Utilizing Biofiltration to Control Air Emissions for Sustainable *Cannabis* Production

---

A Major Qualifying Project Report

Submitted to the faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the Degree of Bachelor of Science in Chemical Engineering with an Environmental Concentration

Submitted by:
Evy Case
Ceana Fuller
Emily Gonzales

Submitted to:
Stephen J. Kmiotek, Ph.D, P.E., Department of Chemical Engineering
John A. Bergendahl, Ph.D., P.E., Department of Civil and Environmental Engineering

April 22, 2022

Abstract

The goal of this project was to assess the potential of using biofiltration to remove terpenes from the exhaust of a *Cannabis* cultivation facility. This is an environmental concern with increased output of VOCs and poses a nuisance of odor. Following the construction of a bench-scale compost biofilter, experiments were conducted to determine the overall effectiveness of removal of isolated terpinolene. From experimentation the removal efficiency of each column was calculated to be an average of 64.5% and 67.3%, respectively. Recommendations were proposed to promote continuation of experimentation as well as to suggest further areas of research to design a full-scale model.

Acknowledgements

We would like to thank our advisors, Professor John Bergendahl and Professor Stephen Kmiotek, for their help, guidance, and enthusiasm throughout this project. We would also like to thank our mentor, Ian Anderson, for his assistance in designing and building our project. Finally, we would like to thank students Sydney Gagne and Alyssa Whitley for their assistance in the full-scale design of this report.

Executive Summary

One of the major social and environmental concerns associated with *Cannabis* growth, cultivation, and extraction is the odor emissions caused by terpenes. Terpenes are volatile organic compounds (VOCs) that contribute to the fine particles in the atmosphere and the formation of the ozone. The *Cannabis* industry is on the rise with the legalization of recreational marijuana in 18 states, leading to an increased number of emissions from the industry. Odor concerns have led to many local governments putting legislation in place that bans smoking in public places or certain indoor buildings (ICMA, 2018). Massachusetts is one of the states that has passed regulations stating that if a complaint is interfering with the ability of a person to enjoy their residential property or business then it is considered a nuisance (Bureau of Waste Prevention, 2003).

Volatile organic compounds (VOCs) have a high vapor pressure and low solubility in water. These VOCs readily vaporize in most indoor or outdoor conditions and pose an immediate threat to air quality and environmental health. High concentrations of VOCs at the tropospheric level have been proven to contribute to health conditions including nausea, liver damage, respiratory irritation, and cancer (Helmer, 2019). VOCs associated with *Cannabis* production can be classified as anthropogenic volatile organic compounds (AVOCs) or biogenic volatile organic compounds (BVOCs). In the *Cannabis* industry, AVOCs are sourced from *Cannabis* oil extraction, where solvents such as butane are used and emitted throughout the process (Samburoya *et al.,2019*). Compared to AVOCs, BVOCs are more chemically reactive and therefore are more likely to react in the lower troposphere, producing ozone and secondary air pollutants (Gu *et al.*, 2021). BVOCs in the *Cannabis* industry are emitted by the *Cannabis* plant throughout its life as terpenes. Terpenes are a diverse group of naturally occurring compounds that are primarily found in plants such as tea, thyme, *Cannabis*, and citrus fruits (Sommano, 2020).

The United States Environmental Protection Agency (EPA) established the Clean Air Act in 1970. The goal of this act is to protect and improve the quality of the nation's air and ozone by looking at six main pollutants, which are carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM2.5 and PM10), and sulfur dioxide (SO_2) (Environmental Protection Agency[5]). These pollutants are regulated by two standards, primary and secondary. Primary standards look at the effects pollutants have on the health of people who are considered sensitive populations and secondary standards look at the effects the pollutants have on the public welfare: visibility, crops, animals, and other buildings (Environmental Protection Agency[3]).

Biofiltration is a sustainable and effective solution to control the release of these pollutants, especially VOCs. This air purification method involves the use of a medium fixed with microorganisms that break down the pollutants present in the air stream (Devinny *et al.*,1999). While biofilters are relatively simple in design, the underlying mechanisms responsible for their operation are very complex. The biofiltration process begins with diffusion and advection from the air phase to the water phase of the biofilter media (Devinny *et al.*,1999). Following this mass transfer process, biotransformation and biodegradation convert the contaminants into carbon dioxide, water, metabolic by-products, and additional biomass (Devinny *et al.*,1999). For a biofilter to be effective there are multiple properties of the system that need to be monitored. These

properties include the concentration of contaminant being treated, the type of biofilter media, the water content of the media, the air stream flow rate, the air stream humidity, and the temperature and pH of both the media, and air stream. It is also important to consider the reactor configuration, computer systems, and the economics of the biofiltration system. To determine if a biofilter is the best option for the *Cannabis* industry, it is important to understand alternative options including incineration, membrane separation, activated carbon adsorption, and more.

