REMOVAL OF BUTYLENE AND PROPYLENE GAS USING BIOFILTRATION

by

MADHU RANI

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ABSTRACT

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Madhu Rani, M.S.

University of Texas at Arlington, 2009

Supervising Professor: Melanie Sattler

Air pollutants are produced from a variety of anthropogenic activities such as food production, wastewater treatment plants, painting, industrial activities, and biomass combustion. Such pollutants are becoming a cause of concern worldwide because of their harmful effects on ecosystems, human health, and the atmosphere. One technology for treatment of these hazardous, odorous, and ozone-forming compounds is biofiltration. Biofilters are relatively inexpensive to install and operate, and can achieve high pollution removal efficiencies.

This research was carried out to determine the removal efficiency of pollutants propylene and butylene using biofilter technology. In a biofilter column, air is passed through a packed bed of media. Pollutants diffuse into the biofilm layer and are then degraded by microorganisms such as fungi and bacteria present in the biofilm. A mixture of compost and hard wood chips was used as media in this research, in 80:20, 50:50, and intermediate ratios by volume at room temperature of 73°F. Initially, the pH of the media was about 7.12 for both gases but it increased slightly to 7.76 in 10 weeks and 7.71 in 11 weeks for butylene and propylene gas, respectively. The moisture content was 40-100% throughout the experiment. The biofilter was effective in removing 100% of the butylene and propylene in 12 weeks. The maximum observed elimination capacity was 807 g/m^3-hr and 13.6 g/m^3-hr for propylene and butylene, respectively, for concentrations ranging from 91 ppm to 643 ppm for butylene and 2.95 x 10^4 ppm to 4.22 x 10^4 for propylene.

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CHAPTER 1

INTRODUCTION

1.1 Removal of Odorous and Hazardous Compounds from Air Streams

Hazardous and odorous compounds are present in the atmosphere, produced from industries such as animal and food product industries, wastewater treatment plants, painting facilities, and biomass combustion. The pollutants produced from these industries are becoming a cause of concern worldwide because of their harmful effects on ecosystems, human health, and the atmosphere. The treatment of these hazardous and odorous compounds is necessary to restore the environmental conditions and reduce nuisance to people. Concentrations should not exceed federal and state ambient air quality standards near these emission sites.

Hazardous and odorous pollutants can be treated by several physical and chemical technologies such as carbon adsorption, chemical scrubbing, incineration, and biofiltration. High removal efficiency of pollutants such as volatile organic compounds and hydrogen sulfide can be achieved by biofilters under proper conditions. Biofilters are most commonly used for highly soluble organic compounds with low molecular weight, such as alcohols, aldehydes, and ketones, and gaseous pollutants, such as ammonia, hydrogen sulfide, styrene and gasoline components benzene and toluene. The operating costs tend to be quite low for biofilters.

1.2 Overview of Biofiltration Technology

In biofiltration, the air is passed through a packed bed of media. Biofilters use microorganisms, which are present in the media, for purification of pollutant gases. Pollutants diffuse into the biofilm layer and are then degraded by microorganisms such as fungi and bacteria of the biofilm. The hazardous and odorous gases can be converted into innocuous compounds such as water and carbon dioxide by the action of microbes. It is a cost effective solution for treating large volume of gases, and there are often no pollution products which form after passing through the biofilter. For example, the odor of hydrogen sulfide and ammonia can be reduced in a biofilter by 100%. (Galera et al., 2008). It is important to maintain the humidity of the system so that the microbes have sufficient water. Hence, air may be passed through a water column before passing through the media to supply humidity. Biofiltration is one of the most effective treatment methods for low concentration polluted air streams. Biofilters also have low capital and operating costs. The cost of making a biofilter is $100-$250 per 1000 cfm and maintenance cost is $5-$10/1000 cfm per year. (Nicolai & Schmidt, 2009). There are typically no health and safety issues related to microbial emissions, pollutant side effects or dust emissions observed in biofilters.

Different gases can be treated in biofilters using different media. The different types of media contain many varieties of microorganisms which are responsible for degradation of gases. Natural media, such as compost, woodchips, peat, vegetable mulch, and synthetic media, such as polypropylene, are available in the market. The lifetime of synthetic media is greater than the natural media; these media are available in the market with multiyear guarantees. The media are present in different sizes and this affects the air flow and biofilm surface area**.** Microorganisms are already present in the natural media or are inoculated along with nutrients in the synthetic media. Compost is often used as organic media due to its microbial population and inherent nutrient properties. Rock wool is an inorganic packing media which has good water holding properties, buffering capacity, high porosity, large surface area and high chemical resistance. Composite media, such as rock wool and compost, has both organic and inorganic media, which has a high potential microbial population with less compaction and pressure drop tendency in the biofilter bed. A similar effect can be achieved by mixing compost with a bulking agent, such as wood chips. Compost shows lesser pressure drop with wood chips as compare to a pure compost bed.

The removal efficiency and degradation rate of gases vary in different types of media under different conditions such as pH, temperature, moisture, and pressure. The pH may vary due to formation of intermediate products such as ammonia or sulfuric acid. The overall effectiveness of the biofilter is mainly dependent on the properties and characteristics of the support medium, such as porosity, degree of compaction, water retention capabilities, and the ability to host microbial populations.

1.3 Research Objectives

The primary objectives of this research were to determine the removal efficiency of propylene and butylene gases using biofiltration for different mixtures of compost and woodchips media. Mass loading and maximum observed elimination capacity, necessary for design, were determined for propylene and butylene gases by developing curves of elimination capacity vs. mass loading.

1.4 Report Organization

Chapter 2 explains the literature review for the specified research objectives to be achieved.

Chapter 3 describes the research methodology followed these experiments.

Chapter 4 describes the results and discussion.

Chapter 5 gives conclusions and recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Incomplete combustion of fossil fuel produces hydrocarbons, such as ethylene, propylene and butylene. According to EPA, 47% of the hydrocarbons emissions originate from on road and off road vehicles (Clean air Systems, 2009). When these hydrocarbons react with nitrogen oxides (NO_x) in the presence of sunlight, ozone can form, which is a serious cause of air pollution and the main component of photochemical smog. Hydrocarbons cause many serious health hazards, such as acute respiratory problems, headache, dizziness, brain damage, coma, reduced cardiovascular function, and severe tissue damage. Many volatile organic compounds (VOCs) are also odor-causing compounds.

Propylene is the world's second largest petrochemical commodity. Propylene is used for the production of polypropylene, acrylonitrile, acrylic acid, acrolein, plasticizer oxo alcohols, propylene oxide, cumene, and acetone. Polypropylene is used in plastics and fibers composing over one third of U.S. consumption. In 1994, propylene was ranked seventh among the top 50 chemicals produced domestically (C & EN, 1995). Propylene is produced as a by-product in petroleum refining, olefin plant steam crackers and combustion of organic matter, such as biomass burning, motor vehicle exhaust, and tobacco smoke. Human beings are exposed to propylene by inhalation of this gas. The annual statewide emissions from facilities reporting under the Air Toxics Hot Spots Act in California, based on the most recent inventory, were estimated to be 696,350 pounds of propylene (CARB, 1999).

Butenes are volatile organic compounds (VOC). High levels of butene exposure can cause dizziness. Tissue freezing, severe cold burn, and/or frostbite may occur due to skin or eye contact in the liquid state of butene. Butene is primarily used as a feedstock to produce industrial chemicals and gasoline blending components. Butenes are manufactured as part of the catalytic cracking or steam cracking processes. Butenes are highly flammable.

Houston/Galveston/Brazoria (HGB) is one of Texas' regions non-attainment for ozone. Recent HGB field studies have found that the highly reactive VOCs (HRVOCs) ethylene, propylene, butylene, and 1,3-butadiene play a critical role in ozone formation. Localized regions with high concentrations of HRVOCs have been found to be frequently associated with rapid ozone formation, leading to exceedances of the ozone standard (Allen et al., 2004). Texas Commission on Environmental Quality (TCEQ) has accordingly adopted regulations to control HRVOC emissions in HGB, which will impact petroleum refineries and chemical manufacturing facilities (TCEQ, 2005).

Besides being important in Houston/Galveston/Brazoria, HRVOCs are also of concern in Texas other ozone non-attainment areas, Beaumont/Port Arthur (BPA) and Dallas/Fort Worth (DFW). Propylene and butylene rank 2 and 5, respectively, among HRVOCs released by HGB, BPA, and DFW, according to TCEQ and Environmental Protection Agency data. Control of HRVOCs may also be useful in Texas' near-nonattainment ozone areas, to ensure that they remain in attainment as population growth occurs in the future.

Unsaturated hydrocarbons such as butene and propylene are of concern to TCEQ because they help in forming ozone in the atmosphere. Unsaturated hydrocarbons are reactive because of rapid addition of the hydroxyl radical (OH°) to C=C double bonds. Ozone production can be ranked using incremental reactivity, kinetic activity, and mechanistic activity of VOCs. Incremental reactivity of hydrocarbons is shown in Figure 2.1, which shows high incremental reactivity of hydrocarbons such as propene. Incremental reactivity is the amount of O_3 formed per unit of VOC added or subtracted from the VOC mixture in a given air mass.

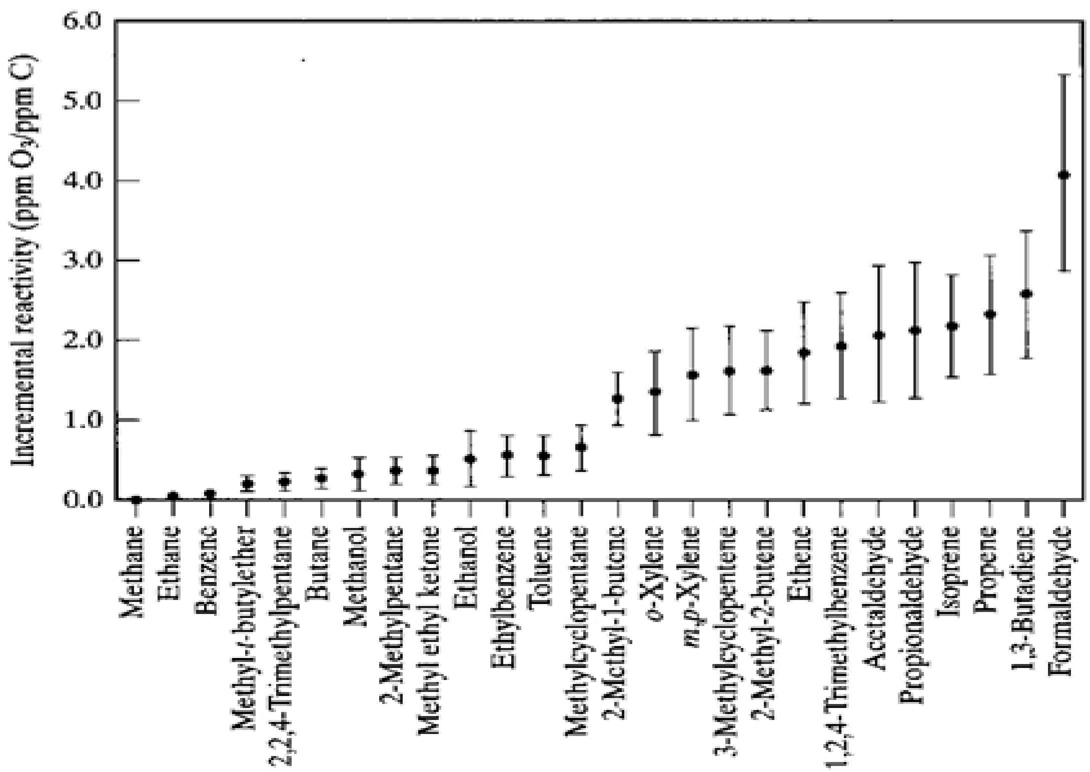

Figure 2.1 Hydrocarbon Reactivities (Russel et al.,1995)

Kinetic activity is the fraction of the VOC that reacts to produce peroxy radicals and mechanistic activity is the number of molecules of NO converted to NO_2 and the number of OH°

radicals and other products generated. Incremental reactivity, kinetic activity, and mechanistic activity of VOCs of propene is higher than other VOCs as shown in Figure 2.2 (Carter,1991).

Compound	Incremental Reactivity (mol O_3/mol C)	Kinetic Reactivity (fraction reacted)	Mechanistic Reactivity (mol O_3/mol C)
Carbon monoxide	0.019	0.043	0.45
Methane	0.0025	0.0016	1.6
Ethane	0.030	0.049	0.61
Propane	0.069	0.21	0.34
n-Butane	0.124	0.37	0.34
n-Octane	0.081	0.75	0.107
Ethene	0.77	0.81	0.95
Propene	0.82	0.97	0.85
trans-2-Butene	0.81	0.99	0.82
Benzene	0.023	0.21	0.111
Toluene	0.106	0.64	0.17
m-Xylene	0.50	0.96	0.52
Formaldehyde	1.26	0.97	1.30
Acetaldehyde	0.70	0.92	0.77
Benzaldehyde	−0.29	0.95	−0.31
Acetone	0.055	0.058	0.95
Methanol	0.147	0.16	0.93
Ethanol	0.19	0.44	0.42
Isoprene	0.70	1.00	0.70
α-Pinene	0.21	0.99	0.21
Urban mix[a]	0.28		

Figure 2.2 Calculated Incremental Reactivities and Kinetic and Mechanistic reactivities for CO and Selected VOCs for maximum Ozone formation Conditions, based on Scenarios for 12 Urban Areas in the Unites States (Carter,1991).

The industrial emissions of odorous compounds reduce air quality, and can cause environmental pollution and health hazards. Production of odor, gas, and dust from livestock and poultry facilities produce trouble to neighbors and the concentration can exceed federal and state ambient air quality standards. Production of odorous gas mixtures from wastewater treatment plant and industries, such as pulp and paper manufacturing and fuel treatment, are a major source of pollution due to nuisance associated with them. Olfactory disorders can occur due to exposure to odorous compounds in the ambient air over a long period. These odorous compounds, emitted from industries and wastewater treatment plants, should be converted into non-odorous compounds.

There are many methods to control hydrocarbons/volatile organic compounds and other odor-causing compounds by physical methods (dilution, physical adsorption, coverage, masking), chemical methods (scrubbing, oxidation, incineration), biological methods (biofiltration), and combined methods (bioscrubbers). A comparison of advantages and disadvantages of various VOC control methods is given in Table 2.1. The comparison of various technologies for VOC control, indicating the general ranges of operation for which they are best suited, are given in Figure 2.3 (Cooper and Alley, 2002).

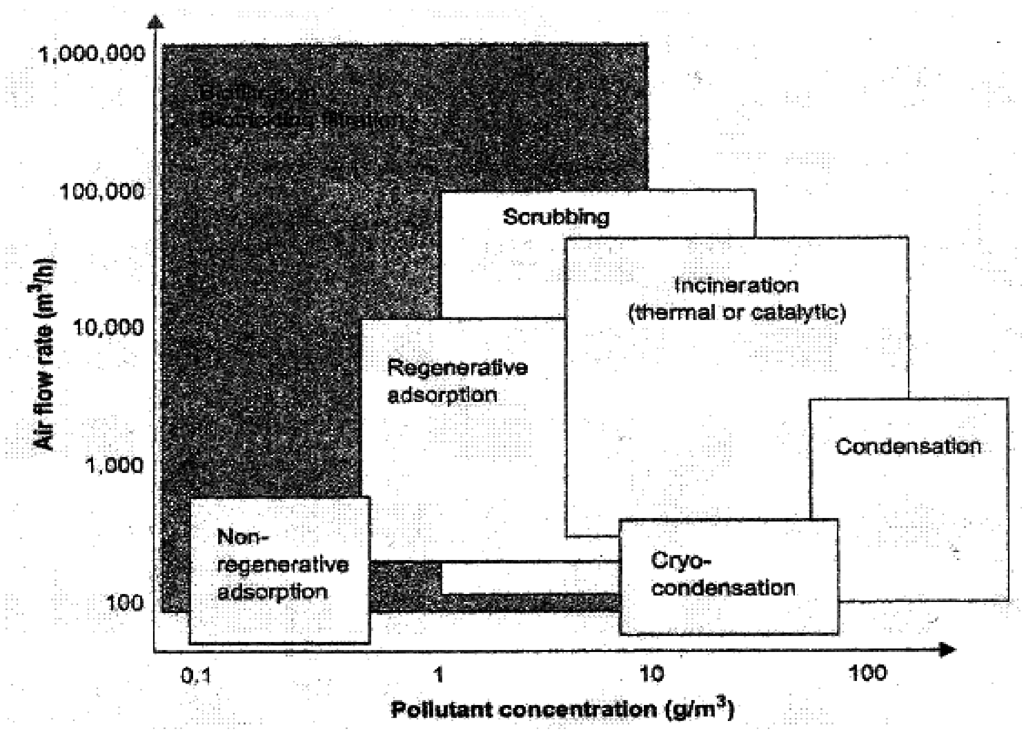

Figure 2.3 Range of Suitability for VOC Control Technologies

Table 2.1 Comparison of Waste Gas Control Technologies (Devinny, Deshusses, & Webster, 1999)

Control Technology	**Advantages**	**Disadvantages**
Biofiltration	• Low operating and capital costs • Effective removal of compounds • Low pressure drop • No further waste streams produced	• Large footprint requirement • Medium deterioration of media will occur • Less suitable for high concentrations • Moisture and pH difficult to control • Particulate matter may clog medium • Leachate may need treatment • Not suitable for all compounds (some may be toxic to microbes and some may not dissolve easily in water)

Table 2.1 – Continued

Biotrickling filters	• Medium operating and capital costs • Effective removal of compounds • Treat acid-producing contaminants • Low pressure drop	• Clogging by biomass • More complex to construct and operate • Further waste streams produced
Wet scrubbing	• Low capital costs • Effective removal of odors • No medium disposal required • Can operate with a moist gas stream • Can handle high flow rates • Ability to handle variable loads	• High operating costs • Need for complex chemical feed systems • Does not remove all VOCs • Water softening often required • Nozzle maintenance often required

Table 2.1 - Continued

Carbon adsorption	• Short retention time/small unit • Effective removal of compounds • Suitable for moderate loads • Consistent, reliable operation	• High operating costs • Moderate capital costs • Carbon life reduced by moist gas stream • Creates secondary waste streams
Incineration	• System is simple • Effective removal of compounds • Suitable for very high loads • Performance is uniform and reliable • Small area required	• High operating and capital costs • High flow/low concentration • Not cost effective • Creates a secondary waste stream • Scrutinized by public

2.2 Biofiltration Technology

"The fundamental principle of biological air pollution control is that gaseous pollutants are utilized by microbes as a food or energy source, and are destroyed in the process, being converted into innocuous metabolic end products (CO_2 and H_2O)"(Cooper and Alley, 2002). The design and construction of the control technology should give maximum contact between the contaminated air and the liquid phase, or the biofilm. In addition, the healthy microbe's population should be maintained in the media. High removal efficiency with low operating cost can be maintained through a biological control system for years by using the right approach. One such treatment technology is biofiltration. Biofilters have proven to be one of the most economical and effective methods for treating emissions from wastewater and solid waste throughout the twentieth century. In biofiltration, a humid, contaminated air stream is passed through a porous support material on which pollutant degrading cultures are immobilized. (Devinny, Deshusses, Webster, 1999). Then, the microorganisms consume these polluted air streams to convert them into innocuous metabolic end products, such as carbon dioxide and water.

$$\text{Organic pollutant} + O_2 \rightarrow CO_2 + H_2O + \text{Heat} + \text{Biomass}$$

Dilute high flow waste gas streams containing volatile organic compounds or odorous compounds have been treated successfully in biofilters.

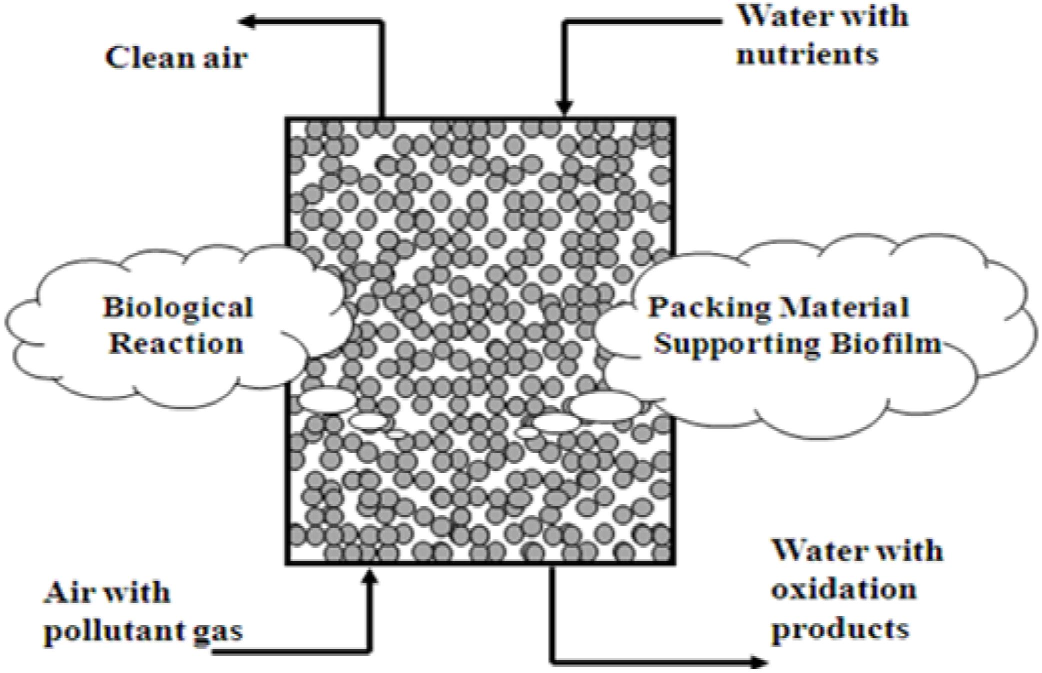

Figure 2.4 Schematic of a Biofilter

The following is a brief timeline of the development of biofilters (Anit & Artuz, 2009):

1923 -- Biological methods were proposed to treat odorous emissions.

1955 -- Biological methods were applied to treat odorous emissions in low concentrations in Germany.

1960's -- Biofiltration was used for the treatment of gaseous pollutants both in Germany and US.

1970's -- Biofiltration is used with high success in Germany.

1980's -- Biofiltration is used for the treatment of toxic emissions and volatile organic compounds (VOCs) from industry.

1990's -- Today, there are more than 500 biofilters operating both in Germany and Netherlands and it is spreading widely in US.

2.3 Basic Factors for Biofiltration

2.3.1 General

Several factors are important in the design and operation of biofilters, such as identifying the concentration and type of contaminants in the air stream, finding the correct microbial population, selecting a compatible medium, maintaining adequate moisture, sizing the bed to provide adequate residence time for the given airflow rate, and controlling pH, nutrient levels, and temperature in the bed. Biofilter technology is best suited for large volumes of gases with low concentrations of pollutant. The operating costs are very reasonable as compared to other alternatives as shown in Figure 2.5.

Technology	Cost per million cubic feet air
Incineration	$ 130
Chlorine	$ 60
Ozone	$ 60
Activated carbon with regeneration	$ 20
Biofiltration	$ 8

Technology	Operating costs	
	Fuel/chemical consumption	Power
Incinerator	$ 15 per cfm	Negligible
Wet chemical scrubber	up to $ 8 per cfm	1 W per cfm
Biofilter	0	0.6 W per cfm

Figure 2.5 Cost of Biofilter Operation Compared to Alternatives (Ambio Biofiltration LTD, 2009)

There are several factors to consider in design of an effective biofilter.

2.3.2 Space Constraints

Space at a site is an important concern during design of a biofiltration system. Biofilters can be designed with stacked beds to minimize space requirements and they can also be run in parallel.

2.3.3 Chemical Constituents and Concentrations

Low molecular weight compounds, such as alcohols, aldehydes, and ketones; odorous gases, such as H_2S and NH_3; and additional compounds, such as styrene and gasoline components like benzene and toluene, have been successfully treated in biofilters. (Cooper and Alley, 2002). Deshusses and Johnson (2000) concluded that removal efficiency of compounds follow a sequence in biofilters: alcohol (best)→esters→ketones→aromatics→alkanes (worst). This sequence also tends to be in order of decreasing solubility in water (increasing Henry's law coefficients). Pollutants with small values of Henry's law constant are easier to degrade, while pollutants with high values of Henry's law constant are slower to degrade.

Analysis of chemical constituents and their concentrations are required to determine if biofiltration is a plausible alternative. Biofilters perform best when treating low concentrations of compounds (<1000 ppm) (Anit and Artuz, 2009). Some chemicals biologically degrade at low rates, such as chlorinated compounds, which require units to be oversized. Some contaminants may be toxic to microbes.

2.3.4 Residence Time

Residence time represents the amount of time the microbes are in contact with the contaminated air stream, and is defined by (Void Volume/Volumetric Flow Rate). Consequently, longer residence times produce higher efficiencies; however, a design must minimize residence time to allow the biofilter to accommodate larger flow rates and to end up with a reasonable biofilter size. For most biofilters, residence times range between 30 seconds to 1 minute (Anit & Artuz, 2009).

2.3.5 Pressure Drop

Pressure drop across the biofilter reactor vessel should be minimized since an increase in pressure drop requires more blower power and can result in air channeling through the media. Pressure drop is directly related to the moisture content in the media and the media pore size. Increased moisture and decreased pore size result in increased pressure drop. Consequently, media filter selection and watering is critical to biofilter performance and energy efficiency.

2.3.6 Maintenance

The operation and maintenance of the biofiltration system would require weekly site visits during initiation of operations for emission control. However, after acclimation and all system problems are resolved, the frequency of site visits could be reduced to biweekly or monthly (Anit & Artuz, 2009).

2.3.7 Moisture Content

The amount of water in the biofilter is the most important factor under the control of the operator. Increases and decreases of water quantity or difficulties in controlling moisture content are the most common reasons for poor biofilter operation. High amounts of moisture will cause clogging, increase the head loss in the biofilter, and eventually wash away nutrients, while low moisture can dry out the bed and cause cracking of the filter bed. The microorganisms will not be activated without moisture. Presence of moisture affects the transfer of contaminant from the air and the physical properties of the medium (Devinny, Deshusses, Webster, 1999). The optimal range of moisture content is 40-70%. However, it can vary from media to media. The optimum ranges moisture for compost and peat are 40-50% and 60-75%, respectively. It is desirable to have media with a high water-holding capacity, and typical media may be 40 to 80 % (by weight) when it is saturated (Devinny, Deshusses, Webster, 1999).

In a particular process, excess and low amount of moisture can cause shrinking and swelling of the media and can also strain the microbial activity. Shrinking and swelling can cause short circuiting of air flow. These problems are found mostly in compost and less in soil based media.

2.3.8 pH

pH is an important factor for the growth of microbes in the biofilter. Each species of microorganisms grow at an optimum range of pH. Microorganisms can die if the pH moves outside this range. Some species do well at high pH and some at low pH, but species tolerant of moderate pH are probably more common. Rapid variation in pH can kill the microorganisms. A pH range of 5 to 8 is recommended as optimal; a pH less than 5 typically decreases the activity of microbes (Cooper and Alley, 2002). However, some sulfur reducing bacteria can survive at pH less than 5. Dolomite, crushed shells or lime can be added to maintain the pH when the end products cause acidity in the media. Neutral pH is an optimum range for VOCs and other organic compounds.

H. Taghipour et al. (2008) reported removal of ammonia from a waste gas stream in a bench-scale biofilter. Due to the presence of nitrate, the pH and alkalinity dropped in the packing material, and nitrifying bacteria reduced the concentration of ammonium in the column. The amount of ammonia and nitrate in the media increased and decreased, respectively. This shows the degradation of ammonia by nitrifying bacteria in the biofilter under steady state condition. The population of nitrifying bacteria was increased from 5.6×10^4 cell/g wet material in the bed column to 2.8×10^8 cell/g wet material (p. 202). The alkalinity of the medium was also decreased due to the nitrification process, and pH was maintained throughout the experiment due to nitrification. A mixture of compost, sludge and pieces of hard plastics gave a suitable environment for maintaining the pH and better conditions for nitrifying bacteria than inorganic material (p. 202).

Pandey et al. (2007) concluded that NH_3 produced by the degradation of pyrimidine increased the pH of the media. However, ammonia transformed into nitrates and nitrites due to buffering capacity of compost. As a result, the pH does not rise in the system due to formation of nitrates and nitrites.

2.3.9 Temperature

Microbial activity and biofilter performance are strongly dependent on the temperature of the system. The optimum temperature range for good microbial activity in the biofilter is above 50°C and below 100°C. The microbial activity is reduced drastically if the temperature falls below 50°C, and temperatures more than 100°C kill the microbial system. Ideally, microbial activity should double for every 10°C rise in temperature, but research indicates that monitoring the temperature of the system is not required for biofilters.

2.3.10 Humidification of the Gas Stream

Humidification of the gas stream is also an important parameter in operating a biofilter. A humidification chamber can be used for the saturation of the gas stream in the short time of the gas stream passing through the humidification chamber of before reaching the biofiltration column. This can be done by spraying water downwards while the gas flows upwards, or flowing water down through a packed tower. In both of these cases, however, more water than that needed for an intimate contact of air-water is needed in the tower. To avoid this, a chamber can be filled with water and arrangement made to pass the gas stream through the water.

2.3.11 Microorganisms

Microbiological activity converts pollutants to harmless products in biofilters and they have high tolerance to changes in pH, moisture content, and nutrient supply. Even an ill suited microbial community can better treat a contaminant when exposed to it over a long period of time. A series of species of genus *Thiobacillus* is capable of oxidizing hydrogen sulfide successfully in environments of lower pH (Islander et al., 1991). Below pH 3, systems are often dominated by *Thiobacillus thiooxidants*, which oxidizes sulfide rapidly. T. *Thiooxidants* is not inhibited until the pH falls below 1(Devinny, Deshusses, Webster, 1999).

E. Jeong, M. Hirai, & M. Shoda (2008) reported the removal of o-xylene in a biofilter which contained Biosol as a packing substance. They inoculated the o-xylene degrading microorganism *Rhodococcus* sp. BTO62 in biofilters to degrade the o-xylene and mono-ring aromatic hydrocarbons, such as benzene, toluene, ethyl benzene, m-and p-xylenes, and styrene. They tested the inoculation of bacterium under sterile and non-sterile conditions (p. 140).

