REMOVAL OF CARBONYL SULFIDE USING COMPOST BIOFILTER: MEASUREMENT OF REMOVAL RATES AND ELIMINATION CAPACITY IN CONJUNCTION WITH HYDROGEN SULFIDE

by

DIVYA RANI GARREPALLI

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2006

ACKNOWLEDGEMENTS

I would like to express my wholehearted gratitude to my thesis advisor, Dr Melanie Sattler. Dr. Sattler has always been an invaluable guide and academic mentor. She has been an enduring pillar of moral support throughout my research work. Her pursuit of excellence instilled a desire in me to excel in my research work and hence has materialized into substantial results that mark the importance of our research.

I would also like to thank Dr. Max Spindler and Dr. Syed R. Qasim for agreeing to be a part of my research committee. I extend my thanks for sparing their valuable time for review of my thesis. The invaluable feedback and suggestions given by them are much appreciated.

I would like to thank Mr. Paul Shover for his tremendous help with my experimental set-up work. I would also like to thank and Mr. Lewis Crow for using his expertise to steer me through many computer related problems. I thank Mr. John Darling for providing me with very good quality compost for the experiments.

I would like to mention my special thanks to Alan Plummer Associates for lending me the hydrogen sulfide sensor. Also, Mr. Scott Evans from International Sensor Technology had been an immense help while patiently answering my queries regarding the operation of sensor, at a very crucial juncture in my research.

I would like to thank my seniors', Mr. S. Rosenberk and Mr. C.P. Nawal who used their previous knowledge and experience with Biofilters to help resolve some difficult issues that came up during my research. I would like to thank Ms.Teresa Rogers, my boss at TTI, without whose co-operation and concern, I would not have been able to handle my research and work on parallel lines.

I would like to thank my friends Sapna and Swarna, for their enduring personal support and patience. Last but not the least; I thank God and my loving family - Mom, Dad and my brother Chintoo. They are my real strength and have always believed in my abilities to not only dream but strive to make those dreams a concrete reality.

December 5, 2005

ABSTRACT

REMOVAL OF CARBONYL SULFIDE USING COMPOST BIOFILTER: MEASUREMENT OF REMOVAL RATES AND ELIMINATION CAPACITY IN CONJUNCTION WITH HYDROGEN SULFIDE

Publication No. __________

Divya Rani Garrepalli, M.S.

The University of Texas at Arlington, 2006

Supervising Professor: Dr. Melanie L. Sattler

Odorous gas emissions from wastewater treatment plants and other industries like pulp and paper manufacturing, petroleum refining, fuel treatment plants and food processing industries are becoming a source of growing concern in air quality. Odors are mainly due to the presence of reduced sulfur compounds like hydrogen sulfide, carbonyl sulfide and methyl mercaptans. The biofiltration process for control of these reduced sulfur compounds is gaining prominence as it is ecologically and economically favorable.

A lab study using biofiltration was conducted using three PVC columns as biofilters, with hardwood chips and compost as the media. Previous research determined the removal efficiency of carbonyl sulfide alone. (Nawal, 2004) Typically, however, H_2S is present with COS in the air streams from wastewater treatment plant

units. In the current study, different combinations of hydrogen sulfide and carbonyl sulfide gases were tested using H_2S/COS ratios typical of the concentrations from wastewater treatment plants. Various runs were conducted using compost and hardwood chips individually and also with an 80:20 ratio by volume of wood chips to compost.

The specific research objectives of the study were:

- To find the critical mass loading for COS by studying the typical elimination capacity versus mass loading curve.
- To study the degradation of carbonyl sulfide in presence of hydrogen sulfide using compost and a mixture of hardwood chips and compost as media.

One of the initial findings of the study was that the Interscan 1000 series sensor used for H_2S interfered with International Sensor Technology Model IQ-350 sensor used for COS and had a negative impact on the COS gas concentration measurement. The setup was altered to avoid the interference of gases. More importantly, critical factors governing the process like moisture content, humidity, air flow rate and pH were carefully analyzed and maintained to obtain the best degradation rates for the combinations tested. The moisture content was maintained in the range of 50- 55% , relative humidity at 90-95% and an air flow rate was monitored to be in the range of 2-3 LPM to provide sufficient gas residence time during the experiment.

A 60 ppm concentration of H_2S, 1:6 and 1:2 ratios by ppm of COS to H_2S respectively yielded 100% removal efficiency for both compounds when the biofilter was operated with compost medium. It was found that the critical load is at least 9 g/m^3-hr for COS with compost media.

TABLE OF CONTENTS

Appendix

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 Treatment of Odorous Mixtures from Various Industries and Wastewater Treatment Plants

Odorous gas mixture emissions from wastewater treatment plants and other industries like pulp and paper manufacturing, petroleum refining, fuel treatment, and food processing, are becoming a cause of growing concern due to the nuisances associated with them. Hydrogen sulfide is recognized to be one of the major components in the emissions from wastewater treatment plant. Although there has been a lot of work associated with hydrogen sulfide (H_2S) in the past, there is increasing concern about other compounds like carbonyl sulfide (COS), methyl mercaptan, methyl disulfide and dimethyl disulfide, which are seen in lower concentrations. The treatment of these odorous emissions is required to restore the living conditions of the people in the areas surrounding the emission sites.

Traditionally, these reduced sulfide emissions have been treated using physical and chemical technologies like carbon adsorption, chemical scrubbing, incineration and biofiltration. Of all the conventional technologies, biofiltration has received increased attention as it is ecologically and economically favorable.

1.2 Overview of Biofiltration Technology

Biofilters use natural or commercial media packed columns to grow naturally occurring bacteria to degrade the pollutants occurring in the contaminated air, which is passed from the bottom of the column and flows up through the biofilter media for treatment. Natural media like compost and hard wood chips are often used in biofiltration, as they are economically viable and efficient. Compost media possesses key properties like high surface area, good air and water permeability, good microbial population, near neutral pH, total organic carbon content, and moisture holding capacity.

Elimination capacity, which is the difference in the mass loading of the pollutant at the inlet and the outlet of the biofilter, is used as a measure of the performance of a biofilter, and can be used to compare the performance of biofilters. Also important is the critical load, which is the mass loading at which the removal efficiency of the biofilter begins to drop below 100%. Critical load is used in biofilter design to size the biofilter. Pollutant mass loading is the mass of the contaminant entering the biofilter per unit volume of the biofilter media per unit time. The contaminant loading on the system can be increased either by increasing the pollutant concentration or decreasing the bed volume, or both. When the mass loading exceeds the elimination capacity, a point is reached at which the elimination capacity is independent of the contaminant concentration.

Although biofiltration has been effectively used in the past to remove H_2S from polluted airstreams (Chitwood et al. 2000), increasing usage of the same technology for other reduced sulfides recently. Previous research determined the removal efficiency of carbonyl sulfide in air by itself. (Nawal, 2004) However in real world situations, the odorous emissions typically come in combination of carbonyl sulfide and hydrogen sulfide. This study emphasizes the impact of the presence of hydrogen sulfide on the degradation of carbonyl sulfide. The presence of hydrogen sulfide could affect the removal of carbonyl sulfide in that the specific sulfide reducing bacteria that proliferate in order to degrade hydrogen sulfide may not be suitable to degrade carbonyl sulfide.

The degradation rates of the carbonyl sulfide in the presence of hydrogen sulfide can be improved in a number of ways. One study (Smet, 1996) showed the removal efficiency of carbonyl sulfide can be improved by addition of nutrients like NH_4Cl and $MgSO_4$. Also the presence of inoculated Thiobacillus Strain TJ330 (Ruskannen, 2001) and Hyphomicrobium sp. I55 (Juhani Ruuskanen, 2001) increased the removal capacity of a biofilter for H_2S. One other important factor to be considered is the maintenance of pH near neutral condition as, for many reduced sulfides, microbes act best at neutral pH. The resulting products from treatment of reduced sulfides, being acidic in nature, decrease the pH below 7 and may thus decrease the microbial efficiency. To keep the pH near neutral, lime, ammonia or dolomite can be added to the biofilter.

1.3 Research Objectives

Many field investigations have been done for gases like H_2S and COS individually and their efficiencies measured. The objectives of the present laboratory study are

1) To determine the critical mass loading for COS by studying the typical elimination capacity versus mass loading curve.
2) To compare the degradation of carbonyl sulfide in presence of hydrogen sulfide using different natural media like compost and hardwood chips in biofiltration.

1.4 Organization of Thesis

- Chapter 2 gives a detailed explanation of the literature review for the specified research objectives to be achieved.
- Chapter 3 describes the research methodology adopted for the study.
- Chapter 4 summarizes the results obtained from the experiments and analyses them.
- Chapter 5 gives conclusions from the present study and recommendations made for further research.

CHAPTER II

LITERATURE REVIEW

2.1 Odor Overview

The need to control and maintain air quality is a source of major concern and the urgency is clearly evident from the regional, national and global environmental air pollution. Perhaps one of the greatest challenges to the contemporary environmental industry will be the changes brought about by increasing application of pollution avoidance technologies through the application of recycling, pollution prevention and substitution of hazardous materials with environmentally compatible materials.

Though the measurement of odors has been proved to be complex from the past, odors continue to be sources of primary nuisance for communities. A systematic approach to odors is arduous due to their complex nature. Apart from the nuisance issue, other problems associated with odors are that they trigger nausea, headaches, loss of appetite, disturb sleep patterns and if persistent can cause emotional disturbance, mental depression and irritability. They not only interfere with the working conditions but also cause depreciation in the property values. (Kehoe *et al.,* 1996)

Presently, there is no particular legislation to regulate odors but the public awareness about the odors is making way for accommodating such regulation by the government. However, regulation and control of odors in the environment is difficult because of the technical difficulties of defining odor limits and their measurement and evaluation. The goal of any odor regulation should be to eliminate annoyance due to odors and this should be applicable to any new and existing source emissions which create community annoyance.

The human nose, which is the perceptor of an odor, is sensitive to very low concentrations of the volatile compounds emitted from the handling and treatment of wastewater at wastewater treatment plants and industrial wastewater processing plants. Hence the goal of odor treatment often is to convert these odorous forms to oxidized non-odorous forms. Though reduced sulfides are prominent odorous emissions, other gaseous emissions include volatile organic compounds and ammonia.

Though major sources of odors are primary treatment processes in wastewater treatment plants, other sources like pulp and paper industries, composting facilities, food processing facilities, animal feedlots and petroleum processing and fuel treatment processes are also gaining importance in the need for treatment of odors. The sequence of the treatment of an odor is evaluating the impacts of sources of the odors, measuring and ranking the odor which is the criterion to decide the extent of controls to be applied, and then establishing control priorities. (Richard Pope, 1996)

The distinct characteristics of the volatile sulfur compounds include their very low threshold values, very high toxicity and potential corrosive effect. The major source of carbonyl sulfide is the oxidation of carbon disulfide (CS_2), and 53% of CS_2 emissions are from oceans and natural terrestrial sources. (Ruuskanen *et al.*, 2001) The common source of the volatile sulfur compounds (VSCs) is the anaerobic degradation process. Table 1 illustrates the emissions of VSCs from natural sources.

Table 2.1: Atmospheric Emissions of VSCs from Natural Sources (E. Smet, 1998)

Compound	Atmospheric Concentration (ppbv)	Total Natural Emissions (Tg-S.Year^{-1})
H_2S	0.2	16.5 – 70.6
COS	0.5	2.7-3.5
CS_2	0.02	3.8 – 4.7
Me_2S	0.001	39.6- 45.4

There are a number of physical methods, chemical methods and biological methods used for treatment of these VSCs. Some of the physical/chemical methods are adsorption, absorption and incineration, while the biological methods used are the biofilters, bio-trickling filters and bio-scrubbers. (E. Smet, 1998) However some conventional clean-up methods, including absorption and adsorption, merely transfer pollutants to other media—separation of the pollutants from these media and disposal or destruction of the pollutants is still necessary. Incineration is costly for decontaminating the low-concentration streams that are commonly encountered in environmental site remediation and industrial waste stream treatment, especially with increasing energy costs.

Biofiltration is a relatively modern technique that is being successfully applied to a wide range of public and industrial sectors for abatement of odors, VOCs and air toxics. In contrast to adsorption and absorption, biofiltration converts volatile organic pollutants to carbon dioxide and water, leaving no remaining pollutant for disposal. Biofiltration is cheaper than incineration for low concentration streams.

2.2 Biofiltration process as a control technology

Biological treatment has been in wide application for decades for treatment of wastewater and solid waste but lately has gained importance in treatment of waste gas streams in the industrial and commercial sectors. One biological treatment technology is biofiltration, where a reactor is packed with solid materials on which a biofilm with a proper microbial population is formed. A moisture-rich air stream is passed through the bed of medium containing the cultures. The gas stream flow is treated under optimal conditions, as microbial catabolic (energy releasing) reactions occur. The end products of the process are basic compounds like CO_2, water and biomass.

Biofiltration has had wide applications globally for the removal of odor causing compounds like hydrogen sulfide, carbonyl sulfide, methyl mercapton, dimethyl disulfide and ammonia.

2.2.1 Advantages and Disadvantages of Biofiltration

Biofiltration as a control process is gaining importance because of its economic and environmental benefits, including the following:

- Removal efficiencies greater than 90% have been demonstrated for many of the more common air pollutants, including some of those listed by the Environmental Protection Agency as hazardous air pollutants (HAPs).(S.F. Adler, 2001)
- Due to lower capital and operating costs, biofiltration may offer economic advantages in applications where the air stream contains contaminants at relatively low concentrations (up to 1,000 ppmv, although this is very contaminant- specific and

varies widely) and moderate to high flow rates (generally 20,000 to 100,000 scfm, depending on the contaminant). (S.F.Adler, 2001)

- Biofiltration does not require large quantities of energy during operation and produces a relatively low-volume, low-toxicity waste stream.
- The residue products resulting from the biofiltration process do not need further treatment and disposal.
- Biofiltration exhibits excellent reliability when properly designed and operated.
- Biofiltration may be suitable for intermittent application.

However there are some disadvantages and limitations attributed to this process compared to the physical and chemical processes:

- Inability to treat very high temperature air streams
- Large experimental setup
- Limited bed-life (3-5 yrs)
- Inability to treat highly concentrated loads and/or extreme fluctuations in loading conditions (Stewart et al., 1999)
- Potential problems associated with a stable pressure drop across the system (Higuchi, 2000)

Biofilter technology involves a number of complex processes, like sorption to wet porous matrices and diffusion coupled with biodegradation by ill defined mixed cultures. The combination of these several elemental steps, sometimes not individually understood, emphasizes the difficulty of elucidating fundamentals of the technology involved in biofilters.

2.3 Biofilter Operation and Design Parameters

Removal in biofiltration process occurs basically in two mechanisms, namely absorption into the biofilter and subsequent biological degradation and chemical oxidation. Micro- organisms in the bio-film oxidize the contaminants and use the energy released for maintenance and growth of cells. The reduced sulfur compounds degraded result in formation of acidic compounds.

For effective operation of the biofilter there are some crucial parameters which have to be considered and maintained at optimum.

2.3.1 Media

Media plays a very important role in determining the operational cost and removal performance of the biofilter unit. There are a variety of natural and engineered media used in biofiltration. Importance is, however, given to the most economical and easily available media.

