work with the pilot scale biofilters. The design requirements included low pressure drop, a good surface for capacitance, and economy. Chicken wire was used in the preliminary tests of the control boards owing to its economy and availability as an easy resource found in a farm. Its electrical capability was tested in order to find if it would work as a set of capacitance plates.

During this test the moisture content was kept constant inside a sealed box and the voltage read with each control board. Figure A.4.1.1 shows that for the three control boards there is a very weak linear regression, with R^2s not bigger than 0.47, between the moisture content and the voltage. The interaction between the boards and the moisture content has some strength with a p-value of 0.006 what is a small p-value but with potential (Figure A.4.1.2).

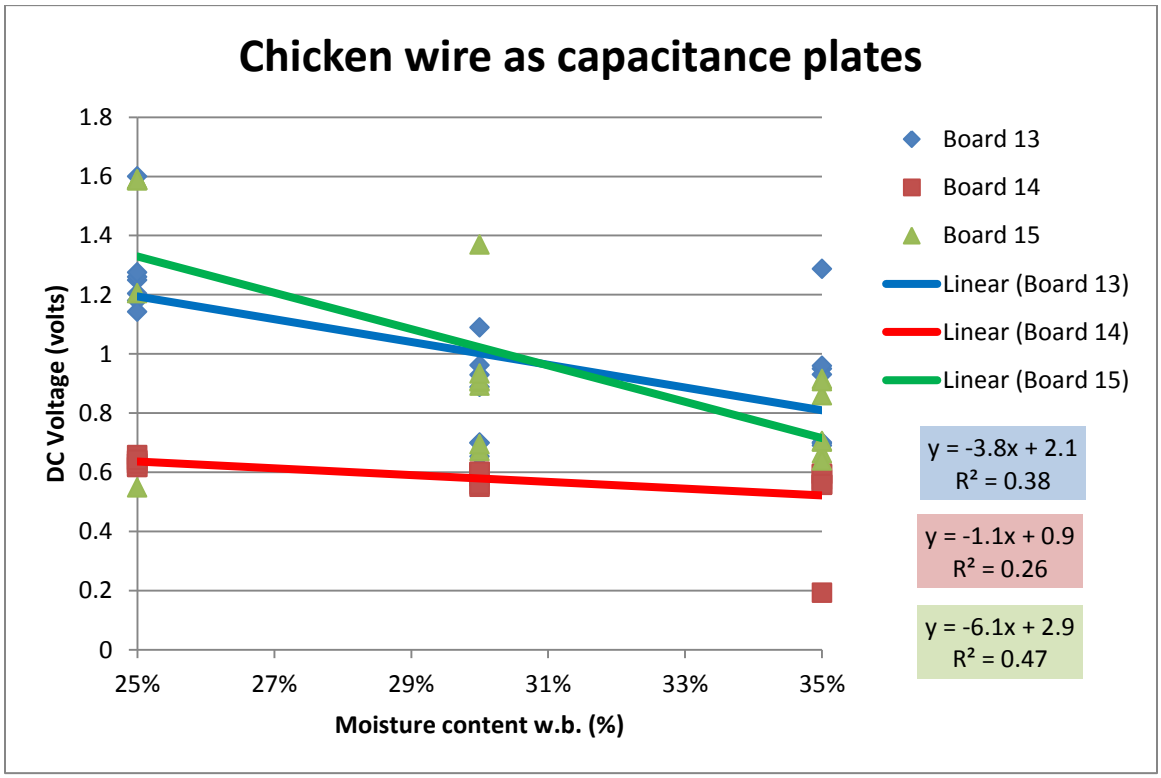

Figure A.4.1.1 DC Voltage across the boards using chicken wire as capacitance plates.

The SAS System 13:47 Sunday, August 15, 2011

The Mixed Procedure

Solution for Fixed Effects

Effect	board	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		2.7403	0.3348	57	8.19	<.0001
board	13	-0.6552	0.4610	57	-1.42	0.1607
board	14	-1.9318	0.4524	57	-4.27	<.0001
board	15	0	.	.	.	.
moisture		-5.5868	1.0782	57	-5.18	<.0001
moisture*board	13	2.0101	1.4950	57	1.34	0.1841
moisture*board	14	4.8382	1.4567	57	3.32	0.0016
moisture*board	15	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
board	2	57	9.65	0.0002
moisture	1	57	30.76	<.0001
moisture*board	2	57	5.64	0.0058

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	57	3.94	0.0521
1 vs 3	1	57	1.81	0.1841
2 vs 3	1	57	11.03	0.0016

Figure A.4.1.2 SAS output to the chicken wire tests.

One problem with the chicken wire is that they are not insulated what would culminate in short circuiting in the compost. Capacitance is the ability of a body to hold an electrical charge, in this case the chicken wire grids, so if the chicken wires are short-circuiting there will be current across the compost masking the measurements of the capacitance and also because of the compost depending on the moisture content can work as conductor and build up electrical charge on it.

A.4.2 Insulated grids: Dynamic Test

Insulated grids were used to avoid short-circuiting across the compost which would directly affect the capacitance. Dynamic tests were performed by placing the insulated grids into the biofilters during a drying test. Samples were taken every hour and the voltage across the control boards measured. The results of this analysis are presented in Figure A.4.2.1. Is possible to see that the relation between moisture content and the voltage is relatively constant, like is shown in Figure A.4.2.2 where the curves for the three boards are not

significantly different from each other and also not different from slope zero, which indicates that no matter the moisture content in the compost the voltage readings does not change.