Many industries, such as pulp and paper factories, rayon and molasses based distilleries, produce Diethydisulphide (DEDS) with an average concentration of 10^{-9} mg/m^3 at 25°C. DEDS containing waste gas was passed through biofilters which contained compost, wooden chips, and DEDS destroying microorganisms (p. 131). Conventional methods were applied for obtaining DEDS destroying microorganism DEDS-S1 and DEDS-S2 from sediments of a stream containing sewage. These microorganisms, known as Hyphomicrobium sps., were transferred into media at the beginning of the experiment. As a result, the removal efficiency obtained was around 94% (Pandey, S. N. Mudliar, & S. Borgaokar, 2009).

2.3.12 Media

A porous solid media is used in biofilters to support microorganisms and expose the biofilm to the contaminants in the air flow. There are different types of media, such as organic materials, natural inorganic solids, or entirely synthetic. Some media contain microorganisms naturally and others must be inoculated with microbes. Natural media is often better than synthetic media because the biofilter works more efficiently for a longer time using naturally occurring environment compared to an engineered environment (Bohn 1996; Devinny 1999; Brock 1997).

A medium ideal for use in biofiltration process should be able to (1) support a large diverse microbial population, (2) provide pH buffering capacities, (3) retain the microbes during shut-downs by providing them with alternative food, hence bearing assimilable organic content (4) be physically stable, (5) have a low pressure drop, (6) hold water content to nurture the microbial population, (7) provide sufficient sorption capacity for the pollutant (Schmidt et al., 2004; Williams and Miller, 1992a; Leson, G. and Winer, 1991). Also important are the physical characteristics like particle size, cross-sectional depth, surface loading rate per square foot, porosity and desired service life (Garrepalli, 2006).

Different types of natural media are described below:

Compost: Compost contains a large number of different microorganisms. It has good moisture retention properties, near neutral pH, buffer capacity and suitable organic content. Compost is mixed with different proportions of bulking agents, such as wood chips and perlite, to avoid bed compaction and high pressure drop (Devinny, Deshusses,Webster, 1999). Previous research showed that there is no difference in maximum removal efficiency and pH of aged and fresh compost and a mixture of compost and wood chips (Nawal, 2004).

Peat: Moisture control for peat is difficult due to acidic and hydrophobic nature of peat. Peat requires inoculation and nutrient supply due to lesser amounts of microorganisms and nutrients, respectively. Peat was commonly used in 1980s due to low pressure drop, but it has been largely replaced by compost due to the good performance of compost in the long run.

Soil: Soil is inexpensive and easily available. Soils are naturally hydrophilic and are less difficult to rehydrate than compost and peat. Soils do not have the tendency to aggregate, but their permeability remains low; therefore, soil beds have large pressure drops and often develop preferential paths for air flow, isolating portions of the biofilter (Devinny, Deshusses, Webster, 1999). Hence, soil media requires large area biofilters.

Wood chips: Wood chips can be used as a bulking agent with different media or can be used alone as a media. Wood chips contain less nutrients compared with compost. Wood chips facilitate homogenous air flow and prevent bed compaction. In some cases, wood chips act as a reservoir of water when the generation of heat is greater. There is no specific tree reported as better for biofilter media so far.

Perlite: Perlite does not have a good microbial population and nutrient supply like peat, but it is a good bulking agent. In addition, perlite can be used alone as a biofilter media.

Synthetic media: Synthetic media does not contain a microbial population or nutrient supply. Hence, these must be added. The constant supply of nutrients and water can be a major problem later because uncontrolled growth of biomass can occur due to the continuous nutrient supply. Synthetic media such as propylene rings require constant trickling to keep surface wet because it does not have water holding capacity.

Media Studies:

E. Dumont et al. (2008) studied the effect of a new packing material UP20, cylindrical shaped extrudate which is made up of calcium carbonate and an organic binder, in the treatment of hydrogen sulfide (H_2S) in biofilters. They used two other biofilters, one containing pine bark and another containing 80:20 ratio of pozzolan and UP20 (p. 121). They reported that pine bark was used as a packing material due to its good physical properties (low bed density) and lower price. Pozzolan is a volcanic siliceous rock that is cheap, inactive, has a lower density and good ability to hold water, with large porosity and specific surface area (p. 121). The three biofilters were investigated for the treatment of H_2S at different rates of loading. It was easy to form a biofilm on UP20, as it gives nutrients for developing biofilm on pozzolan. Also, UP20 layer can be easily placed and removed because it is present on the top of the pozzolan layer (p. 127).

M. M. Galera et al. (2008) reported the change in the pollutant concentration when a mixture of gases passes through the biofilter simultaneously. They passed a tri-component mixed gas system through BRC1 and BRC2 biofilters containing NH_3, H_2S and toluene at around 50-55 ppm each. The packing media was rock wool, a fibrous material which has large surface area and high chemical persistence, good water holding and buffering capacity, and compost, which has a diverse microbial population and inherent nutrients. They mixed the rock wool and compost in a 70:30 weight ratio. 30 ml of PVA solution and a solution of 7.5 g betonite in 15 ml water were mixed in the 130 g rock wool-compost mixture to increase the absorption capacity.

2.4 Advantages and Disadvantages of Biofiltration

Advantages

- Low operating cost, low maintenance requirement, low chemical usage, and no combustion source.
- Removal efficiency more than 90% for low concentrations of pollutants (< 1000 ppm), including some of the pollutants are listed in Clean Air Act as hazardous air pollutants.
- Biofilter systems can be designed for any industry. Biofilters can be designed with stacked beds to minimize space requirements and can also run in parallel.
- Different media, microbes and operating conditions can be used to tailor a biofilter system for many emission points.
- The end products of biofilter do not require further treatment and disposal.

Disadvantages

- Biofiltration cannot degrade organic compounds which have low absorption or degradation rates. This is true for chlorinated VOCs.
- Biofiltration cannot treat very high temperature air streams.
- Large experimental set up.
- Limited bed life (3-5 years).
- High chemical emissions of contaminants would require large biofilter units or open areas to install a biofiltration unit.
- Microbes may take several weeks or months to acclimatize in biofilters, especially for VOC treatment.
- Leachate may need treatment.
- Pressure drop may create problems in the biofilter system.
- Used media may contain toxic substances which are harmful to microbes and other exposed living organisms. Hence, it should be disposed of properly.

2.5 Previous Research and Case Studies

A detailed review of the literature clearly indicated the fact that no research was focused on biofiltration of propylene and butylene gas. These compounds are important because they are highly reactive in forming ozone. However, many researchers have conducted studies on hydrocarbons. Listed below (as shown in Table 2.2, Table 2.3 and Table 2.4) are articles which researched biofiltration as a control technology for various hydrocarbons, reduced sulfides and nitrogen-containing compounds. Study of research on volatile organic compounds guided our study with good attention to detail and right application of operational and design parameters.

Table 2.2 List of Articles that Studied Removal of Organic Compounds using Biofiltration

Author(s)	Year	Compound(s) Tested	Media	Removal Efficiency	Conclusion	Comments
Delhomenie et al.	2003	Toluene Xylene TMB	compost	Toluene- 95% Xylene- 80% TMB- 70%	The removal efficiency decreased in the presence of nitrogen.	
Jeong, Hirai, & Shoda	2008	O-xylene	Biosol	90 %	Composite mixture of organic and inorganic media gives better removal efficiency.	

Table 2.2- Continued

Galera et al.	2008	NH_3, H_2S, & Toluene	Rock Wool, and Compost	NH_3 – 100 % H_2S - 100 % Toluene >97 %	Simultaneous removal of H_2S and NH_3 was not negatively affected by the increase in toluene loading	
Auria, Aycaguer, & Devinny	1998	Ethanol	Peat	-	With water content less than 49%, there was a drastic decrease in the elimination capacity.	Drying of peat caused it to loose its treatment capacity.

Table 2.3 List of Articles that Studied Removal of Sulfides using Biofiltration

Author	Year	Pollutant tested	Media	Removal Efficiency	Conclusion	Comments
Dumont et al.	2008	H_2S	UP20, Pozzolan, Pine bark	UP20/Pozzolan- 69 % Pine bark- 74 %	UP20 provides nutrient for developing biofilm on pozzolon.	
Pandey, Mudliar, & Bargaokar	2009	Diethylsulfide	Compost, Wood chips	94%		

Table 2.3 - Continued

Jones, Martinez, Boswell	2003	H_2S	Compost Commercial media	~ 96 %		
Singleton	1995	Hydrogen Sulfide, Methyl Mercaptan Dimethyl Sulfide Dimethyl Disulfide	peat	H_2S – 100 % CH_3SH – 65% $(CH_3)_2S$ – 21% $(CH_3)_2S_2$ – 7%	NH_3 concentrations seen in the outlet did not effect the H_2S removal.	NH_3 concentrations in the outlet were not expected.

Table 2.4 List of Articles that Studied Removal of Nitrogen Containing Compounds using Biofiltration

Author	**Year**	**Pollutant tested**	**Media**	**Removal Efficiency**	**Conclusion**	**Comments**
Y. Ding	2007	Trimethyamine	Compost, Sludge	100%		Shows pH variation due to ammonia oxidation and nitrification
Taghipour	2008	Ammonia	Compost Sludge Pieces of hard plastics	99.9 %		Maintained pH due to nitrification

Table 2.4 - Continued

Pandey et al.	2007	Pyrimidine	Compost, Woodchips	99 %		pH will be maintained due to buffering capacity of compost and transformation of NH_3 into nitrates and nitrites.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Laboratory Setup Overview

A lab scale study biofiltration system was used to remove propylene and butylene gas separately, after mixing them with air. The mixture of air and pollutant gas was passed through the humidification chamber before entering the biofilter columns. The bacterial colonies grow on the media and as the pollutant gas passes through them; they grow and reproduce by consuming the propylene and butylene gas. The experimental set up consisted of four columns, three of which act as biofilters, filled with 80:20, 50:50, and intermediate ratios of compost and wood chips, and one column acts as a humidification chamber. The set up also contains Teflon flow meters for gas, air flow meter, air cylinder, gas (propylene and butylene) cylinders, Teflon fittings and tubings for connections, and perforated plates for four PVC columns. The experimental set up is shown in Figure 3.1 and schematic diagram of the experimental set up is given in Figure 3.2.

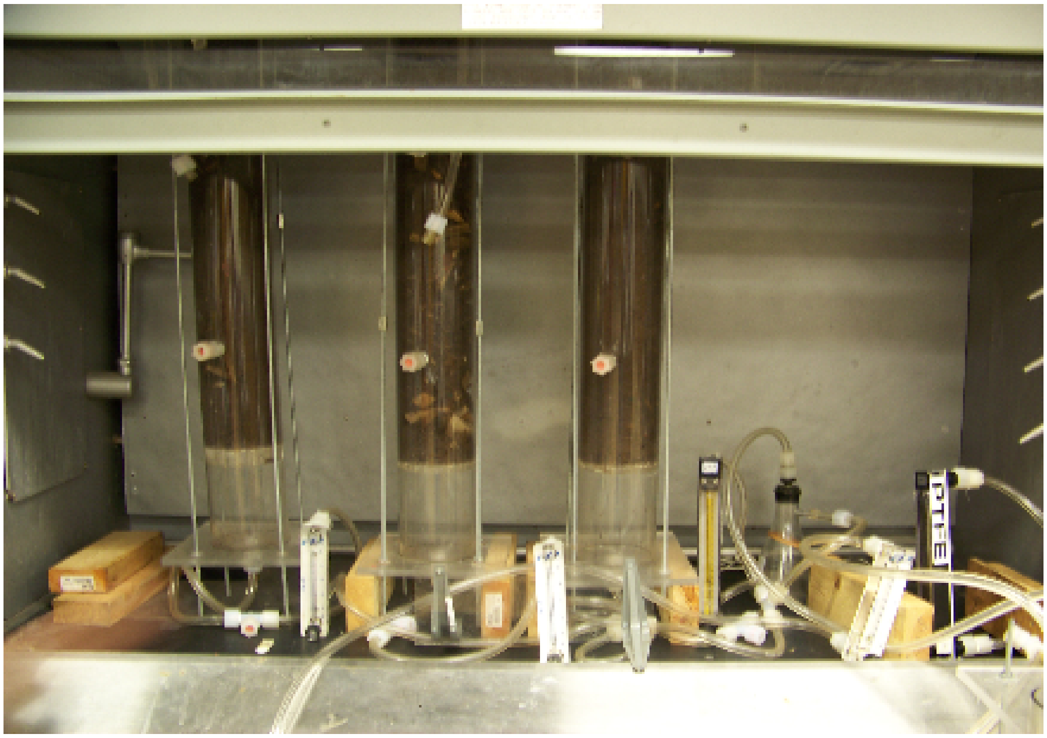

Figure 3.1 Experimental Setup with Compost and Woodchips

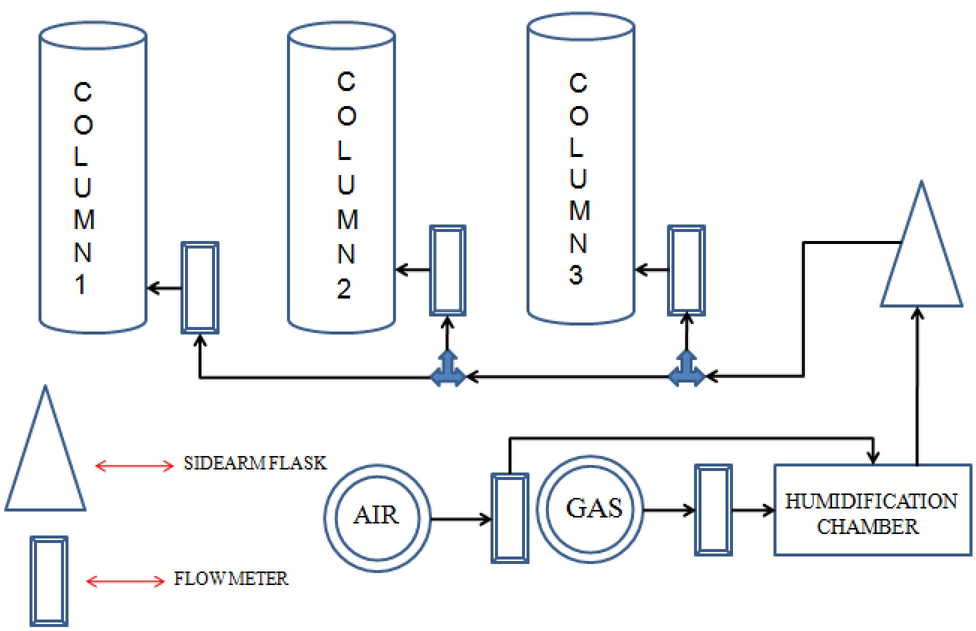

Figure 3.2 Schematic Diagram of the Biofilter

3.2 Details of Experimental Setup

3.2.1 Biofilter Columns

Transparent PVC columns were purchased from Regal Plastics, Fort Worth, TX. The biofilter columns are 3 ft in height and 4-1/4" in inner diameter. The lower ends of the columns were fitted with 8x8" square plates, with an O-ring groove in the middle, with a ½" National Pipe Thread to fit the column. The O-rings are used to make the system air-tight at the bottom. A perforated plate is also fitted at a distance of 5" from the end plate to distribute the gas uniformly throughout the medium. The dimensions of the perforated plate are ½" thick and 4-1/4" in diameter and the diameter of the holes is 3/32" in diameter (Garrapalli, 2004). The physical characteristics of the experimental biofilters are summarized in Table 3.1.

Table 3.1 Summary of Physical Dimensions of Experimental Biofilters

Column No.	**Height (inch)**	**Diameter (inch)**	**Volume (cubic feet)**	**Temperature (°F)**
I, II, III	28	4-1/4	0.23	75

3.2.2 Gas Cylinders, Air Supply, and Regulators

The butylene and propylene gas were ordered from Matheson Tri Gas, Basking Ridge, NJ. The butylene gas has initial pressure 23 psig at 70°F, net weight 16 lb, tare weight 66.8 lb, gross weight 82.8 lb, valve & outlet CGA 510 BR, CAS Nbr 106-98-9. The propylene gas has initial pressure 133 psig at 70F, net weight 13 lb, tare weight 64.9 lb, gross weight 77.9 lb, valve

& outlet CGA 510 BR, CAS Nbr 115-07-1. The biofilter inlet butylene and propylene gas concentrations ranged from 91 ppm to 1017 ppm and 922 ppm to 70053 ppm, respectively. These concentrations were measured at the inlet points before entering through the column by gas chromatography. Each gas was mixed separately with air from the fumehood supply and then passed through the humidification chamber to achieve increased relative humidity. The gas cylinders used in this experiment are shown in Figure 3.3.

Figure 3.3 Butylene and Propylene Gas Cylinders

Gas regulators are used to see the pressure inside and outside of the cylinder. A regulator, as shown in Figure 3.4, regulates the flow of the gas inside the cylinder. The right hand side measurement circle shows the pressure inside the cylinder and the left hand side measurement circle shows the outflow pressure from the cylinder. Gas regulators are attached to needle valves to control the flow of a gas. The flow meters were regulated by flow regulators, which are made of stainless steel with an interior of Teflon coatings. This flow regulator was also connected to a needle valve so that a very low concentration of gas will pass through the biofilter. All compression fittings were fitted with Tygon tubing with the help of Teflon tape to prevent leakage.

Figure 3.4 Gas Regulator with Needle Valve

3.2.3 Humidification Chamber and Condensation Control

The mixture of air and gas was passed through the humidification chamber before entering the biofilter to maintain the moisture content of biofilter media. Moisture is an important factor for the growth of bacteria inside the biofilter columns. The humidification chamber is of same dimensions as the biofilter columns and made from PVC. The upper end plate of the humidification chamber contains two 1/8" NPT threaded holes. The mixture of air and butylene gas was passed through one hole to the bottom of the humidification chamber through a long glass tube that runs to the end of the column. In another experimental set up, end plate contains three holes. Both propylene gas and air were passed through the 1/8" NPT threaded hole to the bottom of the humidification chamber through two different long glass tubes that run to the end of the column. This provides maximum gas contact with water. The water was refilled in the column using the pipe which is attached to the hole. Two stop cocks were attached through the length of the column to prevent the breakage from high pressure. These cocks were also helpful for cleaning and refilling of water after every run.

Figure 3.5 Humidification Chamber

Condensation was noticed in the biofilter system due to continuous running of experiment for many days. Hence, the gas flow, flowing from humidification chamber to flow meters attached to biofilter columns, was connected through side arm flask to avoid the condensation. Then, mixture of air and gas was passed through the flow meters to the biofilter column after passing through the side arm flask.

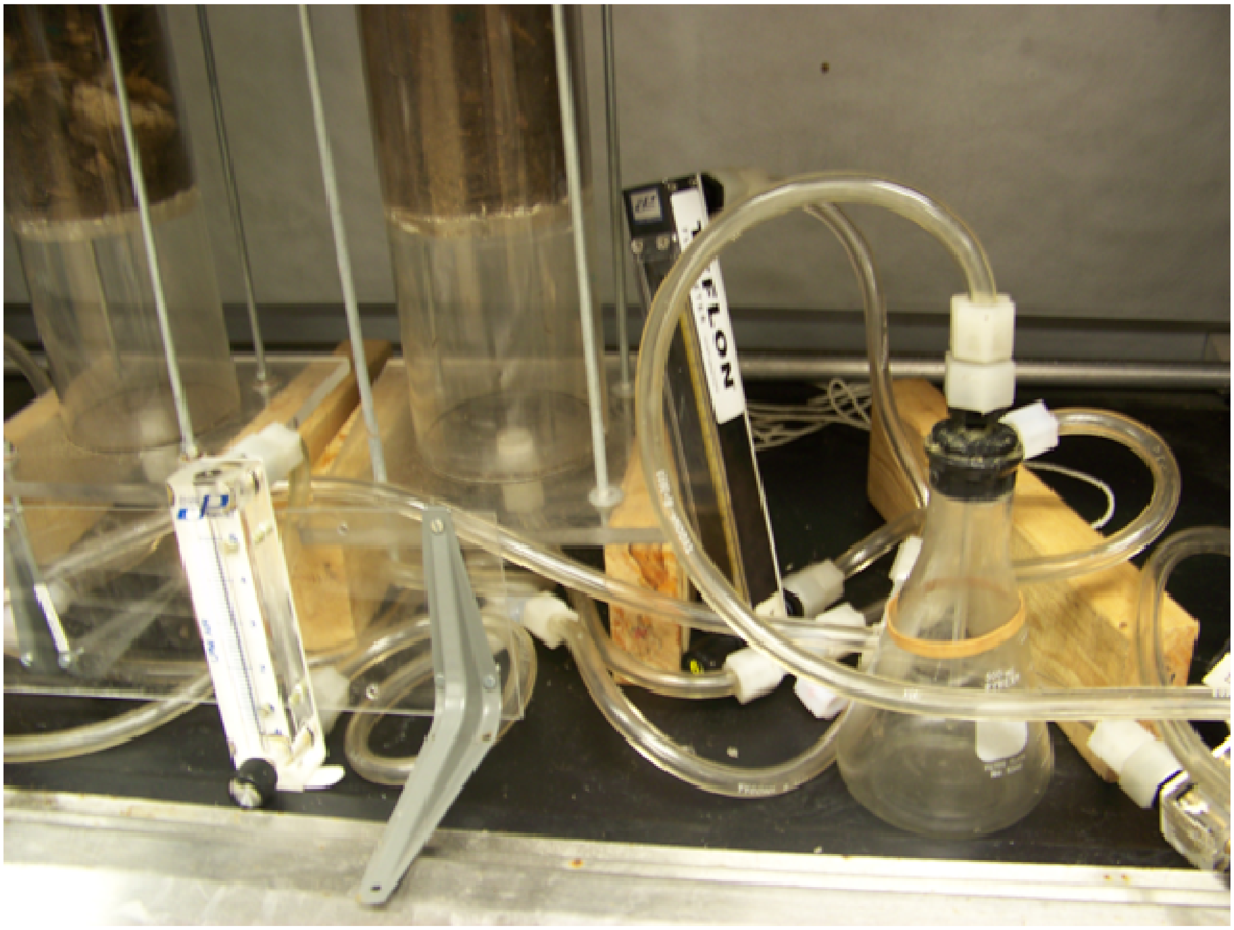

Figure 3.6 Side-arm Flask Setup

3.2.4 Tubing, Connections, and Septa

Teflon tubing, Teflon tape, and various fittings like straight and T-connections were used to connect the tubing. The internal diameter of Teflon tubing was ½". Teflon tape was used to make the connections air tight. These connections and tubing were ordered from Cole Parmer, KY. The septa, which is used to close the sampling ports, were ordered from Chromatographic Research Supplies, Inc. Septa Marathon 17 mm was used in the GC. The Teflon is compatible with propylene and butylene gas and it is cheaper than other tubing materials.

3.2.5 Media and Material

Different types of media were used in the biofilter, to test the degradation rate of propylene and butylene gas: natural compost and hard wood chips. Compost alone may produce some problems, such as compaction and channeling. These problems can be prevented by using a mixture of compost and woodchips. Different ratios of wood chips and compost were used in three columns. 80:20 ratios and 50:50 ratios of compost and woodchips, by volume, were mixed in a bucket before filling the column. An intermediate but unquantified mixture was used in the 3rd column; the ratio of compost to woodchips was between the 80:20 and 50:50 ratio of compost to woodchips. Replicate columns using the same compost to woodchips ratio were not tested in this research; previous research showed that replicates of 80: 20 and 50:50 ratios gave the same result (Nawal, 2004). A sample of the compost media is shown in Figure 3.7.

The bulk density of woodchips and compost used in this research were 0.499 g/cm^3 and 0.202 g/cm^3, respectively. The average length and width of woodchips was 3.24 cm and 1.23 cm. The range of length of woodchips was 5-2.6 cm and the range of width of woodchips was 2.2-0.3 cm. The average depth and weight of woodchips is 3.29 mm and 1.83 gm, and average compost size and weight are 1.45 mm (generally cubic) and 0.017 gm, respectively.

Figure 3.7 Compost Media

The fresh compost was brought from John Darling near Environmental Health & Safety Office, UTA. The compost was made up of 80% oak leaves, alm leaves, pecan leaves and microbes. The hardwood chips came from Good Times Wood Products Inc., TX. Hardwood chips (shown in Figure 3.8) are preferred biofilter media because the air flow through the medium is homogenous and bed compaction is prevented. Also, hardwood chips help in maintaining the moisture content of the bed by absorbing the moisture. The woodchips were obtained mostly from hickory trees.

Figure 3.8 Hardwood Chips

Additional literature review was conducted to determine a good mixture of compost and wood chips.

Table 3.2 Summary of Woodchips and Compost Media Ratios

Author	**Year**	**Ratio (%)(volume basis)** **Wood chips: Compost**
Smet, Van langenhove and Verstracete	1996	32:68 (weight ratio)
Nicolai and Janni	2001	70:30 to 50:50 (weight ratio)
Deshusses and Johnson	2000	80:20 (weight ratio)
Jones, Matinez, Maroo, and Deshpande	2002	80:20 (volume basis)
Pandey, Gangane, Mudliar and Rajvaidya	2006	50:50 (volume basis)
Pandey, Padoley, Mukherji, Vaidya, Rajvaidya, and Subbarao	2007	50:50 (volume basis)

Table 3.2 - Continued

Pandey, Mudliar, & Bargaokar	2009	compost (%w/w carbon 38, nitrogen 1.3, phosphorous 0.02, potassium 0.71, calcium 1.62, magnesium 0.14, and sodium 0.01; other metal elements mg/kg: copper 44, manganese 360, and zinc 70) and wood chips in alternate layers

3.3 Measurement/Analysis Methods

3.3.1 Flow Meters

Flow meters FM-1050 series (Teflon flow meters) were purchased from the Matheson Tri Gas, Joliet, IL. , which were used for measuring propylene and butylene gas (Figure 3.6). The Teflon flow meters had a high resolution 150 mm scale and an accuracy of +5% of the full scale reading. The flow meters were calibrated with the base gas as air, as the gas was flowing in an environment of air. (Garrapalli, 2006) The gas was connected through the flow meter that the flow of gas was measured before mixing to air stream. The flow of the gas can be controlled from the cylinder using the flow meter. The flowmeter regulators were used to control the combined flow of air and gas of about 0.6 LPM for butylene and 0.9 LPM with propylene gas. The air flow meter can measure maximum 3 LPM. Each biofilter column was connected to air flow meter to measure the amount of gas entering in each biofilter. The flow meters used to measure the flow of air and gaseous mixture also came from Cole-Parmer, and these are PTFE high resolution flow meters for precise flow control. The air flow meter was used to measure the air flow rate is a direct reading meter for metric units from Cole Parmer.

Removing moisture from the flow meters was important to obtain accurate readings of the air and gas flow. The system was stopped for sometime around 15-20 minutes. Then, the flow meters were cleaned with isopropyl alcohol to avoid moisture every alternate day.

Figure 3.9 Flow Meters to Measure Gas Flow and Air Flow

3.3.2 pH Measurement

The pH is an important factor in biofilters. pH is necessary to maintain for the efficient removal of the pollutant gas; most bacteria grow best at neutral pH. The pH in the biofilter media may change during an experiment due to contaminant biotransformation. This biotransformation may produce organic acids. This situation can be controlled by using a biofilter media with a high buffer capacity. The pH of the media was measured by using a pH meter, Accumet AR 50 Fisher Scientific (shown in Figure 3.10). A buffer solution with a pH of 10.0 was used as the standard, and the medium was mixed with distilled water and put in contact with the electrode to obtain the pH measurement. The media was mixed with a very small amount of water to make a slurry and the pH was measured after putting the probe of the pH meter in that slurry to obtain the pH of the media.

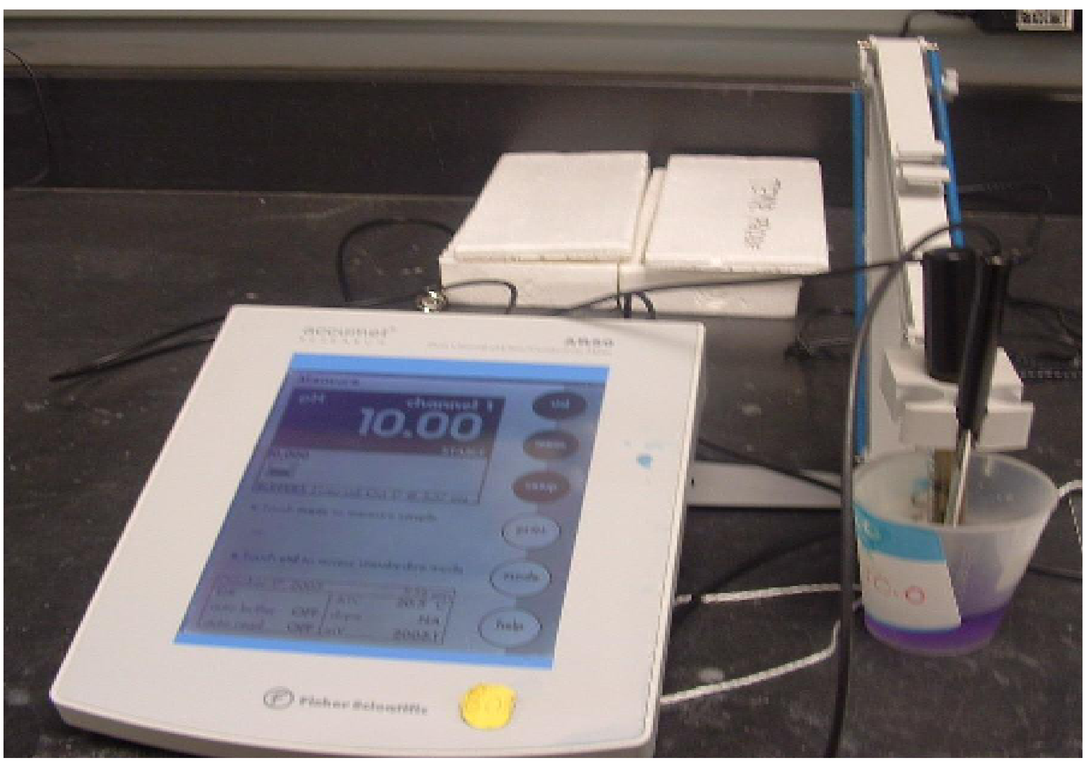

Figure 3.10 pH Meter

3.3.3 Humidity and Temperature Measurement

The humidity was measured by using a Humidity stick (shown in Figure 3.11). The probe of the humidity stick was inserted at the inlet points of the biofilter into the sampling port. Then, the reading was observed between 0% - 100% on the screen of the humidity stick. Temperature was constant throughout the experiment. The temperature was also measured by using the humidity stick. The temperature of the system was room temperature, which is 73°F.