A medium ideal for use in biofiltration process should be able to (1) support 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 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 sizing, cross-sectional depth, surface loading rater per square foot, porosity and desired service life.

Natural media is most preferred because a biofilter ecosystem with more natural self-regulation is likely to operate more efficiently for a longer period of time when compared to a more “engineered” environment (Bohn 1996, Devinny 1999, Brock 1997).

Different types of natural media are described below:

Compost: Compost media possess a large diversity of microbial population. It has good moisture retention properties, near neutral pH buffer capacity and suitable organic content. Due to problems with bed compaction and high pressure drop it is mixed with proper proportions of wood chips (or bulking agents).

Peat: Due to it naturally acidic and hydrophobic nature, control of moisture in peat beds is difficult. Also this medium possesses very less diversity of microbial population, hence requiring inoculation. Low pressure drops occur in using this medium.

Soil: Due to inexpensive easy availability, soil is used as one of the biofilter media but due to its tendency to aggregate and less permeability, deviated air flow is seen isolating parts of the biofilter and high pressure drop occurs. Hence large area reactors are required for soil medium.

Wood chips: Though commonly used as bulking agents, woodchips have also been used as medium by themselves. The nutrient supply however in this case is scarce. Woodchips facilitate homogenous air flow and prevent bed compaction. Also wood chips in some cases provide a channel for moisture content, when the reactor control is low. However there is not a particular species of the tree which is best preferred as the biofilter media.

Perlite: This is another preferred bulking agent but doesn't have any microbial population and nutrient supply. Inert additives such as plastic packing, perilite, and ceramics have been used successfully in conjunction with the natural media. These inert additives are added to media to prevent head losses and uneven distribution of inflowing gases.[8]

Most of the natural media including tree bark, compost, various soils, peat, woodchips, diatomaceous earth, granular activated carbon, and grass have all been tested as biofilter media, solely or in various combinations for removal of reduced sulfur in the biofiltration process.

After evaluating the characteristics of the various natural media available for use, pure compost and compost in combination with wood chips is preferred for good performance of a biofilter. Review of literature gives various combinations tested. One such study used 80:20 ratio by volume of hardwood chips and compost for VOC treatment, and the results of the study indicated that this combination yields good removal rates for experiments running over a period of 3 months. (Deshusses *et al.,* 2000*)* However, another study used 50:50 ratio by volume of hardwood chips and compost, respectively, for removal of H_2S. The results indicated low pressure drop, reduction of compaction and channeling in compost, favorable supply of nutrients and low costs involved with good removal efficiency seen over a long period of time. (Jones *et al.,* 2002) Hence, 80:20 combination of hardwood chips to compost was tested in our study.

Apart from the media configuration, other prominent factors which govern the biofiltration process are moisture control or water-holding capacity, maintenance of near neutral pH, temperature of the process, air flow distribution, and residence time of foul air. (C. Easter, 2000)

2.3.2 Micro-organisms

Micro-organisms best suited to degrade a particular compound under treatment should have high tolerances to changes in pH, moisture content and nutrient supply, so that they are resilient to any variation in the operating conditions. Even an ill suited microbial community can better treat a contaminant when exposed to it over a long period of time. Bacteria, actinomycetes and fungi are the principal microorganisms involved in the biological oxidation process.

It was found that a species of the genus *Thiobacillus Strain TJ 330* and *Hyphomicrobium* MS3 oxidize reduced sulfides to odorless acidic substances at low pH. (The Chemical Engineers Research Page) *Thiobacillus thioparus strain E6* has been reported to oxidize dimethyl disulfide to basic CO_2 and sulfate ions. (Hirai, Ohtake and Shoda, 1990) The bacteria found to degrade carbonyl sulfide gas with compost as the medium are *Stretomyces*, *Bacillus subtilis*, and *Staphylococcus hominis hominis*. The strain found in the media when hydrogen sulfide was being degraded using a mixture of compost and hardwood chips was *Clostridium mangenotii Clostridium cadaveris.* This indicates that different microbes adapt to degrade H_2S and COS. (Nawal, 2004) While, *Thiobacillus Strain TJ 330* was found when treating a mixture of hydrogen sulfide and carbon disulfide, and *Hyphomicrobium MS3* was found when pollutant gas was dimethyl sulfide. (Ruokojarvi*et al.* 2001)

To avoid clogging in the biofilter, the growth of microorganisms in the biofilter may need to be controlled. When the rate of microbial death equals the rate of growth, then the total amount of biomass will be constant and clogging will not happen. The biomass can be controlled by limiting nutrients and washing, which also provides the bed with additional water for moisture control.

2.3.3 Moisture Content

Lack of moisture control is one of the primary causes for low performance in biofilters. The moisture content in the biofilter has to be maintained at an optimum: high or low percent of moisture can lead to failure of the biofilter. A high amount of moisture in the biofilter will cause clogging and increases the head loss in the filter, while very low moisture will dry out the bed and cause cracking of the filter bed. Research has been focused on establishing the optimum moisture content of the filter media. The range for the biofilter medium is typically considered to be 40-70%. However this percent of moisture appears to vary by filter medium. This range for compost is 40-50% and for peat it is 60-75%.

For a particular process, any change in the percentage of the moisture content can cause shrinking and swelling of the media and can also strain the microbial colony. Shrinking or swelling can lead to short circuiting of air flow. These kinds of problems are seen more for media like compost and less for soil based media.

Since the reaction occurring inside the biofilter is exothermic, drying of the bed occurs unless the humidity of the incoming air stream is 98%. When the humid gas stream flows from bottom to the top, the performance is better, as the bed is warmest and driest when the stream enters the column. Pre-humidification alone does not keep the filter from drying. The pollutant gas stream becomes warmer as it passes through the bed; hence, it takes moisture from the media, which expends the water.

2.3.4 pH

Maintenance of the optimal pH is also one of the priorities for good performance by microbes. A pH range of 5 to 8 is recommended as optimal; a pH less then 5 often results in reduced performance. However, some bacteria degrading reduced sulfur compounds survive even at a pH less than 5.

To maintain the pH in this optimal range, additives like dolomite, crushed shells or lime may need to be added for pH buffering. This mainly happens in case of treatments involving reduced sulfide compounds, as they form acidic substances as end products. However, for typical odor applications in wastewater treatment plants and treatment involving VOCs or other organic compounds, near neutral pH is required for good performance.

Allen and Yang recommended that slurries should not be used for pH control as they add fines to the filter medium, which can decrease porosity and increase head loss.

2.3.5 Temperature

Microbial activity and performance of the biofilter depend on the operating temperature of the system. The range of temperature preferred for good microbial activity inside the biofilter is above 50^0C and below 100^0C. The microbial ability is decreased drastically if the temperature falls below 50^0C, and temperature above 100^0C is harmful and kills the microbial system that survives at moderate temperature. Ideally, the microbial activity should double for every 10^0C rise in temperature, but research indicates that monitoring the temperature of the system is not required for biofilters.

2.3.6 Humidification of the gas stream

Humidification of the gas stream is also an important factor in operating a biofilter. The main emphasis for the criteria in constructing a humidification chamber is that maximum saturation of the gas stream should take place in the short time of the gas stream passing through the humidification chamber before reaching the biofiltration columns. 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. Besides decreasing the cost of excess water usage, this also provides for a good air-water contact.

2.4 Previous Research and Case Studies

A detailed review of the literature clearly indicates the fact that very little research was focused on COS. Research based on biofiltration for reduced sulfides was predominantly concentrated on H_2S, mainly because compared to other reduced sulfides, H_2S is seen in very high concentrations in wastewater treatment plants and industries, which are principal emitters of odorous gases. This is one of the key reasons for our study being done on COS, in combination with H_2S. Other reason being, apart from being an odorous gas, COS is listed under hazardous air pollutants according to the Clean Air Act, mainly due to its explosive nature when mixed in different ratios with air.

Previous research using the same lab-scale setup determined the removal rates of COS and H_2S individually using different natural media. The range of concentrations tested were 5-45 ppm of COS and 3-45 ppm of H_2S, respectively. 100% removal of COS was seen with compost and 80:20 ratio by volume of hardwood chips and compost, while the removal efficiency of COS was 93 % with hardwood chips alone. The study also concluded that the removal efficiency did not depend on the age of compost, as removal did not vary when fresh and aged compost was used. 100% removal was seen for H_2S with compost, hard wood chips and 80:20 ratio by volume of hardwood chips and compost for the concentrations tested. The primary focus of the present research is to measure the removal rates and elimination capacity of COS, with different media and media combinations, in the presence of H_2S. It studies any impact on the elimination capacity of COS or H_2S in the presence of the other gas.

Listed below (as shown in Table 2.2 and 2.3) are articles which researched biofiltration as a control technology for various reduced sulfides and volatile organic 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 Various Reduced Sulfides, Mixed with Other Gases using Biofiltration

Air and Waste Management Association: 2005, Paper # 475 Authors: C.P. Nawal, Melanie L.Sattler				
Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Hydrogen sulfide Carbonyl sulfide	Compost, hard wood chips & 80:20 ratio of hardwood chips and compost	H_2S – 100 % with all three media. COS – 85-90% with hardwood chips and 100% with rest of the media	80/20 ratio of hard wood chips decreases the stabilization time as well as improves the removal efficiency.	-
Texas Odor & Corrosion Control Speciality Conference and Expo: 2003 Authors: Quigley C, Easter C				
Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Hydrogen sulfide Dimethyl sulfide Carbonyl sulfide	Soil Organic Media	H_2S – 98% $(CH_3)_2S$-37% COS – 57%	The removal of COS is very less compared to H_2S with soil and organic media	-
Texas Odor & Corrosion Control Speciality Conference and Expo: 2003 Authors: Harvey Wayne, Sorenson				
Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Hydrogen sulfide Methyl disulfide Carbonyl sulfide	Organic Media	H_2S – 100% $(CH_3)SH$ -100% COS – 21%	The removal efficiency increased with the increase in gas residence time and at low inlet gas concentrations.	-

Table 2.2 – Continued

<table>
<tr><td colspan="5">Air and Waste Management Association: 2001, 51:387-392
Authors: Tarja Hattikainen, Juhani Ruuskanen, Pertti J. Martikainen</td></tr>
<tr><td>Compound(s) Tested</td><td>Medium</td><td>Removal Efficiency</td><td>Conclusions</td><td>Other Comments</td></tr>
<tr><td>Hydrogen sulfide
Carbon disulfide</td><td>Peat</td><td>99%</td><td>99% removal efficiency is achieved with concentrations as low as 600 mg S/m^3</td><td>Overloading occurred with concentrations 1300-5000 mg S/m^3</td></tr>
<tr><td colspan="5">Desalination: 2002, 148:281-287
Inge De Bo, Herman Van Langenhove, Jeroen Heyman</td></tr>
<tr><td>Compound(s) Tested</td><td>Medium</td><td>Removal Efficiency</td><td>Conclusions</td><td>Other Comments</td></tr>
<tr><td>Dimethyl sulfide</td><td>Zirfon Composite Membrane</td><td>87-99 %</td><td>The removal efficiency increased with the increase in gas residence time and at low inlet gas concentrations.</td><td>Bioreactors proved to be good for acidic compounds lacking biodegradability</td></tr>
<tr><td colspan="5">Air and Waste Management Association: 1995, 5:183-192
Bruce Singleton, EG&G Biofiltration</td></tr>
<tr><td>Compound(s) Tested</td><td>Medium</td><td>Removal Efficiency</td><td>Conclusions</td><td>Other Comments</td></tr>
<tr><td>Hydrogen Sulfide
Methyl Mercaptan
Dimethyl Sulfide
Dimethyl Disulfide</td><td>Peat</td><td>H_2S – 100 %
CH_3SH – 65%
$(CH_3)_2S$ – 21%
$(CH_3)_2S_2$ – 7%</td><td>NH_3 concentrations seen in the outlet did not effect the H_2S removal.</td><td>NH_3 concentrations in the outlet were not expected.</td></tr>
</table>

Table 2.2 – Continued

Odor and Toxic Air Emissions, 2002
Kim Jones, Al Martinez, Ketankumar Maroo, Sonali Deshpande

Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Hydrogen Sulfide Ammonia	Different ratios of Compost and Hard wood Chips	≥ 97 %	Presence of ammonia did not affect the removal efficiency of H_2S.	10 ppm is too low a concentration of H_2S to be tested.

Air and Waste Management Association: 2003, #69751
Kim Jones, Alvaro Martinez, Jim Boswell

Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Hydrogen Sulfide	Compost Commercial media	≃ 96 %	No impact of sulfur toxicity on removal efficiency	

Journal of Chemical Technology and Biotechnology:1999, 74:9-16
A.H Wani, R.M.R.Branion and AK Lau

Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Hydrogen Sulfide Dimethyl Sulfide Dimethyl Disulfide	Compost hog fuel bed with perlite	-	Hydrogen sulfide elimination capacity did not vary with addition of DMD or DMDS.	Hog fuel media performs better in presence of reduced sulfur gases.

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

Air and Waste Management Association: 1998, 48:65-70
Richard Auria, Anne-Christine Aycaguer, Joseph S.Devinny

Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
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.

Air and Waste Management Association: 2003, 53: 217-226
Marie Caroline Delhomenie, Louise Bibeau, Julie Gendron, Ryszard Brzezinski

Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
Toluene Xylene Trimethyl Benzene	compost	Toluene- 95% Xylene- 80% TMB- 70%	The removal efficiency decreased in the presence of nitrogen.	

Air and Waste Management Association: 2001, 51:1662-1670
Aitor Aizpuru, Luc Malhautier, Jean-Calude Rux and Jean- Louis Fanlo

Compound(s) Tested	Medium	Removal Efficiency	Conclusions	Other Comments
VOCs	Peat	-	Bacteria and the substrates compete for biodegradation.	

CHAPTER III

METHODOLOGY

3.1 Overview of the Experimental Setup

A lab-scale study biofiltration system was used to remove a combination of hydrogen sulfide and carbonyl sulfide, after mixing them with the air stream. The lab setup is a downsized version of a field biofilter constructed with the same height but with smaller diameter than the length and width of a biofilter used in the field. The overall setup of the experiment with compost media is as shown in Figure 3.1.