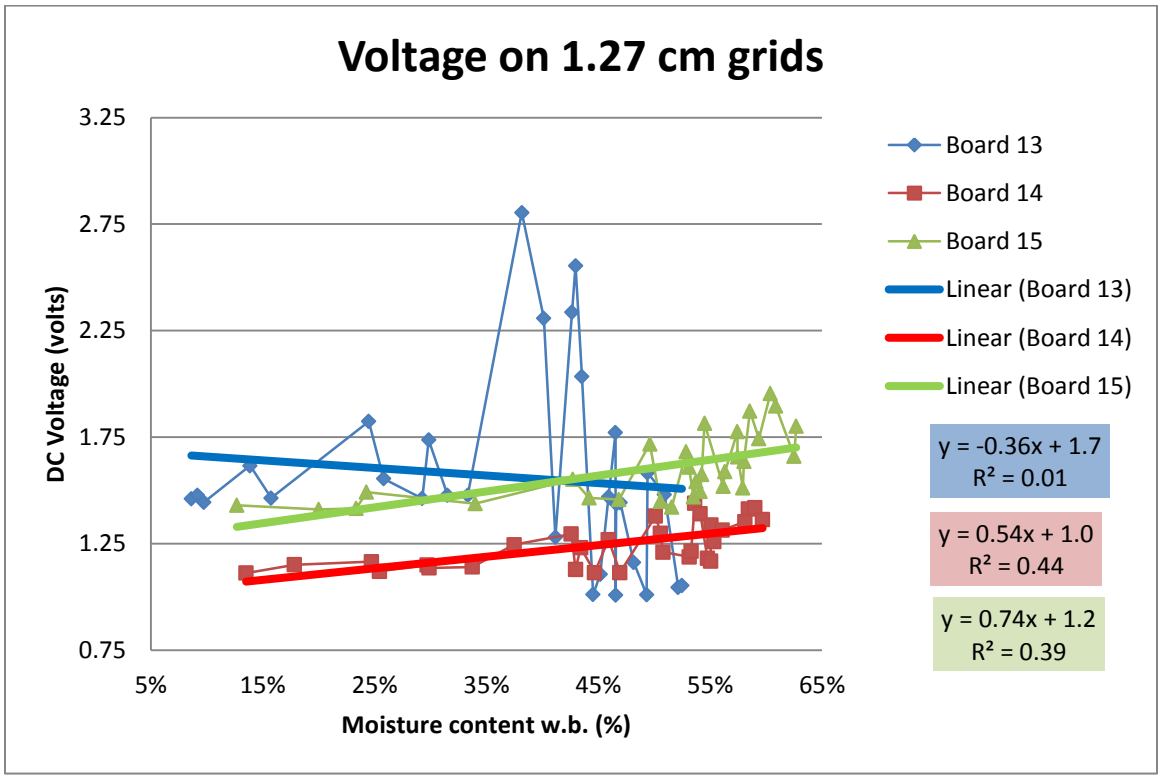

Figure A.4.2.1 DC voltage measured on the control boards during the dynamic test with the 1.27 cm (0.5 in) insulated grids.

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The Mixed Procedure

Solution for Fixed Effects

Effect	board	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		1.2336	0.2004	84	6.15	<.0001
board	13	0.4601	0.2494	84	1.85	0.0685
board	14	-0.2361	0.2755	84	-0.86	0.3940
board	15	0	.	.	.	.
moisture		0.7448	0.3919	84	1.90	0.0608
moisture*board	13	-1.0994	0.5443	84	-2.02	0.0466
moisture*board	14	-0.2011	0.5619	84	-0.36	0.7213
moisture*board	15	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
board	2	84	4.55	0.0133
moisture	1	84	1.90	0.1714
moisture*board	2	84	2.33	0.1037

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	84	2.65	0.1074
1 vs 3	1	84	4.08	0.0466
2 vs 3	1	84	0.13	0.7213

Figure A.4.2.2 SAS output to the insulated grids with wire spacing of 1.27 cm (0.5 in).

The 1.27 cm insulated grids presented very poor linear regressions with R2s not bigger than 0.44 and all the three control boards presented regressions that have small coefficients turning them in almost horizontal lines what means that the voltage across the grids measured with the control board does not vary with the moisture content of the compost. The 0.635 cm (0.25 in) grids also presented similar behavior in what concerns the voltage across the grids with the moisture content (Figure A.4.2.3) with linear regression approximating of horizontal lines, which can be inferred by analyzing the p-values in Figure A.2.4 showing that the slopes are not significantly different from each other or to the zero slope. The results showing horizontal lines mean that the voltage does not change with the moisture content.

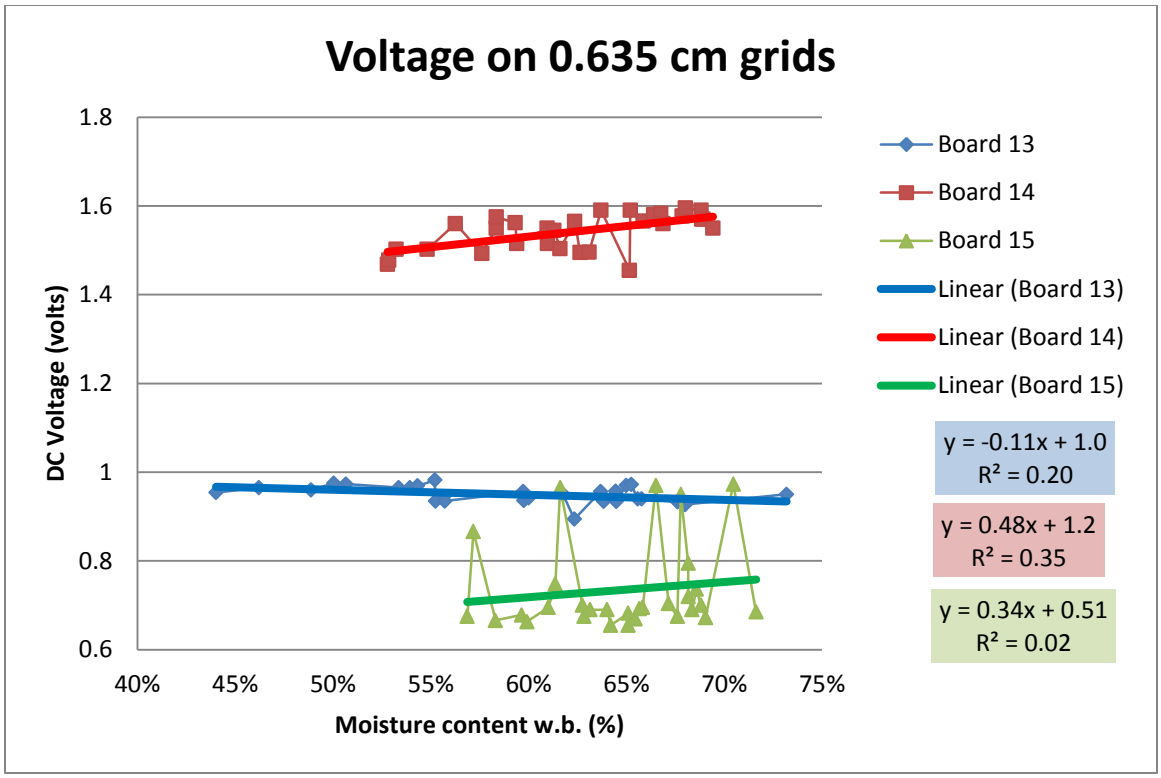

Figure A.4.2.3 DC voltage measured on the control boards during the dynamic test with the 0.635 cm (0.25 in) insulated grids.

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The Mixed Procedure

Solution for Fixed Effects

Effect	board	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5151	0.1917	84	2.69	0.0087
board	13	0.5029	0.2149	84	2.34	0.0216
board	14	0.7291	0.2386	84	3.06	0.0030
board	15	0	.	.	.	.
moisture		0.3385	0.2956	84	1.15	0.2554
moisture*board	13	-0.4538	0.3370	84	-1.35	0.1818
moisture*board	14	0.1393	0.3730	84	0.37	0.7096
moisture*board	15	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
board	2	84	4.69	0.0117
moisture	1	84	2.97	0.0883
moisture*board	2	84	2.57	0.0829

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	84	4.51	0.0366
1 vs 3	1	84	1.81	0.1818
2 vs 3	1	84	0.14	0.7096

Figure A.4.2.4 SAS output to the insulated grids with wire spacing of 0.635 cm (0.25 in).

A.4.3 Insulated grids: Static Test

Static tests were also performed with these insulated grids, this series of tests involved placing the grids into a compost box in which the moisture content was more or less constant and measuring the capacitance across the grids. It was expected that this measurement would be stable because of the association of the capacitance with the moisture content.