Figure 3.11 Humidity Stick

3.3.4 Moisture Content Measurement

To determine the moisture content of the media, samples of media were taken in an empty beaker from each one of the three columns. The samples were heated in an oven set to 105°C for 24 hours, within which time the media was assumed to have lost all its moisture and to be completely dry. The weight of the sample was measured before and after the heating process and the weight of the empty beaker was also measured, using an analytical balance. The percentage moisture content of the media was determined using the equation below:

$$Moisture\ content(\%) = \frac{Weight\ of\ the\ wet\ sample - Weight\ of\ dry\ sample}{Weight\ of\ the\ wet\ sample - Weight\ of\ empty\ beaker} \times 100$$

3.3.5 Gas Concentration Measurement

3.3.5.1 General GC Operations

The concentration of the gases was measured using gas chromatograph (GC). Gas chromatography, defined as separation of compounds while travelling through a stationary phase column, is used for a wide range of chemicals. A gas chromatograph consists of a flowing mobile phase, an injection port, a separation column containing the stationary phase, a detector, and a data recording system. The organic compounds are separated due to differences in their partitioning behavior between the mobile gas phase and the stationary phase in the column and injected into the GC through hot injector port of the GC, which is made up of a rubber septum. The temperature of the injector was set to a higher temperature than the boiling point of the component. As a result, the evaporation of the components of the mixture will occur into the gas phase inside the injector.

An inert carrier gas, helium, flows through the injector and pushes the gaseous components of the sample onto the GC column. The separation of the components will take place within the column between the mobile gas phase and the stationary phase.

Figure 3.12 Gas Chromatography

The partition of the mixture depends on the temperature: the separation column is present in a thermostat – controlled oven. Separating components with a wide range of boiling points is accomplished by starting at a low oven temperature and increasing the temperature over time to elute the high-boiling point components.

After passing the sample through the GC, a pollutant reaches a detector at specific time due to differences in the partitioning between mobile and stationary phases. Then, a signal is received from detector which shows a peak on the computer screen. The area of the peak is proportional to the number of molecules generating the signal.

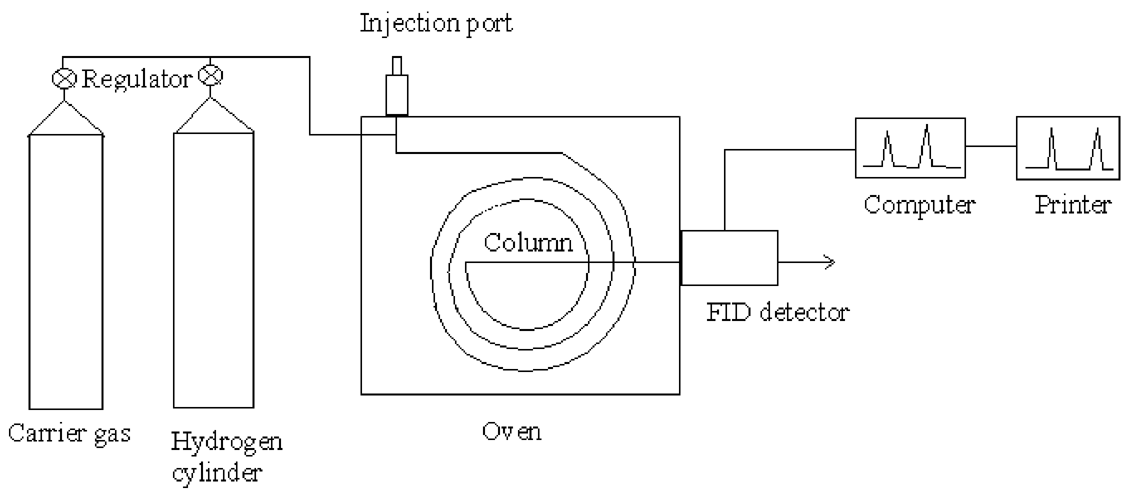

Figure 3.13 Schematic of a Gas Chromatograph

3.3.5.1.1 Factors which affect GC separations

The effective separations of compounds are dependent on the compounds traveling at different rates through the column. The rate of compound travels through a GC system depends on the factors listed below:

- **Volatility of compound**: The travelling speed for low boiling point (volatile) components is higher than for high boiling components.
- **Column temperature**: The speed of the compounds can be increased by raising the column temperature.
- C**olumn packing polarity**: Usually, all compounds will move slower on polar columns, but polar compounds will show a larger effect.
- **Flow rate of the gas through the column**: The speed of the compounds can be increased by raising carrier gas flow through the column.

- **Length of the column**: A longer column takes more time to elute. Thus, it gives better separation of compounds.

3.3.5.1.2 Components of Gas Chromatograph

3.3.5.1.2.1 Carrier Gas

Different types of carrier gases, such as argon, nitrogen, helium and carbon dioxide, can be used in the gas chromatograph. Carrier gases are inert so they do not take part in any reactions while passing through the column. Carrier gas is shown in Figure 3.14. The carrier gas pushes a sample onto the GC column. Each detector works best using a specific carrier gas. A copper tube carries carrier gas from the cylinder to the GC.

3.3.5.1.2.2 Support Gas

Air and hydrogen are the support gases for the flame combination at the jet’s tip of the Flame Ionization Detector (FID). An air compressor is inbuilt in some systems. (Athappan, 2008). Support gas is shown in Figure 3.14.

Figure 3.14 Carrier and Support Gases Attached to the Gas Chromatograph

3.3.5.1.2.3 Injection Port

A direct on –column inject port is present in SRI GC 8610 model. Swagelok stainless steel nut and septa can be used to avoid leaking.

3.3.5.1.2.4 Retention Time (RT)

Retention time is the time takes for a sample to travel from the injection port to the detector, which is shown as a minutes on the computer screen of the GC. The retention time can be measured by the recorder between the time when the start button is pressed and the time the detector shows a peak. The start button should be pressed at the same time the sample is injected to get better results.

3.3.5.1.2.5 Column

Gas columns are of two types: packed and capillary. Packed columns are typically a glass or stainless steel coil that is filled with a stationary phase, or a packing coated with a stationary phase. Packed column diameters range from 2-4 mm and lengths range from 1.5 to 10 m.

Capillary columns are a thin fused-silica that has the stationary phase coated on the inner surface and is an open tube. Packed and capillary columns are shown in Figure 3.15. The choice of column is based on the types of compounds to be measured. Capillary columns provide much higher flexibility, low reactivity with chemicals, high retention time and higher durability separation efficiency than other columns. Capillary columns detect very low quantities of sample compared to packed columns. The capillary column is a few tenths of a millimeter in diameter.

Figure 3.15 Packed Column and Capillary Column

3.3.5.1.2.6 Oven

The column is placed in the oven as shown in Figure 3.17. The oven is a closed container which bakes the column while pollutants are travelling through. The temperature of the oven should be higher than boiling point of tested compounds so that separation of the compounds will show clearly.

3.3.5.1.2.7 Flame Ionization Detector

The detector detects the compounds which passes through the column, and shows the concentration on computer screen. There are many detectors which can be used in gas chromatography (Table 3.3). Different detectors will give different selectivities. The FID detector selectivity is mostly for organic compounds.

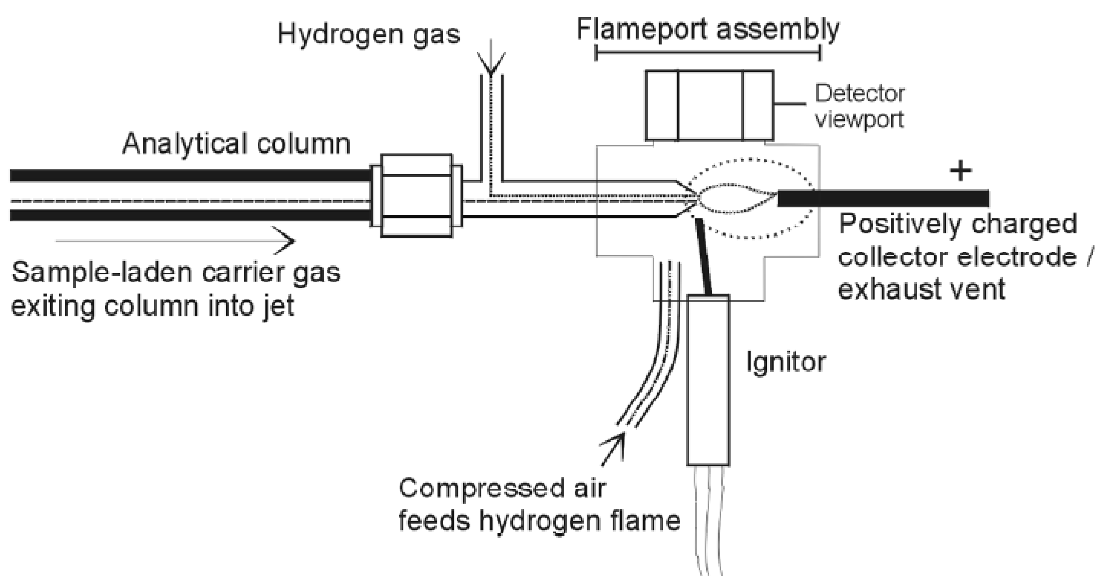

Figure 3.16 Schematic Diagram of FID

The effluent form the column is mixed first with hydrogen and air, and ignited. Organic compounds produce ions and electrons after burning. As a result, a large electrical potential is developed at the burner tip. The electrons and ions are attracted by the collector electrode to the amplifier. The amplifier sends an analog signal to the system to produce a peak. An electromagnetic field is produced by the difference between positive ions and FID**.**

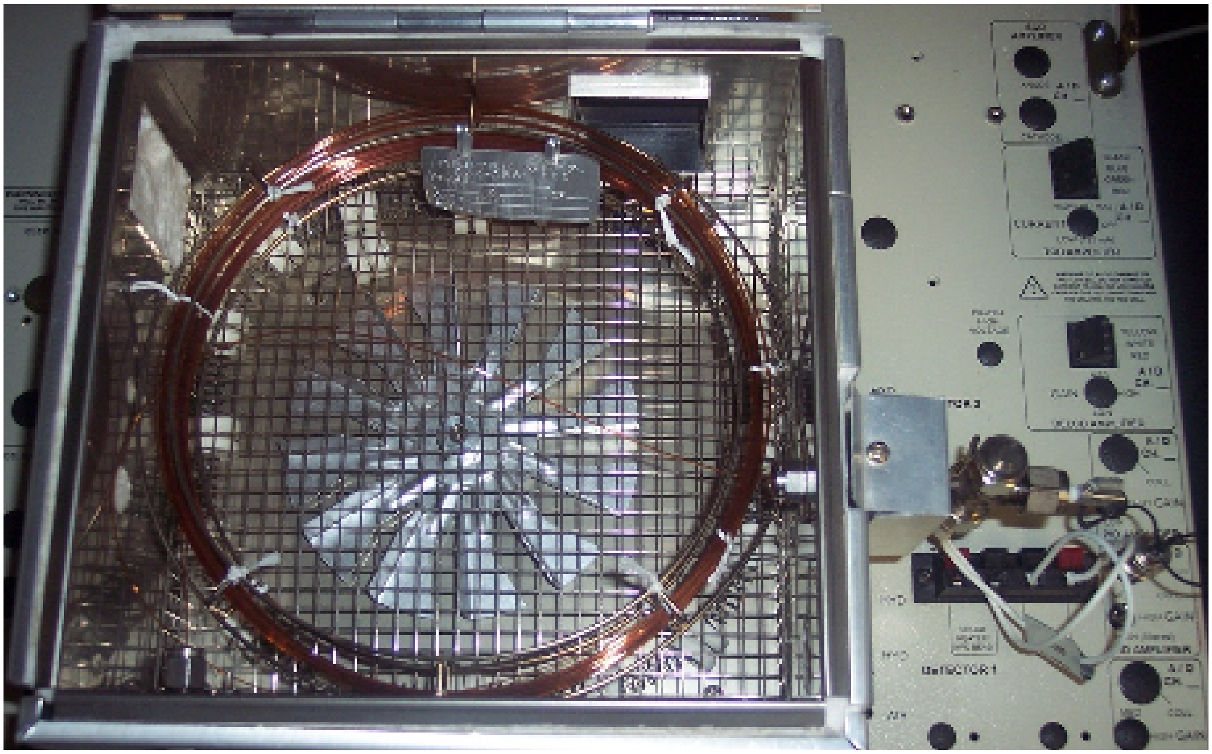

Figure 3.17 Column Placed in Oven

Table 3.3 Different Types of Detectors and their Purposes

Detector	**Type**	**Support Gases**	**Selectivity**	**Detectability**	**Dynamic Range**
Flame ionization (FID)	Mass flow	Hydrogen and air	Most organic compounds	100 pg	10^7
Thermal conductivity (TCD)	Concentration	Reference	Universal	1 ng	10^7
Electron capture (ECD)	Concentration	Make-up	Halides, nitrates, nitriles, peroxides, anhydrides, organometallics	50 fg	10^5
Nitrogen-phosphorus	Mass flow	Hydrogen and air	Nitrogen, phosphorus	10 pg	10^6
Flame photometric (FPD)	Mass flow	Hydrogen and air possibly oxygen	Sulphur, phosphorus, tin, boron, arsenic, germanium, selenium, chromium	100 pg	10^3

Table 3.3 - Continued

Photo-ionization (PID)	Concentration	Make-up	Aliphatics, aromatics, ketones, esters, aldehydes, amines, heterocyclics, organosulphurs, some organometallics	2 pg	10^7
Hall electrolytic conductivity	Mass flow	Hydrogen, oxygen	Halide, nitrogen, nitrosamine, sulphur		

3.3.5.1.2.8 Peak Simple Software

Peak simple software is developed and maintained by SRI Instruments, Inc. This software reads data from the detector and helps in representing data. Software can be downloaded and installed from srigc.com website on the computer desktop. Peak simple has to be calibrated before starting the experiment. A serial port is used to connect the computer with the GC. Chromatographic data is highly variable in terms of peak shapes, interferences, coeluting peaks, signal to noise ratio, selected integration parameters and data acquisition rate (Athappan, 2008). The peak shapes and time differ according to settings in the GC. Hence, settings should be fixed before calibrating the GC. The experiment can be run several times with different settings. Then, the settings are standardized after several trial runs. The temperature settings in the Peak Simple software are linked with the GC. A peak in the Peak Simple software of butylene is shown in Figure 3.18.

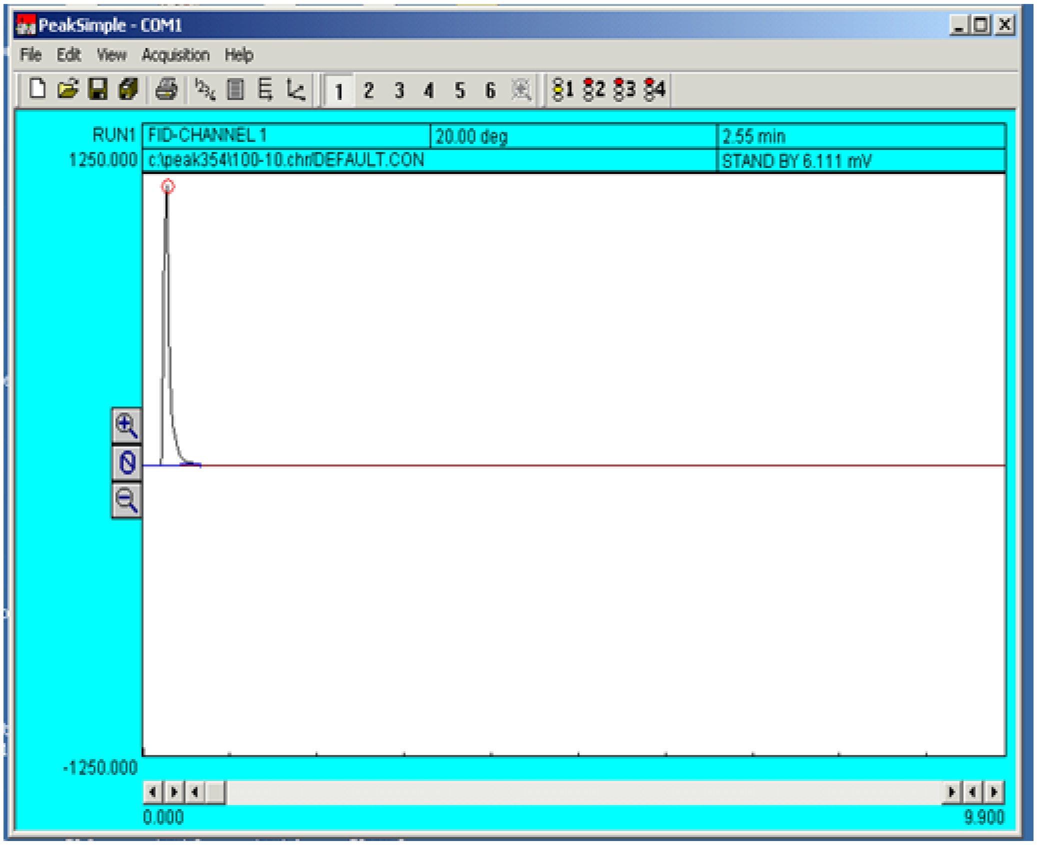

Figure 3.18 Peak of Butylene in GC

Figure 3.19 Tedlar Bag and Syringe Used for Gas Measurement

Propylene and butylene gas was calibrated in GC before measuring the input and output of the columns. A tedlar bag was used for transferring the gas from cylinder to calibrate the GC with several trials of settings, as shown in Figure 3.19. The gases were calibrated five times, as shown in Table 3.4 and Table 3.5. The concentration was the average of the five readings measured during the experiment.

Table 3.4 GC Calibration with 100% and 50% Butylene Gas

Reading No.	Concentration (ppm)	
	100%	50%
1	88.90	44.40
2	90.00	44.50
3	90.20	45.00
4	90.00	45.20
5	89.00	44.50

Table 3.5 GC Calibration with 100% and 50% Propylene Gas

Reading No.	Concentration (ppm)	
	100%	50%
1	166.0	83.0
2	166.0	83.5
3	166.5	84.0
4	167.0	84.0
5	165.5	83.5

3.3.5.2 GC Parameters Used in Experiments

The gas was taken from inlet and outlet points and injected in GC using a syringe. The syringe is shown in Figure 3.19. The syringe and needle were ordered from Sigma- Aldrich Inc, St. Louis, MO. The syringe was 1ml NORM-Ject® and the size of the needle was 27G1$^{1/4}$. 0.5 ml gas was drawn up into a syringe for each injection. The retention time for butylene and propylene gas was 0.23 and 0.25 respectively. A 60 m capillary column was used in this experiment. Helium carrier gas and hydrogen gas for the FID were purchased from Matheson Trigas. The initial settings on the GC were helium as 12 psi, hydrogen 25 psi, air 7 psi, detector temperature 200º C, and initial column oven temperature 40 ºC. The Peak Simple software final temperature was 150°C, hold time three minutes, and ramp 10°C/ minute.

3.3.6 Other Apparatus Used

A digital weighing balance was used to measure the weight of the woodchips and compost.

3.4 Methodology

The first experiment was started on 8th Aug 2008 with mixtures of compost and wood chips in the three biofilter columns. Butylene gas was passed through the biofilters for 4 months. The first and second biofilter columns were filled with 80:20 and 50:50 ratios of compost and wood chips, respectively. The third biofilter column was filled with the intermediate mixture of compost and wood chips. The three columns, air and gas were attached to individual flow meters. The first reading was taken almost after one month on 9th Sep 2008. Initially, the flow rate was not constant and it was fluctuating every day. Finally, the flow rate became constant after 25 days due to a decrease in pressure of the cylinder. In the meantime, the microorganisms were partially acclimated to the environment of butylene gas.

The concentration was measured at the inlet and three outlet points every 24 hours. Each measured concentration was found to be constant for 2 or 3 days, which shows the precision of the readings. All three columns gave the almost same result. Then, the degradation rate started increasing. Butylene gas started giving removal efficiency more than 100% after 5th November 2008 in all biofilter columns and 100% degradation was obtained till 25th November 2008.

The pH of the fresh compost and used compost were measured in the beginning or at the end of the experiment. The flow meters were cleaned properly after every alternate day. The water in the humidified chamber was refilled after one week when the level of water was found to be less than initial level. The system was stopped for 5 minutes at the time of refilling the water.

Similarly, propylene gas was passed through the biofilter columns in the same experimental set up, with one difference. In the other experimental set up, end plate contained three holes. Both gas and air were passed separately through the threaded hole to the bottom of the humidification chamber through two different long glass tubes that ran to the end of the column. In this experiment, the flow rate was fluctuating for a long time and it was difficult to maintain the flow of the gas because the flow rate of air was suppressing the flow rate of propylene gas. As a result, the propylene gas was not able to enter into the biofilter system. Hence, separate holes for propylene and air were made on the glass plate of the humidification chamber. This machine work was done in the Woolf Hall Machine Shop, UTA. After that, it was easier to maintain the flow of propylene.

The experiment was started on 2nd January and the 1st reading was taken on 5th Feb 2009. The experiment was run for almost three months to get 100% degradation rate of propylene gas. The pH of the fresh and used media was measured at the beginning and at the end of the experiment.

3.5 Experimental Procedures

The experimental procedure was carried out in two steps as follows:

3.5.1 Leak Test

The leak of the air or gas was tested in the experimental set up by a leak test. The biofilter system was started to run so that air or gas started passing through the system. Then, soapy water was sprayed on all the joints and connections and pipe fittings. Formation of soap bubbles shows a leak in the system, which was fixed using Teflon tape or changing other joints and connections. If there is no formation of air bubbles from any joints, the system can be run for a long time. The system can be tested after 2 or 3 days to detect any new leakage in the system.

3.5.2 Experimental Procedure

1. Fill the columns with media (mixture of compost and wood chips) in required ratio in the biofilter after proper mixing in the big vessel.

2. Place the three biofilter columns at specific place and attach the columns with flow meters so that air or gas will not leak from the system.

3. Switch on the hood blower in which the set up is placed.

4. The air flow rate was adjusted between 1 to 3 LPM and gas flow was adjusted at specific concentration so that the total flow will be less than 3 LPM.

5. The flow meter of each column was adjusted so that equal flow of gas/ air mixture will enter each column.

6. The mixture of air and gas was passed though the humidifier before entering the biofilter to achieve higher relative humidity.

7. Relative humidity was measured at the three inlet points using the humidity stick.

8. The flow was run continuously through the biofilter columns till the microorganisms acclimatized to the pollutant gas environment. When the microorganisms consume the pollutant gas, the concentration will start decreasing slowly.

9. The inlet and outlet concentrations of pollutant gas of each column were determined, and removal efficiency calculated.

CHAPTER 4

RESULTS

4.1 Removal Efficiency and Elimination Capacity of Propylene and Butylene Gases

The experiments were conducted over six months to attain the research objectives. The removal efficiency of propylene and butylene gases for different combinations of media was determined by varying media bed volume and gas concentration according to the methods described in the previous chapter. A sample of daily experimental inlet concentration for butylene 80: 20 compost to woodchips media ratio is given in Table 4.1. Detailed daily and average experimental inlet and outlet data for butylene and propylene are given in Appendix A. Each column had three different outlet points and three inlet readings taken from the same sampling location. As can be seen from Table 4.1, concentrations were very consistent among the inlets, with small standard deviations (10% or less).

Table 4.1 Sample Daily Experimental Inlet Concentration for Butylene 80:20 Compost to Woodchips Ratio

Date & Time	Inlet I (ppm)	Inlet II (ppm)	Inlet III (ppm)	Average Inlet Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
9/29/08 4.10 PM	110	109	112	110	1.66	1.50
9/30/08 4.10 PM	110	110	103	108	4.21	3.91
10/1/08 4.10 PM	111	109	105	108	2.85	2.63
10/2/08 4.10 PM	198	199	203	200	2.69	1.34
10/3/08 4.00 PM	198	198	209	202	6.59	3.26
10/4/08 4.00 PM	199	199	199	199	0.24	0.12
10/5/08 4.12 PM	570	570.5	590	577	11.63	2.02
10/6/08 4.12 PM	576	576	565	573	6.21	1.08
10/7/08 4.30PM	178	179	182	180	1.93	1.08
10/8/08 4.30PM	177	178	189	181	6.70	3.69

The butylene and propylene concentrations and empty bed residence time (EBRT) are summarized at different flow rates in Table 4.2 and Table 4.3. Residence time is a function of the column depth, cross sectional area and airflow rate. EBRT is determined by dividing the volume of the empty biofilter column by the airflow rate. Typical biofilter EBRTs range from 0.5 to 2 minutes (Devinny et al., 1999). The EBRTs observed in this research are thus longer than typical.

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Table 4.2 Various Flow Rate and EBRT in Biofilters for Butylene

Flow Rate (Butylene + Air) (LPM)	**Typical EBRT (minutes)**
0.9	7.2
0.9	7.2
0.4	16.28
0.5	13.02

Table 4.3 Various Flow Rates and EBRT in Biofilters for Propylene

Flow Rate (Propylene + Air) (LPM)	**Typical EBRT (minutes)**
0.9	7.2
0.9	7.2
0.5	13.02
0.5	13.02

4.2 Removal Efficiency

4.2.1 Butylene Removal Efficiency

The first experiment was started on 8th August 2008. The butylene gas was passed through the media of compost and wood chips. Initially, the gas concentration was not constant; it took around 5 weeks to stabilize. Almost after 7 weeks, the first reading was taken from the biofilter column on 29 September 2009. At 12 weeks, 100% removal efficiency was achieved; by that time the microbes were acclimated in the environment of butylene gas. The experiment was conducted till 15 weeks. Average daily experimental data for date, time, inlet, outlet, humidity, flow rate and calculated values of removal efficiency of butylene gas for 80:20, 50:50, and intermediate ratio of compost and woodchips are given in Table 4.4, Table 4.5 and, Table 4.6, respectively. The graphical information of butylene gas removal efficiency versus time is given in Figure 4.1, Figure 4.2, and Figure 4.3, respectively, for 80:20, 50:50, and intermediate ratios of compost to woodchips. According to the results given in Table 4.4, Table 4.5 and Table 4.6, the removal efficiency of butylene gas for inlet concentrations ranging from 91 ppm to 643 ppm was 100% for all three media ratios because the amount of media was enough to grow sufficient amount of microbes to achieve 100% removal efficiency.