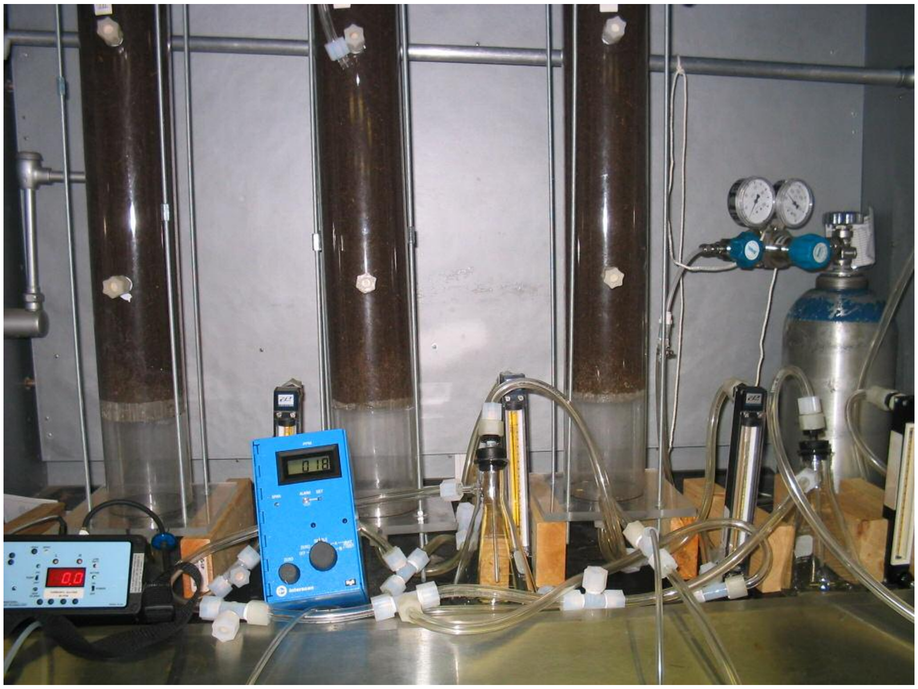

Figure 3.1 Experimental Setup with Compost

The experimental setup typically consists of five PVC columns, three of which act as biofilters and contain a bed of medium (compost or hard wood chips or the combination of compost and hard wood chips). Two of the PVC columns act as humidification chambers for H_2S and COS, respectively. The setup also contains various Teflon fittings and tubing for connections, COS and H_2S gas cylinders, Teflon flow meters for COS and H_2S, air flow meters, air inlet and end plates graduated at both the ends of the PVC columns. The bacterial colonies grow on the media and as the pollutant gas passes through them, they grow and reproduce by consuming the reduced sulfides.

3.2 Description of Different Components of the Setup

3.2.1 Biofilter Columns

The three PVC columns were products from Regal Plastics, Fort Worth, TX. The dimensions of each of the biofilters are identical: each column measures 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 through out 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. (Nawal, 2004) The volume of the bed space is 43 ft^3; a variable bed volume is used for measuring the critical loading of COS.

3.2.2 Gas Cylinders and Air Supply

The source of carbonyl sulfide was a 1I size cylinder from Matheson Tri Gas Company with an internal volume of 141 cubic ft. at a pressure of 2000 psig. The percentage by volume of the carbonyl sulfide present in the cylinder was 3% and the base gas nitrogen concentration was 97%.

The percentage by volume of the H_2S present was 3% and the base gas nitrogen concentration was 97%. The source of hydrogen sulfide was a 3I size cylinder from Matheson Tri gas with an internal volume of 28.3 cu ft at a pressure of 2000 psig.

A dual stage high purity stainless steel gas regulator was used to control the gas flow. The regulator has an interstage relief valve which helps turning off the gas flow at any specific point. The range of COS concentration tested was 5-45 ppm. The concentrations of hydrogen sulfide tested following dilution with air were 30ppm - 100 ppm. The tygon tubing carrying the gases was fitted with Teflon tape to make them air-tight. The cylinders used for this purpose are shown in Figure 3.2.

Figure 3.2 Carbonyl sulfide and H_2S gas cylinders

Measured individual flows of hydrogen sulfide and carbonyl sulfide were mixed with a known flow of air coming from the nozzles provided in the fume hood.

3.2.3 Flow Meters

The flow meters used for measuring COS and H_2S were FM-1050 series of Teflon flow meters from Matheson Tri-gas Company (Figure 3.3). The Teflon flow meters had a high resolution 150 mm scale and had a high accuracy of ±5% of the full scale reading, and thus provided a good precision control for a wide range fluid flow. The flow meters were calibrated with the base gas as air, as the gas was flowing in an environment of air. A small measured and controlled flow of COS and H_2S concentration from the respective gas cylinders was passed through the individual gas flow meters (rotameters) before it was mixed with the air stream.

The flow meter to measure the air flow rate, shown in Figure 3.3 is a direct reading meter for metric units from Cole Parmer. This acrylic flow meter is compatible with the fittings used and provides an accuracy of ±5% for the total flow. 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 rates varied from 1 lpm to 3 lpm and the columns were maintained in the up flow mode.

Figure 3.3 Flow Meter to Measure Gaseous Mixture (left) Air Flow Meter (right)

3.2.4 Tubing, Connections and Septa

The Teflon tubing with an internal diameter of ½”, Teflon tape to make the connections air tight, various fittings like straight and T-connections used to connect the tubing and which also served as sampling ports were from Cole Parmer, KY. The main reason behind selecting Teflon as the tubing material is its satisfactory compatibility with COS and H_2S gas and because of low costs involved compared to other tubing materials. The septa used to close the sampling ports were from Spectrum Chemicals, NJ.

3.2.5 Humidification Chambers and Condensation Control

The combined pollutant air streams were passed through the individual humidification chambers, provided for each gas, to maintain moisture content for the growth of bacteria inside the biofilter columns. The humidification chambers (shown in Figure 3.4) were built from the same PVC column material used for biofilters and were fitted with end plates. Two stop cocks equidistant from each other were provided through the length of the column to enable easy refill and cleaning after every run. The air and gas mixture passed through a 1/8” NPT threaded hole and through a glass tube which ran to the bottom of the chamber. This facilitated maximum gas contact with water. The moistened air-gas mixture emerged through the outlet and passed through a sidearm flask setup to avoid condensation in the flowmeters, which would clog them.

Figure 3.4 COS and H_2S Humidification Chambers

The condensation was due to the continuous running of the experiment for several days. To fix this, the gas flow coming out of each of the humidification chambers was routed into a side-arm flask setup (as shown in Figure 3.5), which also provided for individual gas concentration measurement. The outlet gas mixture from the humidification chamber is sent to individual sidearm flasks through a NPT threaded 1/8” tube, and the Teflon tubing carrying the outlet gas from the flasks was fitted with a T-fitting to provide a port for individual gas concentration measurement. The two individual gas streams containing the pollutants were then mixed, and a mixture of COS and H_2S entered the biofilter columns.

Figure 3.5 Side-arm Flask Setup

3.2.6 Gas Concentration Measurement

The concentrations of the gases were measured at the inlet and outlet of the columns using gas sensors. The sensor used to measure COS (shown in Figure 3.6) was an IQ-350, a solid state sensor from International Sensor Technology. The maximum concentration the sensor could measure was 50 ppm. It was calibrated in an air environment. The sensor power and the sample-pump were left on at all times so there was no warm-up for the COS sensor. A reading was taken 2 minutes after inserting the probe into the gas stream.

The H_2S sensor was Interscan 4000 series (shown in Figure 3.6) from Alan Plummer Associates. The sensor measured concentrations ranging from 0-3000 ppm of

H_2S, but the concentrations used for the experiment ranged from 30-100 ppm. Zeroing the sensor had to be done every time a reading was made, by adjusting the unit to zero before gas sampling. The sensor power was left on at least 8 hrs before the sample was measured and the warm-up time after zeroing the instrument was 15 min. The reading was taken within 2 minutes after inserting the probe into the gas stream.

Figure 3.6 COS and H_2S Sensors

For the experiments involving the combination of H_2S and COS, the concentrations of COS were very low ranging from 5-30 ppm, compared to the concentration of H_2S, ranging from 30-100 ppm. Hence, runs were conducted to study any interference between the sensors. It was observed that the COS sensor was sensitive to the presence of H_2S gas and for any set inlet concentration, the sensor would directly shoot to 50 ppm. On the other hand, the H_2S sensor behaved normally even in the presence of COS sensor. The runs were carried out for 30ppm , 40 ppm and 60 ppm, 80 ppm of COS and H_2S, respectively. The results are as shown in Table 3.1& Table 3.2.

Table 3.1 Illustration of Interference of sensors with 30 ppm COS and 60 ppm H_2S

	COS	H_2S
Inlet concentration	30ppm	60 ppm
Outlet concentration	50 ppm	68ppm
Concentration of COS after H_2S sensor is turned-off	1.3 ppm	-

Table 3.2 Illustration of Interference of sensors with 40 ppm COS and 80 ppm H_2S

	COS	H_2S
Inlet concentration	40ppm	80 ppm
Outlet concentration	50 ppm	82ppm
Concentration of COS after H_2S sensor is turned-off	2.5 ppm	-

The sidearm flask setup helped reduce this problem by mixing the individual streams of the pollutant gases, but the concentration measurement was altered as there was slight mixing of gas in the tubing. To avoid the slightest possible interference, during a run, the inlet concentration of the COS was measured first before H_2S flow would be turned on. For outlet concentrations, the concentration of H_2S would be measured first, and the flow turned off and then the outlet concentration of the COS gas would be measured**.**

3.2.7 Humidity and Temperature Measurement

The humidity in the gas stream entering each one of the columns was measured by using a Humidity Stick (shown in Figure 3.7). The probe of the humidity stick was inserted into the sampling port near the column inlet and the reading gave the humidity in the stream. The humidity for the system under operation was almost 95%. The only constant parameter of the system, temperature was also measured by using the humidity stick. The temperature of the system was room temperature, which is 73^0F.

Figure 3.7 Humidity Stick

3.2.8 pH Measurement

The pH of the media was also one of the critical parameters to be maintained for efficient removal of the pollutant gas, as the growth of most bacteria would be at maximum near neutral conditions. Hence it was important to maintain the pH at nearly 7.0. To measure the pH of the media in the biofilter, a pH meter, Accumet AR 50 Fisher Scientific (shown in Figure 3.8), was used. A buffer solution with a pH of 10.0 was used as the standard, and the medium is mixed with distilled water and put in contact with the electrode to obtain the pH measurement.

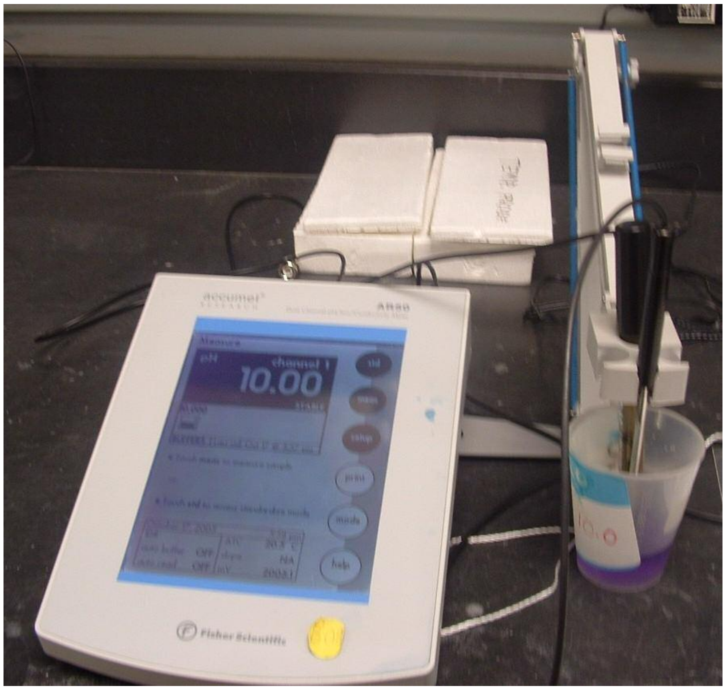

Figure 3.8 pH Meter

3.2.9 Medium Moisture Content Measurement

To determine the moisture content of the media, samples of media were taken from each one of the three columns was an empty beaker. The samples were heated in an oven set to 105^0 C for one hour (ASTM Standards), within which time, the media was assumed to have lost all its moisture and to be completely dry. The weight of the sample before and after the heating process and the weight of the empty beaker were measured using an analytical balance. The percentage moisture content of the media was determined using the equation:

$$\text{Moisture Content (\%)} = \left(\frac{\text{Weight of the wet sample - Weight of dry sample}}{\text{Weight of the wet sample - Weight of the empty beaker}} \right) * 100$$

3.2.10 Biofilter Media

The different media used for this experiment were compost, hardwood chips and a mixture of compost and hardwood chips. The compost came from back yard waste which contained 80% oak leaves, leaf trimmings and animal remains. Compost media was chosen for this experiment as it is economical, easily available and has a wide range of bacterial growth on it. It has good water retention properties, near neutral pH, and a suitable organic content. A sample of the compost media is shown in Figure 3.9. Previous research proved that there is no difference in the removal efficiency and pH of fresh and aged compost. (Nawal, 2004)

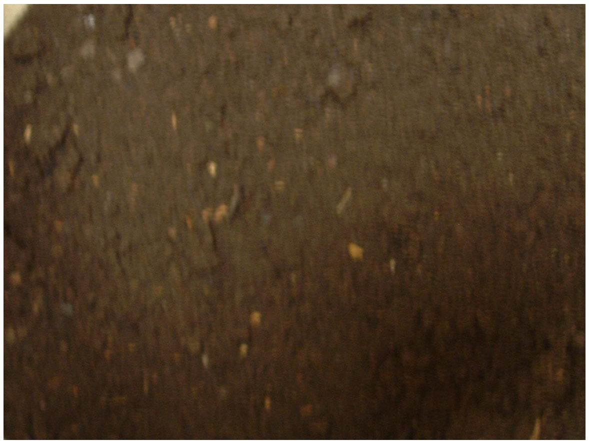

Figure 3.9 Compost Media

The hardwood chips came from Good Times Wood Products Inc., TX. There have been several instances where woodchips have been used as the only media in biofiltration (Paul, 1994; Finn and Spencer, 1997).

Figure 3.10 Hardwood Chips

However, there has not been a particular species of tree better than the other. Hardwood chips (shown in the Figure 3.10) are preferred biofilter media because the air flow through the medium is homogenous and bed compaction is prevented. Also hardwood chips by absorbing the moisture maintain the moisture content of the bed inside the column.

Previous studies showed a mixture of hardwood chips with compost is a good combination to reduce the compaction and channeling problems associated with running the biofilters just with compost medium. A review of the previous research conducted to test various combinations of compost and a hardwood chips is listed in Table 3.3.

Table 3.3 Summary of wood chips and compost media ratio (Nawal, 2004)

Author	**Year**	**Ratio (%)(volume basis)** **Wood chips: Compost**
Deshusses and Johnson	2000	80:20
Smet, Van Langenhove and Verstraete	1996	32:68

Table 3.3 (continued)

Author	**Year**	**Ratio (%)(volume basis) Wood chips: Compost**
Smet, Chasaya, Van Langenhove and Verstraete	1996	61:39
Jones, Martinez, Maroo and Deshpande	2002	50:50
Jones, Martinez, Maroo and Deshpande	2002	20:80
Jones, Martinez, Maroo and Deshpande	2002	80:20

The experimental setup with 80:20 ratio of hardwood chips and compost is shown in Figure 3.11.

Figure 3.11 Experimental Setup with Compost and Hardwood chips

3.3 Experimental Procedure

The experimental procedure of the biofiltration experiment involves three steps mainly. First, conducting a leak test for every setup of the experiment; second, setting up the columns with appropriate media, required air flow rate and odorous gas concentration; and third, running the experiment.

3.3.1 Leak Test

A leak test was conducted for each flow component of the setup to detect any leaks and loss of air or gas. The test was conducted using soapy water which was sprayed onto the component and air when passed through it. The formation of soap bubbles indicated a leak in the component. Same procedure was carried out for the whole setup, in that air instead of the gas mixture was passed through the setup and soapy water was sprayed at various joints. Formation of soap bubbles indicated the leaks at any joint. Leaks were plugged using Teflon tape.

3.3.2 Experimental Setup

The biofilter columns were filled with appropriate media and connected to the individual flow meters after putting them back in the hood.