This project involved modeling a bench-scale biofiltration system which was constructed and experimented on with two different media mixes. The media in biofilter #1 was made from 4 parts compost, 1 part wood chips, and 2 parts activated carbon. Biofilter #2 was made without the activated carbon, consisting of 4 parts of compost to 1 part of wood chips. It was hypothesized that adding activated carbon to the biofilter media would increase contaminant adsorption, resulting in an increased removal efficiency for biofilter #1. To properly model the exhaust from a *Cannabis* facility, a waste air stream containing an isolated terpene called terpinolene was created. Terpinolene is a common terpene found in many strains of *Cannabis sativa* and is known for its pine and citrusy aroma. The contaminated air stream was run through each biofilter, and the outlet stream concentration was compared to the initial stream concentration.

Experimentation was performed utilizing gas chromatography (GC) analysis. GC analysis provided terpinolene concentrations for the contaminated and treated air streams. The data obtained was used to calculate the elimination capacity and removal efficiency of the biofilters. After the data was collected from the GC analysis, the removal efficiency for both media mixes were calculated to be around 60% efficient on average, proving that biofiltration systems can be effective in removing terpenes from the waste stream of *Cannabis* facilities. Biofilter #1 had an average removal efficiency of 64.5%, and Biofilter #2 had an average removal efficiency of 67.3%. These results do not support the hypothesis of increased adsorption in the biofilter integrating activated carbon in the media. Using the information and data collected from the bench-scale model, a full-scale design of a biofiltration system was created. An alternate full-scale design of an activated carbon filtration system was also created to compare with the biofiltration system.

Table of Contents

Table of Figures

Table of Tables

1.0 Introduction and Background

1.1 Introduction

One of the major social and environmental concerns associated with *Cannabis* growth and commercial cultivation is the odor emissions caused by terpenes. Terpenes, which are emitted throughout a *Cannabis* plant's lifecycle, are considered volatile organic compounds (VOCs), which contribute to the formation of ozone and fine particles in the atmosphere. The extraction process of *Cannabis* is also known to release VOCs, which contributes to odor and pollution found in the industry. Because of this, all growing facilities in the state of Massachusetts are required to be indoors; however, the exhaust that exits these facilities still possess a high level of pollutants. This has been leading to environmental concerns regarding these growing facilities as a point source of pollution.

The regulations of air emissions from *Cannabis* growing facilities vary state by state; however, many states exempt agriculture from emission laws. While some facilities may be exempt from the standards, it does not change that the growing and extraction processes of *Cannabis* contributes to a decreased air quality. For *Cannabis* cultivation facilities to avoid controversy, it is important that standards on air emissions are clearly set, followed, and regulated. This will require the facilities to implement air pollution control technology to reduce or eliminate contaminants from the exhausted air.

1.2 Air Pollution

1.2.1 Volatile Organic Compounds

Volatile organic compounds (VOCs) are compounds that have a high vapor pressure and low solubility in water. The Environmental Protection Agency (EPA) defines VOCs as:

> *"any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participates in atmospheric photochemical reactions, except those designated by EPA as having negligible photochemical reactivity"* (Environmental Protection Agency[6]).

The high vapor pressures associated with VOCs allow the compounds to evaporate under normal atmospheric temperatures and pressures (Environmental Protection Agency[6]). This means that VOCs readily vaporize into the air in most indoor and outdoor conditions. VOCs pose an immediate threat to air quality and environmental health due to their photochemical reactivity. The VOCs react with constituents in the atmosphere such as nitrogen oxides (NO_x) and hydroxyl radicals (HO) in addition with sunlight to produce tropospheric ozone (O_3) and secondary pollutants such as formaldehyde, acetaldehyde, and acrolein (Li *et al.*, 2016). The majority of these pollutants are formed in the lower troposphere, which can lead to harmful effects on human health and the environment (Samburova *et al.*, 2019). Additionally, VOCs can produce ozone-degrading nitrate aerosols in the stratosphere, which can deplete stratospheric ozone layer and contribute to climate change (Helmer, 2019).