Graphic representations of the capacitance readings for different moisture contents and the two grids spacing are presented in the Figure A.4.3.1 to Figure A.4.3.6.

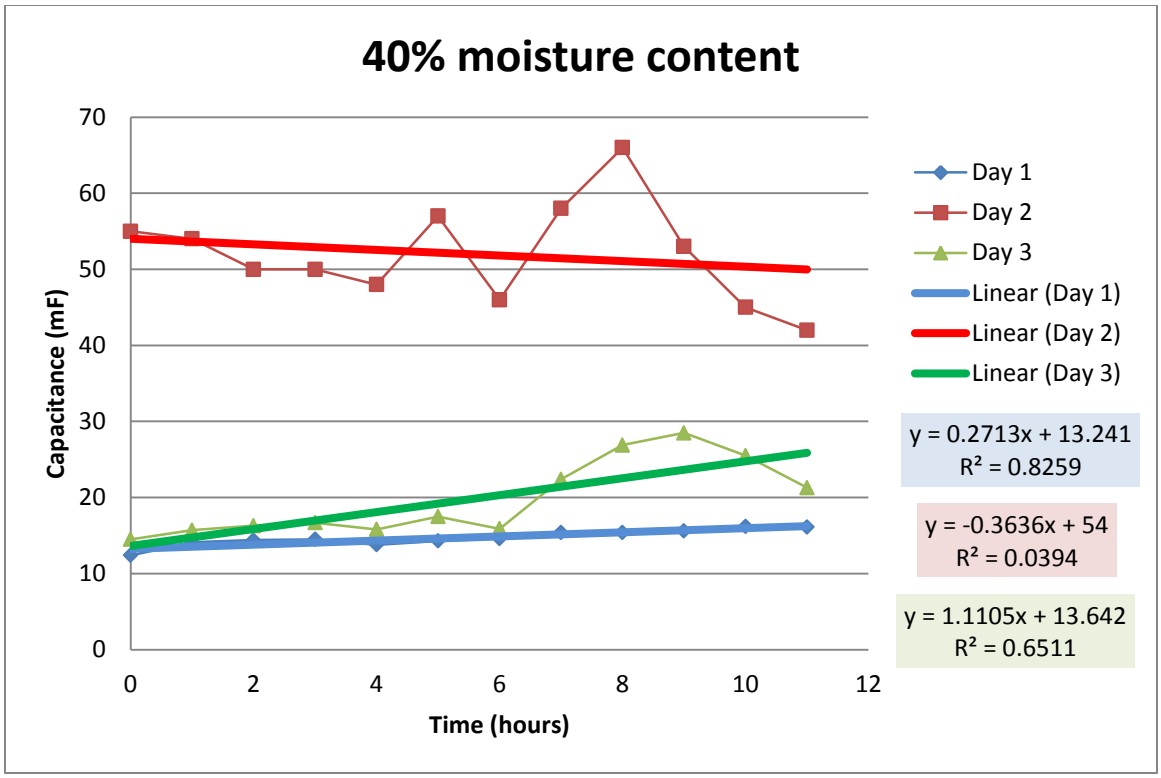

Figure A.4.3.1 Capacitances across the 1.27 cm (0.5 in) grids when moisture content is 40% w.b.

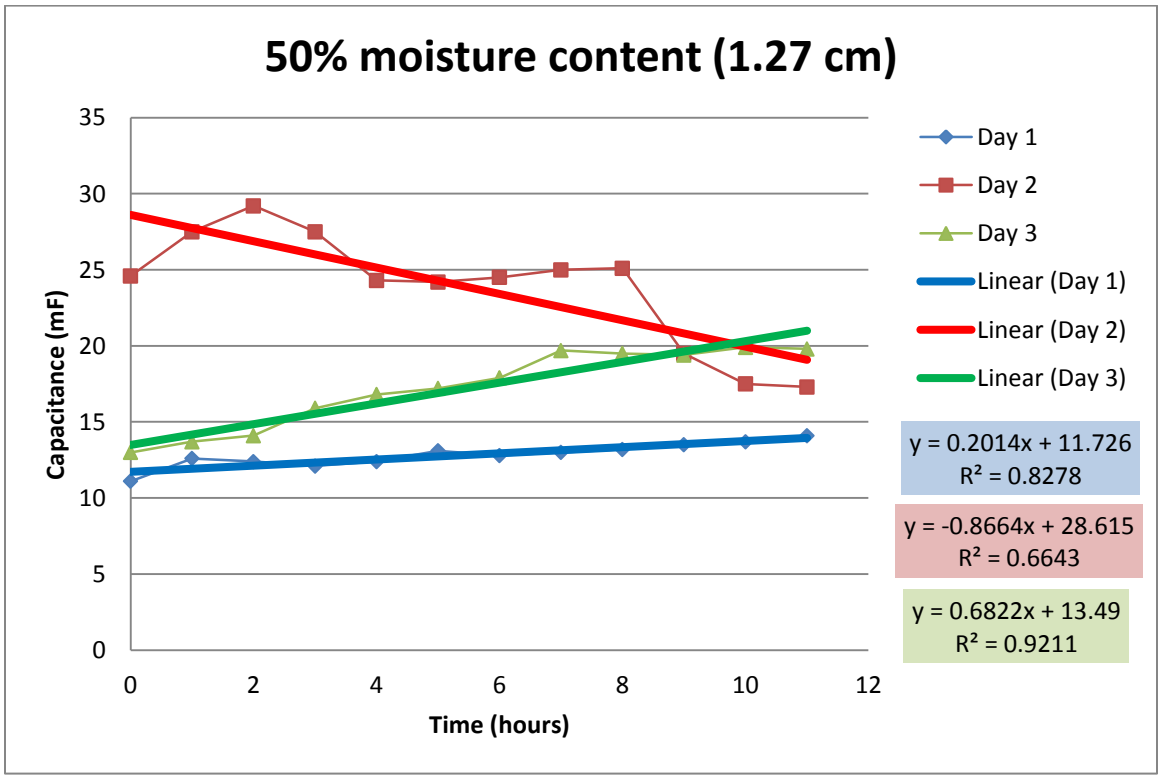

Figure A.4.3.2 Capacitances across the 1.27 cm (0.5 in) grids when moisture content is 50% w.b.