3.3.3 Running Experiments

1. The air flow rate was adjusted as required ranging from 1 lpm-3 lpm.
2. The COS and H_2S gas outlet pressure was maintained at 1atm, or 14.6 psi, and the flow meter was adjusted to maintain the required concentration of the gases, measured using sensors.

3. To avoid interference, the COS gas concentration was measured first and then the flow of H_2S was started.
4. The valves of the individual flow meters of each column were left completely open for maximum flow through the columns.
5. The flow was run continuously till the bacteria acclimatized to the odorous gas environment and started consuming it.
6. To measure the outlet concentration, the H_2S gas concentration was measured first, and then carbonyl sulfide concentration after turning off the H_2S flow.
7. The exhaust in the hood was turned on through out the experiment.
8. The first set of runs were done to measure the critical load of COS and the concentrations varying from 30 ppm- 45 ppm were passed through the columns by varying the volume of the media bed in the column.
9. The runs were done in triplicate for quality assurance purpose, with the same bed height and pollutant inlet concentration in each of the 3 columns.
10. The runs involving both carbonyl sulfide and hydrogen sulfide were done with different combinations of concentrations and various air flow rates, shown in Table 3.4, with different media configurations in each of the columns.

Table 3.4 Various Sets of Concentrations Tested in Biofilters

COS Concentration (ppm)	H_2S Concentration (ppm)	COS:H_2S ratio	Air Flow Rate (LPM)	EBRT(sec)
30	60	1:2	1	390
10	60	1:6	3	130
5	100	1:20	3	146

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Overview

The experimental runs conducted were over a period of 6 months to achieve the research objectives, mainly to measure the critical loading of COS gas by varying the media bed volume and gas concentrations and to study the competitive biodegradation of H_2S and COS gases with compost and a combination of compost and hard wood chips.

4.2 Effect of Presence of H_2S

The presence of a combination of gases caused additional problems like interference. This interference was mainly due to the COS sensor being sensitive to the presence of another gas containing sulfide ion. It was seen that the COS sensor is sensitive to the presence of H_2S gas. Due to the interference (shown in Table 4.1 & Table 4.2), the experimental setup was altered in a way to accommodate separate gas flow for each gas and for individual measurement of H_2S and COS gas. The experimental procedure was also altered accordingly. Even in the absence of COS gas (just H_2S gas flow), the COS sensor would detect a concentration due to the presence of sulfide ion. Hence all the COS gas measurements were taken in absence of H_2S gas.

Table 4.1 Interference Due to the Presence of H_2S Gas with
30 ppm of COS and 60 ppm H_2S

Gases	**Inlet (ppm)**	**Concentration during interference (ppm)**	
		Presence of H_2S	**Absence of H_2S**
COS	31.0	50	33
H_2S	61	62	-

Table 4.2 Interference Due to the Presence of H_2S Gas with
10 ppm of COS and 80 ppm H_2S

Gases	**Inlet (ppm)**	**Concentration during interference (ppm)**	
		Presence of H_2S	**Absence of H_2S**
COS	10	50	9.8
H_2S	80	79	-

4.3 Removal Efficiency of H_2S

Bench scale experiments were conducted to measure the removal efficiency of H_2S gas alone using compost as the medium with a 60 ppm concentration and an air flow rate of 3LPM. The inlet and outlet concentrations are tabulated in Table 4.3 and removal efficiency versus time is plotted in Figure 4.1. The readings shown in table 4.3 are an average of the readings from the three columns.

Removal Efficiency was calculated according to equation 4.1 below:

$$\text{Removal Efficiency} = \frac{Inlet\ concentration - Outlet\ concentration}{Inlet\ concentration} \times 100\% \quad \ldots\ldots\ldots \quad 4.1$$

Table 4.3 Average Daily Experimental Results for H_2S Using Compost Biofilter

Date and Time	**Inlet (ppm)**	**Outlet (ppm)**	**Flow Rate(LPM)**	**EBRT (sec)**	**Removal Efficiency (%)**
03/29/05 4:00 pm	62	0	1.093	5.95	100
03/30/05 3:30 pm	70	0	1.194	5.44	100
04/01/05 6:00 pm	59	0	1.052	6.18	100
04/02/05 2:00 pm	63	0	1.135	5.73	100
04/03/05 3:00 pm	64	0	1.156	5.62	100
04/04/05 1:30 pm	61	0	1.072	6.06	100
04/05/05 2:30pm	66	0	1.170	5.56	100

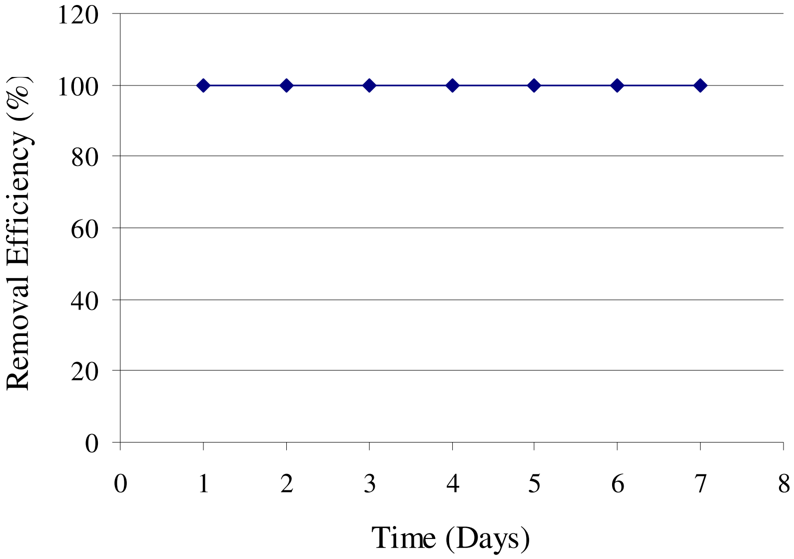

Figure 4.1 Hydrogen Sulfide Removal Efficiency with the Compost Biofilter

As seen from Table 4.3 above, the removal efficiency observed over a 7 day period for a 60 ppm concentration of H_2S was 100%. Hence, it is seen that the compost biofilter gives good removal efficiency for H_2S.

In Table 4.4 below, the elimination capacity is calculated using the inlet and outlet loading of H_2S from the biofilter according to the equation:

$$\text{Elimination Capacity} = \left(C_I - C_0\right) \text{ g/m}^3\text{-hr}$$

where C_I = Inlet Loading, g/m^3- hr

C_0 = Outlet Loading, g/m^3-hr

Table 4.4 Inlet and Outlet H_2S Loading with the Compost Biofilter

Inlet H_2S (ppm)	**Air Flow Rate (LPM)**	**Outlet H_2S (ppm)**	**Inlet H_2S Loading (g/m^3-hr)**	**Outlet H_2S Loading (g/m^3-hr)**	**Elimination Capacity (g/m^3-hr)**
62	1.093	0	0.870	0	0.870
70	1.194	0	1.073	0	1.073
59	1.052	0	0.797	0	0.797
63	1.135	0	0.918	0	0.918
64	1.156	0	0.950	0	0.950
61	1.072	0	0.839	0	0.839
66	1.170	0	0.991	0	0.991

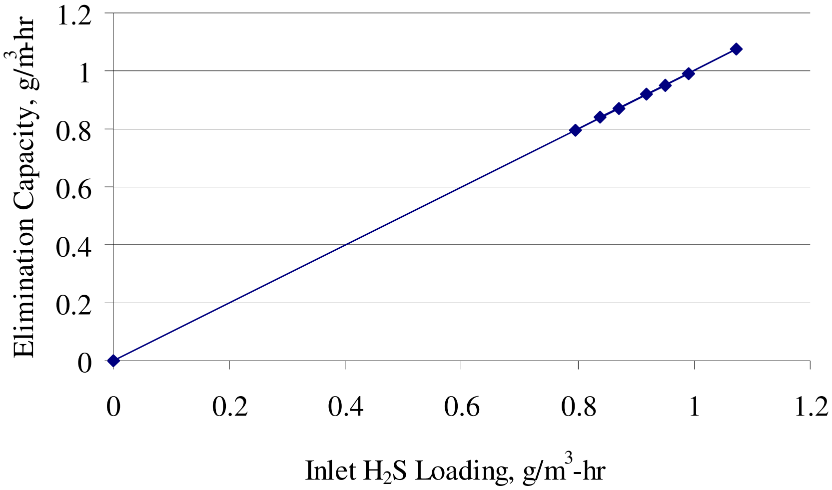

Figure 4.2 Elimination Capacity vs. Inlet H_2S Loading with the Compost Biofilter

Elimination capacity vs Mass loading of H_2S is plotted in Figure 4.2. Since the removal efficiency in this case is 100%, the elimination capacity equals mass loading.

Calculation of Mass loading

According to Cooper & Alley (2002), at standard temperature (25^0C) and pressure (1 atm):

$$C_{\mu g/m3} = (40.9xC_{ppm}xMWp) \tag{4.2}$$

where $C_{\mu g/m3}$ – Concentration in mass units

C_{ppm} – Concentration in volumetric units

MWp – Molecular weight of the component

The overall air flow rate is calculated from the average flow meter reading by using the calibration chart for the flow meter using the interpolation method.

The bed volume is calculated as follows:

$$\text{Volume of the bed (V)} = \frac{\prod \text{ x } \Phi^2 \text{ x H}}{4} \tag{4.3}$$

where Φ - Inner diameter of the column

H - Height of the bed

Finally the mass loading is calculated according to:

$$\text{Mass loading (g/m}^3\text{-hr)} = \frac{(40.9\text{xCppmxMWp})\,\mu g/m^3 \times (Q)LPM \times 60\,\text{min}/hr}{(V)L \times 10^6\,\mu g/g} \tag{4.4}$$

where Q- Flow rate (LPM)

V- Bed volume (liters)

A sample calculation is shown in appendix B.

4.4 Critical Mass Loading of COS

The critical mass loading for COS was assessed using compost as the medium. For the experimental runs estimating critical mass loading, parameters varied were both inlet COS loading on the system and volume of the compost bed. Higher concentrations like 30 ppm and 45 ppm were used for this purpose as, under low load conditions the mass loading equals the elimination capacity due to 100% removal efficiency; thus, the probability of critical mass loading occurring at low concentrations is far less when compared to relatively high concentrations typical of the emissions from wastewater treatment plants and other industries.

Due to the constraints on increasing the concentration of COS higher than 50 ppm (the COS sensor will not read higher than 50 ppm), instead of just increasing the concentration or decreasing the bed volume, both the parameters were varied. Starting from a bed depth of half the height of the column, a set of bed heights were tested for critical loading with 30 ppm concentration of COS, and the rest ranging from 6 in to 1 in bed height with 45 ppm concentration. Table 4.5 summarizes the averaged experimental data from the runs. Table A.2 in Appendix A summarizes all the readings and each reading represents an average of readings from the three columns. Most of the readings in Table 4.5 are the run’s final reading for each bed height, conducted over a period of 1-3 days, data collected at equal intervals. Figure 4.3 is a plot of elimination capacity versus mass loading. The detailed raw data from the lab scale experiments for COS critical load are tabulated in Appendix A.

While conducting the experiments, due to a leak near the inlet of the COS flow meter, a low flow meter reading was being shown compared to the reading seen after the leak was fixed. Hence the air flow rates for the previous bed heights were corrected according to the readings taken after the leak was fixed. Also due to problems like channeling, compaction and disease among bugs in the compost medium, an outlet reading was being seen in the first column. The readings from the first column were thus neglected and the readings from second and third columns were averaged.

Table 4.5 Averaged Experimental Data for Critical Loading of COS

Date & Time	**Bed Height (inches)**	**Bed Volume (Liters)**	**Inlet (ppm)**	**Air Flow rate (Lpm)**	**Mass Loading (g/m^3hr)**	**EBRT (sec)**	**Outlet (ppm)**	**Elimination Capacity (g/m^3-hr)**
06/05/05 11:00am	15	3.91	31	1.042	1.216	225	0	1.216
06/11/05 10:00am	10	2.61	28	1.036	1.64	151	0	1.64
06/29/05 3:00 pm	7.5	1.96	31.5	1.042	2.47	113	0	2.47
07/03/05 11:00am	6	1.56	30.6	1.036	2.991	90	0	2.991
09/29/05 2:00 pm	6	1.56	45	1.041	4.42	90	0	4.42
10/3/05 3:00 pm	5	1.30	46	1.056	5.5	74	0	5.5
11/22/05 7:00 am	3	0.78	45.0	1.056	44	8.97	0	8.97
11/15/05 12:00am	4	1.04	45	1.068	6.8	58	0	6.8
11/22/05 5:00 pm	2	0.52	46.1	1.036	13.52	30	42.9	0.938
11/24/05 8:00 am	1	0.261	46.7	1.102	29.02	14	45.2	0.93

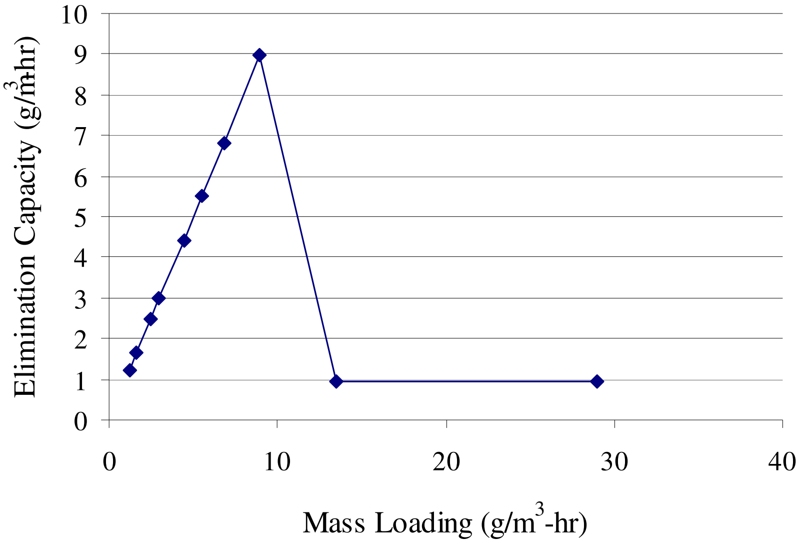

Figure 4.3 Elimination Capacity vs. Mass Loading for COS

In Fig. 4.3, it is inferred from the graph that for low volume of the bed there is a drop in the elimination capacity of the media as most of the gas passes untreated through the column. Due to low residence time for lower range of bed heights, COS gas was not sufficiently diffusing into the bio-film and hence was passing untreated (as seen from the Table 4.5).

The point where the removal efficiency starts to decrease, as loading increases, is the critical loading for the air pollutant. As the inlet concentration could not be increased beyond 50 ppm, the critical loading was not achieved during our study. However, it was found that it is at least 9 g/m^3-hr (Appendix A), the maximum loading achieved prior to break through, in which gas was coming out untreated. It was established that at bed heights lower than 3 inches, the gas was coming out untreated, which means that a minimum bed height of 3 inches is needed for an approach velocity of 0.0017 m/sec and EBRT of 30 sec.