While stratospheric ozone protects the Earth from the Sun's UV radiation, tropospheric ozone is a major greenhouse gas and air pollutant that poses a hazard to human and environmental health (CCAC, 2015). As one of the major constituents in urban smog, tropospheric ozone can worsen health conditions such as bronchitis, asthma, emphysema and cause permanent lung damage to humans and other wildlife (CCAC, 2015). High concentrations of VOCs at the tropospheric level have additionally been proven to contribute to health conditions including nausea, liver damage, respiratory irritation, and cancer (Helmer, 2019). It is estimated that tropospheric ozone is responsible for one million premature deaths per year, with children, the elderly, and people with lung or cardiovascular diseases being the most at-risk (CCAC, 2015).

VOCs associated with *Cannabis* production can be classified as anthropogenic or biogenic VOCs. Anthropogenic VOCs (AVOCs) are VOCs emitted from human activity (Gu *et al.*, 2021). In the *Cannabis* industry, AVOCs are sourced from *Cannabis* oil extraction, where solvents such as butane are used and emitted throughout the process (Samburova *et al.*, 2019). One study found high concentrations of butane in *Cannabis* oil extraction facilities, ranging from 1,080 - 43,000 micrograms per cubic meter (Samburova *et al.*, 2019). Biogenic VOCs (BVOCs) are VOCs emitted from terrestrial ecosystems (Gu *et al.*, 2021). BVOCs from the *Cannabis* industry are emitted by the *Cannabis* plant throughout its life as terpenes. The quantity of terpenes released from a *Cannabis* plant varies depending on the stain of *Cannabis*, the stage of its life, and the growing conditions such as temperature and humidity. BVOCs are more chemically reactive than AVOCs; therefore, they are more likely to react in the lower troposphere to produce ozone and secondary air pollutants (Gu *et al.*, 2021). The study mentioned previously found that one adult *Cannabis* plant can produce approximately 2.6 grams of tropospheric ozone per day (Samburova *et al.*, 2019).

1.2.2 Air Pollution Laws

Air quality in the United States is regulated by the U.S. Environmental Protection Agency (Environmental Protection Agency[3]). Initially created in 1970, the EPA established the Clean Air Act with the goal of protecting and improving the quality of the nation’s air and the ozone (Environmental Protection Agency[3]). This act requires the EPA to set standards for six main pollutants, creating the National Ambient Air Quality Standards (NAAQS). The six main pollutants of concern are carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM2.5 and PM10), and sulfur dioxide (SO_2) (Environmental Protection Agency[5]). These pollutants are regulated by two standards, primary and secondary. Primary standards look at the effects pollutants have on the health of people who are considered sensitive populations. This includes children, elderly, asthmatics, and others deemed at risk of health. Secondary standards look at the effects the pollutants have on the public welfare: visibility, crops, animals, and other buildings (Environmental Protection Agency[3]). Table 1 displays the six main pollutants with the NAAQS limits along with the type of standard, the time, and the form.

Table 1. NAAQS Pollutant Regulations (Environmental Protection Agency[5])

Pollutant	Primary/Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO)	Primary	8 hours	9 ppm	Not to be exceeded more than once per year
		1 hour	35 ppm	

Lead (Pb)	Primary and Secondary	Rolling 3-month average	0.15 $\mu g/m^3$	Not to be exceeded
Nitrogen Dioxide (NO_2)	Primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	Primary and Secondary	1 year	53 ppb	Annual Mean
Ozone (O_2)	Primary and Secondary	8 hours	0.070 ppm	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particle Pollution ($PM_{2.5}$)	Primary	1 year	12.0 $\mu g/m^3$	Annual mean, averaged over 3 years
	Secondary	1 year	15.0 $\mu g/m^3$	Annual mean, averaged over 3 years
	Primary and Secondary	24 hours	35 $\mu g/m^3$	98th percentile, averaged over 3 years
Particle Pollution (PM_{10})	Primary and Secondary	24 hours	150 $\mu g/m^3$	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide (SO_2)	Primary	1 hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	Secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

The EPA created the National Volatile Organic Compound Emission Standards which sets regulations for the level of VOCs in selected consumer products such as insecticides, oven cleaners, air fresheners, and many more. These VOC emissions can contribute to high levels of ozone that could potentially violate the NAAQS.

1.3 The *Cannabis* Industry

Since the legalization of recreational marijuana in 18 states, the *Cannabis* industry has been growing exponentially. This growth will lead to an increased number of emissions that the industry produces. As the *Cannabis* industry continues to expand, it is important to understand the potential effects of its production. It is crucial for *Cannabis* facilities to have a method in place to help limit the emission of harmful VOCs into the atmosphere.