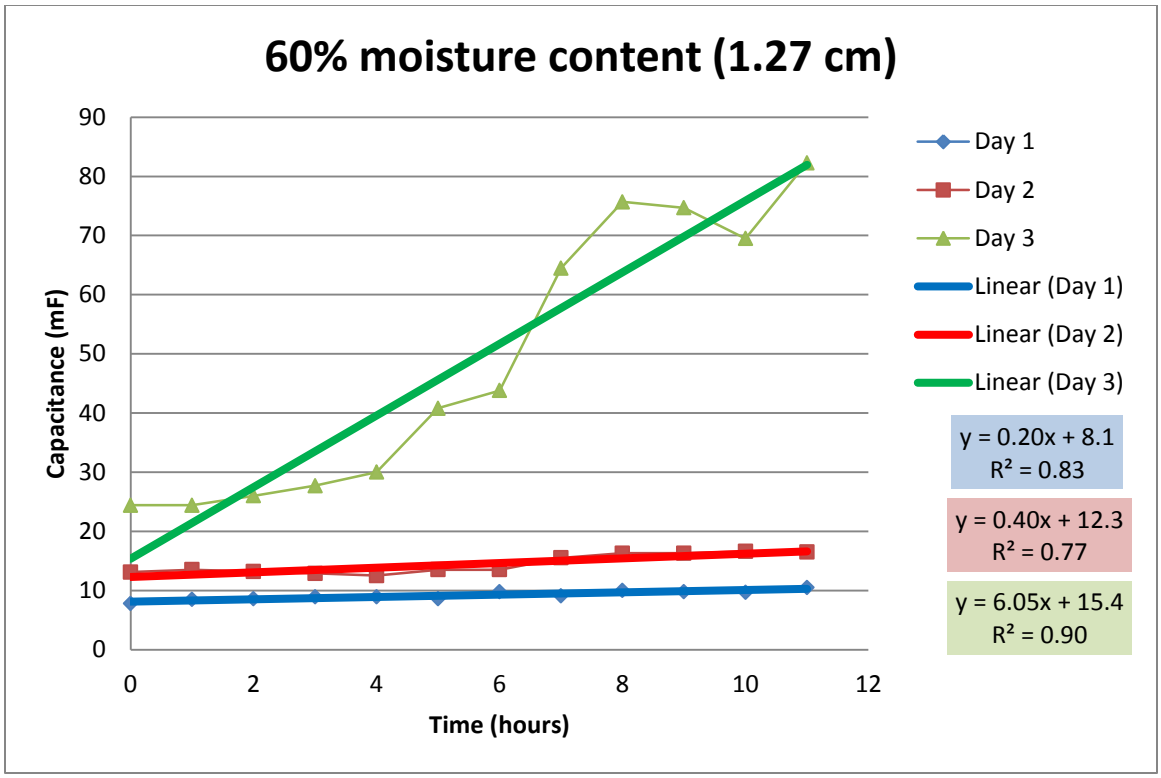

Figure A.4.3.3 Capacitances across the 1.27 cm (0.5 in) grids when moisture content is 60% w.b.

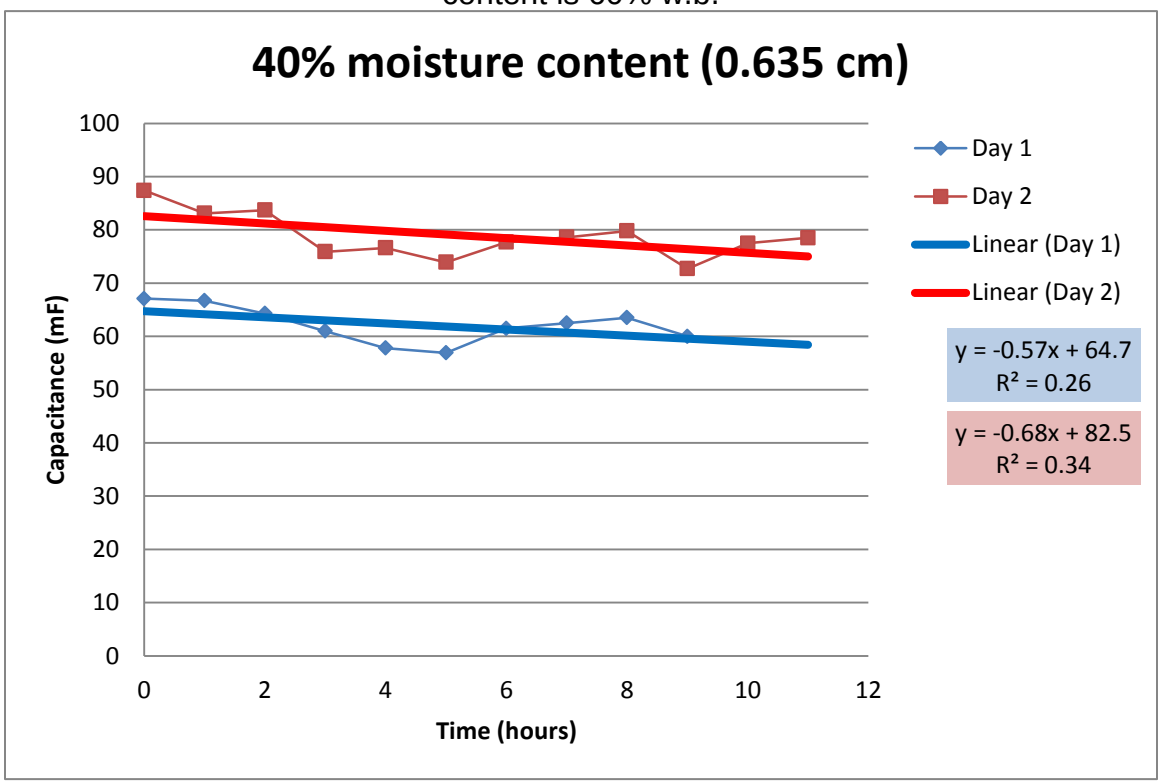

Figure A.4.3.4 Capacitances across the 0.635 cm (0.25 in) grids when moisture content is 40% w.b.