4.5 Removal Efficiency and Elimination Capacity of Combination of H_2S and COS

For experiments to study the relative degradation of H_2S and COS, various ratios of gases were selected and the removal efficiency using different media was measured over a period of time. As the amount of H_2S in odorous emissions is predominantly high compared to other reduced sulfides, higher concentrations of H_2S were selected for the runs. The averaged results for compost medium are as summarized in Table 4.6, Table 4.7 and Table 4.8. Apart from varying the ratio of the gas combination, the air (oxygen) flow to the columns was also varied to vary the empty bed residence time. Gas ratios of 10: 60, 30:60 and 5:100 by ppm ratio of COS and H_2S were tested. A smaller flow rate provides for high residence time for the gas passing through the column, enabling good contact with the microorganisms, while a larger flow rate decreases the residence time. However the impact of this variation in the residence time for compost medium is less. This was because of the good acclimatization of micro-organisms in the medium and a diversified microbial population. A 100 % removal efficiency of compost was seen for all the ratios of both H_2S and COS, as seen from Figures 4.4, 4.5, 4.6, 4.7, 4.8 and 4.9.

Table 4.6 Removal Efficiency for a 1:2 Ratio of COS to H_2S, Using Compost Biofilter

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		COS	H_2S
05/04/2005 9:00 pm	27.4	0	56	0	91	100	100
05/05/2005 10:00 pm	33	0	59	0	88	100	100
05/6/2005 10:00pm	32	0	61	0	94.2	100	100
05/7/2005 9:00 pm	30.8	0	63	0	96.7	100	100
05/8/2005 10:00 pm	32	0	52	0	91.3	100	100
05/9/2005 11:00 pm	32.5	0	58	0	93.3	100	100
05/10/2005 11:00 pm	29	0	55	0	95.8	100	100
05/11/2005 8:00 pm	33	0	63	0	95.1	100	100
05/12/2005 4:00 pm	28	0	54	0	95.1	100	100

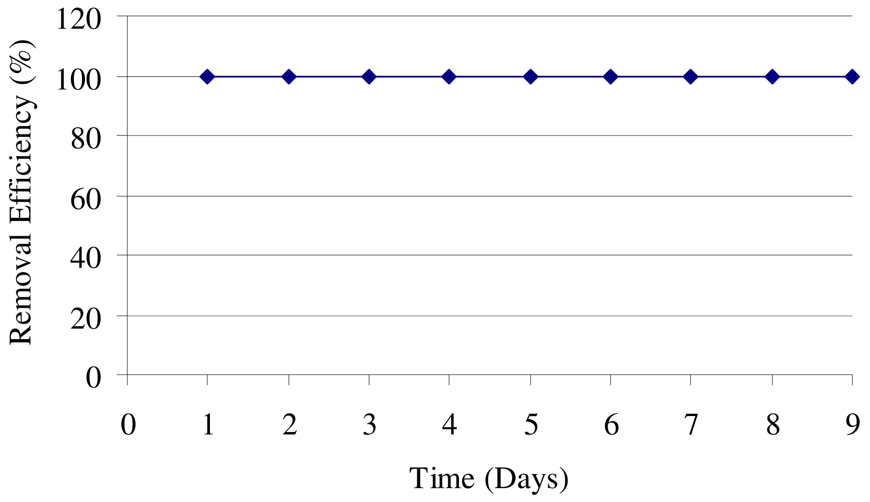

Figure 4.4 Removal Efficiency of COS in the Presence of H_2S for a 1:2 COS: H_2S Ratio

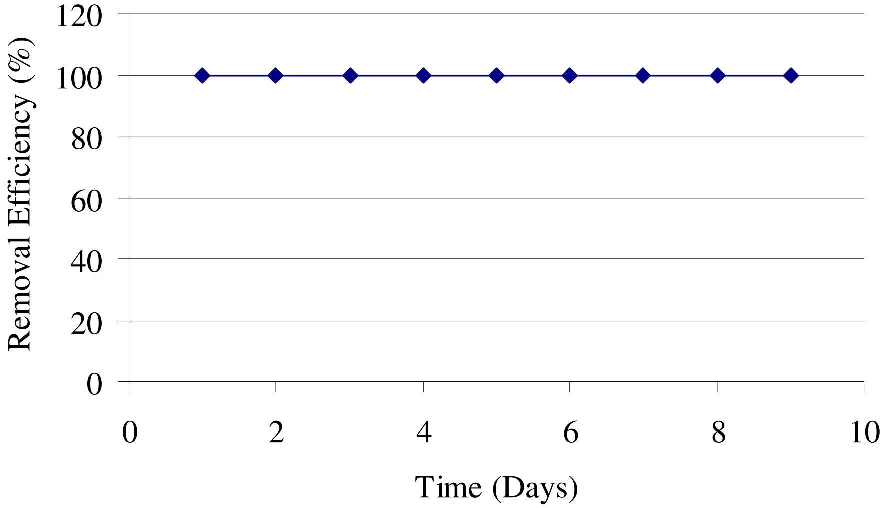

Figure 4.5 Removal Efficiency of H_2S in the Presence of COS for a 1:2 COS: H_2S Ratio

Table 4.7 Removal Efficiency for a 1:6 Ratio of COS to H_2S, Using Compost Biofilter

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		COS	H_2S
05/15/2005 10:00 pm	10.2	0	58	0	93	100	100
05/16/2005 12:00 pm	9.8	0	62	0	92	100	100
05/17/2005 12:00 pm	8.4	0	65	0	92.5	100	100
05/18/2005 7:00pm	11.3	0	65	0	95.6	100	100
05/19/2005 3: 00 pm	12	0	63	0	95.4	100	100
05/20/2005 12:00pm	12	0	55	0	94.2	100	100
05/21/2005 9:00 pm	9.6	0	56	0	95.4	100	100

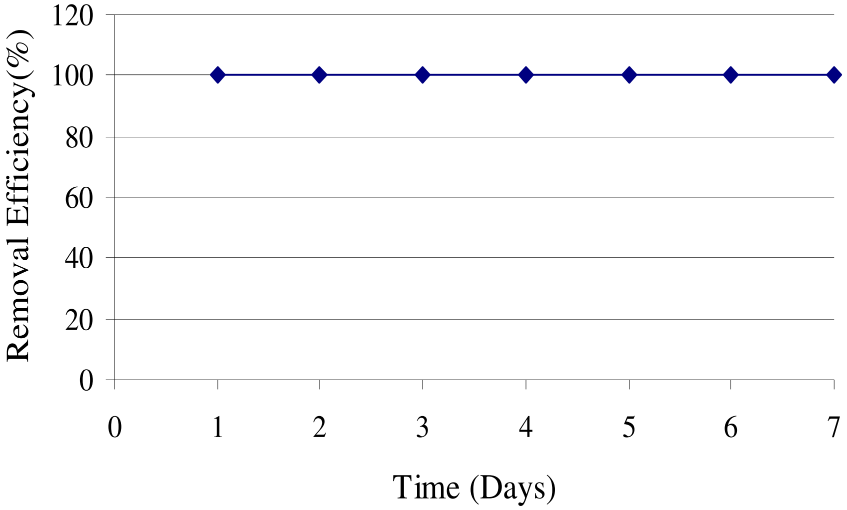

Figure 4.6 Removal Efficiency of COS in the Presence of H_2S for a 1:6 COS: H_2S Ratio

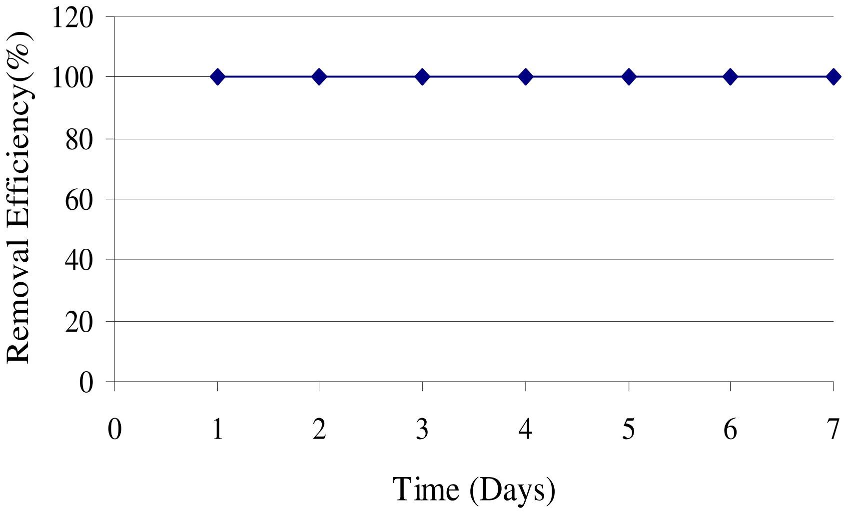

Figure 4.7 Removal Efficiency of H_2S in the Presence of COS for a 1:6 COS: H_2S Ratio

Table 4.8 Removal Efficiency for a 1:20 Ratio of COS to H_2S, Using Compost Biofilter

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		COS	H_2S
11/30/2005 10:00 pm	7.2	0	98	23	91.5	100	100
12/01/2005 1000 pm	6.4	0	95	22	92.3	100	100
12/02/2005 11:00 pm	6.7	0	93	20	93.5	100	100
12/03/2005 7:00pm	6.0	0	105	33	92.7	100	100
12/04/2005 8 :00 pm	6.9	0	103	32	93.5	100	100
12/05/2005 10:00pm	5.4	0	108	34	93.9	100	100
12/06/2005 9:00 pm	6.5	0	110	35.5	94.5	100	100

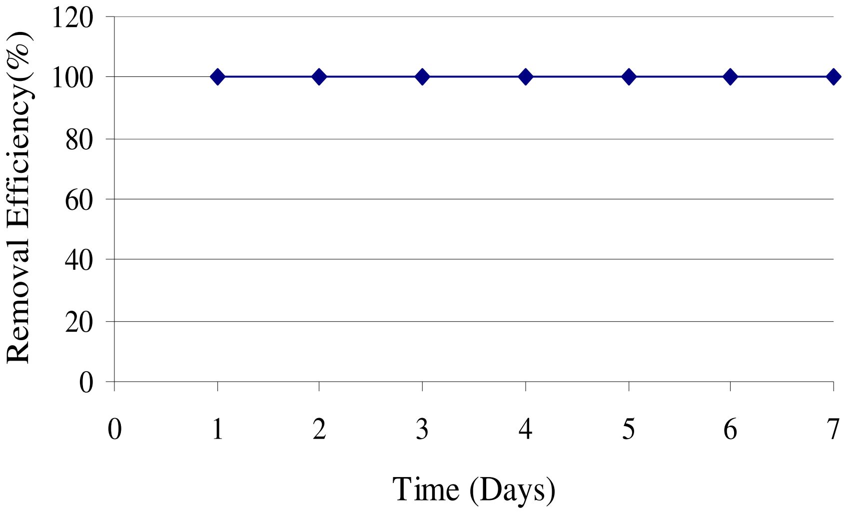

Figure 4.8 Removal Efficiency of COS in the Presence of H_2S for a 1:20 COS: H_2S Ratio with Compost Medium

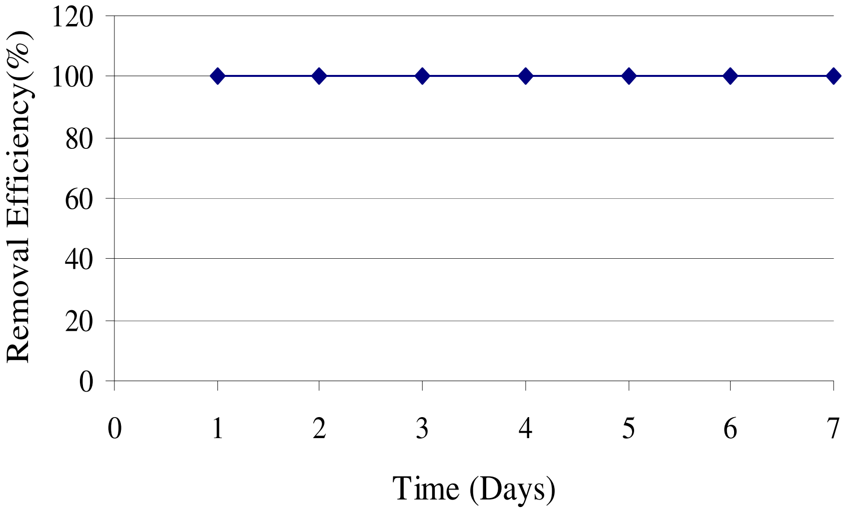

Figure 4.9 Removal Efficiency of H_2S in the Presence of COS for a 1:20 COS: H_2S Ratio using Compost Medium

The averaged results from the runs of 1:20 ratio of COS and H_2S using 80:20 ratio by volume of hardwood chips and compost are summarized in Table 4.9. As can be inferred from the table below, there was no variation in the removal efficiency of COS from 100%. For H_2S, the removal efficiency was less for this media combination. The removal efficiency was better initially compared to the later period, probably because there was complete acclimatization of the microbes to the gas flow during the later period of the run (after 3 days which is usually the stabilization time for H_2S for an EBRT of 146 sec). (Nawal, 2004) The removal rate was, however, constant during the last part of the run. The removal rates for COS and H_2S with time with this media combination are as illustrated in Figure 4.10 and Figure 4.11.

Table 4.9 Removal Efficiency for a 1:20 Ratio of COS to H_2S, Using 80:20 Ratio by Volume of Hard wood Chips and Compost

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		COS	H_2S
11/30/2005 10:00 pm	7.2	0	98	23	91.5	100	76.5
12/01/2005 1000 pm	6.4	0	95	22	92.3	100	76.8
12/02/2005 11:00 pm	6.7	0	93	20	93.5	100	78.0
12/03/2005 7:00pm	6.0	0	105	33	92.7	100	68.6
12/04/2005 8 :00 pm	6.9	0	103	32	93.5	100	68.9
12/05/2005 10:00pm	5.4	0	108	34	93.9	100	68.5
12/06/2005 9:00 pm	6.5	0	110	35.5	94.5	100	67.7

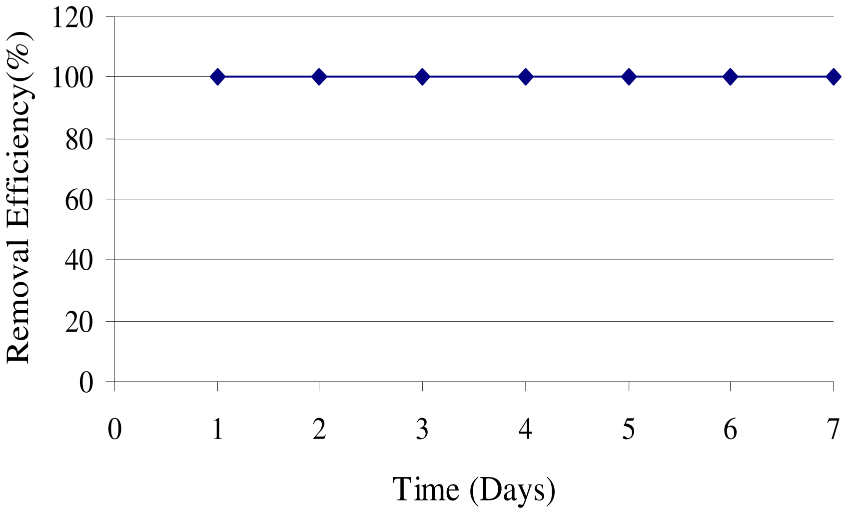

Figure 4.10 Removal Efficiency of COS in the Presence of H_2S for a 1:20 COS: H_2S Ratio, using 80:20 Ratio by Volume of Hard wood Chips and Compost

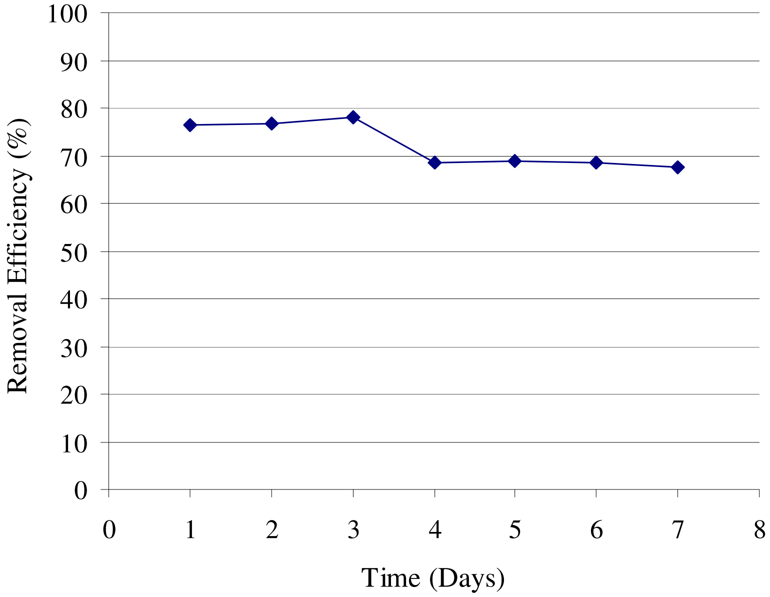

Figure 4.11 Removal Efficiency of H_2S in the Presence of COS for a 1:20 COS: H_2S Ratio, using 80:20 Ratio by Volume of Hard wood Chips and Compost

The loading of both H_2S and COS using compost media is calculated as seen in Tables 4.10, 4.11, 4.12, 4.13, 4.14 and 4.15. Elimination capacity vs. inlet mass loading is graphed in Figures 4.8, 4.9, 4.10, 4.11, 4.12 and 4.13. Due to the 100% removal efficiency, using compost media there was no impact on the elimination capacity due to the presence of H_2S on COS, and vice-versa.