1.3.1 Terpenes

Terpenes, also referred to as terpenoids, are a diverse group of naturally occurring compounds that are primarily found in plants. The most common plant sources of terpenes are tea, thyme, *Cannabis*, and citrus fruits (Sommano, 2020). Terpenes are known to have many medicinal benefits, including anti-inflammatory and antioxidant properties. Specifically in *Cannabis*, terpenes are responsible for the aromatic characteristics, and enhance the therapeutic benefits of the plant. There are two main types of terpenes are typically found in *Cannabis* plants: monoterpenes and sesquiterpenes (Cox-Georgian, 2019). Some *Cannabis* monoterpenes include α-pinene, β-pinene, limonene, terpinolene, and β-myrcene and the main *Cannabis* sesquiterpenes are β-caryophyllene and α-humulene (Cox-Georgian, 2019).

Although there are many studies that showcase the benefits of terpenes, there are also negative environmental impacts regarding terpenes and air emissions. Terpenes are considered biogenic volatile organic compounds (BVOCs) and are released from *Cannabis* plants throughout its lifecycle. As mentioned previously, when mixed with nitrogen oxides and UV radiation from sunlight, terpenes create tropospheric ozone, which has been proven to cause adverse health and environmental impacts (CCAC, 2015). Additionally, terpenes form ozone-degrading nitrate aerosols in the stratosphere, which can deplete the protective ozone layer and contribute to climate change (Helmer, 2019).

Cannabis growing and extraction facilities are typically located in urban areas that have high concentrations of nitrogen oxides in the surrounding air (Samburova *et al.*, 2019). This makes *Cannabis* growing and extraction facilities a point source of emission for VOCs and their subsequent reaction products. One study found that measured concentrations of BVOCs inside growing facilities ranged from 110 - 5,500 micrograms per cubic meter (Samburova *et al.*, 2019).

1.3.2 Impacts of *Cannabis* Legalization

Although *Cannabis* is not federally legal in the United States, the industry has been growing due to individual states legalizing *Cannabis* for medical and/or recreational purposes. As of 2021, 36 states and 4 territories allow the medical use of *Cannabis* products; of those 18 states and 2 territories have legislation in place for recreational use (NCSL, 2022). With this rapid industrial growth and no guidance from the federal government, these states and territories are responsible for the economic, safety, and environmental concerns associated with the *Cannabis* industry.

Current federal laws require *Cannabis* sales to be a cash-based industry, which could affect local governments. If there is an increase in paper bills, local governments may need to increase security to protect the facilities, as well as purchase cash-counting machines (ICMA, 2018). To counter this issue, local governments can set their own fees or taxes on *Cannabis* businesses for various reasons. Another concern of cash-based industries is that they can attract criminal activities (ICMA, 2018). Some precautionary measures can be taken to prevent such activities, including security systems, background checks on employees, and proper lighting around the building

(ICMA, 2018). There are some beliefs that federally legalizing *Cannabis* will cause illegal growers to conform to new laws and regulations.

The *Cannabis* extraction process poses a safety hazard because volatile solvents are used. These solvents should only be used in regulated environments with the correct equipment (ICMA, 2018). Individuals may attempt the process in settings that are not regulated such as their own homes, which could lead to fires and explosions that could cause harm to surrounding buildings in a neighborhood.

A major concern of many individuals is the odor associated with growing and consuming *Cannabis*. These concerns have prompted many local governments to put legislation in place that bans smoking in public places and/or certain indoor buildings (ICMA, 2018). Not all states have regulations concerning odors, specifically related to *Cannabis*. Massachusetts is one of the states that has passed regulations for general odor complaints (Bureau of Waste Prevention, 2003). These regulations state that if a complaint is interfering with the ability of a person to enjoy their residential property and/or business then it is considered a nuisance (Bureau of Waste Prevention, 2003). If the source of the odor is a business that has the necessary papers to be operating, it is taken into consideration when determining if the odor is a nuisance. If the individuals responsible for the odor comply with the officials responding to the report, the offenders are left with a warning. Most areas' local officials will respond to odor complaints and try to assist in the situation, but they may not necessarily have any regulations or law to abide by (Bureau of Waste Prevention, 2003).