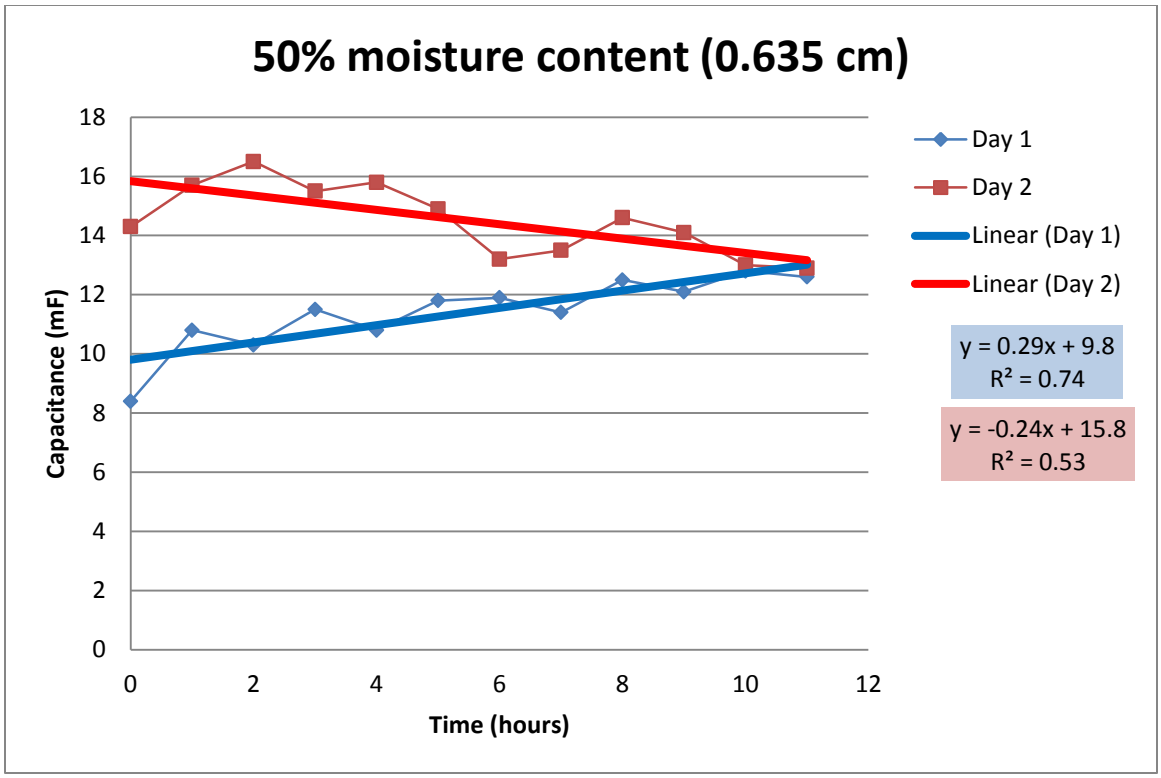

Figure A.4.3.5 Capacitances across the 0.635 cm (0.25 in) grids when moisture content is 50% w.b.

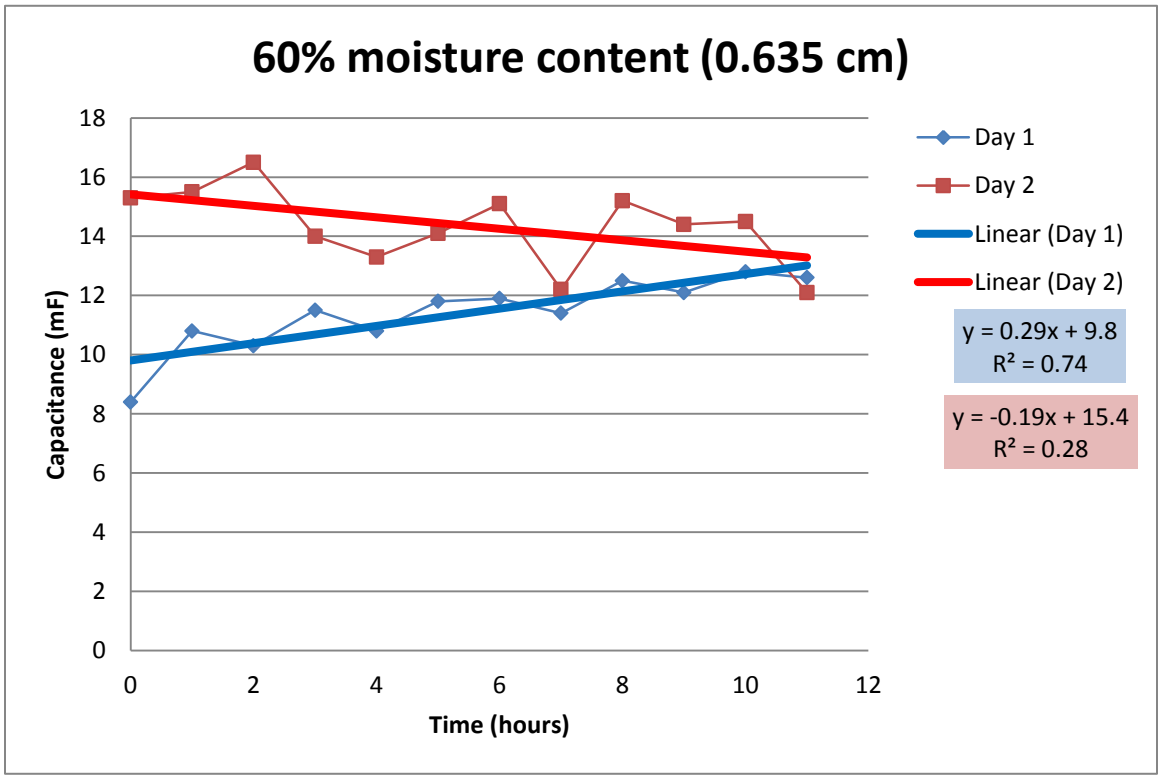

Figure A.4.3.6 Capacitances across the 0.635 cm (0.25 in) grids when moisture content is 60% w.b.

These graphic representations of the capacitance being tested with constant moisture showed that the capacitance was changing over time. Some of the regressions have larges R^2's what means good fit for the period of the experiment. But during the experiment the observations was that the number were constantly increasing. This behavior can be associated to the use of DC voltage during the experiment which can lead to the accumulation of charge in the compost.

To verify this behavior where the capacitance increases with time, a further test was performed with the same boxes with the moisture sealed to keep constant over time. So the capacitance was measured every hour for 12 hours for five days. Figure A.4.3.7 shows the capacitance readings for 6 different moisture levels with the 1.27 cm (0.5 in), a Pearson correlation analysis (Table A.4.3.1) were performed to verify the correlation of the capacitance with time that showed a very strong correlation.

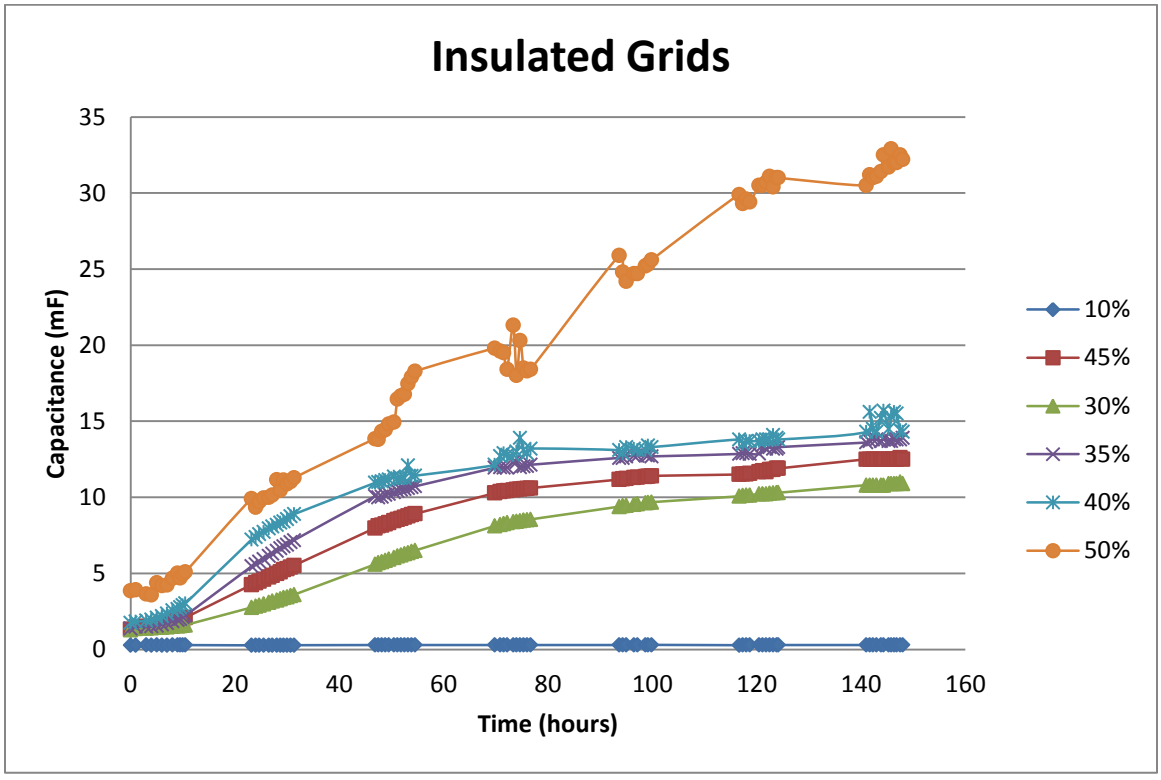

Figure A.4.3.7 Insulated grids capacitance readings for DC voltage excitation for different moisture contents.