Using 80:20 ratio by volume of hard wood chips and compost, the results for COS and H_2S gas are summarized in Tables 4.13 and 4.14, respectively. As inferred from the tables, there is no impact of the presence of H_2S on COS gas due to 100% removal of COS. However, for H_2S gas there are varied removal rates seen, the elimination capacity was seen to be decreasing over the period of time. The elimination capacities varied in the range of 0.7 g/m^3- hr to 0.97 g/m^3-hr. The elimination capacity vs. inlet mass loading plots for this media combination for COS and H_2S are illustrated in Figure 4.16 and 4.17, respectively.

Table 4.10 Inlet and Outlet COS Loading in the Presence of H_2S in a Compost Biofilter, for a 1:2 COS: H_2S Ratio

Date & Time	COS Concentration		Flow Rate (LPM)		COS Loading (g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
05/04/2005 9:00 pm	27.4	0	1.147	1.121	0.712	0	0.712
05/05/2005 10:00 pm	33	0	1.161	1.131	0.868	0	0.868
05/6/2005 10:00pm	32	0	1.159	1.154	0.840	0	0.840
05/7/2005 9:00 pm	30.8	0	1.183	1.168	0.825	0	0.825

Table 4.10 (Continued)

05/8/2005 10:00 pm	32	0	1.141	1.102	0.827	0	0.827
05/9/2005 11:00 pm	32.5	0	1.161	1.128	0.855	0	0.855
05/10/2005 11:00 pm	29	0	1.158	1.115	0.761	0	0.761
05/11/2005 8:00 pm	33	0	1.183	1.171	0.884	0	0.884
05/12/2005 4:00 pm	28	0	1.152	1.123	0.731	0	0.731

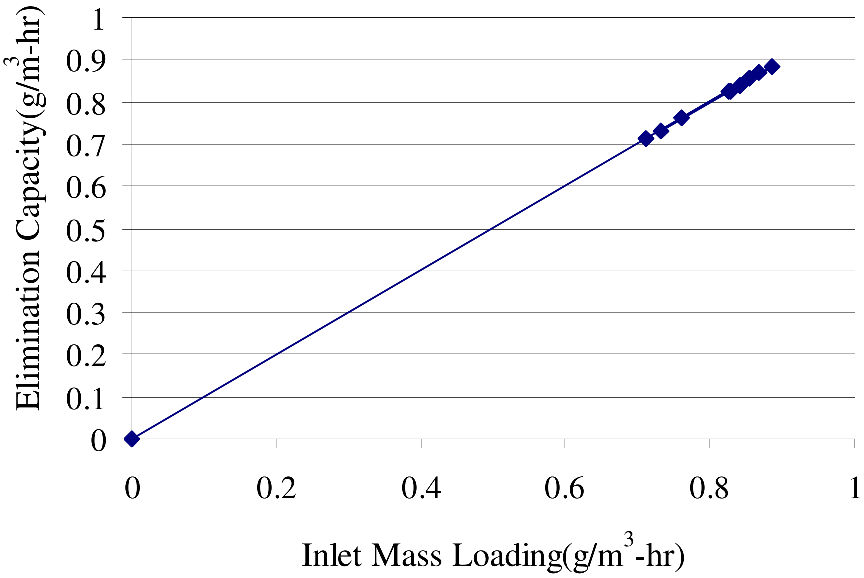

Figure 4.12 Elimination Capacity of COS in the Presence of H_2S for a 1:2 COS:H_2S Ratio using Compost Medium

Table 4.11 Inlet and Outlet H_2S Loading in the Presence of COS in a Compost Biofilter for a 1:2 Ratio of COS:H_2S Ratio

Date & Time	H_2S Concentration		Flow Rate (LPM)		H_2S Loading (g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Inlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
05/04/2005 9:00 pm	56	56	1.147	1.121	0.806	0	0.806
05/05/2005 10:00 pm	59	59	1.161	1.131	0.857	0	0.857
05/05/2005 10:00 pm	59	59	1.161	1.131	0.857	0	0.857
05/6/2005 10:00pm	61	61	1.159	1.154	0.904	0	0.904
05/7/2005 9:00 pm	63	63	1.183	1.168	0.945	0	0.945
05/8/2005 10:00 pm	52	52	1.141	1.102	0.736	0	0.736
05/9/2005 11:00 pm	58	58	1.161	1.128	0.840	0	0.840
05/10/2005 11:00 pm	55	55	1.158	1.115	0.787	0	0.787
05/11/2005 8:00 pm	63	63	1.183	1.171	0.947	0	0.947
05/12/2005 4:00 pm	54	54	1.152	1.123	0.778	0	0.778

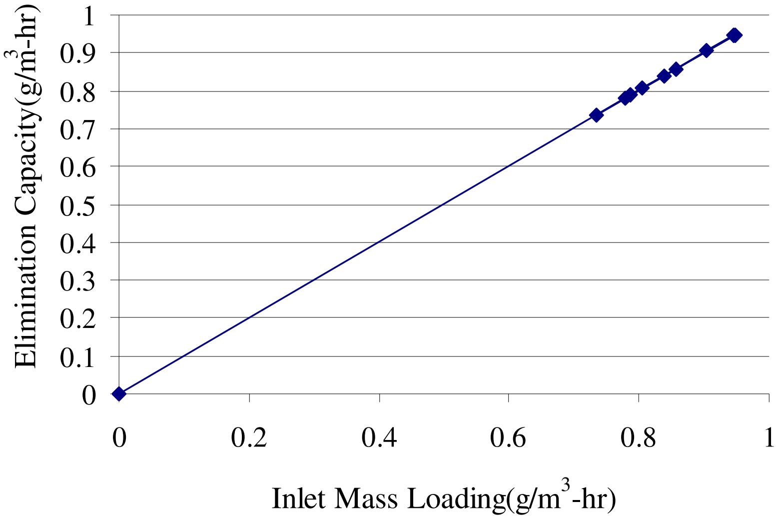

Figure 4.13 Elimination Capacity of H_2S in the Presence of COS for a 1:2 COS: H_2S Ratio using Compost Medium

Table 4.12 Inlet and Outlet COS Loading in the Presence of H_2S in a Compost Biofilter for a 1:6 COS:H_2S Ratio

Date & Time	COS Concentration		Flow Rate		Loading (g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
05/15/2005 10:00 pm	10.2	0	1.427	1.43	0.330	0	0.330
05/16/2005 12:00 pm	9.8	0	1.452	1.403	0.322	0	0.322
05/17/2005 12:00 pm	8.4	0	1.514	1.460	0.288	0	0.288
05/18/2005 7:00pm	11.3	0	1.399	1.37	0.358	0	0.358
05/19/2005 3: 00 pm	12	0	1.365	1.369	0.371	0	0.371
05/20/2005 12:00pm	12	0	1.501	1.450	0.408	0	0.408
05/21/2005 9:00 pm	9.6	0	1.515	1.422	0.329	0	0.329

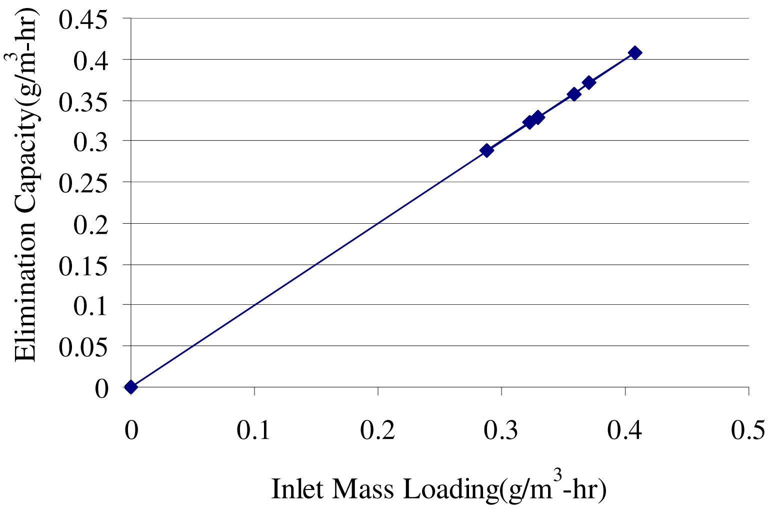

Figure 4.14 Elimination Capacity of COS in the Presence of H_2S for a 1:6 COS:H_2S Ratio using Compost Medium

Table 4.13 Inlet and Outlet H_2S Loading in the Presence of COS in a Compost Biofilter for a 1:6 COS: H_2S Ratio

Date & Time	H_2S Concentration		Flow Rate(LPM)		Loading(g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
05/15/2005 10:00 pm	58	0	1.427	1.43	1.07	0	1.07
05/16/2005 12:00 pm	62	0	1.452	1.403	1.12	0	1.12
05/17/2005 12:00 pm	65	0	1.514	1.460	1.22	0	1.22
05/18/2005 7:00pm	65	0	1.399	1.37	1.14	0	1.14
05/19/2005 3: 00 pm	63	0	1.365	1.369	1.11	0	1.11
05/20/2005 12:00pm	55	0	1.501	1.450	1.02	0	1.02
05/21/2005 9:00 pm	56	0	1.515	1.422	1.02	0	1.02

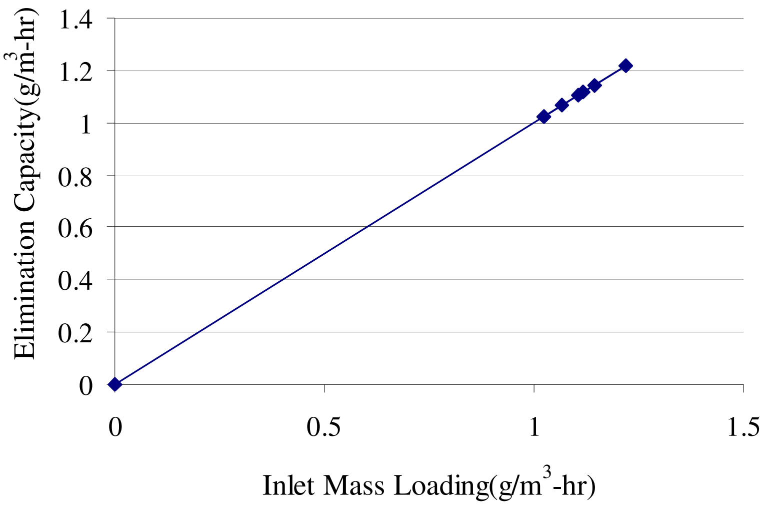

Figure 4.15 Elimination Capacity of H_2S in the Presence of COS for a 1:6 COS:H_2S Ratio using Compost Medium

Table 4.14 Inlet and Outlet COS Loading in the Presence of H_2S, in a Compost Biofilter for a 1:20 COS: H_2S Ratio

Date & Time	COS Concentration		Flow Rate		Loading (g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
11/30/2005 10:00 pm	7.2	0	1.427	1.445	0.13	0	0.13
12/01/2005 1000 pm	6.4	0	1.452	1.424	0.12	0	0.12
12/02/2005 11:00 pm	6.7	0	1.514	1.40	0.13	0	0.13
12/03/2005 7:00pm	6.0	0	1.399	1.435	0.11	0	0.11
12/04/2005 8 :00 pm	6.9	0	1.365	1.449	0.12	0	0.12
12/05/2005 10:00pm	5.4	0	1.501	1.450	0.10	0	0.10
12/06/2005 9:00 pm	6.5	0	1.515	1.467	0.13	0	0.13

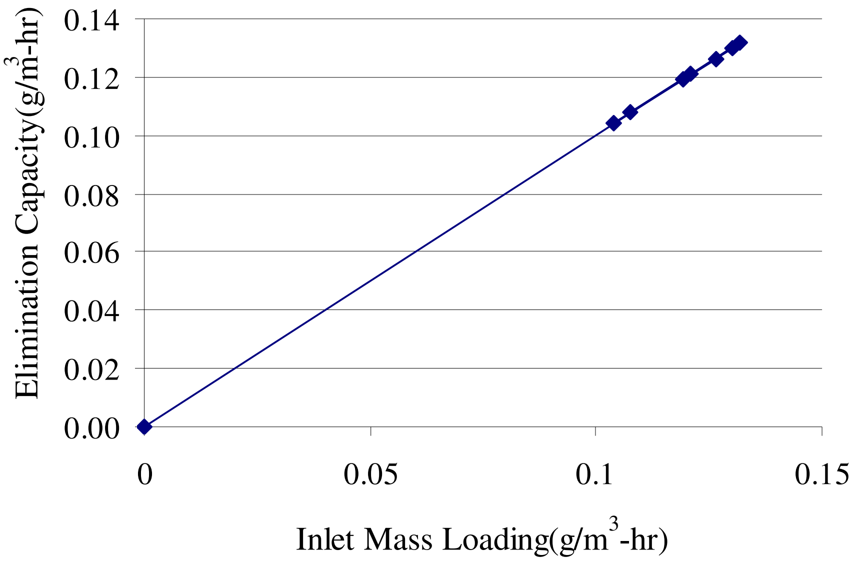

Figure 4.16 Elimination Capacity of COS in the Presence of H_2S in a Compost Biofilter for a 1:20 COS: H_2S Ratio

Table 4.15 Inlet and Outlet H_2S Loading in the Presence of COS in a Compost Biofilter for a 1:20 COS: H_2S Ratio