Table 4.4 Average Daily Experimental Results for Butylene with Mixture of Compost and Woodchips (80:20)

Date & Time	Average Inlet (ppm)	Average Outlet (ppm)	Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)
				Inlet (Air + Butylene)	Butylene	
9/29/08 4.10 PM	110.4	90.68	65	0.9	0.002	17.87
9/30/08 4.10 PM	107.6	89.79	55	0.9	0.002	16.53
10/1/08 4.10 PM	108.5	90.68	57	0.9	0.002	16.39
10/2/08 4.10 PM	200.0	163.58	65	0.9	0.002	18.22
10/3/08 4.00 PM	201.8	164.47	69	0.9	0.002	18.50
10/4/08 4.00 PM	199.1	163.58	50	0.9	0.002	17.86
10/5/08 4.12 PM	577.0	381.38	71	0.9	0.003	33.90
10/6/08 4.12 PM	572.5	381.38	62	0.9	0.003	33.39
10/7/08 4.30PM	179.6	124.46	72	0.9	0.002	30.69
10/8/08 4.30PM	181.4	125.35	52	0.9	0.002	30.88
10/9/08 4.30PM	1017.0	426.72	60	0.5	0.002	58.04
10/10/08 4.30PM	1015.2	417.83	67	0.5	0.002	58.84
10/11/08 4.30PM	1016.1	426.72	75	0.5	0.002	58.01
10/12/08 4.15PM	946.8	365.38	65	0.5	0.001	61.41
10/13/08 4.15PM	948.6	368.94	73	0.5	0.001	61.11
10/14/08 4.15PM	922.8	345.82	70	0.5	0.002	62.52
10/15/08 4.15PM	924.6	349.38	71	0.5	0.002	62.21
10/16/08 12.25PM	874.8	302.26	62	0.5	0.001	65.45
10/17/08 4.15PM	872.1	296.93	61	0.5	0.001	65.95
10/18/08 4.05PM	827.7	244.48	72	0.5	0.001	70.46
10/19/08 4.15PM	830.3	256.92	77	0.5	0.001	69.06
10/20/08 4.15PM	832.1	248.92	80	0.5	0.001	70.09
10/21/08 4.15PM	825.0	240.03	75	0.5	0.001	70.91

Table 4.4 - Continued

11/22/08 4.12PM	757.4	179.58	64	0.5	0.002	76.29
10/23/08 4.15PM	759.2	186.69	60	0.5	0.002	75.41
10/24/08 4.15PM	761.9	184.91	59	0.5	0.002	75.73
10/25/08 4.07PM	706.8	133.35	62	0.5	0.002	81.13
10/26/08 4.15PM	709.4	128.91	58	0.5	0.002	81.83
10/27/08 4.15PM	705.9	132.46	57	0.5	0.002	81.23
10/28/08 4.45PM	720.1	115.57	55	0.5	0.002	83.95
10/29/08 4.15PM	710.3	114.68	61	0.5	0.002	83.85
10/30/08 4.15PM	721.9	119.13	67	0.5	0.002	83.50
10/31/08 4.15PM	729.0	122.68	73	0.5	0.002	83.17
11/1/08 4.15PM	705.9	111.13	63	0.5	0.002	84.26
11/2/08 4.35PM	705.9	111.13	47	0.5	0.001	84.26
11/3/08 4.15PM	705.0	112.01	50	0.5	0.001	84.11
11/4/08 4.15PM	711.2	113.79	55	0.5	0.001	84.00
11/5/08 4.15PM	577.9	51.56	75	0.5	0.001	91.08
11/6/08 4.15PM	595.6	53.34	71	0.5	0.001	91.04
11/7/08 4.15PM	591.2	53.34	66	0.5	0.001	90.98
11/8/08 4.20PM	90.6	0	66	0.9	0.002	100
11/9/08 4.15PM	91.6	0	67	0.9	0.002	100
11/10/08 4.15PM	92.0	0	56	0.9	0.002	100
11/11/08 4.00PM	99.6	0	63	0.9	0.002	100
11/12/08 4.15PM	100.0	0	64	0.9	0.002	100
11/13/08 4.15PM	103.6	0	69	0.9	0.002	100
11/14/08 4.00PM	103.6	0	55	0.9	0.003	100
11/15/08 4.15PM	104.0	0	57	0.9	0.003	100
11/16/08 4.45PM	376.5	0	49	0.4	0.002	100

Table 4.4 - Continued

11/17/08 4.15PM	375.0	0	51	0.4	0.002	100
11/18/08 4.15PM	376.5	0	50	0.4	0.002	100
11/19/08 7.25PM	365.1	0	79	0.4	0.002	100
11/20/08 4.15PM	366.0	0	74	0.4	0.002	100
11/21/08 4.15PM	547.6	0	65	0.5	0.002	100
11/22/08 4.15PM	547.6	0	65	0.5	0.001	100
11/23/08 4.15PM	549.0	0	63	0.5	0.001	100
11/24/08 4.15PM	553.8	0	51	0.5	0.001	100
11/25/08 4.15PM	554.0	0	55	0.5	0.001	100

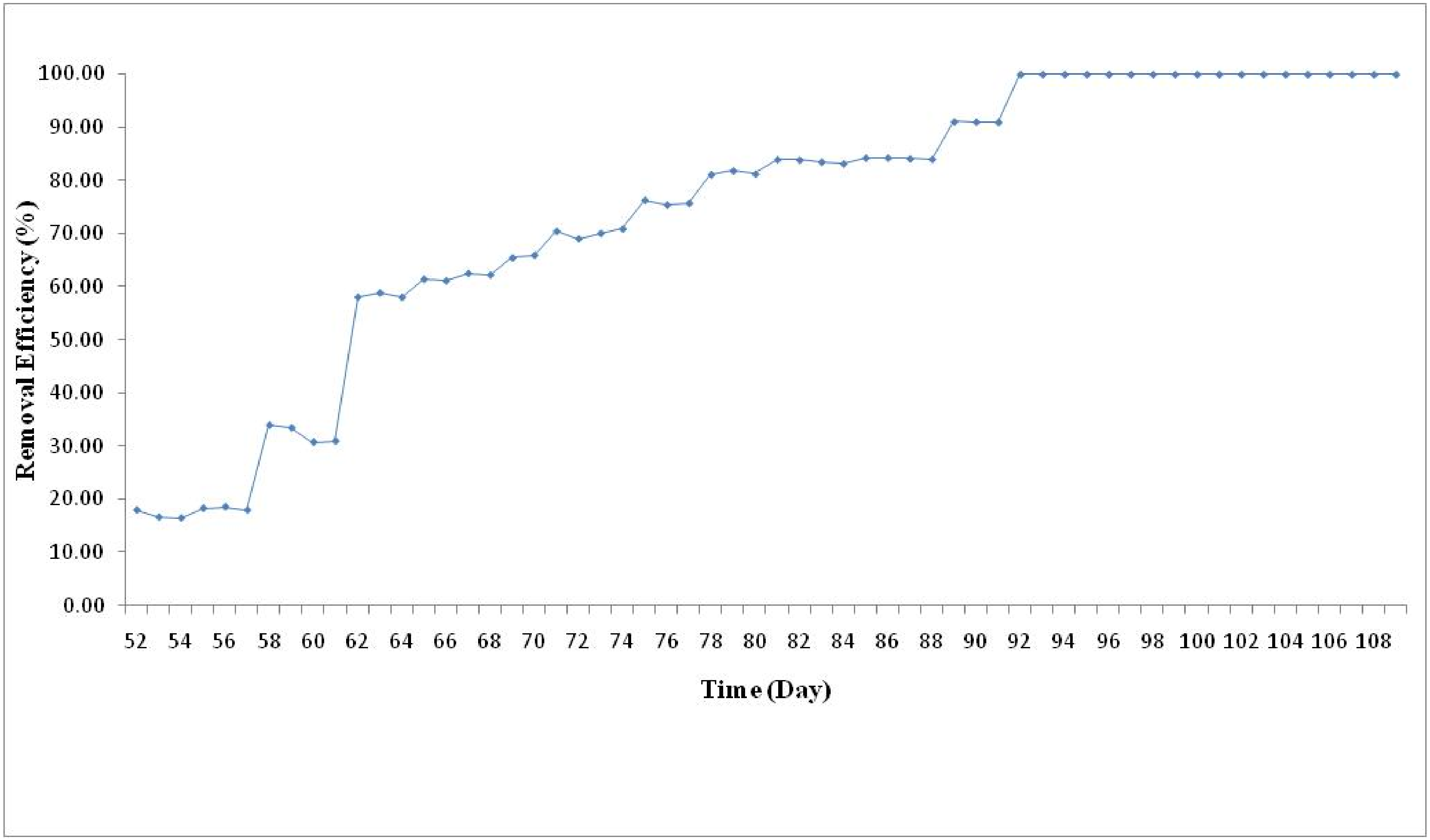

Figure 4.1 Butylene Removal Efficiency with Compost and Woodchips Media (80:20)

Table 4.5 Average Daily Experimental Results for Butylene with the Mixture of Compost and Woodchips (50:50)

Date & Time	Average Inlet (ppm)	Average Outlet (ppm)	Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)
				Inlet (Air + Butylene)	Butylene	
9/29/08 4.05PM	190.25	18.22	60	0.9	0.002	18.22
9/30/08 4.11 PM	189.36	18.78	64	0.9	0.002	18.78
10/1/08 4.12 PM	190.25	18.22	65	0.9	0.002	18.22
10/2/08 4.17 PM	488.06	323.60	62	0.9	0.002	33.70
10/3/08 4.11 PM	484.51	322.71	55	0.9	0.002	33.39
10/4/08 4.11 PM	483.62	320.93	59	0.9	0.002	33.64
10/5/08 4.35 PM	200.03	139.57	67.2	0.9	0.002	30.22
10/6/08 4.13 PM	203.58	141.35	65	0.9	0.002	30.57
10/7/08 4.35PM	928.12	382.27	60	0.5	0.002	58.81
10/8/08 4.32PM	924.56	382.27	63	0.5	0.002	58.65
10/9/08 4.20PM	937.90	356.49	68	1.0	0.003	61.99
10/10/08 4.32PM	933.45	355.60	64	1.0	0.003	61.90
10/11/08 4.31PM	936.12	357.38	70	1.0	0.003	61.82
10/12/08 4.20 PM	887.22	336.93	67	0.5	0.002	62.02
10/13/08 4.17PM	889.00	334.26	71	0.5	0.002	62.40
10/14/08 4.30PM	865.89	295.15	62	0.5	0.001	65.91
10/15/08 4.15PM	864.11	295.15	55	0.5	0.001	65.91
10/16/08 4.10 PM	799.21	239.14	64.6	0.5	0.001	70.08
10/17/08 4.16PM	797.43	238.25	61	0.5	0.001	70.12
10/18/08 4.17 PM	710.31	167.13	64	0.5	0.002	76.47
10/19/08 4.17PM	710.31	167.13	59	0.5	0.002	76.47

Table 4.5 - Continued

10/20/08 4.16 PM	711.20	165.35	71	0.5	0.002	76.75
10/21/08 4.16PM	711.20	165.00	73	0.5	0.002	77.00
11/22/08 4.12PM	662.31	124.46	61.6	0.7	0.002	81.21
10/23/08 4.16PM	657.86	120.02	60	0.7	0.002	81.76
10/24/08 4.17PM	664.08	122.68	62	0.7	0.002	81.53
10/25/08 4.50PM	631.19	106.68	72	0.5	0.002	83.10
10/26/08 4.16PM	631.19	107.57	64	0.5	0.002	82.96
10/27/08 4.17PM	634.75	106.68	61	0.5	0.002	83.19
10/28/08 4.40 PM	643.64	101.35	69	0.5	0.002	84.25
10/29/08 4.16PM	641.86	100.46	55	0.5	0.002	84.35
10/30/08 4.15PM	640.97	101.35	57	0.5	0.002	84.19
10/31/08 4.17PM	641.86	100.46	58	0.5	0.002	84.35
11/1/08 4.18PM	640.97	101.35	56	0.5	0.002	84.19
11/2/08 4.20 PM	488.95	42.67	82	0.5	0.002	91.27
11/3/08 4.19PM	480.06	41.78	87	0.5	0.002	91.30
11/4/08 4.25PM	488.95	42.67	88	0.5	0.002	91.27
11/5/08 4.25 PM	110.24	0.00	66	1.0	0.002	100
11/6/08 4.16PM	108.46	0.00	56	1.0	0.002	100
11/7/08 4.17PM	109.35	0.00	58	1.0	0.002	100
11/8/08 4.05 PM	188.47	0.00	63	0.9	0.002	100
11/9/08 4.17PM	190.25	0.00	67	0.9	0.002	100
11/10/08 4.18PM	192.91	0.00	72	0.9	0.002	100
11/11/08 4.05 PM	103.57	0.00	63	0.9	0.003	100
11/12/08 4.16PM	103.21	0.00	61	0.9	0.003	100
11/13/08 4.17PM	103.39	0.00	59	0.9	0.003	100

Table 4.5 - Continued

11/14/08 4.50 PM	465.39	0.00	64	0.4	0.002	100
11/15/08 4.17 PM	466.73	0.00	68	0.4	0.002	100
11/16/08 7.30 PM	454.01	0.00	64	0.4	0.002	100
11/17/08 4.19PM	453.39	0.00	53	0.4	0.002	100
11/18/08 4.18PM	454.28	0.00	69	0.4	0.002	100
11/19/08 4.20 PM	636.52	0.00	65	0.5	0.001	100
11/20/08 4.17PM	638.30	0.00	56	0.5	0.001	100
11/21/08 4.16PM	640.08	0.00	59	0.5	0.001	100
11/22/08 4.20 PM	642.75	0.00	69	1.0	0.001	100
11/24/08 4.20 PM	640.08	0.00	71	1.0	0.001	100
11/25/08 4.20 PM	639.19	0.00	73	1.0	0.001	100

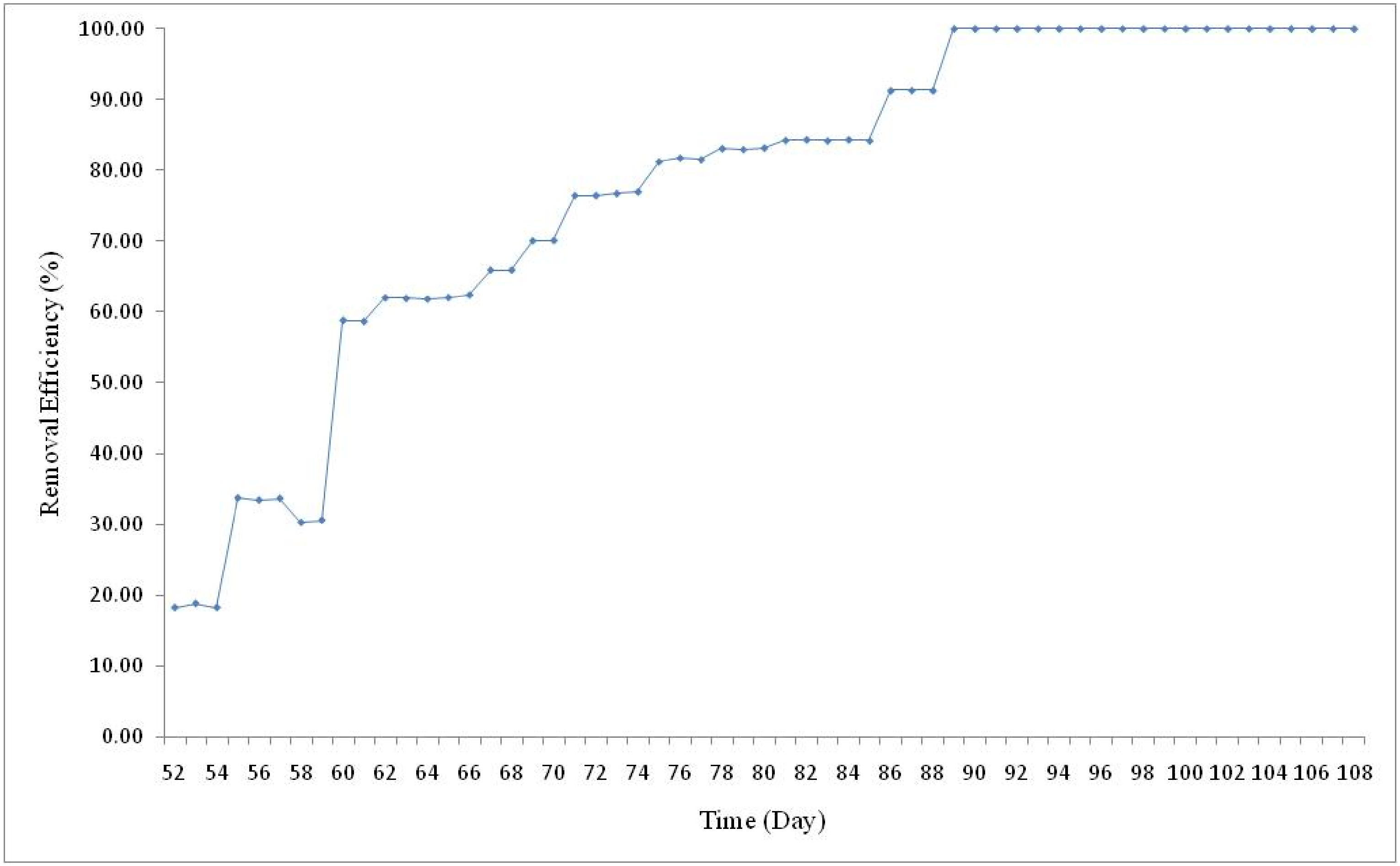

Figure 4.2 Butylene Removal Efficiency with Compost and Woodchips Media (50:50)

Table 4.6 Average Daily Experimental Results for Butylene with the Mixture of Compost and Woodchips (Intermediate Mixture)

Date & Time	Average Inlet (ppm)	Average Outlet (ppm)	Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)
				Inlet (Air + Butylene)	Butylene	
9/29/08 4.10PM	222.3	182.2	60	0.9	0.002	18.00
9/30/08 4.12 PM	217.8	177.8	55	0.9	0.002	18.37
10/1/08 4.13 PM	226.7	185.8	62	0.9	0.002	18.04
10/2/08 4.22 PM	532.5	356.5	68	0.9	0.002	33.06
10/3/08 4.13 PM	529.0	351.2	65	0.9	0.002	33.61
10/4/08 4.12 PM	529.0	351.2	63	0.9	0.002	33.61
10/5/08 4.40 PM	215.1	149.4	61	0.8	0.002	30.58
10/6/08 4.14 PM	213.4	147.6	70	0.8	0.002	30.83
10/7/08 4.40 PM	1067.7	442.7	50	0.5	0.002	30.21
10/8/08 4.33PM	1066.8	442.7	59	0.5	0.002	30.21
10/9/08 4.25 PM	978.8	374.3	65	0.5	0.003	58.53
10/10/08 4.33 PM	977.9	373.4	71	0.5	0.003	58.50
10/11/08 4.32PM	977.9	373.4	73	0.5	0.003	58.92
10/12/08 4.25 PM	967.2	365.4	66	0.5	0.002	62.22
10/13/08 4.18 PM	960.1	364.5	66	0.5	0.002	62.04
10/14/08 4.35 PM	898.8	365.4	62	0.5	0.001	65.38
10/15/08 4.16 PM	969.0	364.5	55	0.5	0.001	65.60
10/16/08 4.15 PM	738.8	217.8	61.6	0.7	0.001	70.52
10/17/08 4.17 PM	733.4	215.1	63	0.7	0.001	70.67
10/18/08 4.22 PM	801.0	187.6	73	0.5	0.002	76.58
10/19/08 4.18 PM	795.7	186.7	79	0.5	0.002	76.54
10/20/08 4.17 PM	789.4	182.2	80	0.5	0.002	76.91
10/21/08 4.17 PM	789.4	182.2	75	0.5	0.002	76.91
11/22/08 4.17 PM	713.0	128.9	61.6	0.5	0.002	81.92

Table 4.6 - Continued

10/23/08 4.17 PM	706.8	130.7	65	0.5	0.002	81.51
10/24/08 4.18 PM	706.8	129.8	66	0.5	0.002	81.64
10/25/08 4.55 PM	568.1	88.0	76	0.5	0.002	84.51
10/26/08 4.17 PM	564.5	88.9	72	0.5	0.002	84.25
10/27/08 4.18 PM	659.6	102.2	80	0.5	0.002	84.50
10/28/08 4.45 PM	713.0	114.7	69	1.0	0.002	83.92
10/29/08 4.17 PM	715.6	114.7	72	1.0	0.002	83.98
10/30/08 4.16 PM	717.4	115.6	75	1.0	0.002	83.89
10/31/08 4.18 PM	715.6	114.7	74	1.0	0.002	83.98
11/1/08 4.19 PM	717.4	115.6	67	1.0	0.002	83.89
11/2/08 4.25 PM	502.3	42.7	68	0.5	0.002	91.50
11/3/08 4.20 PM	506.7	43.6	66	0.5	0.002	91.40
11/4/08 4.26 PM	506.7	44.5	79	0.5	0.002	91.23
11/5/08 4.30 PM	90.6	0	77	0.9	0.002	100
11/6/08 4.17 PM	99.6	0	82	0.9	0.002	100
11/7/08 4.18 PM	102.2	0	74	0.9	0.002	100
11/8/08 4.10 PM	99.6	0	63	0.9	0.002	100
11/9/08 4.18 PM	97.8	0	68	0.9	0.002	100
11/10/08 4.19 PM	93.3	0	81	0.9	0.002	100
11/11/08 4.10 PM	103.6	0	63	0.9	0.003	100
11/12/08 4.17 PM	100.5	0	85	0.9	0.003	100
11/13/08 4.18 PM	100.5	0	85	0.9	0.003	100
11/14/08 4.55 PM	376.5	0	84	0.4	0.002	100
11/15/08 4.18 PM	373.4	0	77	0.4	0.002	100
11/16/08 7.35PM	365.1	0	64	0.4	0.002	100
11/17/08 4.20 PM	367.2	0	67	0.4	0.002	100
11/18/08 4.19 PM	364.5	0	69	0.4	0.002	100

Table 4.6 -Continued

11/19/08 4.25 PM	547.6	0	65	0.5	0.001	100
11/20/08 4.18 PM	551.2	0	72	0.5	0.001	100
11/21/08 4.17 PM	551.2	0	73	0.5	0.001	100
11/22/08 4.25 PM	553.8	0	69	0.5	0.001	100
11/23/08 4.25 PM	555.6	0	70	0.5	0.001	100
11/24/08 4.25 PM	555.6	0	71	0.5	0.001	100

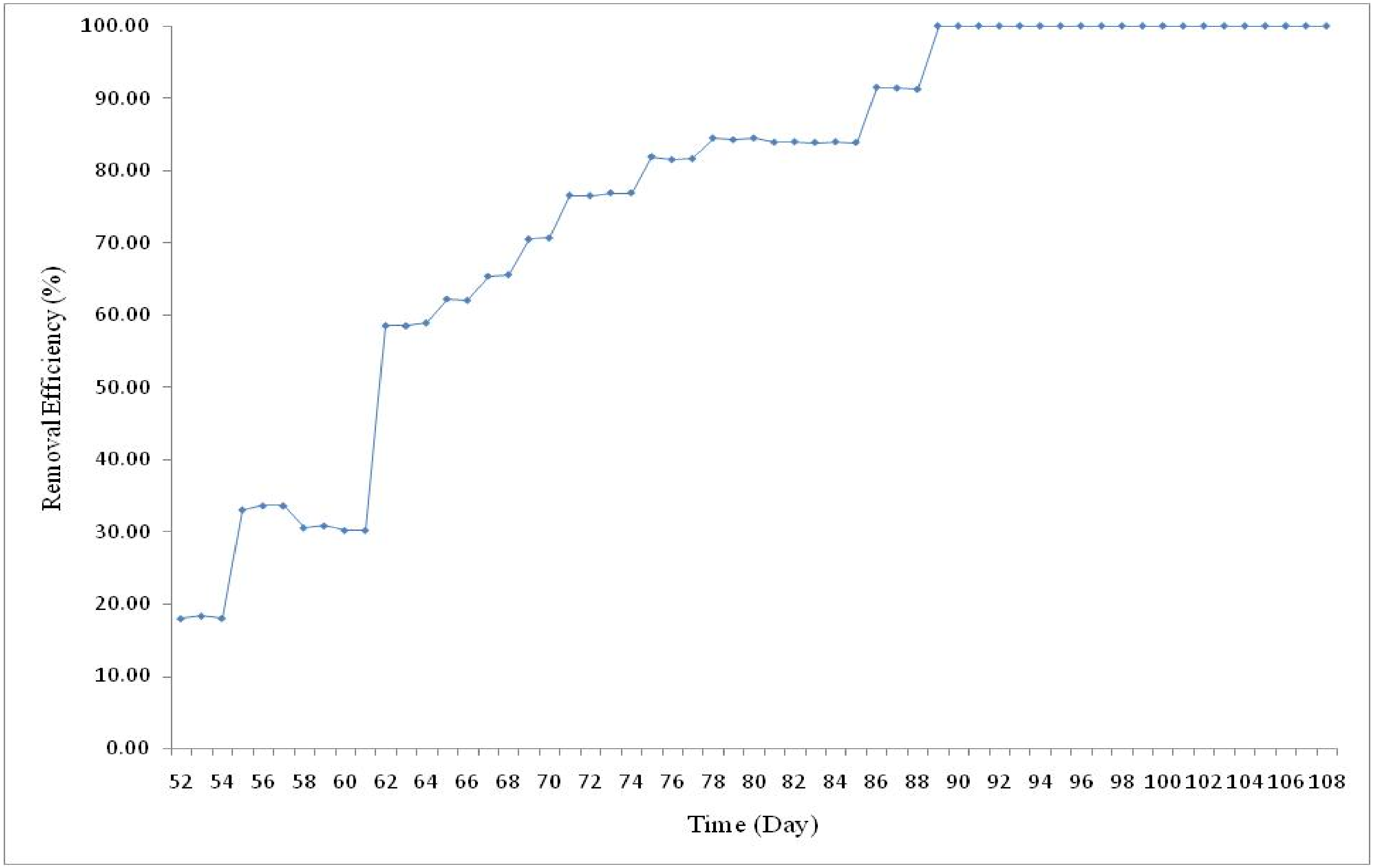

Figure 4.3 Butylene Removal Efficiency with Compost and Woodchips Media (Intermediate Mixture)

4.2.2 Propylene Removal Efficiency

In the second set of experiments, propylene gas was passed through the biofilter. The experiment was started on 2nd January and the first reading was taken on 5th Feb 2009. Microbes took 12 weeks to acclimate in the environment of propylene. Average daily experimental data for date, time, inlet, outlet, humidity, flow rate and calculated values of removal efficiency of propylene gas for 80:20, 50:50, and intermediate ratio of compost and woodchips are given in Table 4.7, Table 4.8, and Table 4.9, respectively. The graphical information of propylene gas removal efficiency versus time is given in Figure 4.4 Figure 4.5, and Figure 4.6, respectively, for 80:20, 50:50, and intermediate ratios of compost to woodchips.

According to the results shown in Table 4.7, Table 4.8, and Table 4.9, the maximum 100% removal efficiency was achieved on 28th March 2009. The removal efficiency of propylene gas for inlet concentration ranging from 2.95 x 10^4 ppm to 4.22 x 10^4 ppm was 100% for all the combinations of compost and woodchips.

Table 4.7 Average Daily Experimental Results for Propylene with the Mixture of Compost and Woodchips (80:20)

Date & Time	Average Inlet (ppm)	Average Outlet (ppm)	Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)
				Inlet (Air + Propylene)	Propylene	
2/5/09 3.25PM	988	409	60	0.5	0.002	58.6
2/6/09 3.25PM	987	405	68	0.5	0.002	59.0
2/7/09 3.45PM	947	360	62	0.5	0.002	62.0
2/8/09 3.45PM	945	364	55	0.5	0.002	61.5
2/9/09 3.45PM	949	363	59	0.5	0.002	61.8
2/10/09 4.00PM	891	346	64	0.5	0.002	61.2
2/11/09 3.45PM	876	338	61	0.5	0.002	61.4
2/12/09 3.45PM	885	341	62	0.5	0.002	61.4
2/13/09 4.15PM	28537	11646	60	0.5	0.002	59.2
2/14/09 4.15PM	28448	11557	69	0.5	0.002	59.4
2/15/09 4.15PM	28359	11646	73	0.5	0.002	58.9
2/16/09 4.25PM	64097	25337	71	0.9	0.003	60.5
2/17/09 4.25PM	64186	25781	72	0.9	0.003	59.8
2/18/09 4.25PM	63919	25425	75	0.9	0.003	60.2
2/19/09 4.25PM	64186	25781	63	0.9	0.003	59.8
2/20/09 4.05PM	62230	23647	66	0.9	0.002	62.0
2/21/09 4.05PM	70053	26581	68	0.9	0.002	62.1
2/22/09 4.05PM	69787	26226	57	0.9	0.002	62.4
2/23/09 4.05PM	54229	16233	55	0.9	0.001	70.1
2/24/09 4.05PM	53785	16091	49	0.9	0.001	70.1
2/25/09 4.05PM	54674	16447	47	0.9	0.001	69.9

Table 4.7 - Continued

2/26/09 4.25PM	53251	15913	58	0.9	0.001	70.1
2/27/09 4.05PM	53340	15913	62	0.9	0.001	70.2
2/28/09 4.05PM	53785	16180	68	0.9	0.001	69.9
3/1/09 4.20PM	45428	6134	64	0.5	0.002	86.5
3/2/09 4.20PM	45339	6223	70	0.5	0.002	86.3
3/3/09 4.20PM	45517	6223	71	0.5	0.002	86.3
3/4/09 4.25PM	43917	6045	62	0.5	0.002	86.2
3/5/09 4.25PM	43739	5956	65	0.5	0.002	86.4
3/6/09 4.25PM	43561	6223	71	0.5	0.002	85.7
3/7/09 4.15PM	39916	4790	69	0.5	0.003	88.0
3/8/09 4.15PM	39561	4623	74	0.5	0.003	88.3
3/9/09 4.15PM	39827	4890	67	0.5	0.003	87.7
3/10/09 10.15PM	31204	4267	50	0.4	0.002	86.3
3/11/09 10.15PM	31115	4356	55	0.4	0.002	86.0
3/12/09 11AM	28804	3645	72	0.4	0.002	87.3
3/13/09 11AM	28626	3645	73	0.4	0.002	87.3
3/14/09 4.14PM	41961	3922	75	0.9	0.002	90.7
3/15/09 4.14PM	41783	3912	78	0.9	0.002	90.6
3/16/09 4.14PM	41605	3823	80	0.9	0.002	90.8
3/17/09 4.15PM	39205	2859	55	0.9	0.002	92.7
3/18/09 4.15PM	39116	2756	59	0.9	0.002	93.0
3/19/09 4.15PM	39027	2756	61	0.9	0.002	92.9
3/20/09 4.05PM	37783	1867	63	0.5	0.003	95.1
3/21/09 4.05PM	37605	1778	66	0.5	0.003	95.3
3/22/09 4.25PM	37516	1689	64	0.5	0.003	95.5

Table 4.7 - Continued

3/23/09 10.00AM	35649	1867	52	0.5	0.003	94.8
3/24/09 10.00AM	44361	2223	56	0.5	0.003	95.0
3/25/09 4.14PM	39916	978	65	0.5	0.001	97.6
3/26/09 4.14PM	39738	800	69	0.5	0.001	98.0
3/27/09 4.14PM	39561	889	77	0.5	0.001	97.8
3/28/09 4.30PM	62408	400	72	0.5	0.001	99.4
3/29/09 4.14PM	62230	382	75	0.5	0.001	99.4
3/30/09 4.30 PM	48806	268	65	0.5	0.002	99.5
3/31/09 4.14PM	48451	266	69	0.5	0.002	99.5
4/1/09 4.30 PM	42228	0	47	0.9	0.002	100.0
4/2/09 4.30 PM	42050	0	55	0.9	0.002	100.0
4/3/09 4.30 PM	41961	0	59	0.9	0.002	100.0