1.3.2.1 Case Study: Carpinteria, California

Located in Santa Barbara County, California, Carpinteria is a city bordered by the Pacific Ocean with a population of 13,500 residents (U.S. Census Bureau, 2019). Area's north and northwest of Carpinteria have a relatively large population of greenhouses which were primarily used for the cut flower industry prior to the legalization of recreational marijuana in California (Local Impacts of Commercial *Cannabis*, 2019). As the popularity of the cut flower industry dwindled, unoccupied greenhouses became prime real estate for *Cannabis* cultivation. Over multiple years, the number of *Cannabis* cultivation facilities have been increasing in the County, shown as green dots on the map in Figure 1 below. Santa Barbara County acted quickly to establish regulations on *Cannabis* cultivation in 2016 by proposing the *Cannabis* Land Use Ordinance and Licensing Program, referred to as the Project for short (Local Impacts, 2019). The Project regulates all commercial *Cannabis* cultivation, which includes protecting the environment, and the quality of life of the population by addressing public concerns on health, safety, and welfare of the community regarding the *Cannabis* industry (County of Santa Barbara, 2017).

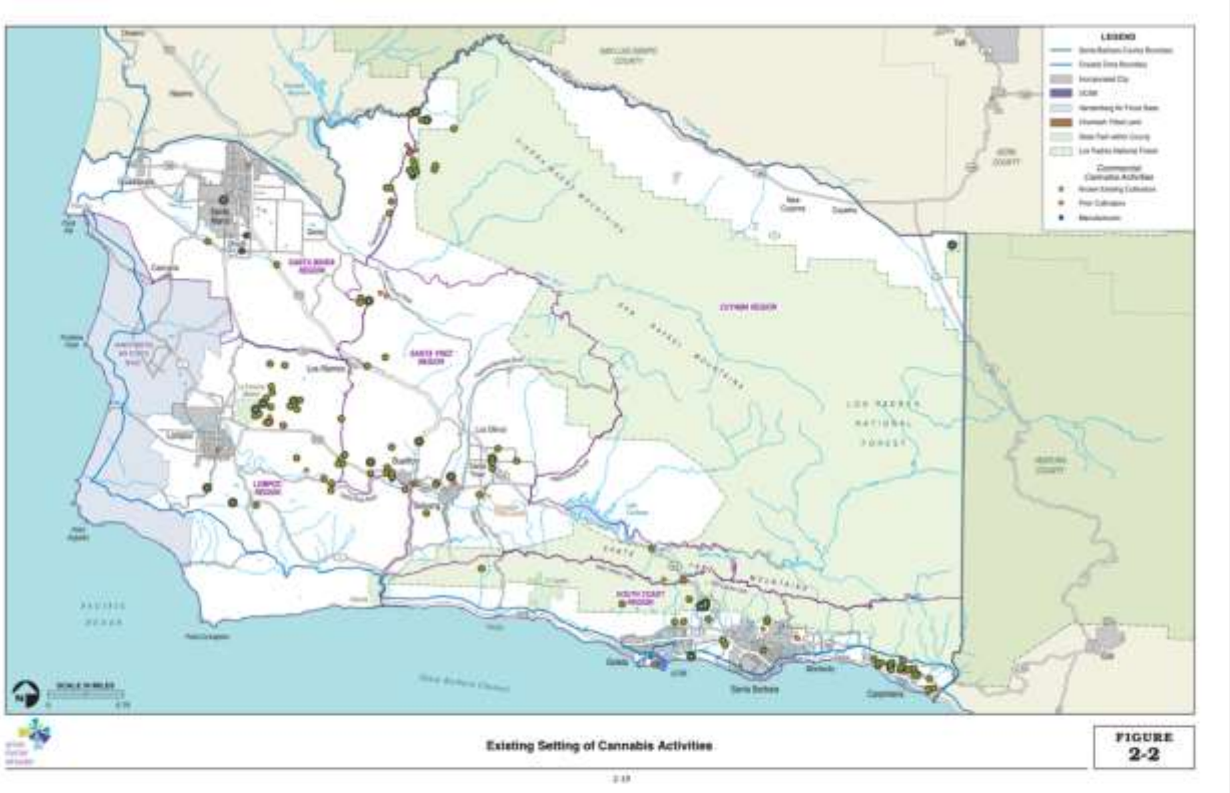

Figure 1. Existing Settling of Cannabis Activities

A main finding of this Project was addressing public concern of odor and air quality in areas surrounding *Cannabis* cultivation facilities. Typically, commercial agricultural operations are not monitored for odor complaints under the County's Right to Farm Ordinance (County of Santa Barbara, 2017). However, due to the amount of public concern, odor emitted from commercial *Cannabis* facilities has been classified as a public nuisance and thus unlawful (County of Santa Barbara). To mitigate odor, the Project requires facilities to have a "buffer zone" of at least 600 feet from areas of sensitive receptors including schools, daycares, and youth centers (County of Santa Barbara, 2017). Additionally, facilities must adopt an Odor Abatement Plan (OAP) for facilities to follow and report to the Planning and Development Department. The OAP is intended to reduce nuisance odors in residentially zoned areas and keep odors confined to the property boundaries of the facilities (County of Santa Barbara, 2017). The requirements for a *Cannabis* facility's OAP can be found in Appendix A.