Date & Time	H_2S Concentration		Flow Rate(LPM)		Loading(g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
11/30/2005 10:00 pm	98	0	1.427	1.445	1.82	0	1.82
12/01/2005 1000 pm	95	0	1.452	1.424	1.74	0	1.74
12/02/2005 11:00 pm	93	0	1.514	1.40	1.67	0	1.67
12/03/2005 7:00pm	105	0	1.399	1.435	1.93	0	1.93
12/04/2005 8 :00 pm	103	0	1.365	1.449	1.92	0	1.92
12/05/2005 10:00pm	108	0	1.501	1.450	2.01	0	2.01
12/06/2005 9:00 pm	110	0	1.515	1.467	2.07	0	2.07

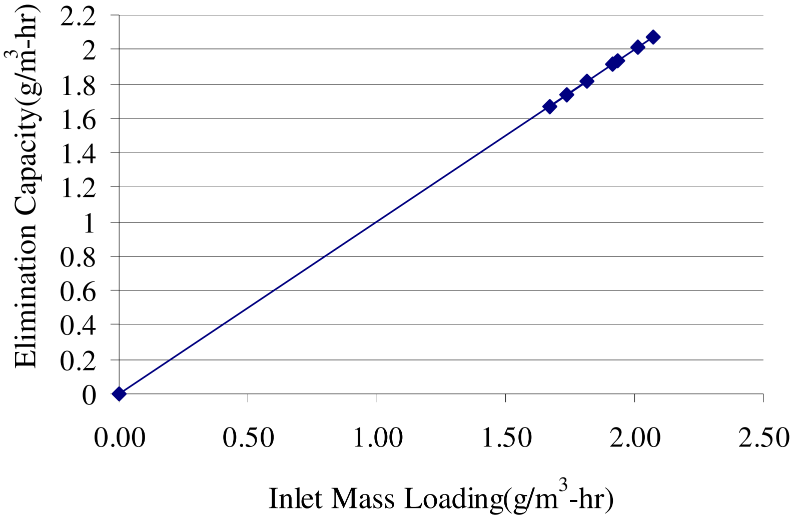

Figure 4.17 Elimination Capacity of H_2S in the Presence of COS for a 1:20 COS:H_2S Ratio using Compost Medium

Table 4.16 Inlet and Outlet COS Loading in the Presence of H_2S, for a 1:20 COS: H_2S Ratio using 80:20 ratio by Volume of Hardwood Chips and Compost

Date & Time	COS Concentration		Flow Rate		Loading (g/m^3-hr)		Elimination Capacity (g/m^3-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
11/30/2005 10:00 pm	7.2	0	1.427	1.445	0.13	0	0.13
12/01/2005 1000 pm	6.4	0	1.452	1.424	0.12	0	0.12
12/02/2005 11:00 pm	6.7	0	1.514	1.40	0.13	0	0.13
12/03/2005 7:00pm	6.0	0	1.399	1.435	0.11	0	0.11
12/04/2005 8 :00 pm	6.9	0	1.365	1.449	0.12	0	0.12
12/05/2005 10:00pm	5.4	0	1.501	1.450	0.10	0	0.10
12/06/2005 9:00 pm	6.5	0	1.515	1.467	0.13	0	0.13

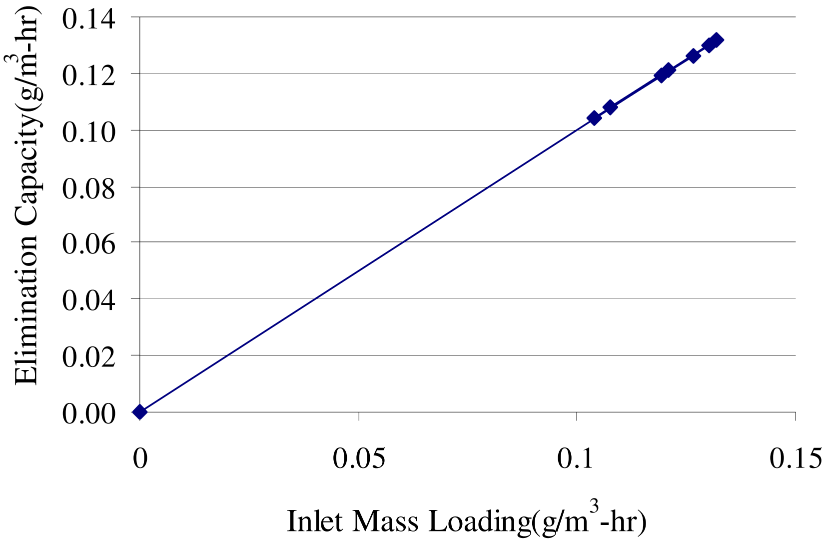

Figure 4.18 Elimination Capacity of COS in the Presence of H_2S for a 1:20 COS:H_2S Ratio using 80:20 ratio by Volume of Hardwood Chips and Compost

Table 4.17 Inlet and Outlet H_2S Loading in the Presence of COS, for a 1:20 COS: H_2S Ratio, using 80:20 ratio by Volume of Hardwood Chips and Compost

Date & Time	H_2S Concentration		Flow Rate(LPM)		Loading(g/m³-hr)		Elimination Capacity (g/m³-hr)
	Inlet (ppm)	Outlet (ppm)	Air + COS	Air + H_2S	Inlet	Outlet	
11/30/2005 10:00 pm	98	23	1.427	1.445	1.82	0.85	0.97
12/01/2005 1000 pm	95	22	1.452	1.424	1.74	0.81	0.93
12/02/2005 11:00 pm	93	20	1.514	1.40	1.67	0.75	0.92
12/03/2005 7:00pm	105	33	1.399	1.435	1.93	1.20	0.73
12/04/2005 8 :00 pm	103	32	1.365	1.449	1.92	1.16	0.76
12/05/2005 10:00pm	108	34	1.501	1.450	2.01	1.29	0.72
12/06/2005 9:00 pm	110	35.5	1.515	1.467	2.07	1.36	0.71

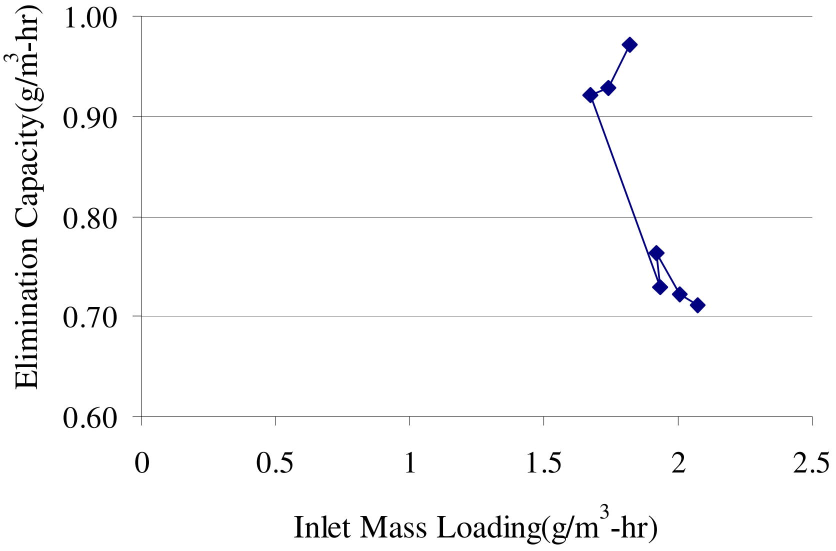

Figure 4.19 Elimination Capacity of H_2S in the Presence of COS for a 1:20 COS:H_2S Ratio using 80:20 ratio by Volume of Hardwood Chips and Compost

4.6 Impact of the Operational Parameters

4.6.1 Relative Humidity

As seen from Table 4.5 and 4.6, it is evident that the relative humidity was being maintained in the range of 90-95 % for the combination of H_2S and COS. This was because each one of the gases was provided with an individual humidification chamber. The optimum relative humidity for a biofiltration process is 100%; thus, the relative humidity that was being maintained during the experiment was good. Hence, enough moisture was being supplied to the microbes for biodegradation of the pollutant gases. This might have been one of the reasons for good removal efficiency.

4.6.2 Moisture Content

As described in the methods chapter, the moisture content of the compost was measured during the COS critical mass loading runs and the averaged results are as shown in the Table 4.11. The range of moisture content suitable for good degradation by the microbes is 40-80 %. The optimum moisture content seen during the process was in the range of 50-55 %. As the moisture content is a very crucial parameter for biofiltration, maintenance of such moisture content also led to good degradation of COS and H_2S. For the run involving 20:1 ratio of H_2S and COS, the compost media used was very aged (over 1 year old). Hence the moisture content was very less at about 20%. Also for hard wood chips and compost combination, because the hardwood chips were absolutely dry. Running the experiment for sustainable period of time, probably would increase the moisture content of the medium.

Table 4.18 Moisture Content for Compost Media

Date	Medium	Gas	Moisture Content (%)
06/28/2005	Compost	COS	54.7
09/30/2005	Compost	COS	52.9
10/20/2005	Compost	COS	50.3
12/05/2005	Compost	COS + H_2S	21
12/05/2005	Compost + Hard wood chips	COS + H_2S	20

4.6.3 pH

The pH for the media used in the experiments was determined using a pH meter by collecting three samples from the top, middle and bottom of the media bed of each column. The pH for the compost media from critical loading measurement runs was measured as 6.5. This is a near neutral pH, hence indicating less deposition of sulfides.

The pH values from the 5:100 ratio by ppm of COS to H_2S combination runs for different media samples are as listed in Table 4.12.

Table 4.19 Average pH values for Different Biofilter Media

Media	**Position of the Sample**	**pH**
Compost	Top	6.2
	Middle	5.8
	Bottom	6.2
Hard wood Chips + Compost	Top	6.9
	Middle	6.9
	Bottom	6.3

It can be inferred from the above tables that for the compost, the media is comparatively acidic in the middle of the column, while for the mixture of compost and hard wood chips the pH is comparatively lower at the bottom. This indicates that acidic sulfides deposit at this position of the column for each media.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Conclusions from the Present Study

The purpose of this research was to study whether the presence of H_2S would have an impact on the elimination capacity and removal rates of COS. The inlet concentrations of H_2S and COS gases being treated in the study ranged from 5 - 30 ppm of COS and 30- 150 ppm of H_2S. These concentrations fall in the range of typical emissions from a wastewater treatment plants; other industrial emissions may contain higher concentrations of these gases. The removal efficiency of H_2S and COS was found to be 100% when compost was used as the media, clearly indicating that the degradation of one gas was not affected by the presence of the other.

The other objective of the study which was to measure the critical loading of COS using compost media could not be achieved due to constraints on the range of COS concentration that could be measured with the IQ-350 sensor, which was calibrated for a maximum of 50 ppm COS concentration. However it was found that for media heights lower than 3 inches, the gas residence time ranged from 10-30 sec, too low for any gas degradation to occur. The results from the study indicate that the critical loading for COS does not occur till a mass loading of 9 g/m^3- hr.

The other findings of the study were 1) 100% removal efficiency for a 60 ppm concentration of H_2S using compost as the media, 2) maintenance of the crucial operating parameters like relative humidity near 95 % and moisture content of the media at 50-55% provided good operating conditions.

5.2 Recommendations to Improve Present Research

- To test higher concentrations of COS to measure the critical loading of the gas.
- To recalibrate IQ-350 COS sensor for a higher concentration than 50 ppm.
- To resolve problems due to channeling and compaction seen when using compost media.

5.3 Recommendations for Future Research

- To run the experiments for a considerable period of time, to achieve sustainable elimination capacity and to observe for variations in pH.
- To study the removal rates of H_2S and COS sulfides by feeding higher loads of gases to the biofilter.
- To test the removal efficiency for more combinations of reduced sulfides.

APPENDIX A

RAW DATA FROM LABORATORY MEASUREMENTS

Table A.1 Experimental Runs to Measure the Critical Loading of COS

Date & Time	Bed Height (inches)	Bed Volume (Liters)	Inlet (ppm)	Air Flow rate (Lpm)	EBRT (sec)	Mass Loading (g/m^3-hr)	Outlet (ppm)	Elimination Capacity (g/m^3-hr)
06/05/05 11:00 am	15	3.91	31	1.042	225	1.216	0	1.216
06/06/05 11:00 am	15	3.91	33	1.046	224	1.299	0	1.299
06/07/05 10:00 am	15	3.91	32	1.046	224	1.26	0	1.26
06/09/05 10:00 am	10	2.61	27	1.026	152	1.56	0	1.56
06/10/05 11:00 am	10	2.61	28	1.031	151	1.63	0	1.63

Table A.1- Continued

Date & Time	Bed Height (inches)	Bed Volume (Liters)	Inlet (ppm)	Air Flow rate (Lpm)	EBRT (sec)	Mass Loading (g/m^3-hr)	Outlet (ppm)	Elimination Capacity (g/m^3-hr)
06/11/05 10:00 am	10	2.61	28	1.036	151	1.64	0	1.64
06/28/05 2:00 pm	7.5	1.96	33	1.056	111	2.617	0	2.617
06/29/05 3:00 pm	7.5	1.96	31.5	1.042	113	2.47	0	2.47
06/30/05 3:00 pm	7.5	1.96	32	1.049	112	2.52	0	2.52
07/02/05 10:00 am	6	1.56	29	1.039	90	2.84	0	2.84

Table A.1- Continued

Date & Time	Bed Height (inches)	Bed Volume (Liters)	Inlet (ppm)	Air Flow rate (Lpm)	EBRT (sec)	Mass Loading (g/m^3-hr)	Outlet (ppm)	Elimination Capacity (g/m^3-hr)
07/03/05 11:00 am	6	1.56	30.6	1.036	90	2.991	0	2.991
07/04/05 11:00 am	6	1.56	31.2	1.039	90	3.06	0	3.06
09/29/05 2:00 pm	6	1.56	45	1.041	90	4.42	0	4.42
09/30/2005 2:00 pm	6	1.56	45.2	1.011	92.5	4.32	0	4.32
10/1/05 3:00 pm	6	1.56	46	1.041	90	4.52	0	4.52

Table A.1- Continued

Date & Time	Bed Height (inches)	Bed Volume (Liters)	Inlet (ppm)	Air Flow rate (Lpm)	EBRT (sec)	Mass Loading $(g/m^3\text{-hr})$	Outlet (ppm)	Elimination Capacity $(g/m^3\text{-hr})$
10/3/05 3:00 pm	5	1.30	46	1.056	74	5.5	0	5.5
10/4/05 3:00 pm	5	1.30	46.2	1.026	76	5.37	0	5.37
10/5/05 3:00 pm	5	1.30	45.7	1.079	72	5.58	0	5.58
11/15/05 12:00 am	4	1.04	45	1.068	58	6.8	0	6.8
11/15/05 11:30 am	4	1.04	45.2	0.995	63	6.37	0	6.37

Table A.1- Continued

Date & Time	Bed Height (inches)	Bed Volume (Liters)	Inlet (ppm)	Air Flow rate (Lpm)	EBRT (sec)	Mass Loading (g/m^3-hr)	Outlet (ppm)	Elimination Capacity (g/m^3-hr)
11/16/05 8:00 am	4	1.04	45.2	1.023	61	6.54	0	6.54
11/21/05 3:00 pm	3	0.78	45.4	1.041	45	8.91	0	8.91
11/21/05 9:00 pm	3	0.78	45.0	1.046	45	8.88	0	8.88
11/22/05 7:00 am	3	0.78	45.0	1.056	44	8.97	0	8.97
11/22/05 5:00 pm	2	0.52	46.1	1.036	30	13.52	42.9	0.938