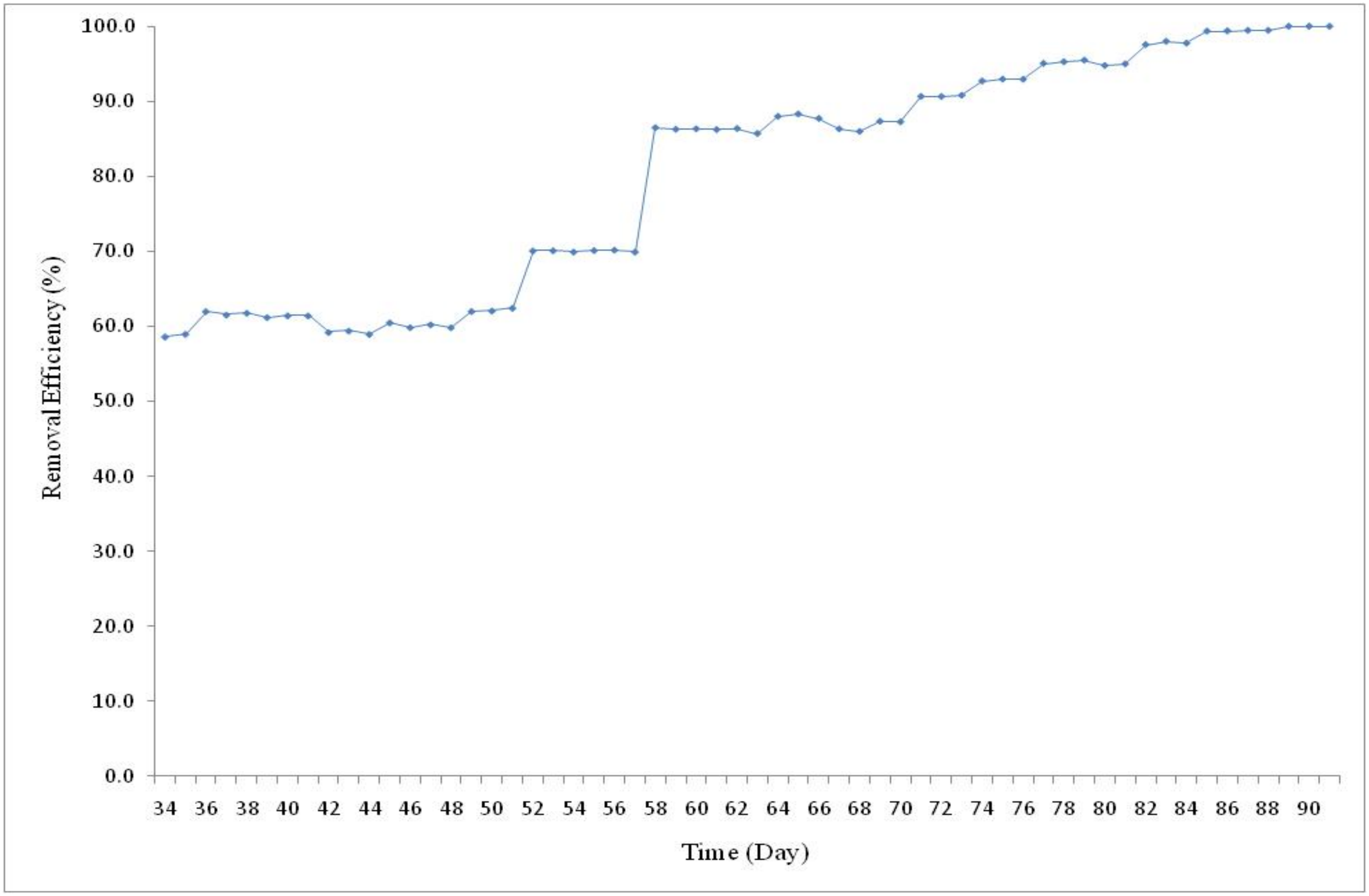

Figure 4.4 Propylene Removal Efficiency with Compost and Woodchips Media (80:20)

Table 4.8 Average Daily Experimental Results for Propylene with the Mixture of Compost and Woodchips (50:50)

Date & Time	Average Inlet (ppm)	Average Outlet (ppm)	Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)
				(propylene + air)	propylene	
2/5/09 3.30PM	928	382	60	0.5	0.002	58.8
2/6/09 3.30PM	925	381	65	0.5	0.002	58.8
2/7/09 3.50PM	887	347	62	0.5	0.002	60.9
2/8/09 3.30PM	885	342	67	0.5	0.002	61.3
2/9/09 3.30PM	880	347	70	0.5	0.002	60.6
2/10/09 4.05PM	1009	346	61	0.5	0.002	65.7
2/11/09 3.30PM	1006	342	63	0.5	0.002	66.0
2/12/09 3.30PM	1005	338	65	0.5	0.002	66.4
2/13/09 4.20PM	28626	11468	60	0.5	0.002	59.9
2/14/09 3.30PM	28448	11379	62	0.5	0.002	60.0
2/15/09 3.30PM	28359	11290	61	0.5	0.002	60.2
2/16/09 4.30PM	64541	25603	65	0.9	0.003	59.9
2/17/09 3.30PM	64364	25692	69	0.9	0.003	60.0
2/18/09 3.30PM	64275	25781	71	0.9	0.003	60.2
2/19/09 3.30PM	64275	25781	70	0.9	0.003	60.2
2/20/09 4.10PM	62141	23559	66	0.9	0.003	62.1
2/21/09 3.30PM	62052	23470	69	0.9	0.003	62.2
2/22/09 3.30PM	61786	23203	71	0.9	0.003	62.4
2/23/09 4.10PM	54407	16322	72	0.9	0.001	70.0
2/24/09 3.30PM	53340	16002	73	0.9	0.001	70.0
2/25/09 3.30PM	54674	16447	68	0.9	0.001	69.9
2/26/09 4.30PM	53429	15913	62	0.9	0.001	70.2
2/27/09 3.30PM	52540	15558	67	0.9	0.001	70.4

Table 4.8 - Continued

2/28/09 3.30PM	52896	16002	61	0.9	0.001	69.7
3/1/09 4.25PM	45161	6134	64	0.5	0.002	86.4
3/2/09 3.30PM	44450	6223	67	0.5	0.002	86.0
2/3/09 3.30PM	44806	6223	65	0.5	0.002	86.1
3/4/09 4.30PM	44006	6223	62	0.5	0.002	85.9
3/5/09 3.30PM	43561	6045	66	0.5	0.002	86.1
3/6/09 3.30PM	43739	6045	69	0.5	0.002	86.2
3/7/09 4.20PM	39738	4623	62	0.5	0.002	88.4
3/8/09 3.30PM	39561	4890	68	0.5	0.002	87.6
3/9/09 3.30PM	39738	4801	69	0.5	0.002	87.9
3/10/09 10.20PM	31115	4267	69	0.4	0.002	86.3
3/11/09 3.30PM	31293	4534	68	0.4	0.002	85.5
3/12/09 11.05AM	28893	3556	68	0.4	0.002	87.7
2/13/09 3.30PM	28804	3378	62	0.4	0.002	88.3
3/14/09 4.20PM	41872	3922	66	0.9	0.002	90.6
2/15/09 3.30PM	41694	3556	71	0.9	0.002	91.5
2/16/09 3.30PM	41339	3912	55	0.9	0.002	90.5
3/17/09 4.20PM	39027	2756	45	0.9	0.002	92.9
2/18/09 3.30PM	38672	2845	59	0.9	0.002	92.6
2/19/09 3.30PM	39116	2667	61	0.9	0.002	93.2
3/20/09 4.10PM	37694	1778	63	0.5	0.003	95.3
2/21/09 3.30PM	37338	1600	67	0.5	0.003	95.7
3/22/09 4.30PM	35471	1778	64	0.5	0.002	95.0
3/23/09 10.05AM	39827	800	64	0.5	0.002	98.0
3/24/09 3.30PM	39561	711	61	0.5	0.002	98.2
3/25/09 9.20AM	62230	427	50	0.5	0.001	99.3

Table 4.8 - Continued

3/26/09 3.30PM	62675	400	45	0.5	0.001	99.4
3/27/09 3.30PM	62230	373	51	0.5	0.001	99.4
3/28/09 4.20PM	49073	182	55	0.5	0.001	100.0
3/29/09 3.30PM	48895	178	57	0.5	0.001	100.0
3/30/09 4.35PM	42228	0	65	0.9	0.002	100.0
3/31/09 3.30PM	41783	0	72	0.9	0.002	100.0
3/1/09 4.35 PM	29515	0	79	0.5	0.002	100.0
3/1/09 4.35 PM	29337	0	81	0.5	0.002	100.0
3/1/09 4.35 PM	29782	0	78	0.5	0.002	100.0

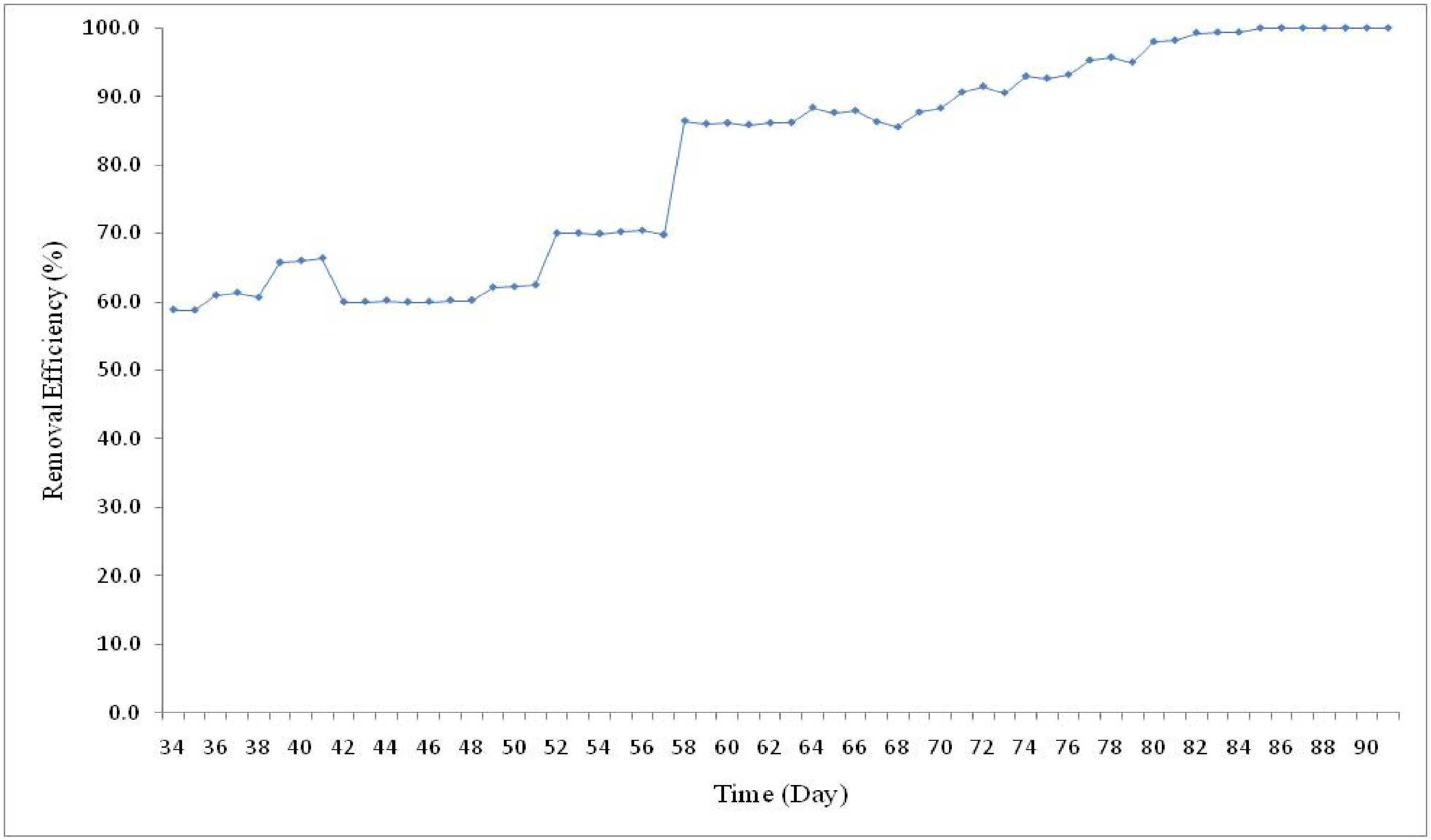

Figure 4.5 Propylene Removal Efficiency with Compost and Woodchips Media (50:50)

Table 4.9 Average Daily Experimental Results for Propylene with the Mixture of Compost and Woodchips (Intermediate Mixture)

Date & Time	Average Inlet (ppm)	Average Outlet (ppm)	Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)
				(Propylene +Air)	Propylene	
2/5/09 3.35PM	1017	427	60	0.5	0.002	58.0
2/6/09 3.30PM	1013	418	59	0.5	0.002	58.8
2/7/09 3.55PM	923	346	62	0.5	0.002	62.5
2/8/09 3.30PM	920	342	64	0.5	0.002	62.8
2/9/09 3.30PM	925	345	66	0.5	0.002	62.7
2/10/09 4.10PM	947	365	61	0.9	0.002	61.4
2/11/09 3.30PM	938	360	55	0.9	0.002	61.6
2/12/09 3.30PM	933	360	59	0.9	0.002	61.4
2/13/09 4.25PM	28448	11557	60	0.5	0.002	59.4
2/14/09 3.30PM	28715	11735	66	0.5	0.002	59.1
2/15/09 3.30PM	28893	11824	63	0.5	0.002	59.1
2/16/09 4.35PM	64453	25781	65	0.9	0.003	60.0
2/17/09 3.30PM	64008	25337	69	0.9	0.003	60.4
2/18/09 3.30PM	64186	25337	70	0.9	0.003	60.5
2/19/09 3.30PM	64186	25337	71	0.9	0.003	60.5
2/20/09 4.15PM	62230	23647	66	0.5	0.002	62.0
2/21/09 3.30PM	62052	23470	69	0.5	0.002	62.2
2/22/09 3.30PM	61786	23292	66	0.5	0.002	62.3
2/23/09 4.15PM	54407	16322	62	0.9	0.001	70.0
2/24/09 3.30PM	54229	16180	67	0.9	0.001	70.2
2/25/09 3.30PM	53785	16002	66	0.9	0.001	70.2
2/26/09 4.35PM	53340	16002	62	0.9	0.001	70.0
2/27/09 3.30PM	54229	15913	66	0.9	0.001	70.7

Table 4.9 - Continued

2/28/09 3.30PM	53785	15824	66	0.9	0.001	70.6
3/1/09 4.30PM	45339	6045	64	0.5	0.002	86.7
3/2/09 3.30PM	44895	5956	63	0.5	0.002	86.7
3/3/09 3.30PM	45339	6134	63	0.5	0.002	86.5
3/4/09 4.35PM	44006	6223	62	0.5	0.002	85.9
3/5/09 3.30PM	43561	6401	61	0.5	0.002	85.3
3/6/09 3.30PM	43561	6134	59	0.5	0.002	85.9
3/7/09 4.25PM	39916	4790	62	0.5	0.002	88.0
3/8/09 3.30PM	39561	4623	65	0.5	0.002	88.3
3/9/09 3.30PM	39116	4623	67	0.5	0.002	88.2
3/10/09 10.25PM	31115	4356	69	0.4	0.002	86.0
3/11/09 3.30PM	30937	4356	70	0.4	0.002	85.9
3/12/09 11.10AM	28893	3556	68	0.4	0.002	87.7
3/13/09 3.30PM	28804	3645	71	0.4	0.002	87.3
3/14/09 4.24PM	42050	4011	66	0.9	0.002	90.5
3/15/09 3.30PM	41783	3556	68	0.9	0.002	91.5
3/16/09 3.30PM	42050	3734	61	0.9	0.002	91.1
3/17/09 4.25PM	39116	2948	63	0.9	0.002	92.5
3/18/09 3.30PM	39561	3112	62	0.9	0.002	92.1
3/19/09 3.30PM	39116	2845	59	0.9	0.002	92.7
3/20/09 4.15PM	37871	1778	63	0.5	0.003	95.3
3/21/09 3.30PM	37516	1778	67	0.5	0.003	95.3
3/22/09 4.35PM	35560	1778	64	0.5	0.002	95.0
3/23/09 10.10AM	40005	889	64	0.5	0.002	97.8
3/24/09 3.30PM	40450	889	69	0.5	0.002	97.8
3/25/09 9.25AM	62230	427	65	0.5	0.001	99.3

Table 4.9 - Continued

3/26/09 3.30PM	62052	400	70	0.5	0.001	99.4
3/27/09 3.30PM	61786	445	75	0.5	0.001	99.3
3/28/09 4.24PM	48895	244	69	0.5	0.001	100.0
3/29/09 3.30PM	48451	240	68	0.5	0.001	100.0
3/30/09 4.40PM	42405	0	65	0.9	0.002	100.0
3/31/09 3.30PM	42139	0	66	0.9	0.002	100.0
4/1/09 4.40PM	29782	0	67	0.5	0.002	100.0
4/1/09 4.40PM	29693	0	68	0.5	0.002	100.0
4/1/09 4.40PM	29515	0	70	0.5	0.002	100.0

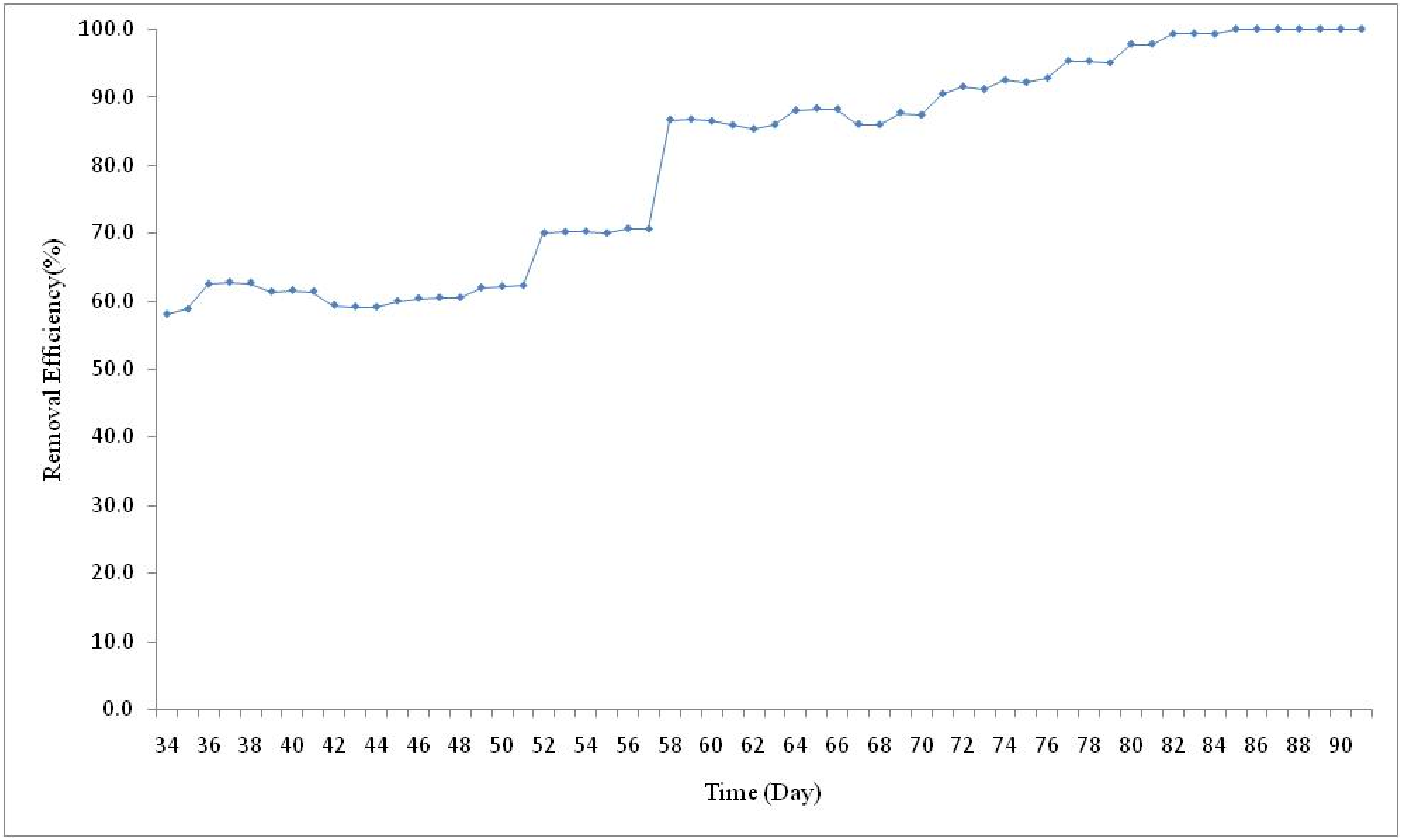

Figure 4.6 Propylene Removal Efficiency with Compost and Woodchips Media (Intermediate Mixture)

4.2.3 Summary of Propylene and Butylene Maximum Removal Efficiency with Different Combinations of Media

A summary of maximum removal efficiency of butylene and propylene gas with different combinations of media is given in Table 4.10, along with the number of weeks to attain 100% removal efficiency.

Table 4.10 Maximum Removal Efficiency of Butylene and Propylene Gas in Various Combinations of Media

Ratio (Compost to Woodchips)	**Column**	**Maximum Removal Efficiency**	**No. of Weeks to achieve 100% Removal Efficiency**	
			Butylene	**Propylene**
80:20	I	100%	13	12
50:50	II	100%	12	12
Intermediate	III	100%	12	12

Both propylene and butylene gas gave 100% removal efficiency with all ratios of compost and wood chips because the amount of media was enough to grow sufficient number of microbes to achieve 100% removal efficiency.

Butylene and propylene gave 100% removal efficiency in 12 weeks for most ratios of compost to woodchips. This time to achieve maximum removal efficiency was longer than that for many compounds, which is around 2 weeks. Acclimation periods may, however, vary from a few minutes to a year. “A biofilter operated to degrade methyl tertiarybutyl ether (MTBE), for example showed no acitivity for a year, then suddenly became very effective”. (Devinny, Deshusses, & Webster, 1999). During the acclimation period, microbes capable of degrading the pollutant increase in number, and those not capable of degrading the pollutant die off. If a microbe capable of degrading the pollutant is not initially present in the compost and woodchips, degradation of the compound may be possible after a cell undergoes a random mutation or until a specific gene transfer occurs from one organism to another. The relatively long acclimation period required for propylene and butylene means that the microbes most adept at degrading these compounds were not present in the original media in significant numbers, as will be discussed in Section 4.5.

The relatively long acclimation period for microbes to degrade propylene and butylene may present a practical problem in using biofiltration to degrade these compounds in the field. Compost media must typically be changed every 3-5 years; each time the compost media is changed, another 12 week acclimation period would be required. For a facility required to meet a permit, emitting pollutant for 12 weeks is not an option. One solution would be to install a temporary activated carbon adsorption system during the acclimation period. Another solution would be to acclimate the new compost while the old compost is still on-line, by running two biofilters in series (new compost biofilter followed by old compost biofilter). This would result in a higher pressure drop for the 12-week acclimation period, but would result in continuous treatment of pollutant.

4.3 Elimination Capacity

4.3.1 Butylene Elimination Capacity

The inlet loading, outlet loading, and elimination capacity of butylene for 80:20, 50:50, and the intermediate ratios of compost and woodchips are given in Table 4.11, Table 4.12, and Table 4.13, respectively. Graphs of elimination capacity versus inlet loading of butylene gas are shown in Figure 4.7, Figure 4.8, and Figure 4.9, respectively for 80:20, 50:50, and intermediate ratio of compost to woodchips. Best fit regression equations and corresponding R^2 values are shown on the graphs. The only points shown in the graph are those after 100% removal efficiency was achieved, or the microbes were fully acclimated to the butylene.

Table 4.11 Inlet and Outlet Butylene Loading with the Mixture of Compost and Hard Wood Chips Biofilter (80:20)

Average Inlet (ppm)	**Inlet Loading (g/m^3-hr)**	**Average Outlet (ppm)**	**Outlet Loading (g/m^3-hr)**	**Elimination capacity (g/m^3-hr)**	**Removal Efficiency (%)**
110	2.1	90.7	1.7	0.4	21.8
200	3.8	163.6	3.1	0.7	18.2
577	11.0	381.4	7.3	3.7	33.9
180	3.4	124.5	2.4	1.0	30.7
1017	10.8	426.7	4.5	6.2	58.0
947	10.0	365.4	3.9	6.1	61.4
923	9.8	345.8	3.7	6.1	62.5
875	9.2	302.3	3.2	6.1	65.4
828	8.7	244.5	2.6	6.2	70.5
757	8.0	179.6	1.9	6.1	76.3
707	7.5	133.4	1.4	6.1	81.1
720	7.6	115.6	1.2	6.4	84.0
706	7.5	111.1	1.2	6.3	84.3
578	6.1	51.6	0.5	5.6	91.1
91	1.7	0.0	0.0	1.7	100.0
100	1.9	0.0	0.0	1.9	100.0
104	2.0	0.0	0.0	2.0	100.0
376	3.2	0.0	0.0	3.2	100.0
365	3.1	0.0	0.0	3.1	100.0
548	5.8	0.0	0.0	5.8	100.0
554	5.9	0.0	0.0	5.9	100.0

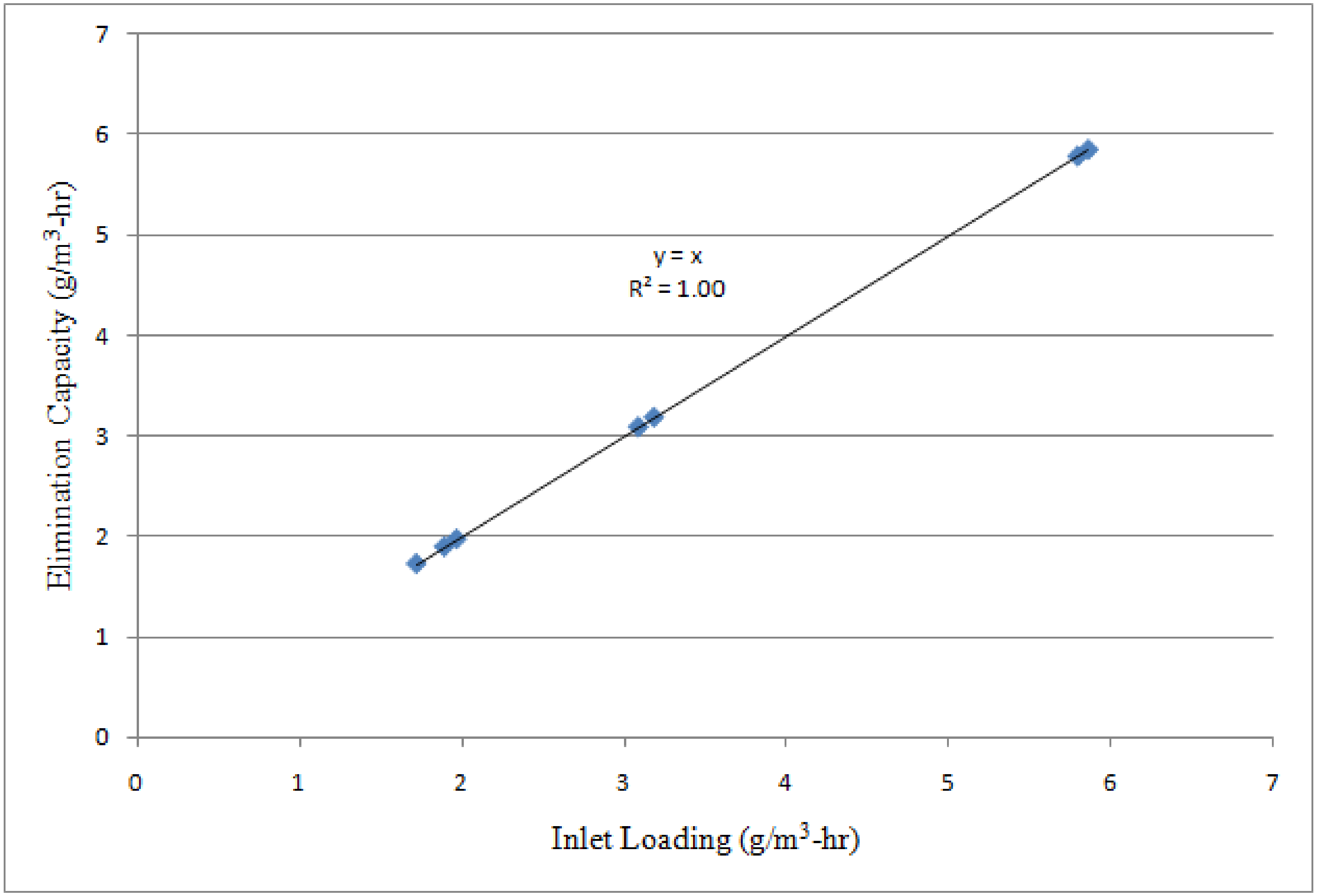

Figure 4.7 Inlet Butylene Loading vs. Elimination Capacity for the Mixture of Compost and Hard Wood Chips (80:20)

Table 4.12 Inlet and Outlet Butylene Loading with the Mixture of Compost and Hard Wood Chips Biofilter (50:50)

Average Inlet (ppm)	Inlet Loading (g/m^3-hr)	Average Outlet (ppm)	Outlet Loading (g/m^3-hr)	Elimination Capacity (g/m^3-hr)	Removal Efficiency (%)
190	3.6	155.6	3.0	0.7	18.2
488	9.3	323.6	6.2	3.1	33.7
200	3.8	139.6	2.7	1.2	30.2
928	9.8	382.3	4.0	5.8	58.8
938	19.8	356.5	7.5	12.3	62.0
887	9.4	336.9	3.6	5.8	62.0
866	9.2	295.1	3.1	6.0	65.9
799	8.4	239.1	2.5	5.9	70.1
710	7.5	167.1	1.8	5.7	76.5
662	9.8	124.5	1.8	8.0	81.2
631	6.7	106.7	1.1	5.5	83.1
644	6.8	101.3	1.1	5.7	84.3
489	5.2	42.7	0.5	4.7	91.3
110	2.3	0.0	0.0	2.3	100.0
188	3.6	0.0	0.0	3.6	100.0
104	2.0	0.0	0.0	2.0	100.0
465	3.9	0.0	0.0	3.9	100.0
454	3.8	0.0	0.0	3.8	100.0
637	6.7	0.0	0.0	6.7	100.0
643	13.6	0.0	0.0	13.6	100.0