1.4 Air Pollution Control Technology

Since the establishment of the Clean Air Act, methods of controlling air pollution have greatly increased. In 1970, air pollution had reached an extreme high due to industrial growth happening across the world. Since then, scientists have researched and experimented with different methods to remove various pollutants that are present in the air we breathe. There are numerous technologies that have been developed in the last decade, which will be discussed in this section.

1.4.1 Biofiltration

Biofiltration is a process of air purification where a porous filter medium is fixed with microorganisms that break down pollutants present in an airstream (Devinny *et al.*, 1999). This process is typically utilized to remove biodegradable VOCs which can be present in a variety of industrial processes, including *Cannabis* cultivation. A compost biofilter uses a mixture of porous media with organic material to provide the microbial component. There are many different physical and chemical processes that take place to remove contaminants from the air stream. The microbes attach to the surface of the filter media to create a biofilm which captures the contaminants. The microbes may also be suspended in the water phase surrounding the medium particles (Devinny *et al.*, 1999).

The filter medium must be an inert substance with a large surface area and is typically used to provide some additional nutrient supply to keep the microorganisms living. The properties and characteristics of the filter media are largely what determines the effectiveness of a biofilter. A materials' porosity, degree of compaction, capability to retain water, and ability to host microbial populations is usually considered when deciding which filter media to use (Devinny *et al*, 1999). Common examples of biofilter media include peat, wood chips or compost. Water is another necessary component of the biofilter, as the organic medium must be moist to keep the biological components alive. This is usually incorporated by humidifying the air stream to prevent the media from drying out, or through direct irrigation which may be combined with additional nutrients to increase the biological activity (Devinny *et al*, 1999).

Biofilters are designed based on the airflow and volume of air being treated and the characteristics of the gas stream, such as pollutant concentration. Air streams from the exhaust of a facility could contain particulates, biodegradable compounds or nonbiodegradable compounds at various concentrations.

1.4.2 An Overview of the Theory and Mechanisms Behind Biofiltration

Biofilters transform gaseous contaminants into less harmful by-products through biological activity. While biofilters are relatively simple in design, the underlying mechanisms responsible for their operation are very complex. The process begins with mass transfer of the contaminants from the air to the water phase of the biofilter media through diffusion and advection (Devinny *et al.*, 1999). Next, biotransformation and biodegradation convert the contaminants into carbon dioxide, water, metabolic by-products, and additional biomass (Devinny *et al.*, 1999). Typically, biofilters are either mass transfer or kinetically (biodegradation) limited as the rate-determining step (Kraakman *et al.*, 2011). It is important to thoroughly understand each step in the biofiltration process in order to identify potential points of failure, or potential improvements that can be made to the process.

1.4.2.1 Mass Transfer

The first step in the removal of contaminants from a waste air stream through biofiltration is the mass transfer of contaminants from the gas phase to the aqueous phase of the filter media (Devinny *et al.*, 1999). This process is related to the vapor/liquid partition coefficients, or Henry's law constants (Zhu *et al.*, 2004). From Henry's Law, the equilibrium contaminant concentrations in the water (C_L*) is proportional to the concentration of contaminants in the air (C_G), with Henry's Law constant (H) as the proportionality (Devinny *et al.*, 1999).

$$C_G = HC_L^* \tag{1}$$

This relationship shows that biofilters will work best with species that have smaller Henry's Law constants. Henry's Law describes the partition between the gas and liquid phase of a biofilter if the system has reached equilibrium. In practice, equilibrium reached in a biofilter does not act how it is described in Henry's Law because concentrations of contaminants will vary substantially throughout the filter (Devinny *et al.*, 1999). Instead, the mass transfer can be described using two-film theory. In two-film theory, equilibrium and contaminant movement only occurs at the gas/liquid interface. It can be described using mass transfer coefficients, which are a function of the pollutant properties, the media properties, the biofilter characteristics, and the operating conditions (Kraakman *et al.*, 2011). The overall volumetric mass transfer rate (R) can be described by the following equation:

$$R = k_L a\left(\frac{C_G}{H} - C_L^*\right) \tag{2}$$

where, k_L= the mass transfer rate coefficient for the liquid phase, and a= the interfacial area (Kraakman *et al.*, 2011).