Table A.4.3.1 Correlation of capacitance with time.

Pearson Correlation Coefficients, N = 162 ***Prob > |r| under H0: Rho=0***		
	Time	**logcap**
Time	1.00000	-0.31154 <.0001
logcap	-0.31154 <.0001	1.00000

A.5 Conclusions

Although these experimentations were not conclusive about the capability of the capacitance as an method for moisture content measurement, because during this experiment the frequency was not adjusted, also it was not used the AC current, is important to point out that the insulated wire grids are an interesting approach for future works when evaluating the capacitance in the compost media. Also from these tests is possible to take the correct protocol to test, where the compost stays at constant moisture content and the capacitance is recorded over time for further correlation.

Appendix B. Statistical Analysis for Flow meters tests

Table B.1 Annova for the flow meters connected to the pump through the mass flow controller.

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
FM3	7	223	31.85714	384.8095
FM2	7	215	30.71429	374.9048
FM1	7	186	26.57143	196.9524

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	108.2857	2	54.14286	0.169786	0.845181	3.554557
Within Groups	5740	18	318.8889			
Total	5848.286	20				

Table B.2 Annova for the flow meters connected to the pump through the mass flow controller in the reduced operation range for the research.

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
FM3	5	113	22.6	189.8
FM2	5	107	21.4	164.8
FM1	5	106	21.2	169.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.733333	2	2.866667	0.016418	0.983738	3.885294
Within Groups	2095.2	12	174.6			
Total	2100.933	14				

Table B.3 Annova for the flow meters connected in series with the pump using the mass flow controller with a flow of 20 ml/min.

Flow meters connected in series with the pump MFC 20 SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
1	3	7.3	2.4	0.4		
2	3	9.5	3.2	1.6		
3	3	10	3.3	0.6		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.4	2	0.7	0.8	0.49	5.1
Within Groups	5.1	6	0.8			
Total	6.4	8				

Table B.4 Annova for the flow meters connected in series with the pump using the mass flow controller with a flow of 20 ml/min.

Flow meters connected in series with the pump MFC 25 SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
1	3	18.0	6.0	3.3		
2	3	23.5	7.8	5.1		
3	3	24.5	8.2	0.6		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.2	2	4.1	1.4	0.32	5.1
Within Groups	17.8	6	3.0			
Total	26	8				

Table B.5 Annova for the flow meters connected to the tank through the mass flow controller.

Flow meters conected to the air cylinder through MFC

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
FM3	7	289	41.3	103.2
FM2	7	286	40.9	89.2
FM1	7	278	39.7	107.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.2	2	4.6	0.0	0.95	3.6
Within Groups	1798.2	18	99.9			
Total	1807.5	20				

Table B.6 Annova for the flow meters connected in series with the air cylinder using the mass flow controller with a flow of 20 ml/min.

Anova: Single Factor

MFC 20

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	3	40	13.33	14.58
2	3	68	22.67	16.33
3	3	57.5	19.17	27.08

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	133.388889	2	66.69	3.45	0.10	5.14
Within Groups	116	6	19.33			
Total	249.388889	8				

Table B.7 Annova for the flow meters connected in series with the air cylinder using the mass flow controller with a flow of 25 ml/min.

Anova: Single Factor
MFC 25
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	3	52.5	17.5	18.75
2	3	85	28.33	27.08
3	3	78	26	28

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	195.055556	2	97.53	3.96	0.08	5.14
Within Groups	147.666667	6	24.61			
Total	342.722222	8				

Appendix C. Statistical Analysis for the drying front movement

The drying front movement was described in order to visualize the different drying processes that happen inside the biofilter and with these data to show where the and if the moisture is constant when the slopes are not significantly different from zero. Below find the SAS code for these comparisons and the output for each of the region. Information from this analysis is the uniformity of the biofilters as replicates.

Table C.1 SAS code used for comparing the slopes of the drying front for each of the region in the biofilters.

```
data dry;
input time biofilter sample moisture;
cards;

(data collected)



;

proc mixed data=dry;
class biofilter;
model moisture = biofilter time biofilter*time/solution;
contrast '1 vs 2' biofilter*time 1 -1 0;
contrast '1 vs 3' biofilter*time 1 0 -1;
contrast '2 vs 3' biofilter*time 0 1 -1;
run;
```

The first analysis performed is the drying period on the lower region, which happens from 0 to 52 hours. In Table C.2 is possible to see that the slopes are different from zero but not significantly different from each other, what enforces that the three biofilters are true replicates.

Table C.2 SAS output for slope analysis of the drying period in the lower region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5107	0.02567	30	19.90	<.0001
biofilter	1	-0.09032	0.03630	30	-2.49	0.0186
biofilter	2	-0.04438	0.03630	30	-1.22	0.2310
biofilter	3	0	.	.	.	.
time		-0.00721	0.000751	30	-9.60	<.0001
time*biofilter	1	0.000890	0.001062	30	0.84	0.4084
time*biofilter	2	0.001038	0.001062	30	0.98	0.3362
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	30	3.10	0.0599
time	1	30	229.28	<.0001
time*biofilter	2	30	0.56	0.5775

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	30	0.02	0.8904
1 vs 3	1	30	0.70	0.4084
2 vs 3	1	30	0.96	0.3362

After the drying period starting at 52 hours the lower region gets into equilibrium moisture content around 10% wet basis. This equilibrium can be seen on Table C.3 where the slopes are not significantly different from zero what means a constant slope and also not significantly different from each other.

Table C.3 SAS output for slope analysis of the equilibrium period in the lower region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.08035	0.04903	48	1.64	0.1078
biofilter	1	-0.05090	0.06934	48	-0.73	0.4665
biofilter	2	-0.1110	0.06934	48	-1.60	0.1161
biofilter	3	0	.	.	.	.
time		0.000161	0.000507	48	0.32	0.7524
time*biofilter	1	0.000468	0.000717	48	0.65	0.5172
time*biofilter	2	0.001357	0.000717	48	1.89	0.0646
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	48	1.28	0.2864
time	1	48	6.90	0.0115
time*biofilter	2	48	1.85	0.1690

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	48	1.53	0.2215
1 vs 3	1	48	0.43	0.5172
2 vs 3	1	48	3.58	0.0646

In the middle region during the firsts 52 hours the moisture content stays in equilibrium while the lower region is drying. This equilibrium period is shown in Table C.4 whit the same output as the equilibrium period in the lower region where the slopes are not significantly different from zero and from each other.