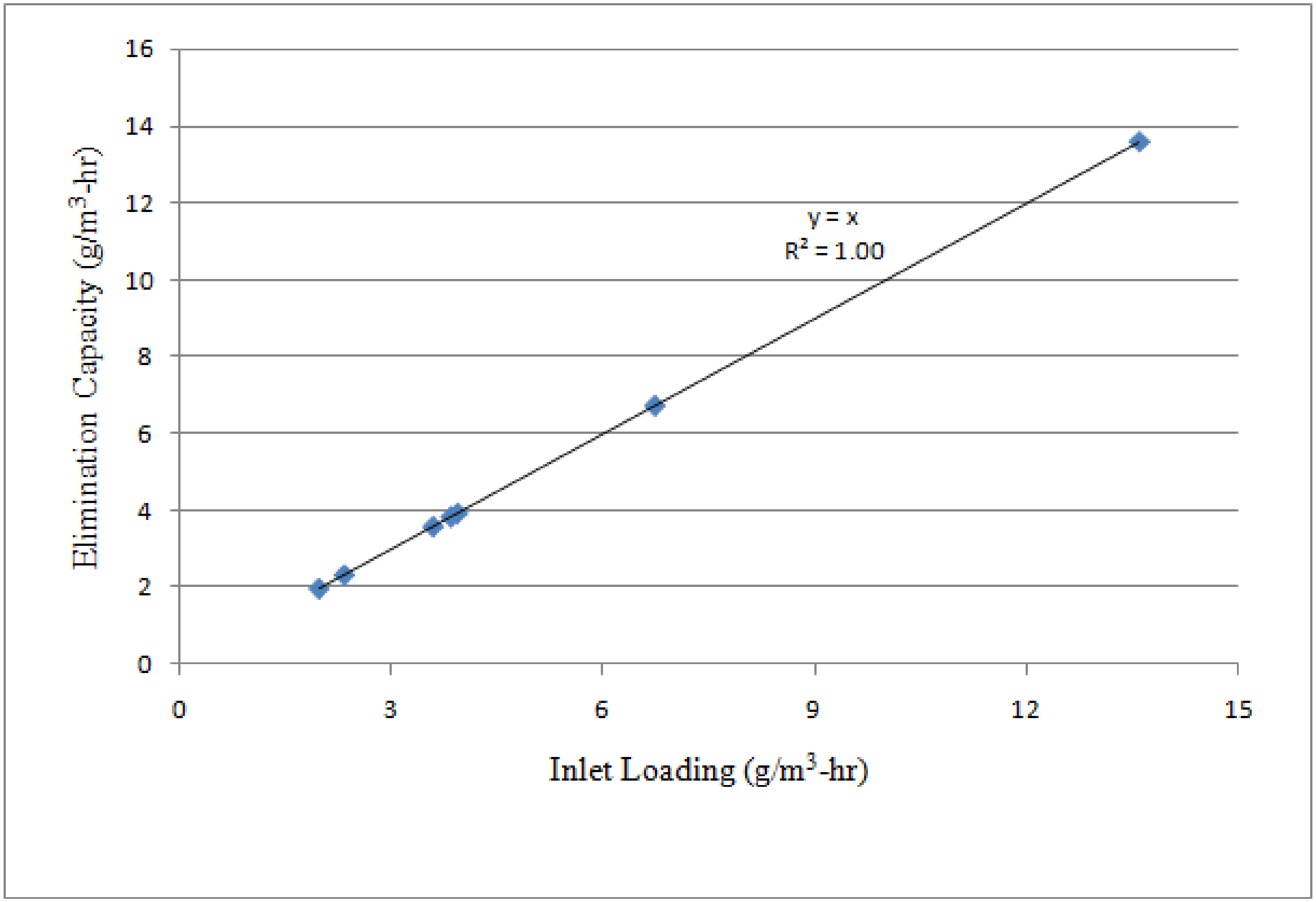

Figure 4.8 Inlet Butylene Loading vs. Elimination Capacity for the Mixture of Compost and Hard Wood Chips (50:50)

Table 4.13 Inlet and Outlet Butylene Loading with the Mixture of Compost and Hard Wood Chips Biofilter (Intermediate Mixture)

Average Inlet (ppm)	**Inlet Loading (g/m^3-hr)**	**Average Outlet (ppm)**	**Outlet Loading (g/m^3-hr)**	**Elimination Capacity (g/m^3-hr)**	**Removal Efficiency (%)**
222	4.2	182.2	3.5	0.8	18.0
533	10.1	356.5	6.8	3.3	33.1
215	3.6	149.4	2.5	1.1	30.6
1068	11.3	442.7	4.7	6.6	58.5
979	10.3	374.3	4.0	6.4	61.8
967	10.2	365.4	3.9	6.4	62.2
899	9.5	311.2	3.3	6.2	65.4
739	10.9	217.8	3.2	7.7	70.5
801	8.5	187.6	2.0	6.5	76.6
713	7.5	128.9	1.4	6.2	81.9
568	6.0	88.0	0.9	5.1	84.5
713	15.1	114.7	2.4	12.6	83.9
502	5.3	42.7	0.5	4.9	91.5
91	1.7	0.0	0.0	1.7	100.0
100	1.9	0.0	0.0	1.9	100.0
104	2.0	0.0	0.0	2.0	100.0
376	3.2	0.0	0.0	3.2	100.0
365	3.1	0.0	0.0	3.1	100.0
548	5.8	0.0	0.0	5.8	100.0
554	5.9	0.0	0.0	5.9	100.0

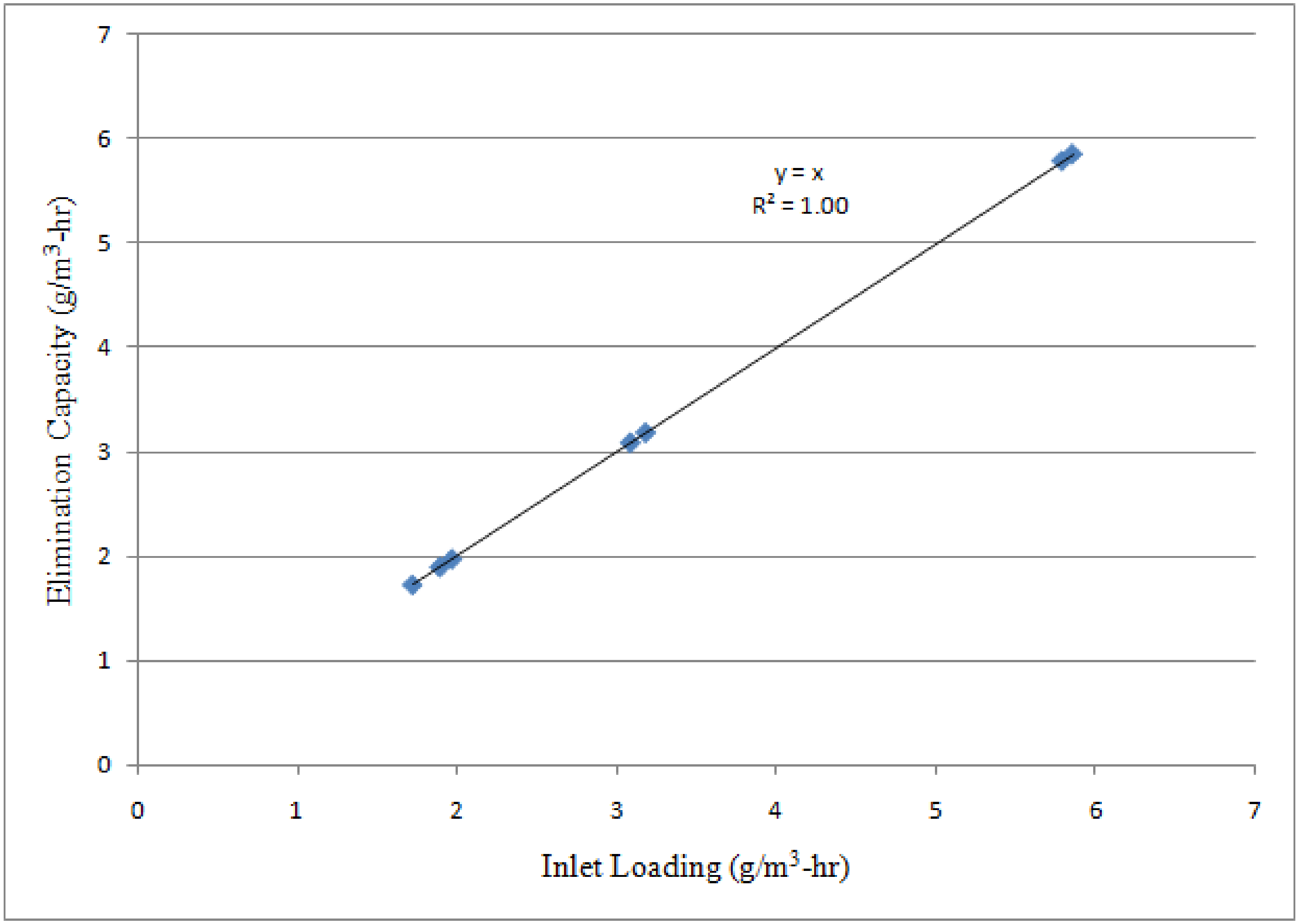

Figure 4.9 Inlet Butylene Loading vs. Elimination Capacity for the Mixture of Compost and Hard Wood Chips (Intermediate Mixture)

4.3.2 Propylene Elimination Capacity

The inlet loading, outlet loading, and elimination capacity of propylene for 80:20, 50:50, and the intermediate ratios of compost and woodchips are given in Table 4.14, Table 4.15, and Table 4.16, respectively. Graphs of elimination capacity versus inlet loading of butylene gas are shown in Figure 4.10, Figure 4.11, and Figure 4.12, respectively for 80:20, 50:50, and intermediate ratio of compost to woodchips. The only points shown in the graph are those after 100% removal efficiency was achieved, or the microbes were fully acclimated to the propylene. If inlet loading had been increased, higher elimination capacities would likely have been observed.

Table 4.14 Inlet and Outlet Propylene Loading with the Mixture of Compost and Hard Wood Chips (80:20)

Average Inlet (ppm)	Inlet Loading (g/m^3-hr)	Average Outlet (ppm)	Outlet Loading (g/m^3-hr)	Elimination Capacity (g/m^3-hr)	Removal Efficiency (%)
988	10	409	4	6.12	58.6
947	10	365	4	6.15	61.4
891	9	346	4	5.76	61.2
28537	302	11646	123	179	59.2
64097	1220	25337	482	738	60.5
62230	1184	23647	450	734	62.0
54229	1032	16233	309	723	70.1
53251	1013	15913	303	710	70.1
45428	480	6134	65	415	86.5
43917	464	6045	64	400	86.2
39916	422	4790	51	371	88.0
31204	264	4267	36	228	86.3
28804	244	3645	31	213	87.3
41961	798	3922	75	724	90.7
39205	746	2859	54	692	92.7
37783	399	1867	20	380	95.1
35649	377	1867	20	357	94.8
39916	422	978	10	412	97.6
62408	660	400	4	655	99.4
48806	516	268	3	513	99.5
42228	804	0	0	804	100.0
29604	313	0	0	313	100.0

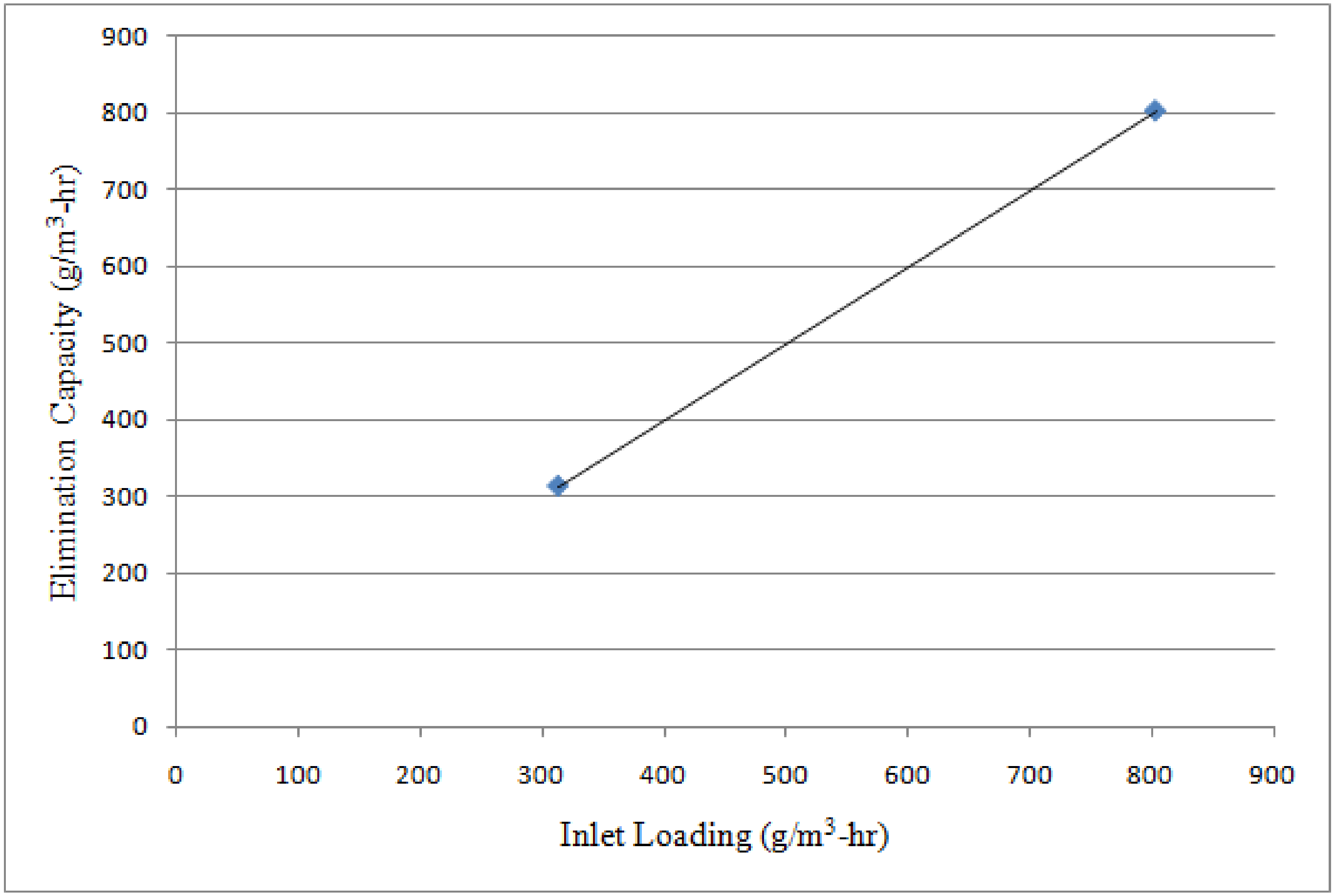

Figure 4.10 Inlet Propylene Loading vs. Elimination Capacity for the Mixture of Compost and Hard Wood Chips (80:20)

Table 4.15 Inlet and Outlet Propylene Loading with the Mixture of Compost and Hard Wood Chips (50:50)

Average Inlet (ppm)	**Inlet Loading (g/m^3-hr)**	**Average Outlet (ppm)**	**Outlet Loading (g/m^3-hr)**	**Elimination Capacity (g/m^3-hr)**	**Removal Efficiency (%)**
928	10	382	4	6	58.8
887	9	346	4	6	61.0
1009	11	346	4	7	65.7
28626	303	11468	121	181	59.9
64541	1228	25603	487	741	60.3
62141	1182	23559	448	734	62.1
54407	1035	16322	311	725	70.0
53429	1017	15913	303	714	70.2
45161	477	5956	63	414	86.8
44006	465	6223	66	399	85.9
39738	420	5234	55	365	86.8
31293	265	4267	36	229	86.4
28893	244	3556	30	214	87.7
41872	797	3922	75	722	90.6
39027	743	2948	56	687	92.4
37694	398	1778	19	380	95.3
35471	375	1778	19	356	95.0
39827	421	800	8	413	98.0
62230	658	427	5	653	99.3
49073	519	270	3	516	99.4
42228	804	0	0	804	100.0
29515	312	0	0	312	100.0

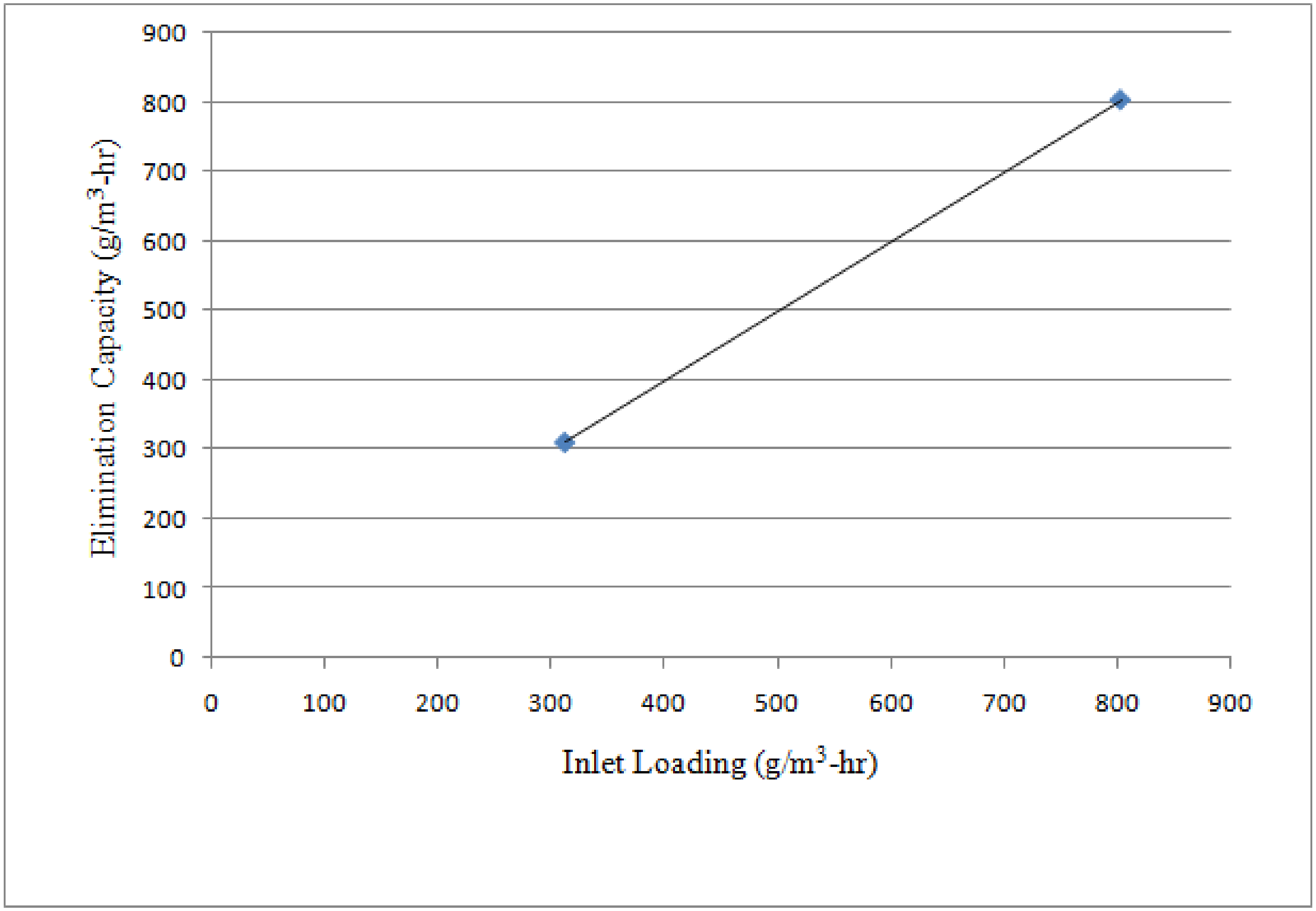

Figure 4.11 Inlet Propylene Loading vs. Elimination Capacity for the Mixture of Compost and Hard Wood Chips (50:50)

Table 4.16 Inlet and Outlet Propylene Loading with the Mixture of Compost and Hard Wood Chips (Intermediate Mixture)

Average Inlet (ppm)	Inlet Loading (g/m^3-hr)	Average Outlet (ppm)	Outlet Loading (g/m^3-hr)	Elimination Capacity (g/m^3-hr)	Removal Efficiency (%)
1017	11	427	5	6	58.0
923	10	346	4	6	62.5
947	10	365	4	6	61.4
28448	301	11557	122	179	59.4
64453	1226	25781	491	736	60.0
62230	1184	23647	450	734	62.0
54407	1035	16322	311	725	70.0
53340	1015	16002	304	710	70.0
45339	479	6045	64	415	86.7
44006	465	6223	66	399	85.9
39916	422	4790	51	371	88.0
31115	263	4356	37	226	86.0
28893	244	3556	30	214	87.7
42050	800	4011	76	724	90.5
39116	744	2948	56	688	92.5
37871	400	1778	19	382	95.3
35560	376	1778	19	357	95.0
40005	423	889	9	413	97.8
62230	658	427	5	653	99.3
48895	517	250	3	514	99.5
42405	807	0	0	807	100.0
29782	315	0	0	315	100.0

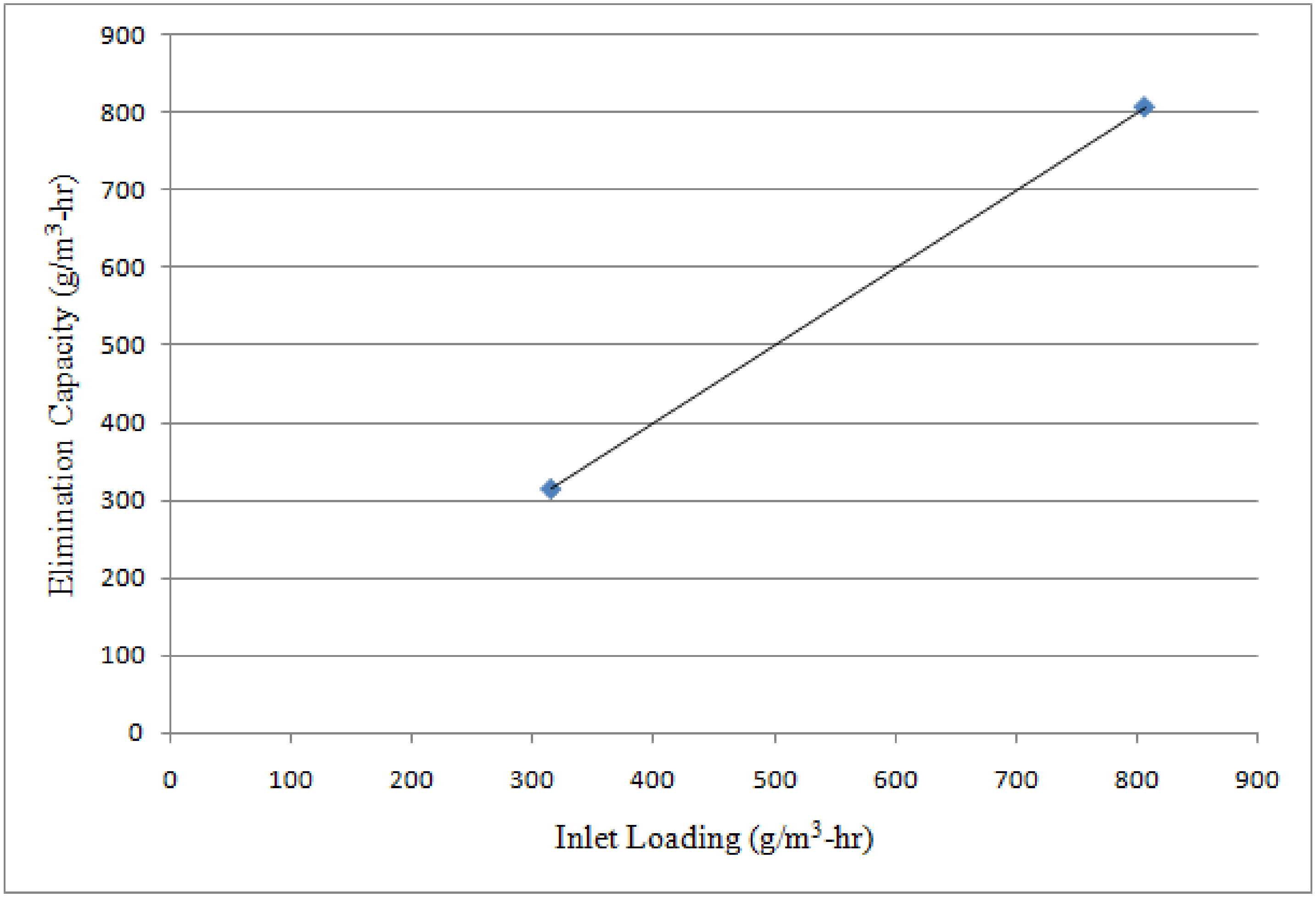

Figure 4.12 Inlet Propylene Loading vs Elimination Capacity for the Mixture of Compost and Hard Wood Chips (Intermediate Mixture)

4.3.3 Propylene and Butylene Maximum Observed Elimination Capacity with Different Combinations of Media

A summary of maximum observed elimination capacity of butylene and propylene gas with different combinations of media is given in Table 4.17.

Table 4.17 Maximum Observed Elimination Capacity of Butylene and Propylene in Different Combinations of Media

Compound	**Media (Compost to Woodchips)**	**Maximum Observed Elimination Capacity (g/m^3-hr)**
Butylene	80:20	5.9
	50:50	13.6
	Intermediate	12.6
Propylene	80:20	804
	50:50	804
	Intermediate	807

Although the media ratio did not impact maximum removal efficiency, it did impact observed maximum observed elimination capacity, as discussed below. As shown in Table 4.19, butylene gave maximum observed elimination capacity for 50:50 compost to woodchips ratio, and lower elimination capacities for intermediate and 80:20 ratio of compost to woodchips. Propylene has essentially the same maximum elimination capacity for all compost to woodchips ratios.

The maximum observed elimination capacity of propylene is much higher than butylene because the concentration of propylene was higher at the time of entering the biofilter. Initially, the concentration of butylenes gas was varying every day; it took so much time to fix the flow of the gas. By that time, the concentration of butylene gas was decreased due to lower cylinder pressure. However, there was no as such problem at the time of propylene gas. High concentration of propylene was passed in the biofilter from the 1st day of experiment. Hence, high value of maximum elimination capacity was obtained with propylene gas.

Microbes are completely acclimated at 100% removal efficiency in these experiments. If the inlet loading had been increased after microbe acclimation, the removal efficiency eventually would have started to decrease at the point that the microbes cannot eat more. Critical loading is the inlet loading value when removal efficiency is ≈ 95%.

4.4 Media pH, Gas Stream Relative Humidity, and Moisture Content

4.4.1 Media pH

Samples were taken from the bottom of the three biofilter columns to compare the pH of the media at the experiment's beginning and after three months. The initial and final pH readings of the media with butylene and propylene gas are given in Table 4.18 and Table 4.19.

Table 4.18 pH Value of Different Combinations of Biofilter Media Treating Butylene

Ratio	Column	pH (1st day)	pH (After 15 weeks)
80 : 20	I	7.12	7.73
50 : 50	II	7.14	7.76
Intermediate	III	7.12	7.46

Table 4.19 pH Value of Different Combinations of Biofilter Media Treating Propylene

Ratio	Column	pH (1st day)	pH (After 13 weeks)
80 : 20	I	7.12	7.5
50 : 50	II	7.12	7.71
Intermediate	III	7.12	7.67

In the 1st set of experiment with butylene, pH of the compost was found to be 7.12 in the beginning and 7.7 after 15 weeks. Both the pH values are close to neutral. Although the pH increased slightly, there was likely no significant formation of acidic or basic byproducts which would hinder continued pollutant removal. pH values of the three media combinations were similar.

In the second set of experiments, the initial pH was 7.12 and final pH obtained 7.5 to 7.7 again, pH values of the three media combinations were similar after 13 weeks, which are also close to neutral. This shows no formation of acidic byproducts.

4.4.2 Gas Stream Relative Humidity

Gas stream relative humidity during the experiment during the experiment ranged from 50-80%, which is lower than the 95-100%, typically recommended for biofilter operation (Devinny, Deshusses, & Webster, 1999). However, 100% removal efficiency was still achieved.

4.4.3 Moisture Content

Moisture content of the media is given in Table 4.20. These moisture contents are lower than typical for organic media (40-80%) (Devinny, Deshusses, & Webster, 1999). However, 100% removal efficiency was still achieved.

Table 4.20 Moisture Content of Different Types of Media

Media	**Moisture Content (%)**
Fresh Compost	17.4
Fresh Woodchips	11.6
Used compost + Woodchips (Propylene)	20.4
Used Compost + Woodchips (Butylene)	22.6

4.5 Microbes in the Media

The media was sent to the Microchek, VT for determining the different types of microbes present in the fresh compost, fresh woodchips, and used compost and woodchips of butylene and propylene. Different types of microbes such as aerobic bacterium (B), fungus (F), and actinomycetes (AC) were found in media as given in Table 4.21. The detailed information of microbes is given in Appendix C.

Fresh woodchips and compost contain different species of same genus *Bacillus*. However, fresh compost has only some *Streptomyces*, *Pseudomonas*, and *Paenibacillus* species. Used compost and woodchips of butylene have some new species of *Bacillus*, *Rhodococcus*, *Doratomyces*, *Trichurus*, *Aspergillus*, and *Chaetomium*, which are not present in fresh compost and fresh woodchips. In addition, used compost and woodchips and fresh compost contain different species of same genus *Steptomycetes*. Used compost and woodchips of propylene contain new species of *Sphingobacterium*, *Parapedobacter*, *Brachybacterium*, *Cellulomonas*, *Trichoderma*, *Sphingopyxis*, *Microbacterium*, *Bordetella*, *Serratia*, and *Trochoderma*, which are not present in fresh compost and woodchips. Used media of butylene and propylene contains different microbes except some microbes of same genus *Streptomyces*. This shows that different types of microbes were grown up in the used media of propylene and butylene after 12 weeks of acclimation period, which were not able to grow up in the fresh compost and woodchips, or genetic mutation occurred in 12 weeks which changed microbes from one species to another.