Contaminant movement in a biofilter is commonly modeled in a four-step process shown below in Figure 2.

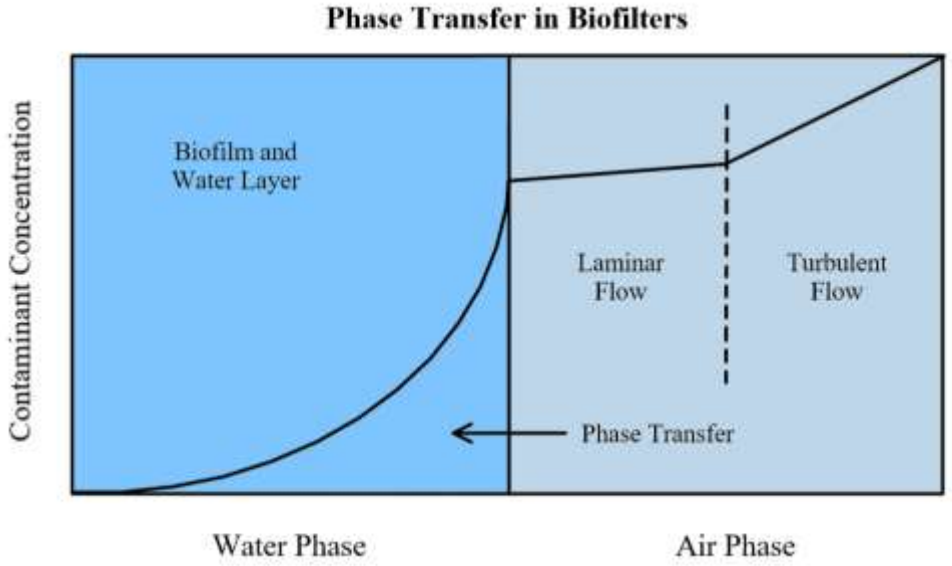

Figure 2 Phase Transfer in Biofilters (adapted from Devinny et al., 1999)

Here, the bulk air flow is turbulent, and the contaminants move by advection and diffusion, also called "convection". Most biofilter models assume that the air within a biofilter can be modeled as "plug-flow" (Devinny and Ramesh, 2005). As the air flow approaches the gas/liquid interface, it becomes laminar and molecular diffusion is the only transport mechanism. The contaminants enter the laminar water phase through the gas/liquid interface, where it is then transferred to the bulk water phase by dissolution, and eventually the biofilm layer or medium by adsorption (Devinny *et al.*, 1999). The adsorption or dissolution process in a biofilter involves several mechanisms which are illustrated below in Figure 3.