Table C.4 SAS output for slope analysis of the equilibrium period in the middle region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.5223	0.01846	30	28.29	<.0001
biofilter	1	-0.00771	0.02611	30	-0.30	0.7697
biofilter	2	-0.06191	0.02611	30	-2.37	0.0244
biofilter	3	0	.	.	.	.
time		-0.00090	0.000540	30	-1.67	0.1051
time*biofilter	1	-0.00057	0.000764	30	-0.74	0.4628
time*biofilter	2	0.001100	0.000764	30	1.44	0.1603
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	30	3.34	0.0490
time	1	30	5.41	0.0269
time*biofilter	2	30	2.46	0.1021

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	30	4.77	0.0370
1 vs 3	1	30	0.55	0.4628
2 vs 3	1	30	2.07	0.1603

The drying period in the middle region starts after the 52 hours period which is proved in the Table C.5 with the slopes being significantly different from zero. And like the other analysis the biofilters are all working uniformly.

Table C.5 SAS output for slope analysis of the drying period in the middle region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.8032	0.06621	48	12.13	<.0001
biofilter	1	-0.02445	0.09363	48	-0.26	0.7951
biofilter	2	-0.1092	0.09363	48	-1.17	0.2491
biofilter	3	0	.	.	.	.
time		-0.00607	0.000685	48	-8.87	<.0001
time*biofilter	1	0.000306	0.000969	48	0.32	0.7536
time*biofilter	2	0.000897	0.000969	48	0.93	0.3589
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	48	0.75	0.4780
time	1	48	205.67	<.0001
time*biofilter	2	48	0.44	0.6444

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	48	0.37	0.5443
1 vs 3	1	48	0.10	0.7536
2 vs 3	1	48	0.86	0.3589

As in the middle region the upper region has a constant moisture content period and starts to dry after a point. But even though the upper part has a similar pattern as the middle the constant moisture content period goes until 65 hours and them starts to dry, these periods of constant moisture content and drying for the upper region are presented in Table C.6.

Table C.6 SAS output for slope analysis of the equilibrium period in the upper region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.4952	0.01754	39	28.24	<.0001
biofilter	1	0.01170	0.02480	39	0.47	0.6396
biofilter	2	-0.02141	0.02480	39	-0.86	0.3933
biofilter	3	0	.	.	.	.
time		-0.00078	0.000416	39	-1.87	0.0694
time*biofilter	1	-0.00037	0.000588	39	-0.63	0.5300
time*biofilter	2	0.000231	0.000588	39	0.39	0.6968
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	39	0.92	0.4082
time	1	39	11.78	0.0014
time*biofilter	2	39	0.54	0.5892

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	39	1.05	0.3111
1 vs 3	1	39	0.40	0.5300
2 vs 3	1	39	0.15	0.6968

Table C.7 SAS output for slope analysis of the drying period in the upper region.

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The Mixed Procedure

Solution for Fixed Effects

Effect	biofilter	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		0.8252	0.1125	39	7.34	<.0001
biofilter	1	-0.03699	0.1590	39	-0.23	0.8173
biofilter	2	0.08492	0.1590	39	0.53	0.5964
biofilter	3	0	.	.	.	.
time		-0.00526	0.001104	39	-4.76	<.0001
time*biofilter	1	0.000116	0.001562	39	0.07	0.9411
time*biofilter	2	-0.00103	0.001562	39	-0.66	0.5155
time*biofilter	3	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
biofilter	2	39	0.31	0.7360
time	1	39	76.06	<.0001
time*biofilter	2	39	0.32	0.7256

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
1 vs 2	1	39	0.53	0.4694
1 vs 3	1	39	0.01	0.9411
2 vs 3	1	39	0.43	0.5155

Appendix D. Nitrous Oxide Removal efficiencies Statistics

When there was no water being applied into the biofilter the nitrous oxide generation and/or removal was not significantly different from zero, this performance is due to the fact that the nitrous oxide can only be generated by microbial activity and this microbial activity cannot happens on low moisture conditions. The descriptive statistics for the slopes of removal are presented in Table D.1, Table D.2 and Table D.3.

Table D.1 Descriptive statistics for nitrous oxide removal efficiency when no water is being applied into the biofilter 1.

Biofilter 1 (No Water)

	Lower	*Middle*	*Upper*	*Headspace*	*Overall*
Mean	**0.00**	**0.00**	**-0.01**	**0.00**	**0.00**
Standard Error	0.01	0.00	0.00	0.01	0.01
Median	0.00	0.00	0.00	0.00	0.00
Mode	-0.01	0.00	0.00	0.00	0.00
Standard Deviation	0.07	0.06	0.06	0.07	0.08
Sample Variance	0.01	0.00	0.00	0.01	0.01
Kurtosis	47.15	38.58	56.60	33.83	45.20
Skewness	5.57	-4.33	-5.87	4.86	5.42
Range	0.83	0.64	0.65	0.70	0.86
Minimum	-0.15	-0.53	-0.56	-0.16	-0.14
Maximum	0.68	0.11	0.09	0.54	0.72
Sum	0.53	-0.23	-0.87	0.69	0.12
Count	163.00	163.00	163.00	163.00	163.00
Confidence Level(95.0%)	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**

Table D.2 Descriptive statistics for nitrous oxide removal efficiency when no water is being applied into the biofilter 2.

Biofilter 2 (No Water)

	Lower	*Middle*	*Upper*	*Headspace*	*Overall*
Mean	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**
Standard Error	0.01	0.01	0.01	0.00	0.00
Median	0.00	0.00	-0.01	0.01	0.00
Mode	0.00	#N/A	#N/A	#N/A	0.00
Standard Deviation	0.07	0.12	0.09	0.05	0.06
Sample Variance	0.01	0.01	0.01	0.00	0.00
Kurtosis	31.03	99.39	98.88	14.55	13.64
Skewness	-1.51	-8.27	8.81	-0.82	2.49
Range	0.95	1.81	1.15	0.57	0.53
Minimum	-0.58	-1.31	-0.15	-0.33	-0.16
Maximum	0.37	0.50	1.00	0.25	0.37
Sum	-0.40	-0.36	0.19	0.85	0.27
Count	163.00	163.00	163.00	163.00	163.00
Confidence Level(95.0%)	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**

Table D.3 Descriptive statistics for nitrous oxide removal efficiency when no water is being applied into the biofilter 3.