Table 4.21 List of Microorganisms in Media

Fresh Compost	**Fresh Woodchips**	**Used Compost and Woodchips (Butylene)**	**Used Compost and Woodchips (Propylene)**
Bacillus mojavensis *Bacillus licheniformis*	*Enterococcus durans*	*Bacillus megaterium*	*Sphingobacterium thalpophilum* **Parapedobacter koreensis*
Streptomyces althioticus	*Nocardia brasiliensis*	*Rhodococcus koreensis*	*Sphingobacterium multivorum* **Sphingobacterium composti*
Bacillus amyloliquefaciens	*Bacillus simplex*	*Doratomyces stemonitis* **Trichurus spiralis*	*Brachybacterium nesterenkovii* **Janibacter melonis*
Bacillus firmus	*Bacillus oleronius*	*Bacillus barbaricus* **Bacillus* species	*Cellulomonas gelida* **Promicromonospora* species
Paenibacillus lautus **Paenibacillus ginsengagri*	*Bacillus megaterium*	*Stenotrophomonas maltophilia* **Luteimonas* species	*Trichoderma aureoviride* *Trichoderma harzianum* *Trichoderma inhamatum* *Trichoderma virens*
Bacillus barbaricus **Bacillus arsenicus*	*Bacillus fusiformis*	*Streptomyces antibioticus* **Streptomyces shandonggensis*	*Streptomyces griseinus*
Pseudomonas resinovorans **Pseudomonas* species		*Aspergillus versicolor*	*Sphingopyxis macrogoltabida*
Pseudomonas resinovorans **Pseudomonas* species		*Chaetomium brasiliense* **Chaetomium piluliferum*	*Microbacterium ketosireducens* **Microbacterium* species
			Bordetella petrii
			Pseudomonas corrugate
			Trichoderma aureoviride *Trichoderma harzianum* *Trichoderma inhamatum* *Trichoderma virens*
			Serratia marcescens

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research compared propylene and butylene removal using biofiltration technology with different composition of compost and woodchips. Three different ratios of 80:20, 50:50, and random mixture of compost and woodchips were used in the experiments.

It was found that different ratios of media (compost to woodchips) gave 100% removal efficiency with both gases (propylene & butylene). Different ratios of media did not affect removal efficiency results. Butylene and propylene gave 100% removal efficiency in 12 weeks. Hence, both gases take almost same time to attain 100% removal efficiency. The acclimation time, which was longer than typical for many compounds, was due to the fact that microbes adept at degrading propylene and butylene were not present in significant numbers in the original media.

Maintenance of gas stream relative humidity between 50-80%, and media moisture content around 20% gave good results. The pH was approximately constant throughout the experiment, near neutral with both propylene and butylene. This shows no formation of significant acidic byproducts which will decrease the pH of the media. Butylene has highest observed elimination capacity 13.6 g/m^3-hr for 50:50 ratio of compost to woodchips and propylene has highest observed elimination capacity 807 for random ratio of compost to woodchips. If inlet loadings had been increased, higher elimination capacities would likely have been observed.

Fresh compost and woodchips contain different microbes except genus *Bacillus*, and used media contain even different types of microbes. Microbes are different for used media of butylene and propylene except *Streptomyces*. This indicates that used media of butylene and propylene contain different types of microbes after 12 weeks of acclimation period, which were not able to grow up in the fresh compost and woodchips. Genetic mutations can also occur in 12 weeks which changes microbes from one species to another.

5.2 Recommendations

5.2.1 Recommendations for Improving Experimental Procedure

- Use desiccants in the condensation flask to avoid excessive moisture in tubes and flowmeters.
- Two needle valves can be used in parallel or series to reduce the concentration of gas.
- Syringe of small volume can give better peaks of propylene and butylene gas.

5.2.2 Recommendations for Further Research

- Determine the removal efficiency in biofilters for other pollutants, particularly ethene, a highly-reactive VOC in terms of ozone formation.

- Test different compositions of media such as 10:90 and 30:70 compost to woodchips media.

- Test the removal efficiency of different combinations of hydrocarbons.

- Determine maximum elimination capacity and critical loading for propylene and butylene gases.

- Identify genes of microbes responsible for removal of butylene and propylene gases so that removal efficiency can be obtained with short acclimation period by inoculating the biofilter with appropriate microbes.

APPENDIX A

DAILY EXPERIMENTAL INLET AND OUTLET CONCENTRATIONS

Table A.1 Daily Experimental Inlet Concentrations for Butylene 80:20 Compost to Woodchips Ratio

Date & Time	**Inlet I (ppm)**	**Inlet II (ppm)**	**Inlet III (ppm)**	**Average Concentration (ppm)**	**Standard Deviation (ppm)**	**Standard Deviation (%)**
9/29/08 4.10 PM	110	109	112	110	1.66	1.50
9/30/08 4.10 PM	110	110	103	108	4.21	3.91
10/1/08 4.10 PM	111	109	105	108	2.85	2.63
10/2/08 4.10 PM	198	199	203	200	2.69	1.34
10/3/08 4.00 PM	198	198	209	202	6.59	3.26
10/4/08 4.00 PM	199	199	199	199	0.24	0.12
10/5/08 4.12 PM	570	571	590	577	11.63	2.02
10/6/08 4.12 PM	576	576	565	573	6.21	1.08
10/7/08 4.30PM	178	179	182	180	1.93	1.08
10/8/08 4.30PM	177	178	189	181	6.70	3.69
10/9/08 4.30PM	1015	1016	1020	1017	2.67	0.26
10/10/08 4.30PM	1016	1016	1014	1015	1.32	0.13
10/11/08 4.30PM	1017	1017	1015	1016	1.11	0.11
10/12/08 4.15PM	945	945	950	947	3.09	0.33
10/13/08 4.15PM	944	945	957	949	7.06	0.74
10/14/08 4.15PM	921	922	925	923	2.28	0.25
10/15/08 4.15PM	922	922	930	925	4.43	0.48
10/16/08 12.25PM	874	874	876	875	1.18	0.13
10/17/08 4.15PM	873	874	869	872	2.46	0.28
10/18/08 4.05PM	826	827	830	828	2.45	0.30
10/19/08 4.15PM	825	826	840	830	8.80	1.06
10/20/08 4.15PM	826	827	844	832	10.14	1.22

Table A.1- Continued

10/21/08 4.15PM	824	826	825	825	0.88	0.11
11/22/08 4.12PM	757	757	759	757	1.20	0.16
10/23/08 4.15PM	757	757	764	759	3.82	0.50
10/24/08 4.15PM	756	754	776	762	11.95	1.57
10/25/08 4.07PM	705	705	710	707	3.04	0.43
10/26/08 4.15PM	706	705	718	709	7.68	1.08
10/27/08 4.15PM	706	706	705	706	0.42	0.06
10/28/08 4.45PM	721	721	718	720	1.58	0.22
10/29/08 4.15PM	720	720	691	710	5.34	2.36
10/30/08 4.15PM	721	722	723	722	0.81	0.11
10/31/08 4.15PM	721	719	747	729	2.35	2.20
11/1/08 4.15PM	704	704	710	706	3.67	0.52
11/2/08 4.35PM	705	705	708	706	1.50	0.21
11/3/08 4.15PM	704	705	706	705	1.28	0.18
11/4/08 4.15PM	703	704	727	711	13.35	1.88
11/5/08 4.15PM	576	577	581	578	2.39	0.41
11/6/08 4.15PM	576	578	633	596	9.12	5.49
11/7/08 4.15PM	578	578	618	591	8.16	3.94
11/8/08 4.20PM	90	91	91	91	0.52	0.58
11/9/08 4.15PM	90	90	95	92	3.20	3.49
11/10/08 4.15PM	88	89	99	92	6.08	6.61
11/11/08 4.00PM	98	99	102	100	2.30	2.31
11/12/08 4.15PM	99	100	102	100	1.32	1.32

Table A.1- Continued

11/13/08 4.15PM	102	103	106	104	1.92	1.85
11/14/08 4.00PM	103	103	105	104	0.98	0.95
11/15/08 4.15PM	103	104	106	104	1.80	1.73
11/16/08 4.45PM	375	376	379	376	2.16	0.57
11/17/08 4.15PM	376	375	374	375	1.00	0.27
11/18/08 4.15PM	365	364	401	377	5.32	5.64
11/19/08 7.25PM	364	364	368	365	2.10	0.58
11/20/08 4.15PM	364	365	369	366	2.65	0.72
11/21/08 4.15PM	546	547	550	548	2.01	0.37
11/22/08 4.15PM	547	547	549	548	1.08	0.20
11/23/08 4.15PM	546	547	555	549	4.77	0.87
11/24/08 4.15PM	553	553	556	554	1.92	0.35
11/25/08 4.15PM	553	553	557	554	2.18	0.39

Table A.2 Daily Experimental Outlet Concentrations for Butylene 80:20 Compost to Woodchips Ratio

Date & Time	Outlet I (ppm)	Outlet II (ppm)	Outlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
9/29/08 4.10 PM	88	89	95	91	3.81	4.20
9/30/08 4.10 PM	90	90	89	90	0.37	0.41
10/1/08 4.10 PM	88	89	95	91	3.81	4.20
10/2/08 4.10 PM	161	162	168	164	3.63	2.22
10/3/08 4.00 PM	162	162	169	164	4.27	2.60
10/4/08 4.00 PM	161	161	169	164	4.46	2.73
10/5/08 4.12 PM	379	378	387	381	5.02	1.31
10/6/08 4.12 PM	378	376	390	381	7.65	2.01
10/7/08 4.30PM	122	122	129	124	4.26	3.42
10/8/08 4.30PM	123	123	130	125	4.07	3.25
10/9/08 4.30PM	422	423	435	427	7.33	1.72
10/10/08 4.30PM	423	424	406	418	9.83	2.35
10/11/08 4.30PM	423	424	433	427	5.60	1.31
10/12/08 4.15PM	362	363	371	365	5.01	1.37
10/13/08 4.15PM	364	363	380	369	9.43	2.56
10/14/08 4.15PM	343	343	352	346	5.32	1.54
10/15/08 4.15PM	343	343	362	349	6.45	3.16
10/16/08 12.25PM	300	300	307	302	3.91	1.30
10/17/08 4.15PM	301	300	290	297	6.21	2.09
10/18/08 4.05PM	242	243	248	244	3.46	1.41
10/19/08 4.15PM	243	244	284	257	3.43	9.22

Table A.2 - Continued

10/20/08 4.15PM	241	243	263	249	12.03	4.83
10/21/08 4.15PM	242	243	236	240	3.85	1.61
11/22/08 4.12PM	176	177	186	180	5.35	2.98
10/23/08 4.15PM	177	178	205	187	4.34	8.53
10/24/08 4.15PM	178	178	199	185	11.97	6.47
10/25/08 4.07PM	130	131	139	133	4.96	3.72
10/26/08 4.15PM	132	132	123	129	5.36	4.16
10/27/08 4.15PM	130	131	136	132	3.43	2.59
10/28/08 4.45PM	115	114	118	116	1.92	1.66
10/29/08 4.15PM	114	115	115	115	0.59	0.51
10/30/08 4.15PM	115	116	126	119	6.30	5.29
10/31/08 4.15PM	114	113	141	123	5.76	12.97
11/1/08 4.15PM	109	108	116	111	4.57	4.12
11/2/08 4.35PM	109	110	114	111	2.86	2.57
11/3/08 4.15PM	108	109	119	112	6.11	5.45
11/4/08 4.15PM	109	111	121	114	6.64	5.84
11/5/08 4.15PM	49	48	58	52	5.33	10.33
11/6/08 4.15PM	50	51	59	53	4.94	9.27
11/7/08 4.15PM	51	51	58	53	4.05	7.60

Table A.3 Daily Experimental Inlet Concentrations for Butylene 50:50 Compost to Woodchips Ratio

Date & Time	Inlet I (ppm)	Inlet II (ppm)	Inlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
9/29/08 4.05PM	190	191	190	190.25	0.67	0.35
9/30/08 4.11 PM	189	190	190	189.36	0.31	0.16
10/1/08 4.12 PM	190	190	191	190.25	0.27	0.14
10/2/08 4.17 PM	489	487	488	488.06	1.01	0.21
10/3/08 4.11 PM	484	484	486	484.51	1.33	0.27
10/4/08 4.11 PM	483	483	485	483.62	1.52	0.31
10/5/08 4.35 PM	199	201	201	200.03	0.89	0.44
10/6/08 4.13 PM	203	203	205	203.58	1.46	0.72
10/7/08 4.35PM	927	928	929	928.12	1.18	0.13
10/8/08 4.32PM	924	924	926	924.56	1.43	0.15
10/9/08 4.20PM	937	937	940	937.90	1.55	0.17
10/10/08 4.32PM	933	934	933	933.45	0.51	0.05
10/11/08 4.31PM	936	936	937	936.12	0.68	0.07
10/12/08 4.20 PM	887	887	888	887.22	0.85	0.10
10/13/08 4.17PM	888	889	890	889.00	1.00	0.11
10/14/08 4.30PM	865	865	868	865.89	1.53	0.18
10/15/08 4.15PM	864	864	864	864.11	0.10	0.01
10/16/08 4.10 PM	799	799	800	799.21	0.84	0.10
10/17/08 4.16PM	797	797	798	797.43	0.75	0.09
10/18/08 4.17 PM	709	710	712	710.31	1.49	0.21
10/19/08 4.17PM	709	709	713	710.31	2.27	0.32

Table A.3 - Continued

10/20/08 4.16 PM	711	710	713	711.20	1.31	0.18
10/21/08 4.16PM	711	711	712	711.20	0.35	0.05
11/22/08 4.12PM	661	663	663	662.31	1.13	0.17
10/23/08 4.16PM	656	657	661	657.86	2.41	0.37
10/24/08 4.17PM	664	664	664	664.08	0.14	0.02
10/25/08 4.50PM	631	630	633	631.19	1.30	0.21
10/26/08 4.16PM	631	631	632	631.19	0.33	0.05
10/27/08 4.17PM	634	634.8	635	634.75	0.52	0.08
10/28/08 4.40 PM	643	643	645	643.64	1.10	0.17
10/29/08 4.16PM	642	641	642	641.86	0.49	0.08
10/30/08 4.15PM	640	641	642	640.97	1.06	0.17
10/31/08 4.17PM	640	641	645	641.86	2.40	0.37
11/1/08 4.18PM	640	642	641	640.97	1.00	0.16
11/2/08 4.20 PM	488	488	491	488.95	1.82	0.37
11/3/08 4.19PM	481	480	479	480.06	0.91	0.19
11/4/08 4.25PM	488	488	491	488.95	1.94	0.40
11/5/08 4.25 PM	111	110	110	110.24	0.68	0.61
11/6/08 4.16PM	108	108	109	108.46	0.79	0.73
11/7/08 4.17PM	108	109	111	109.35	1.55	1.42
11/8/08 4.05 PM	188	188	189	188.47	0.81	0.43
11/9/08 4.17PM	191	190	190	190.25	0.67	0.35
11/10/08 4.18PM	192	192	195	192.91	1.58	0.82
11/11/08 4.05 PM	103	103	105	103.57	1.44	1.39
11/12/08 4.16PM	103	104	102	103.21	0.70	0.68

Table A.3 - Continued

11/13/08 4.17PM	103	104	103	103.39	0.35	0.34
11/14/08 4.50 PM	465	465	466	465.39	0.68	0.15
11/15/08 4.17 PM	467	466	467	466.73	0.63	0.14
11/16/08 7.30 PM	454	455	453	454.01	0.98	0.22
11/17/08 4.19PM	453	453	454	453.39	0.68	0.15
11/18/08 4.18PM	454	455	454	454.28	0.29	0.06
11/19/08 4.20 PM	637	637	637	636.52	0.04	0.01
11/20/08 4.17PM	638	638	639	638.30	0.52	0.08
11/21/08 4.16PM	639	639	642	640.08	1.87	0.29
11/22/08 4.20 PM	642	642	644	642.75	1.29	0.20
11/24/08 4.20 PM	640	640	640	640.08	0.14	0.02
11/25/08 4.20 PM	640	639	639	639.19	0.73	0.11

Table A.4 Daily Experimental Outlet Concentrations for Butylene 50:50 Compost to Woodchips Ratio

Date & Time	Outlet I (ppm)	Outlet II (ppm)	Outlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
9/29/08 4.05PM	18	18	18	18.22	0.24	1.30
9/30/08 4.11 PM	17	19	20	18.78	1.67	8.92
10/1/08 4.12 PM	17	18	20	18.22	1.35	7.41
10/2/08 4.17 PM	322	322	327	323.60	2.76	0.85
10/3/08 4.11 PM	323	322	324	322.71	0.83	0.26
10/4/08 4.11 PM	319	320	324	320.93	2.92	0.91
10/5/08 4.35 PM	140	139	140	139.57	0.52	0.37
10/6/08 4.13 PM	140	140	145	141.35	2.78	1.97
10/7/08 4.35PM	381	382	384	382.27	1.42	0.37
10/8/08 4.32PM	382	383	383	382.27	0.68	0.18
10/9/08 4.20PM	355	356	358	356.49	1.78	0.50
10/10/08 4.32PM	355	355	357	355.60	1.04	0.29
10/11/08 4.31PM	357	357	358	357.38	0.65	0.18
10/12/08 4.20 PM	335	336	340	336.93	2.53	0.75
10/13/08 4.17PM	334	334	335	334.26	0.92	0.28
10/14/08 4.30PM	294	294	297	295.15	1.99	0.67
10/15/08 4.15PM	295	295	295	295.15	0.26	0.09
10/16/08 4.10 PM	239	239	240	239.14	0.72	0.30
10/17/08 4.16PM	238	238	239	238.25	0.44	0.18
10/18/08 4.17 PM	166	166	169	167.13	1.96	1.17

Table A.4 - Continued

10/19/08 4.17PM	167	167	167	167.13	0.23	0.14
10/20/08 4.16 PM	165	165	167	165.35	1.48	0.89
10/21/08 4.16PM	166	166	164	165.00	1.32	0.80
11/22/08 4.12PM	123	124	127	124.46	2.11	1.70
10/23/08 4.16PM	121	120	119	120.02	0.98	0.81
10/24/08 4.17PM	122	123	124	122.68	0.79	0.64
10/25/08 4.50PM	106	107	107	106.68	0.59	0.55
10/26/08 4.16PM	107	108	108	107.57	0.61	0.56
10/27/08 4.17PM	107	107	107	106.68	0.28	0.26
10/28/08 4.40 PM	100	102	102	101.35	1.2	1.15
10/29/08 4.16PM	100	100	102	100.46	1.25	1.24
10/30/08 4.15PM	101	101	103	101.35	1.06	1.05
10/31/08 4.17PM	100	100	101	100.46	0.79	0.79
11/1/08 4.18PM	99	101	105	101.35	2.86	2.83
11/2/08 4.20 PM	42	42	45	42.67	1.62	3.79
11/3/08 4.19PM	41	42	43	41.78	1.45	3.46
11/4/08 4.25PM	42	43	44	42.67	0.77	1.81

Table A.5 Daily Experimental Inlet Concentrations for Butylene Random Mixture of Compost to Woodchips Ratio

Date & Time	Inlet I (ppm)	Inlet II (ppm)	Inlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
9/30/08 4.12 PM	175	178	180	177.80	2.71	1.52
10/1/08 4.13 PM	182	186	189	185.80	3.71	1.99
10/2/08 4.22 PM	353	354	362	356.49	5.20	1.46
10/3/08 4.13 PM	349	353	351	351.16	2.02	0.57
10/4/08 4.12 PM	350	352	351	351.16	1.04	0.29
10/5/08 4.40 PM	147	150	151	149.35	2.10	1.41
10/6/08 4.14 PM	146	148	149	147.57	1.41	0.96
10/7/08 4.40 PM	440	442	446	442.72	3.15	0.71
10/8/08 4.33PM	443	444	441	442.72	1.44	0.32
10/9/08 4.25 PM	373	376	374	374.27	1.55	0.41
10/10/08 4.33 PM	373	373	374	373.38	0.66	0.18
10/11/08 4.32PM	374	375	371	373.38	2.00	0.54
10/12/08 4.25 PM	366	367	363	365.38	2.00	0.55
10/13/08 4.18 PM	363	365	365	364.49	1.31	0.36
10/14/08 4.35 PM	365	367	364	365.38	1.47	0.40
10/15/08 4.16 PM	366	362	365	364.49	2.17	0.60
10/16/08 4.15 PM	215	218	220	217.81	2.71	1.25
10/17/08 4.17 PM	214	216	215	215.14	1.03	0.48
10/18/08 4.22 PM	187	188	188	187.58	0.52	0.28
10/19/08 4.18 PM	184	186	190	186.69	3.09	1.66

Table A.5 - Continued

10/20/08 4.17 PM	180	183	184	182.25	1.98	1.09
10/21/08 4.17 PM	183	185	179	182.25	3.20	1.76
11/22/08 4.17 PM	126	128	133	128.91	3.45	2.67
10/23/08 4.17 PM	132	130	130	130.68	1.14	0.87
10/24/08 4.18 PM	127	130	132	129.79	2.70	2.08
10/25/08 4.55 PM	87	88	89	88.01	1.02	1.16
10/26/08 4.17 PM	88	90	89	88.90	1.01	1.14
10/27/08 4.18 PM	103	105	99	102.24	3.22	3.15
10/28/08 4.45 PM	114	115	115	114.68	0.59	0.51
10/29/08 4.17 PM	116	113	115	114.68	1.53	1.34
10/30/08 4.16 PM	116	117	114	115.57	1.69	1.46
10/31/08 4.18 PM	116	115	113	114.68	1.50	1.31
11/1/08 4.19 PM	114	116	117	115.57	1.41	1.22
11/2/08 4.25 PM	40	43	45	42.67	2.52	5.91
11/3/08 4.20 PM	42	44	45	43.56	1.39	3.20
11/4/08 4.26 PM	45	46	42	44.45	1.89	4.24

Table A.6 Daily Experimental Outlet Concentrations for Butylene Random Mixture Compost to Woodchips Ratio

Date & Time	**Outlet I (ppm)**	**Outlet II (ppm)**	**Outlet III (ppm)**	**Average Concentration (ppm)**	**Standard Deviation (ppm)**	**Standard Deviation (%)**
9/30/08 4.12 PM	217	218	218	217.81	0.73	0.33
10/1/08 4.13 PM	225	226	229	226.70	2.13	0.94
10/2/08 4.22 PM	532	532	534	532.51	0.89	0.17
10/3/08 4.13 PM	528	529	530	528.96	0.98	0.19
10/4/08 4.12 PM	529	529	529	528.96	0.08	0.01
10/5/08 4.40 PM	215	215	215	215.14	0.12	0.06
10/6/08 4.14 PM	213	213	214	213.36	0.62	0.29
10/7/08 4.40 PM	1066	1067	1070	1067.69	2.12	0.20
10/8/08 4.33PM	1067	1067	1066	1066.80	0.35	0.03
10/9/08 4.25 PM	978	978	980	978.79	1.37	0.14
10/10/08 4.33 PM	977	778	1179	977.90	201	20.52
10/11/08 4.32PM	977	978	979	977.90	0.95	0.10
10/12/08 4.25 PM	967	967	968	967.23	0.40	0.04
10/13/08 4.18 PM	961	960	959	960.12	0.83	0.09
10/14/08 4.35 PM	898	898	900	898.78	1.18	0.13
10/15/08 4.16 PM	968	968	971	969.01	1.75	0.18
10/16/08 4.15 PM	738	738	740	738.76	1.31	0.18
10/17/08 4.17 PM	733	732	735	733.43	1.68	0.23
10/18/08 4.22 PM	800	800	803	800.99	1.71	0.21
10/19/08 4.18 PM	794	795	798	795.66	2.45	0.31
10/20/08 4.17 PM	789	789	790	789.43	0.75	0.09

Table A.6 - Continued

10/21/08 4.17 PM	789	789	790	789.43	0.75	0.09
11/22/08 4.17 PM	712	712	715	712.98	1.69	0.24
10/23/08 4.17 PM	706	707	707	706.76	0.67	0.09
10/24/08 4.18 PM	706	706	708	706.76	1.31	0.19
10/25/08 4.55 PM	567	569	568	568.07	1.01	0.18
10/26/08 4.17 PM	564	564	566	564.52	0.89	0.16
10/27/08 4.18 PM	660	659	660	659.64	0.52	0.08
10/28/08 4.45 PM	712	713	714	712.98	0.97	0.14
10/29/08 4.17 PM	714	715	718	715.65	2.05	0.29
10/30/08 4.16 PM	717	716	719	717.42	1.68	0.23
10/31/08 4.18 PM	716	715	716	715.65	0.56	0.08
11/1/08 4.19 PM	717	717	718	717.42	0.73	0.10
11/2/08 4.25 PM	501	502	504	502.29	1.45	0.29
11/3/08 4.20 PM	506	505	509	506.73	2.19	0.43
11/4/08 4.26 PM	507	506	507	506.73	0.64	0.13
11/5/08 4.30 PM	92	95	85	90.59	5.26	5.81
11/6/08 4.17 PM	101	102	96	99.57	3.38	3.40
11/7/08 4.18 PM	102	103	102	102.24	0.68	0.66
11/8/08 4.10 PM	101	100	98	99.57	1.69	1.70
11/9/08 4.18 PM	98.0	98	97	97.79	0.36	0.37
11/10/08 4.19 PM	94.0	93	93	93.35	0.63	0.68
11/11/08 4.10 PM	104	104	103	103.57	0.40	0.39
11/12/08 4.17 PM	101	100	100	100.46	0.52	0.51

Table A.6 - Continued

11/13/08 4.18 PM	100	101	101	100.46	0.24	0.24
11/14/08 4.55 PM	376	377	376	376.49	0.27	0.07
11/15/08 4.18 PM	374	373	374	373.38	0.33	0.09
11/16/08 7.35PM	365	364	366	365.11	1.17	0.32
11/17/08 4.20 PM	366	367	369	367.16	1.59	0.43
11/18/08 4.19 PM	364	364	365	364.49	0.54	0.15
11/19/08 4.25 PM	547	547	549	547.62	1.08	0.20
11/20/08 4.18 PM	551	550	553	551.18	1.28	0.23
11/21/08 4.17 PM	549	553	552	551.18	2.02	0.37
11/22/08 4.25 PM	555	556	551	553.85	2.91	0.52
11/23/08 4.25 PM	556	557	554	555.63	1.60	0.29
11/24/08 4.25 PM	557	558	552	555.63	3.29	0.59

Table A.7 Daily Experimental Inlet Concentrations for Propylene 80:20 Compost to Woodchips Ratio

Date & Time	Inlet I (ppm)	Inlet II (ppm)	Inlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
2/6/09 3.25PM	987	987	987	986.79	0.21	0.02
2/7/09 3.45PM	948	948	945	946.79	1.31	0.14
2/8/09 3.45PM	945	945	945	945.01	0.01	0.00
2/9/09 3.45PM	949	949	949	948.56	0.06	0.01
2/10/09 4.00PM	891	891	891	890.78	0.22	0.02
2/11/09 3.45PM	876	876	876	875.67	0.21	0.02
2/12/09 3.45PM	885	885	884	884.56	0.44	0.05
2/13/09 4.15PM	28537	28538	28536	28536.90	0.60	0.00
2/14/09 4.15PM	28448	28449	28448	28448.00	0.50	0.00
2/15/09 4.15PM	28359	28360	28358	28359.10	0.90	0.00
2/16/09 4.25PM	64097	64096	64098	64096.90	0.90	0.00
2/17/09 4.25PM	64186	64185	64187	64185.80	0.80	0.00
2/18/09 4.25PM	63919	63920	63919	63919.10	0.40	0.00
2/19/09 4.25PM	64186	64186	64186	64185.80	0.10	0.00
2/20/09 4.05PM	62230	62231	62229	62230.00	1.00	0.00
2/21/09 4.05PM	70053	70054	70053	70053.20	0.30	0.00
2/22/09 4.05PM	69787	69786	69787	69786.50	0.53	0.00
2/23/09 4.05PM	54229	54228	54230	54229.00	0.80	0.00
2/24/09 4.05PM	53785	53785	53784	53784.50	0.50	0.00
2/25/09 4.05PM	54673	54673	54675	54673.50	0.87	0.00
2/26/09 4.25PM	53251	53251	53251	53251.10	0.17	0.00
2/27/09 4.05PM	53341	53340	53339	53340.00	1.00	0.00

Table A.7 - Continued

2/28/09 4.05PM	53785	53784	53785	53784.50	0.50	0.00
3/1/09 4.20PM	45428	45427	45429	45427.90	0.70	0.00
3/2/09 4.20PM	45339	45338	45340	45339.00	1.00	0.00
3/3/09 4.20PM	45517	45517	45517	45516.80	0.30	0.00
3/4/09 4.25PM	43917	43916	43917	43916.60	0.60	0.00
3/5/09 4.25PM	43739	43738	43740	43738.80	1.00	0.00
3/6/09 4.25PM	43561	43562	43561	43561.00	0.50	0.00
3/7/09 4.15PM	39917	39916	39916	39916.10	0.87	0.00
3/8/09 4.15PM	39561	39560	39561	39560.50	0.50	0.00
3/9/09 4.15PM	39827	39828	39827	39827.20	0.60	0.00
3/10/09 10.15PM	31205	31203	31204	31203.90	0.85	0.00
3/11/09 10.15PM	31115	31115	31115	31115.00	0.00	0.00
3/12/09 11AM	28804	28803	28804	28803.60	0.52	0.00
3/13/09 11AM	28626	28625	28627	28625.80	0.80	0.00
3/14/09 4.14PM	41961	41960	41962	41960.80	0.98	0.00
3/15/09 4.14PM	41783	41784	41782	41783.00	1.00	0.00
3/16/09 4.14PM	41605	41605	41606	41605.20	0.35	0.00
3/17/09 4.15PM	39205	39204	39206	39204.90	0.85	0.00
3/18/09 4.15PM	39116	39116	39116	39116.00	0.00	0.00
3/19/09 4.15PM	39027	39027	39027	39027.10	0.17	0.00
3/20/09 4.05PM	37783	37782	37783	37782.50	0.50	0.00
3/21/09 4.05PM	37605	37604	37605	37604.70	0.30	0.00
3/22/09 4.25PM	37516	37515	37517	37515.80	0.80	0.00
3/23/09 10.00AM	35649	35648	35650	35648.90	0.70	0.00
3/24/09 10.00AM	44360	44361	44363	44361.10	1.49	0.00

Table A.7 - Continued

3/25/09 4.14PM	39916	39916	39916	39916.10	0.10	0.00
3/26/09 4.14PM	39738	39738	39739	39738.30	0.30	0.00
3/27/09 4.14PM	39561	39560	39561	39560.50	0.50	0.00
3/28/09 4.30PM	62408	62406	62410	62407.80	1.80	0.00
3/29/09 4.14PM	62230	62231	62229	62230.00	1.00	0.00
3/30/09 4.30 PM	48806	48806	48806	48806.10	0.10	0.00
3/31/09 4.14PM	48451	48450	48451	48450.50	0.50	0.00
4/1/09 4.30 PM	42228	42228	42227	42227.50	0.50	0.00
4/2/09 4.30 PM	42049	42049	42051	42049.70	1.04	0.00
4/3/09 4.30 PM	41961	41961	41961	41960.80	0.26	0.00