Table A.1- Continued

Date & Time	Bed Height (inches)	Bed Volume (Liters)	Inlet (ppm)	Air Flow rate (Lpm)	EBRT (sec)	Mass Loading (g/m^3-hr)	Outlet (ppm)	Elimination Capacity (g/m^3-hr)
11/22/05 9:00 pm	2	0.52	45.5	1.069	29	13.76	43.1	0.738
11/23/05 8:00 am	2	0.52	45.5	1.072	29	13.8	43.1	0.728
11/24/05 8:00 am	1	0.261	46.7	1.102	14	29.02	45.2	0.93
11/24/05 3:00 pm	1	0.261	46.7	1.096	14	28.9	45.3	0.868
11/24/05 10:00 pm	1	0.261	46.7	1.082	14	28.61	45.5	0.735

Table A.2 Daily Experimental Results for Different Combinations of H_2S and COS Using Compost as the Medium

(a) 1: 2 Ratio of COS to H_2S, Air Flow Rate - 2 LPM

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		Air + COS	Air + H_2S	COS	H_2S
05/04/2005 9:00 pm	27.4	0	56	0	91	1.147	1.121	100	100
05/05/2005 10:00 pm	33	0	59	0	88	1.161	1.131	100	100
05/6/2005 10:00pm	32	0	61	0	94.2	1.159	1.154	100	100
05/7/2005 9:00 pm	30.8	0	63	0	96.7	1.183	1.168	100	100
05/8/2005 10:00 pm	32	0	52	0	91.3	1.141	1.102	100	100
05/9/2005 11:00 pm	32.5	0	58	0	93.3	1.161	1.128	100	100
05/10/2005 11:00 pm	29	0	55	0	95.8	1.158	1.115	100	100
05/11/2005 8:00 pm	33	0	63	0	95.1	1.183	1.171	100	100
05/12/2005 4:00 pm	28	0	54	0	95.1	1.152	1.123	100	100

Table A.2- Continued

(b) 1: 6 Ratio of COS to H_2S, Air Flow Rate - 3 LPM

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		Air + COS	Air + H_2S	COS	H_2S
05/15/2005 10:00 pm	10.2	0	58	0	93	1.427	1.43	100	100
05/16/2005 12:00 pm	9.8	0	62	0	92	1.452	1.403	100	100
05/17/2005 12:00 pm	8.4	0	65	0	92.5	1.514	1.460	100	100
05/18/2005 7:00pm	11.3	0	65	0	95.6	1.399	1.37	100	100
05/19/2005 3: 00 pm	12	0	63	0	95.4	1.365	1.369	100	100
05/20/2005 12:00pm	12	0	55	0	94.2	1.501	1.450	100	100
05/21/2005 9:00 pm	9.6	0	56	0	95.4	1.515	1.422	100	100

Table A.2- Continued

(c) 1: 20 Ratio of COS to H_2S

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		Air + COS	Air + H_2S	COS	H_2S
11/30/2005 10:00 pm	7.2	0	58	0	91.5	1.427	1.445	100	100
12/01/2005 1000 pm	6.4	0	62	0	92.3	1.452	1.424	100	100
12/02/2005 11:00 pm	6.7	0	65	0	93.5	1.514	1.40	100	100
12/03/2005 7:00pm	6.0	0	65	0	92.7	1.399	1.435	100	100
12/04/2005 8 :00 pm	6.9	0	63	0	93.5	1.365	1.449	100	100
12/05/2005 10:00pm	5.4	0	55	0	93.9	1.501	1.450	100	100
12/06/2005 9:00 pm	6.5	0	56	0	94.5	1.515	1.467	100	100

Table A.3 Daily Experimental Results for Combination of H_2S and COS Using Mixture of Compost and Hardwood Chips as the Medium

(c) 80:20 Ratio by Volume of Hardwood Chips and Compost 1: 20 Ratio of COS to H_2S

Date & Time	COS Concentration		H_2S Concentration		Humidity (%)	Flow Rate (LPM)		Removal Efficiency (%)	
	Inlet (ppm)	Outlet (ppm)	Inlet (ppm)	Outlet (ppm)		Air + COS	Air + H_2S	COS	H_2S
11/30/2005 10:00 pm	7.2	0	58	23	91.5	1.427	1.445	100	78
12/01/2005 1000 pm	6.4	0	62	22	92.3	1.452	1.424	100	75
12/02/2005 11:00 pm	6.7	0	65	20	93.5	1.514	1.40	100	80
12/03/2005 7:00pm	6.0	0	65	33	92.7	1.399	1.435	100	69
12/04/2005 8 :00 pm	6.9	0	63	32	93.5	1.365	1.449	100	69.5
12/05/2005 10:00pm	5.4	0	55	34	93.9	1.501	1.450	100	68
12/06/2005 9:00 pm	6.5	0	56	35.5	94.5	1.515	1.467	100	67.7

APPENDIX B

SAMPLE CALCULATIONS

Sample Calculations

Data from experiment on 03/29/05

Inlet concentration of H_2S is 62 ppm

Outlet concentration of H_2S is 0 ppm

Hence Removal efficiency = $\frac{62-0}{62}\times 100\% = 100\%$

Inlet Mass loading of H_2S = $\frac{(40.9\times 62\times 34)\times Q\times 60}{V\times 10^6}$

Flow rate of the gas and air through the column = 1.093 LPM

Volume of the bed = $\frac{\prod \text{ x } (2.25'')^2 \text{ x } 25''}{4 \text{ x } 12^3}$ = 0.229 ft^3 =6.5 L

Inlet Mass loading of H_2S = $\frac{(40.9\times 62\times 34)\mu g/m^3\times 1.093 LPM\times 60\min/hr}{6.5L\times 10^6\mu g/g}$

= 0.870 g/m^3-hr

Outlet Mass loading of H_2S = $\frac{(40.9\times 0\times 34)\mu g/m^3\times 1.093 LPM\times 60\min/hr}{6.5L\times 10^6\mu g/g}$

= 0.0 g/m^3-hr

Hence elimination capacity = (0.870 – 0) g/m^3-hr = 0.870 g/m^3-hr

REFERENCES

Adler, S. F. “Biofiltration- A Primer” CEP- April 2001, Vol. 97, No.4 Section: Environmental Protection (/www.aiche.org/cep/).

Aizpuru, A., Malhautier, L., Roux, J.C., & Fanlo, J.L. (2001). “ Biofiltration of a Mixture of Volatile Organice Emissions”. *Journal of the Air & Waste Management Association, 51,* 1662-1670.

Auria, R., Aycaguer, A.C., & Devinny, J.S. (1998). “Influence of Water Content on Degradation Rates for Ethanol in Biofiltration”. *Journal of the Air & Waste Management Association, 48, 65-70.*

Bo, I.D., Langenhove, H.V., Heyman, J. (2002). “Removal of Dimethyl Sulfide from Waste Air in a Membrane Bioreactor.” *Desalination 148:* 281-287.

Boyette, R. A., and Eliot Epstein. (April, 2000). “Design and Operating Experiences from the Biofilters,” *Proceedings of the Odor and VOC Emissions Conference, Cincinnati, Ohio.*

Chou, M.S., and Chen, W.H. (1997). “Screening of Biofiltering Material for VOC Treatment” *Journal of the Air & Waste Management Association, 78, 674-681.*

Chou, M.S., and Wu, S.L., (1996) "Bioconversion of Dimethylformamide in Biofilters" *Journal of the Air & Waste Management association, 48, 306-318.*

Cooper, C. David., & Alley, F.C. (2002). *Air Pollution Control: A Design Approach*. Illinois: Waveland Press Inc.

Delhomenie, M.C., Bibeau, L., Gendron, J., Brzezinski, R., & Heitz, M. (2003). "Degradation of Toluene, Xylene, and Trimethylbenzene Vapors by Biofiltration: A Comparision". *Journal of the Air & Waste Management Association, 53: 217-226.*

Deshusses, M.A. (1994). "Biodegradation of mixtures of Ketone Vapours in Biofilters for the Treatment of Waste Air," *Swiss Federal Institute of Technology Zurich.*

Deshusses, M.A., & Johnson, C.T. (2000). "Development and Validation of a Simple Protocol to Rapidly Determine the Performance of Biofilters for VOC Treatment." *Environmental Science & Technology, 34(3), 461-467.*

Devinny, J.S., Chitwood, D.E., & Reynolds, Jr., F.E. (1998) "Two Stage Biofiltration for Wastewater Treatment Off-gases". *Proceedings of the91 st Annual Meeting of the Air & Waste Management Association.*

Devinny, J.S., Deshusses M.A., & Webster T.S. (1999). "*Biofiltration for Air Pollution Control"*. New York: Lewis Publisher.

Easter, C. C., Okonak C. C., (2000) "Biofilter Systems for Odor Control in Wastewater Treatment Applications: An Overview of Issues and Options". *Odors and VOŒmissions Conference Cincinnati, Ohio*

Hartikainen, T., Ruuskanen, J., & Martikainen, P.J. (2001). “Carbon Disulfide and Hydrogen Removal with a Peat Biofilter,” *Journal of the Air & Waste Management Association, 51, 387-392.*

J. Environmental Science and Health, Part A: Environmental Science Engineering.Toxic Hazardous Substance Control. Vol. 32A, No. 7, pp. 2027-2055. (1997)

Jones K., Martinez A., Maroo, K., Deshpande, S. & Banuelos, C. (2002). “Biofilter Applications for Air Emission Control using Natural Media: Media Stability and Design Optimization”. *Water Environment Federation Odors and Toxic Air Emission Conference Proceedings, 2002.*

Jones, K., Martinez, A., Rizwan, M., & Boswell, J. (2003). “ Evaluation of Sulfur Toxicity and Media Capacity for H_2S Removal in Biofilters Packed with Both Natural and Commercial Media”. *Proceedings of the 96th Annual Meeting of the Air and Waste Management Association, Paper # 69751.*

Kehoe, J.D., Harcus, J., Warren, M.J., Smith, M., Gynp, A. (Aug. 1996). “Acquisition, Review, and Correlation of Odor Literature for the Air & Waste Management Association EE-6 Odour Committee”. University of Windsor.

Kuter, G.A., Harper, J.E., Naylo, L.M., & Gormsen, P.J. (Nov. 1993). “Design, Construction and Operation of Biofilters for Controlling Odors at Composting Facilities,” *Proceedings of the 86th Annual Meeting & Exhibition of the Air & Waste Management Association,* Denver, Colorado.

Lee, E. Y., Cho, K. S., Han, H. D., and Ryu, H.W. (2002) “Hydrogen Sulfide Effects on Ammonia Removal by a Biofilter Seeded with Earthworm Casts,” *Journal of Environmental Quality, 31,*1781-1788.

Leson, G. and Winer, A.M. (1997). “Biofiltration: An Innovative Air Pollution Control Technology for VOC Emissions”. *Journal of the Air and Waste Management Association* 41(8): 1045-1054.

Nawal, C.P., (2004). *Removal of Carbonyl Sulfide using Biofiltration*, Thesis presented for the partial fulfillment of the Masters Degree Course Requirement at University of Texas at Arlington, Dept. of Civil & Environmental Engineering.

Quigley, C., & Easter, C., (2003). “Biotechnology for Odor Control: A Design and Performance Review”. *Texas Odor & Corrosion Control Speciality Conference and Expo.*

Rosenberk, S.R., (2004). *Removal of Carbonyl Sulfide using Carbon Adsorption*, Thesis presented for the partial fulfillment of the Masters Degree Course Requirement at University of Texas at Arlington, Dept. of Civil & Environmental Engineering.

Ruokojarvi, A., Ruuskanen, J., Martikainen, P.J., & Olkkonen, M. (2001). “Oxidation of Gas Mixtures Containing Dimethyl Sulfide, Hydrogen Sulfide, and Methanethiol Using a Two-Stage Biotrickling Filter”. *Journal of the Air & Waste Management Association, 51,* 11-16.

Sarina, J.E., Micheal, S.S., Beatriz, C.G. (1999). “Characterization of Compost Biofiltration Media,” *Journal of the Air & Waste Management association, 49, 784-793.*

Schmidt, D., Janni, K., Nicolai, R. (March 2004). “Biofilter Design Information”, Biosystems and Agricultural Engineering Update, Dept. of Biosystems and Agricultural Engineering, University of Minnesota Extension Service.

Singleton, B., Milligan, D., & Blanchard, J. (1995). “ An Effective Sequential Biofiltration Design Applied to Control Odors Caused by Reduced Sulfur Compounds at a Wet Well.”

Smet, E., Chasaya, G., Langenhove, H.V., & Verstraete, W. (1996). “The Effect of Inoculation and Type of Carrier material Used in the Biofiltration of Methyl Sulfides.” *Applied Microbial Biotechnology, 45,* 293-298.

Sorenson, H.W. (2003). “Organice Media Biofiltration Performance”. *Texas Odor & Corrosion Control Speciality Conference and Expo.*

Stewart, C. W., Barton, A. T., “High VOC Loadings in Biofilters - Petroleum and Industrial Applications,” *Presented at the Gas Research Institute-* Gas Industry Air Toxics Conference.

The Chemical Engineers Research Page; “Trickling Biofilters for Hydrogen Sulfide Control”. http://www.chemresources.com/biofilters.html (05/04).

Wani, A.H., Branion, R., & Lau, A.K. (2001). “Biofiltration Using Compost and Hog Fuel as a Means of Removing Reduced Sulfur Gases from Air Emissions”. *Pulp & Paper Canada, T(122-127), 27-32.*

Williams, T.O. and Miller, F.C. (1992a). “Odor Control Using Biofilters Part 1”. *Biocycle* (October):73-77.

.

BIOGRAPHICAL INFORMATION

The author, Divya Rani Garrepalli, was born on August 15, 1982 in Hyderabad, Andhra Pradesh, India to Shri Madhukar Rao Garrepalli and Madhumathi Garrepalli. She completed her high school education from Nalanda Jr. College, Hyderabad, India in 1999. Her inclination to science encouraged her to take up Chemical Engineering for her bachelors and she earned her Bachelor of Technology degree from Chaitanya Bharathi Institute of Technology, Hyderabad, Andhra Pradesh, India, in May 2003.

Driven to pursue her higher education in environmental engineering not only because of her strong conviction of its importance in today's world, but also due to her personal association with the acutely high air pollution levels in her city, Divya Garrepalli had started her M.S. (Master of Science) degree in Civil Engineering at The University of Texas at Arlington, Arlington, Texas in August 2003.

During her masters', she was appointed as the Graduate Research Assistant of Dr. Melanie L. Sattler. Her thesis/research was based on biofiltration and dealt with measuring elimination capacities and removal rates of carbonyl sulfide in conjunction with hydrogen sulfide. A technical paper, based on her research work, has been selected for presentation at the Air and Waste Management Association's 99 th annual conference to be conducted in June 2006. She is the acting secretary to AWMA student chapter at

UTA. She is also working as a Research Intern with the Texas Transportation Institute, where her duties involve wide application of Geographical Information Systems.