Biofilter 3 (No Water)

	Lower	*Middle*	*Upper*	*Headspace*	*Overall*
Mean	**0.00**	**-0.01**	**0.01**	**0.00**	**0.00**
Standard Error	0.00	0.01	0.01	0.00	0.00
Median	0.00	0.00	0.00	0.00	0.00
Mode	#N/A	0.00	0.00	#N/A	-0.01
Standard Deviation	0.05	0.10	0.09	0.04	0.06
Sample Variance	0.00	0.01	0.01	0.00	0.00
Kurtosis	15.99	96.02	97.17	1.12	8.73
Skewness	-0.42	-8.29	8.78	0.34	1.26
Range	0.62	1.48	1.08	0.24	0.53
Minimum	-0.35	-1.12	-0.12	-0.09	-0.22
Maximum	0.27	0.35	0.96	0.15	0.31
Sum	-0.08	-1.35	1.27	-0.02	-0.18
Count	163.00	163.00	163.00	163.00	163.00
Confidence Level(95.0%)	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**

In the other hand when water is applied to the biofilter is possible to identify some activities happening in the biofilter because now there enough water in the biofilter to maintain biological activity. This activity can be described by the descriptive statistics presented on Table D.4, Table D.5 and Table D.6.

Table D.4 Descriptive statistics for nitrous oxide removal efficiency when water is being applied into the biofilter 1.

	Biofilter 1 (Water)				
	Lower	*Middle*	*Upper*	*Headspace*	*Overall*
Mean	**0.01**	**-0.01**	**-0.09**	**0.07**	**-0.02**
Standard Error	0.01	0.01	0.01	0.01	0.01
Median	0.02	-0.01	-0.08	0.06	-0.01
Mode	#N/A	#N/A	#N/A	#N/A	#N/A
Standard Deviation	0.16	0.12	0.14	0.14	0.18
Sample Variance	0.03	0.01	0.02	0.02	0.03
Kurtosis	28.99	15.13	21.75	31.24	13.78
Skewness	-2.92	1.20	-3.53	-2.32	-1.77
Range	2.01	1.33	1.36	1.87	1.77
Minimum	-1.26	-0.56	-1.06	-1.09	-1.14
Maximum	0.75	0.76	0.30	0.78	0.63
Sum	1.13	-1.28	-13.05	10.10	-3.09
Count	151.00	151.00	151.00	151.00	151.00
Confidence Level(95.0%)	**0.03**	**0.02**	**0.02**	**0.02**	**0.03**

Table D.5 Descriptive statistics for nitrous oxide removal efficiency when water is being applied into the biofilter 2.

	Biofilter 2 (Water)				
	Lower	*Middle*	*Upper*	*Headspace*	*Overall*
Mean	**-0.02**	**0.03**	**-0.10**	**0.07**	**-0.02**
Standard Error	0.01	0.02	0.02	0.01	0.01
Median	-0.01	0.03	-0.09	0.08	-0.01
Mode	-0.01	#N/A	#N/A	#N/A	-0.11
Standard Deviation	0.12	0.19	0.21	0.16	0.17
Sample Variance	0.01	0.04	0.04	0.03	0.03
Kurtosis	22.81	45.78	36.93	37.92	22.21
Skewness	-3.36	-4.21	3.62	-4.71	-3.31
Range	1.18	2.59	2.50	1.91	1.80
Minimum	-0.95	-1.69	-0.81	-1.31	-1.29
Maximum	0.23	0.91	1.70	0.60	0.51
Sum	-2.84	4.31	-15.34	11.24	-2.63
Count	151.00	151.00	151.00	151.00	151.00
Confidence Level(95.0%)	**0.02**	**0.03**	**0.03**	**0.03**	**0.03**

Table D.6 Descriptive statistics for nitrous oxide removal efficiency when water is being applied into the biofilter 2.

	Biofilter 3 (Water)				
	Lower	*Middle*	*Upper*	*Headspace*	*Overall*
Mean	**-0.01**	**0.00**	**-0.02**	**0.06**	**0.02**
Standard Error	0.03	0.03	0.02	0.01	0.01
Median	0.02	0.00	-0.03	0.04	0.03
Mode	#N/A	0.00	#N/A	#N/A	0.00
Standard Deviation	0.34	0.40	0.25	0.12	0.15
Sample Variance	0.11	0.16	0.06	0.01	0.02
Kurtosis	122.11	68.51	42.63	23.63	15.01
Skewness	-10.55	4.91	5.40	3.68	-1.68
Range	4.22	5.88	2.69	1.17	1.63
Minimum	-3.90	-1.99	-0.76	-0.17	-0.95
Maximum	0.32	3.89	1.92	1.00	0.69
Sum	-1.86	-0.49	-3.66	9.53	3.52
Count	151.00	151.00	151.00	151.00	151.00
Confidence Level(95.0%)	**0.05**	**0.06**	**0.04**	**0.02**	**0.02**

Appendix E. Water replacement calculation

The water replaced during the soaker hoses positioning test was a fixed value calculated based on a previous test of drying. In this test it would be calculate the drying rate in kg of water lost per hour. And the biggest rate found during this drying test would be used as reference. It was assumed that if the hoses could deliver enough water to replace this amount, even when the drying rates are smaller it would have the water replaced.

Table E.1 Moisture content wet base for the drying test.

	Lower	**Middle**	**Upper**
0	48%	49%	49%
17	34%	50%	48%
41	19%	49%	47%
52	15%	44%	47%
65	9%	43%	42%
76	11%	32%	37%
89	9%	22%	37%
100	9%	16%	33%
113	8%	11%	26%

Each region of the biofilter was filled with an average of 31.2 kg of wet compost. To transform the Table E.1 in water content is necessary to transform the wet basis moisture content into dry basis shown in Table E.2, with the equation E.1.

$$M_D = \frac{M_W}{(1 - M_W)} \qquad \text{E.1}$$

M_W = moisture content (wet basis)

M_D= moisture content (dry basis)

Table E.2 Moisture content dry base for the drying test.

	Lower	**Middle**	**Upper**
0	92%	95%	94%
17	51%	98%	91%
41	23%	97%	88%
52	18%	79%	89%
65	9%	74%	71%
76	12%	47%	58%
89	9%	29%	58%
100	10%	19%	48%
113	8%	13%	35%

The initial water content among with the dry mass of the compost is calculated by multiplying the initial moisture content wet basis by the mass of compost. Table E.3 shows the dry mass and water content in each region.

Table E.3 Water content and dry mass content of compost in the biofilter in kg.

	Lower	**Middle**	**Upper**
Water	15.0	15.2	15.1
Dry Mass	16.2	16.0	16.1

The dry mass in the compost is constant during the whole experiment, what makes it the unit used to calculate the exactly amount of water present in the compost, the results are in Table E.4.

Table E.4 Water content in kg of water in each region during the drying test.

	Lower	**Middle**	**Upper**
0	14.97	15.21	15.14
17	8.23	15.70	14.60
41	3.76	15.54	14.09
52	2.91	12.55	14.23
65	1.53	11.86	11.45
76	1.91	7.55	9.34
89	1.53	4.64	9.39
100	1.55	3.07	7.73
113	1.37	2.04	5.66

When the difference between water contents by the time of the measurements a drying rate is found in kg of water per hour (Table E.5).

Table E.5 Drying rates for each region in kg of water per hour.

	Lower	**Middle**	**Upper**
0	0.00	0.00	0.00
17	0.40	-0.06	0.03
41	0.19	-0.01	-0.35
52	0.08	-0.08	0.00
65	0.11	-0.01	-0.07
76	-0.03	-0.07	-0.04
89	0.03	-0.04	0.00
100	0.00	-0.02	-0.02
113	0.01	-0.01	-0.02

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