Table A.8 Daily Experimental Outlet Concentrations for Propylene 80:20 Compost to Woodchips Ratio

Date & Time	Outlet I (ppm)	Outlet II (ppm)	Outlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
2/6/09 3.25PM	404	404	407	405.00	1.73	0.43
2/7/09 3.45PM	360	360	360	360.00	0.00	0.00
2/8/09 3.45PM	363	364	364	363.60	0.53	0.15
2/9/09 3.45PM	362	363	363	362.71	0.90	0.25
2/10/09 4.00PM	347	345	346	345.82	0.76	0.22
2/11/09 3.45PM	337	338	338	337.82	0.75	0.22
2/12/09 3.45PM	341	340	344	341.38	1.97	0.58
2/13/09 4.15PM	11645	11645	11648	11645.90	1.42	0.01
2/14/09 4.15PM	11556	11557	11558	11557.00	0.87	0.01
2/15/09 4.15PM	11644	11646	11648	11645.90	2.35	0.02
2/16/09 4.25PM	25334	25335	25341	25336.50	3.91	0.02
2/17/09 4.25PM	25778	25782	25783	25781.00	2.65	0.01
2/18/09 4.25PM	25424	25424	25429	25425.40	2.87	0.01
2/19/09 4.25PM	25779	25781	25783	25781.00	1.91	0.01
2/20/09 4.05PM	23645	23644	23653	23647.40	4.89	0.02
2/21/09 4.05PM	26581	26581	26581	26581.10	0.17	0.00
2/22/09 4.05PM	26226	26224	26227	26225.50	1.80	0.01
2/23/09 4.05PM	16230	16231	16238	16233.14	4.60	0.03
2/24/09 4.05PM	16089	16090	16094	16090.90	2.48	0.02
2/25/09 4.05PM	16444	16445	16451	16446.50	3.50	0.02

Table A.8 - Continued

2/26/09 4.25PM	15910	16445	15384	15913.10	530.36	3.33
2/27/09 4.05PM	15913	15912	15914	15913.10	1.15	0.01
2/28/09 4.05PM	16177	16178	16184	16179.80	4.01	0.02
3/1/09 4.20PM	6134	6133	6135	6134.10	1.15	0.02
3/2/09 4.20PM	6223	6221	6225	6223.00	2.00	0.03
3/3/09 4.20PM	6221	6222	6226	6223.00	2.65	0.04
3/4/09 4.25PM	6044	6044	6048	6045.20	2.08	0.03
3/5/09 4.25PM	5954	5955	5960	5956.30	3.16	0.05
3/6/09 4.25PM	6220	6222	6227	6223.00	3.61	0.06
3/7/09 4.15PM	4785	4788	4797	4789.93	6.13	0.13
3/8/09 4.15PM	4619	4620	4629	4622.80	5.74	0.12
3/9/09 4.15PM	4885	4887	4897	4889.50	6.14	0.13
3/10/09 10.15PM	4265	4266	4271	4267.20	2.99	0.07
3/11/09 10.15PM	4354	4355	4359	4356.10	2.82	0.06
3/12/09 11AM	3642	3644	3649	3644.90	3.44	0.09
3/13/09 11AM	3644	3644	3647	3644.90	1.56	0.04
3/14/09 4.14PM	3920	3921	3926	3922.27	3.10	0.08
3/15/09 4.14PM	3910	3910	3915	3911.60	2.77	0.07
3/16/09 4.14PM	3820	3820	3828	3822.70	4.16	0.11
3/17/09 4.15PM	2859	2858	2860	2859.02	1.04	0.04
3/18/09 4.15PM	2753	2754	2761	2755.90	4.19	0.15
3/19/09 4.15PM	2753	2755	2759	2755.90	3.18	0.12

Table A.8 - Continued

3/20/09 4.05PM	1865	1867	1869	1866.90	2.13	0.11
3/21/09 4.05PM	1777	1777	1780	1778.00	1.73	0.10
3/22/09 4.25PM	1688	1689	1690	1689.10	1.15	0.07
3/23/09 10.00AM	1865	1866	1870	1866.90	2.48	0.13
3/24/09 10.00AM	2220	2223	2225	2222.50	2.29	0.10
3/25/09 4.14PM	975	976	983	977.90	4.19	0.43
3/26/09 4.14PM	799	801	800	800.10	1.01	0.13
3/27/09 4.14PM	888	890	889	889.00	1.00	0.11
3/28/09 4.30PM	388	400	412	400.05	12.08	3.02
3/29/09 4.14PM	380	381	386	382.27	3.11	0.81
3/30/09 4.30 PM	269	268	266	267.59	1.66	0.62
3/31/09 4.14PM	266	266	265	265.81	0.33	0.12

Table A.9 Daily Experimental Inlet Concentrations for Propylene 50:50 Compost to Woodchips Ratio

Date & Time	Inlet I (ppm)	Inlet II (ppm)	Inlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
2/5/09 3.30PM	928	927	929	928.12	1.18	0.13
2/6/09 3.30PM	924	923	927	924.56	1.90	0.21
2/7/09 3.50PM	886	887	889	887.22	1.35	0.15
2/8/09 3.30PM	884	884	886	884.56	1.42	0.16
2/9/09 3.30PM	880	879	881	880.11	1.17	0.13
2/10/09 4.05PM	1008	1007	1012	1009.02	2.67	0.26
2/11/09 3.30PM	1006	1005	1008	1006.35	1.55	0.15
2/12/09 3.30PM	1004	1004	1006	1004.57	0.99	0.10
2/13/09 4.20PM	28625	28624	28628	28625.80	2.31	0.01
2/14/09 3.30PM	28447	28447	28450	28448.00	1.73	0.01
2/15/09 3.30PM	28358	28357	28362	28359.10	2.82	0.01
2/16/09 4.30PM	64540	64539	64545	64541.40	3.33	0.01
2/17/09 3.30PM	64364	64363	64364	64363.60	0.53	0.00
2/18/09 3.30PM	64272	64273	64279	64274.70	3.84	0.01
2/19/09 3.30PM	64273	64273	64278	64274.70	2.94	0.00
2/20/09 4.10PM	62140	62141	62142	62141.10	1.15	0.00
2/21/09 3.30PM	62051	62051	62055	62052.20	2.08	0.00
2/22/09 3.30PM	61785	61784	61788	61785.50	1.80	0.00
2/23/09 4.10PM	54406	54408	54406	54406.80	1.06	0.00
2/24/09 3.30PM	53341	53342	53337	53340.00	2.65	0.00
2/25/09 3.30PM	54672	54673	54676	54673.50	1.80	0.00
2/26/09 4.30PM	53429	53427	53431	53428.90	1.85	0.00

Table A.9 - Continued

2/27/09 3.30PM	52538	52538	52544	52539.90	3.29	0.01
2/28/09 3.30PM	52895	52895	52897	52895.50	0.87	0.00
3/1/09 4.25PM	45160	45161	45163	45161.20	1.31	0.00
3/2/09 3.30PM	44451	44449	44450	44450.00	1.00	0.00
2/3/09 3.30PM	44804	44805	44808	44805.60	1.97	0.00
3/4/09 4.30PM	44004	44005	44008	44005.50	2.00	0.00
3/5/09 3.30PM	43561	43560	43562	43561.00	1.00	0.00
3/6/09 3.30PM	43739	43739	43738	43738.80	0.35	0.00
3/7/09 4.20PM	39737	39739	39739	39738.30	1.13	0.00
3/8/09 3.30PM	39560	39561	39561	39560.50	0.50	0.00
3/9/09 3.30PM	39738	39737	39740	39738.30	1.47	0.00
3/10/09 10.20PM	31114	31114	31124	31115.00	5.77	0.02
3/11/09 3.30PM	31292	31291	31295	31292.80	2.31	0.01
3/12/09 11.05AM	28891	28891	28896	28892.50	2.60	0.01
2/13/09 3.30PM	28801	28804	28806	28803.60	2.42	0.01
3/14/09 4.20PM	41870	41870	41876	41871.90	3.29	0.01
2/15/09 3.30PM	41693	41693	41696	41694.10	1.91	0.00
2/16/09 3.30PM	41337	41338	41341	41338.50	2.18	0.01
3/17/09 4.20PM	39025	39024	39032	39027.10	4.53	0.01
2/18/09 3.30PM	38670	38670	38675	38671.50	2.60	0.01
2/19/09 3.30PM	39114	39115	39119	39116.00	2.65	0.01
3/20/09 4.10PM	37692	37694	37695	37693.60	1.44	0.00
2/21/09 3.30PM	37337	37336	37341	37338.00	2.65	0.01
3/22/09 4.30PM	35470	35470	35473	35471.10	1.39	0.00
3/23/09 10.05AM	39827	39828	39827	39827.20	0.72	0.00

Table A.9 - Continued

3/24/09 3.30PM	39561	39562	39559	39560.50	1.80	0.00
3/25/09 9.20AM	62231	62231	62228	62230.00	1.73	0.00
3/26/09 3.30PM	62673	62675	62676	62674.50	1.32	0.00
3/27/09 3.30PM	62231	62229	62230	62230.00	1.00	0.00
3/28/09 4.20PM	49072	49072	49074	49072.80	1.39	0.00
3/29/09 3.30PM	48895	48895	48895	48895.00	0.00	0.00
3/30/09 4.35PM	42229	42229	42225	42227.50	2.60	0.01
3/31/09 3.30PM	41782	41783	41784	41783.00	1.00	0.00
3/1/09 4.35 PM	29512	29513	29519	29514.80	4.01	0.01
3/1/09 4.35 PM	29338	29339	29334	29337.00	2.65	0.01
3/1/09 4.35 PM	29780	29780	29785	29781.50	2.60	0.01

Table A.10 Daily Experimental Outlet Concentrations for Propylene 50:50 Compost to Woodchips Ratio

Date & Time	Outlet I (ppm)	Outlet II (ppm)	Outlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
2/5/09 3.30PM	390	380	375	382.27	7.64	2.00
2/6/09 3.30PM	385	375	384	381.38	5.54	1.45
2/7/09 3.50PM	341	350	349	346.71	4.96	1.43
2/8/09 3.30PM	351	347	335	342.27	8.33	2.43
2/9/09 3.30PM	338	341	340	346.71	1.53	0.44
2/10/09 4.05PM	347	345	346	345.82	0.76	0.22
2/11/09 3.30PM	337	338	352	342.27	8.27	2.42
2/12/09 3.30PM	341	340	333	337.82	4.22	1.25
2/13/09 4.20PM	11465	11470	11460	11468.10	5.00	0.04
2/14/09 3.30PM	11375	11385	11380	11379.20	5.00	0.04
2/15/09 3.30PM	11296	11295	11280	11290.30	8.96	0.08
2/16/09 4.30PM	25615	25614	25609	25603.20	3.21	0.01
2/17/09 3.30PM	25700	25695	25695	25692.10	2.89	0.01
2/18/09 3.30PM	25779	25774	25789	25781.00	7.86	0.03
2/19/09 3.30PM	25779	25781	25783	25781.00	1.91	0.01
2/20/09 4.10PM	23560	23559	23555	23558.50	2.65	0.01
2/21/09 3.30PM	23481	23481	23484	23469.60	1.73	0.01
2/22/09 3.30PM	23201	23202	23206	23202.90	2.48	0.01
2/23/09 4.10PM	16320	16323	16323	16322.04	1.77	0.01
2/24/09 3.30PM	16001	16000	16005	16002.00	2.65	0.02
2/25/09 3.30PM	16445	16447	16448	16446.50	1.32	0.01

Table A.10 - Continued

2/26/09 4.30PM	15912	15912	15915	15913.10	1.39	0.01
2/27/09 3.30PM	15556	15558	15559	15557.50	1.32	0.01
2/28/09 3.30PM	16000	16001	16005	16002.00	2.65	0.02
3/1/09 4.25PM	6133	6134	6136	6134.10	1.49	0.02
3/2/09 3.30PM	6220	6219	6230	6223.00	6.08	0.10
2/3/09 3.30PM	6221	6222	6226	6223.00	2.65	0.04
3/4/09 4.30PM	6220	6224	6225	6223.00	2.65	0.04
3/5/09 3.30PM	6044	6044	6048	6045.20	2.08	0.03
3/6/09 3.30PM	6046	6045	6045	6045.20	0.72	0.01
3/7/09 4.20PM	4620	4621	4627	4622.80	4.01	0.09
3/8/09 3.30PM	4886	4888	4895	4889.50	4.44	0.09
3/9/09 3.30PM	4802	4798	4802	4800.60	2.25	0.05
3/10/09 10.20PM	4266	4266	4270	4267.20	2.08	0.05
3/11/09 3.30PM	4530	4532	4540	4533.90	5.12	0.11
3/12/09 11.05AM	3555	3554	3559	3556.00	2.65	0.07
2/13/09 3.30PM	3376	3375	3384	3378.20	4.70	0.14
3/14/09 4.20PM	3922	3921	3924	3922.27	1.42	0.04
2/15/09 3.30PM	3553	3554	3561	3556.00	4.36	0.12
2/16/09 3.30PM	3910	3909	3916	3911.60	3.67	0.09
3/17/09 4.20PM	2754	2755	2759	2755.90	2.48	0.09
2/18/09 3.30PM	2843	2845	2846	2844.80	1.71	0.06
2/19/09 3.30PM	2665	2666	2670	2667.00	2.65	0.10
3/20/09 4.10PM	1775	1776	1783	1778.00	4.36	0.25
2/21/09 3.30PM	1601	1602	1598	1600.20	2.31	0.14

Table A.10 - Continued

3/22/09 4.30PM	1776	1775	1783	1778.00	4.36	0.25
3/23/09 10.05AM	799	810	805	800.10	5.51	0.69
3/24/09 3.30PM	710	709	715	711.20	2.99	0.42
3/25/09 9.20AM	425	425	430	426.72	2.98	0.70
3/26/09 3.30PM	401	400	399	400.05	0.93	0.23
3/27/09 3.30PM	373	374	373	373.38	0.54	0.15
3/28/09 4.20PM	182	182	183	182.25	0.42	0.23
3/29/09 3.30PM	178	179	176	177.80	1.31	0.74

Table A.11 Daily Experimental Inlet Concentrations for Propylene Random Mixture Compost to Woodchips Ratio

Date & Time	Inlet I (ppm)	Inlet II (ppm)	Inlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
2/5/09 3.35PM	1016	1018	1017	1017.02	1.00	0.10
2/6/09 3.30PM	1012	1013	1015	1013.46	1.74	0.17
2/7/09 3.55PM	922	921	925	922.78	2.28	0.25
2/8/09 3.30PM	920	921	919	920.12	0.83	0.09
2/9/09 3.30PM	923	924	927	924.56	1.90	0.21
2/10/09 4.10PM	945	946	949	946.79	2.28	0.24
2/11/09 3.30PM	935	937	942	937.90	3.79	0.40
2/12/09 3.30PM	931	932	937	933.45	3.41	0.37
2/13/09 4.25PM	28446	28447	28451	28448.00	2.65	0.01
2/14/09 3.30PM	28712	28713	28719	28714.70	3.84	0.01
2/15/09 3.30PM	28892	28891	28895	28892.50	1.80	0.01
2/16/09 4.35PM	64452	64451	64455	64452.50	1.80	0.00
2/17/09 3.30PM	64006	64007	64011	64008.00	2.65	0.00
2/18/09 3.30PM	64185	64185	64187	64185.80	1.39	0.00
2/19/09 3.30PM	64184	64186	64188	64185.80	1.97	0.00
2/20/09 4.15PM	62231	62231	62229	62230.00	1.32	0.00
2/21/09 3.30PM	62051	62052	62054	62052.20	1.31	0.00
2/22/09 3.30PM	61784	61785	61788	61785.50	1.80	0.00
2/23/09 4.15PM	54405	54406	54409	54406.80	2.31	0.00
2/24/09 3.30PM	54228	54228	54231	54229.00	1.73	0.00
2/25/09 3.30PM	53783	53784	53787	53784.50	1.80	0.00
2/26/09 4.35PM	53339	53341	53340	53340.00	1.00	0.00

Table A.11 - Continued

2/27/09 3.30PM	54228	54228	54231	54229.00	1.73	0.00
2/28/09 3.30PM	53784	53785	53785	53784.50	0.50	0.00
3/1/09 4.30PM	45338	45338	45341	45339.00	1.73	0.00
3/2/09 3.30PM	44895	44895	44894	44894.50	0.87	0.00
3/3/09 3.30PM	45340	45340	45337	45339.00	1.73	0.00
3/4/09 4.35PM	44004	44005	44008	44005.50	2.18	0.00
3/5/09 3.30PM	43560	43561	43562	43561.00	1.00	0.00
3/6/09 3.30PM	43561	43562	43561	43561.00	0.50	0.00
3/7/09 4.25PM	39915	39915	39918	39916.10	1.57	0.00
3/8/09 3.30PM	39561	39560	39561	39560.50	0.50	0.00
3/9/09 3.30PM	39116	39117	39115	39116.00	1.00	0.00
3/10/09 10.25PM	31114	31115	31117	31115.00	1.32	0.00
3/11/09 3.30PM	30937	30938	30937	30937.20	0.53	0.00
3/12/09 11.10AM	28892	28892	28894	28892.50	0.87	0.00
3/13/09 3.30PM	28804	28803	28804	28803.60	0.53	0.00
3/14/09 4.24PM	42049	42050	42051	42049.70	0.82	0.00
3/15/09 3.30PM	41782	41782	41785	41783.00	1.73	0.00
3/16/09 3.30PM	42048	42050	42051	42049.70	1.57	0.00
3/17/09 4.25PM	39115	39116	39117	39116.00	1.00	0.00
3/18/09 3.30PM	39561	39567	39554	39560.50	6.76	0.02
3/19/09 3.30PM	39115	39115	39118	39116.00	1.73	0.00
3/20/09 4.15PM	37870	37871	37873	37871.40	1.64	0.00
3/21/09 3.30PM	37516	37517	37514	37515.80	1.31	0.00
3/22/09 4.35PM	35560	35560	35560	35560.00	0.00	0.00

Table A.11 - Continued

3/23/09 10.10AM	40004	40003	40008	40005.00	2.65	0.01
3/24/09 3.30PM	40448	40449	40452	40449.50	1.80	0.00
3/25/09 9.25AM	62231	62231	62228	62230.00	1.73	0.00
3/26/09 3.30PM	62051	62052	62054	62052.20	1.31	0.00
3/27/09 3.30PM	61786	61786	61785	61785.50	0.50	0.00
3/28/09 4.24PM	48894	48894	48897	48895.00	1.73	0.00
3/29/09 3.30PM	48451	48450	48451	48450.50	0.50	0.00
3/30/09 4.40PM	42404	42405	42407	42405.30	1.84	0.00
3/31/09 3.30PM	42139	42138	42139	42138.60	0.40	0.00
4/1/09 4.40PM	29781	29781	29783	29781.50	0.87	0.00
4/1/09 4.40PM	29691	29692	29695	29692.60	1.97	0.01
4/1/09 4.40PM	29513	29514	29517	29514.80	2.31	0.01

Table A.12 Daily Experimental Outlet Concentrations for Propylene Random Mixture Compost to Woodchips Ratio

Date & Time	Outlet I (ppm)	Outlet II (ppm)	Outlet III (ppm)	Average Concentration (ppm)	Standard Deviation (ppm)	Standard Deviation (%)
2/5/09 3.35PM	425	422	433	426.72	5.78	1.35
2/6/09 3.30PM	416	415	422	417.83	4.07	0.97
2/7/09 3.55PM	342	343	352	345.82	5.77	1.67
2/8/09 3.30PM	340	343	344	342.27	2.00	0.58
2/9/09 3.30PM	342	344	349	344.93	3.49	1.01
2/10/09 4.10PM	366	362	368	365.38	3.12	0.85
2/11/09 3.30PM	361	358	361	360.05	1.77	0.49
2/12/09 3.30PM	361	362	357	360.05	2.57	0.71
2/13/09 4.25PM	11555	11554	11562	11557.00	4.36	0.04
2/14/09 3.30PM	11733	11734	11737	11734.80	2.31	0.02
2/15/09 3.30PM	11820	11825	11826	11823.70	3.25	0.03
2/16/09 4.35PM	25782	25780	25781	25781.00	1.00	0.00
2/17/09 3.30PM	25335	25337	25338	25336.50	1.32	0.01
2/18/09 3.30PM	25338	25339	25333	25336.50	3.50	0.01
2/19/09 3.30PM	25334	25335	25341	25336.50	3.50	0.01
2/20/09 4.15PM	23645	23646	23651	23647.40	3.33	0.01
2/21/09 3.30PM	23465	23467	23477	23469.60	6.32	0.03
2/22/09 3.30PM	23290	23293	23292	23291.80	1.59	0.01
2/23/09 4.15PM	16320	16323	16323	16322.04	1.77	0.01
2/24/09 3.30PM	16177	16179	16183	16179.80	3.27	0.02
2/25/09 3.30PM	16000	16004	16002	16002.00	2.00	0.01

Table A.12 - Continued

2/26/09 4.35PM	16005	16003	15998	16002.00	3.61	0.02
2/27/09 3.30PM	15914	15912	15913	15913.10	1.01	0.01
2/28/09 3.30PM	15822	15823	15828	15824.20	2.99	0.02
3/1/09 4.30PM	6043	6046	6047	6045.20	1.93	0.03
3/2/09 3.30PM	5954	5970	5945	5956.30	12.71	0.21
3/3/09 3.30PM	6132	6135	6135	6134.10	1.82	0.03
3/4/09 4.35PM	6220	6222	6227	6223.00	3.61	0.06
3/5/09 3.30PM	6402	6399	6401	6400.80	1.59	0.02
3/6/09 3.30PM	6132	6135	6135	6134.10	1.82	0.03
3/7/09 4.25PM	4787	4790	4793	4789.93	2.90	0.06
3/8/09 3.30PM	4621	4623	4624	4622.80	1.71	0.04
3/9/09 3.30PM	4622	4624	4622	4622.80	1.06	0.02
3/10/09 10.25PM	4355	4357	4356	4356.10	1.01	0.02
3/11/09 3.30PM	4355	4357	4356	4356.10	1.01	0.02
3/12/09 11.10AM	3557	3558	3553	3556.00	2.65	0.07
3/13/09 3.30PM	3643	3642	3650	3644.90	4.19	0.11
3/14/09 4.24PM	4010	4009	4015	4011.17	2.93	0.07
3/15/09 3.30PM	3554	3557	3557	3556.00	1.73	0.05
3/16/09 3.30PM	3732	3731	3738	3733.80	4.01	0.11
3/17/09 4.25PM	2948	2946	2950	2947.92	1.89	0.06
3/18/09 3.30PM	3111	3112	3112	3111.50	0.50	0.02
3/19/09 3.30PM	2843	2842	2849	2844.80	4.01	0.14
3/20/09 4.15PM	1777	1779	1778	1778.00	1.00	0.06

Table A.12 - Continued

3/21/09 3.30PM	1778	1780	1776	1778.00	2.00	0.11
3/22/09 4.35PM	1777	1777	1780	1778.00	1.73	0.10
3/23/09 10.10AM	888	887	892	889.00	2.65	0.30
3/24/09 3.30PM	886	890	891	889.00	2.65	0.30
3/25/09 9.25AM	425	426	429	426.72	2.17	0.51
3/26/09 3.30PM	399	401	400	400.05	1.00	0.25
3/27/09 3.30PM	443	445	446	444.50	1.32	0.30
3/28/09 4.24PM	243	245	245	244.48	1.29	0.53
3/29/09 3.30PM	241	242	237	240.03	2.59	1.08

APPENDIX B

SAMPLE CALCULATIONS

B.1 Removal Efficiency

The butylene removal efficiency is calculated by equation B.1 given below.

Data from experiment on 9/29/08 at 4.10PM

Inlet concentration of butylene is 110 ppm
Outlet concentration of butylene is 91 ppm

$$Removal\ Efficency = \frac{Inlet - Outlet}{Inlet} \times 100\ \% \ldots\ldots\ldots\ldots\ldots..Equation\ B.1$$

$$Removal\ Efficency = \frac{110 - 91}{110} \times 100\ \%$$

$$Removal\ Efficiency = 17.87\ \%$$

Where

Inlet = Butylene concentration entering the biofilter column

Outlet = Butylene concentration coming out of the biofilter column

B.2 Butylene Loading

The butylene loading is calculated by equation B.2 given below.

Data from experiment on 9/29/08 at 4.10PM

$$Butylene\ Loading = \frac{(40.9 \times Cppm \times MWp) \times Q \times 60}{V \times 10^6} \ldots\ldots\ldots\ldots\ldots\ldots Equation\ B.2$$

$$Butylene\ Loading = \frac{(40.9 \times 110 \times 56) \times \frac{\mu g}{m^3} \times 0.9\,\frac{l}{min} \times 60\,\frac{min}{hr}}{6.5l \times 10^6\,\frac{\mu g}{g}}$$

$$Butylene\ Loading = 2.10\ \frac{g}{m^3 - hr}$$

Where

Cppm = Butylene concentration in parts per million (ppm)

MWp = Molecular weight of pollutant gas (butylene)

Q = Flow Rate (LPM)

V = Bed Volume (Liters)

B.3 Elimination Capacity

The butylene loading is calculated by equation B.3 given below.

Data from experiment on 9/29/08 at 4.10PM

$$Elimination\ Capacity = (C_i - C_o)\frac{g}{m^3 - \text{hr}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.Equation\ B.3$$

$$Elimination\ Capacity = (2.10 - 1.73)$$

$$Elimination\ Capacity = 0.38\frac{g}{m^3 - hr}$$

Where

C_i = *Inlet butylene loading, g/m^3-hr*

C_o = *Outlet Loading, g/m^3-hr*

APPENDIX C

MICROBES IN MEDIA

Table C.1 List of Microorganisms Present in Fresh Woodchips

COLONY NUMBER	COLONY-FORMING UNITS PER GRAM (CFU/G)	MICROORGANISM	TYPE
1	3.8×10^{8}	*Enterococcus durans*	B
2	9.6×10^{7}	*Nocardia brasiliensis*	AC
3	2.9×10^{5}	*Bacillus simplex*	B
4	3.8×10^{4}	*Bacillus oleronius*	B
5	9.6×10^{2}	*Bacillus megaterium*	B
6	9.6	*Bacillus fusiformis*	B

Table C.2 List of Microorganisms Present in Used Compost & Woodchips (butylene)

COLONY NUMBER	COLONY-FORMING UNITS PER GRAM (CFU/G)	MICROORGANISM	TYPE
1	9.4×10^5	*Bacillus megaterium*	B
2	9.4×10^5	*Rhodococcus koreensis*	B
3	9.4×10^4	*Doratomyces stemonitis* **Trichurus spiralis*	F
4	1.9×10^5	*Bacillus barbaricus* **Bacillus* species	B
5	9.4×10^4	*Stenotrophomonas maltophilia* **Luteimonas* species	B
6	2.8 x 105	*Streptomyces antibioticus* **Streptomyces shandonggensis*	AC
7	9.4×10^3	*Aspergillus versicolor*	F
8	9.4×10^3	*Chaetomium brasiliense* **Chaetomium piluliferum*	F

Table C.3 List of Microorganisms Present in Fresh Compost

COLONY NUMBER	COLONY-FORMING UNITS PER GRAM (CFU/G)	MICROORGANISM	TYPE
1	9.3×10^{7}	*Bacillus mojavensis* *Bacillus licheniformis*	B
2	9.3×10^{6}	*Streptomyces althioticus*	AC
3	2.8×10^{6}	*Bacillus amyloliquefaciens*	B
4	5.6×10^{6}	*Bacillus firmus*	B
5	9.3×10^{5}	*Paenibacillus lautus* **Paenibacillus ginsengagri*	B
6	7.4×10^{5}	*Bacillus barbaricus* **Bacillus arsenicus*	B
7	3.7×10^{5}	*Pseudomonas resinovorans* **Pseudomonas* species	B
8	1.9×10^{4}	*Pseudomonas resinovorans* **Pseudomonas* species	B

Table C.4 List of Microorganisms Present in used Compost & Woodchips (propylene)

COLONY NUMBER	COLONY-FORMING UNITS PER GRAM (CFU/G)	MICROORGANISM	TYPE
1	1.1×10^8	*Sphingobacterium thalpophilum* **Parapedobacter koreensis*	B
2	1.1×10^8	*Sphingobacterium multivorum* **Sphingobacterium composti*	B
3	2.1×10^8	*Brachybacterium nesterenkovii* **Janibacter melonis*	B
4	2.1×10^7	*Cellulomonas gelida* **Promicromonospora* species	B
5	2.1×10^6	*Trichoderma aureoviride* *Trichoderma harzianum* *Trichoderma inhamatum* *Trichoderma virens*	F
6	2.1×10^6	*Streptomyces griseinus*	AC
7	7.4×10^6	*Sphingopyxis macrogoltabida*	B
8	2.1×10^6	*Microbacterium ketosireducens* **Microbacterium* species	B
9	1.1×10^6	*Bordetella petrii*	B
10	1.1×10^5	*Pseudomonas corrugata*	B

Table C.4 - Continued

11	2.1 x 10^5	*Trichoderma aureoviride* *Trichoderma harzianum* *Trichoderma inhamatum* *Trichoderma virens*	F
12	2.1 x 10^2	*Serratia marcescens*	B

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BIOGRAPHICAL INFORMATION

Madhu Rani was born on October 13, 1980 in Dhanbad, India, the daughter of Sushila Singh and Maya Ram Singh. She completed her high school education at Saraswati Vidya Mandir, Dhanbad in 1997. Then she enrolled to Banaras Hindu University, Varanasi, India and earned her B.Sc (Bachelor of Science) in Botany, Zoology and Chemistry, in May 2002. Then she did her Master's in biotechnology from Jiwaji University, Gwalior, India. She also worked as an Project Assistant at National Institute of Oceanography, Mumbai, India for 2 years.

Madhu Rani has started her M.S. (Master of Science) program in Environmental and Earth Sciences at the University of Texas at Arlington, Arlington, Texas, in August 2006 and earned M.S. degree in Environmental and Earth Sciences in August 2009. Her thesis was on removal of butylene and propylene gas using biofiltration.