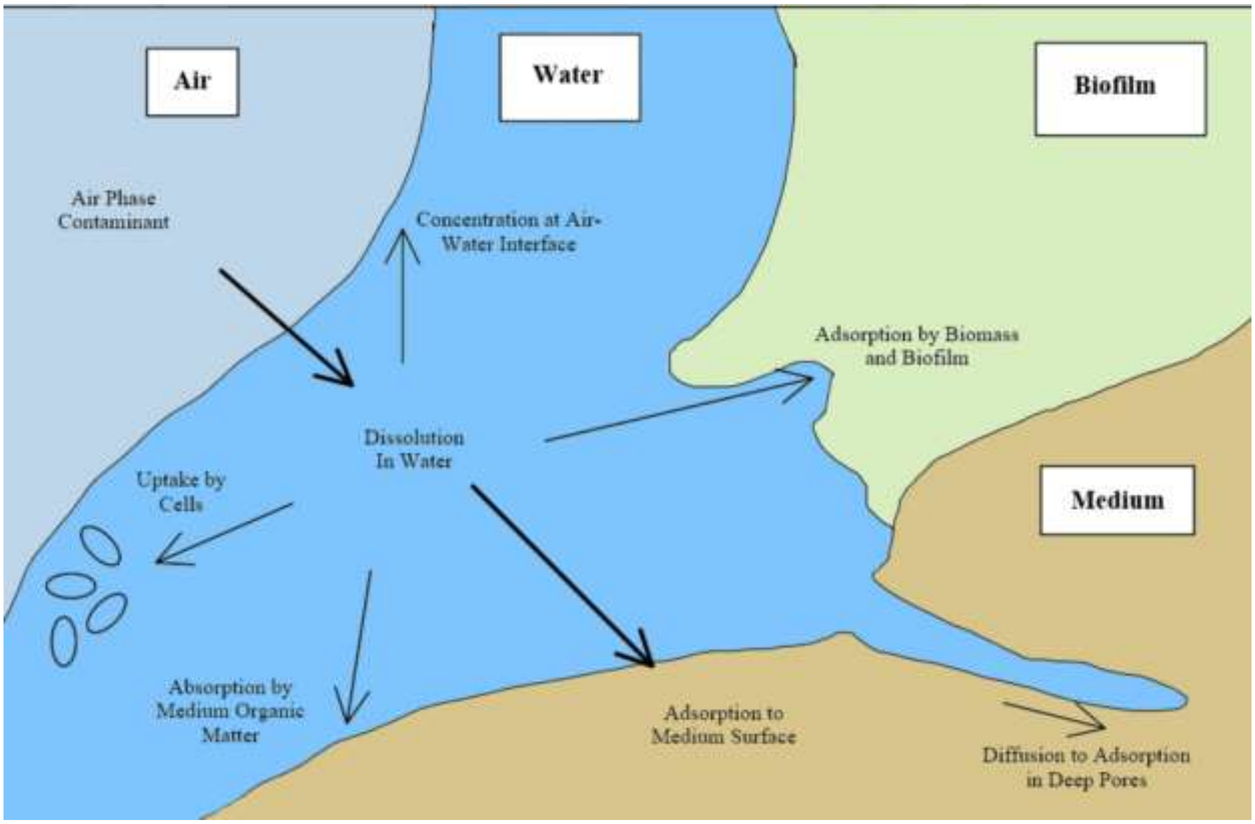

Figure 3 Adsorption and Dissolution in Biofilters (adapted from Devinny et al., 1999)

Here, contaminants can be up taken by cells, adsorbed on the surface of the biofilter medium, adsorbed on the surface of the biomass and biofilm, or collected at the surface of the water (Devinny *et al.*, 1999). Adsorption rates are dependent on the filter media properties, the contaminant properties, and the biofilter operating conditions. A biofilter is designed with a goal to maximize contaminant adsorption so that they are available for biodegradation.

1.4.2.2 Contaminant Biodegradation Kinetics

A key element to biofiltration is the biodegradation (also called biotransformation) of contaminants within the filter media. Biofiltration is set apart from other air filtration methods because of its ability to eliminate contaminants through the biotransformation mechanism. Biotransformation is the process of converting organic chemicals into simpler and safer compounds through microbial activity (Hodzic, 2004). Biofilters utilize biotransformation in the biofilm layer of the water phase. The biofilm layer is a complex microbial ecosystem that behaves similarly to bioremediation in soil or bioactive treatments in wastewater (Devinny et al.,1999). The rate of growth of the biomass is assumed to be modeled by Monod kinetics (Devinny and Ramesh, 2005):

$$\frac{dX}{dt} = \mu X \tag{3}$$

$$\mu = \frac{\mu_{max} C_L}{K_m + C_L} \tag{4}$$

where, X= the biomass density; μ= the growth constant, or specific growth rate; μ_{max}= the maximum value of the growth constant; and K_m= the Monod half-saturation constant. For high concentrations, the growth rate is constant and is assumed to follow zero order kinetics (Devinny and Ramesh, 2005). For low concentrations, the growth rate will be linear with contaminant concentration, and it is assumed first order kinetics (Devinny et al.,1999). In some cases, high concentrations of substrate can inhibit growth, in which case it is modeled by the Haldane equation (Devinny et al.,1999):

$$\mu = \frac{\mu_{max} C_L}{K_m + C_L \left(C_L^2 / K_i \right)} \tag{5}$$

where, K_i= the inhibition constant.

The kinetics for biodegradation in the biofilm layer can differ from what is observed in practice for multiple reasons. One likely reason is that the rate-determining step in the filtration process is the contaminant diffusion into the biofilm. This can occur when concentrations of the contaminant in the air are low and the species do not diffuse rapidly enough to reach the full depth of the biofilm (Devinny et al., 1999). Additionally, nutrients or oxygen may be limited in the filter media. Limited oxygen causes issues because the desired biodegradation process is aerobic (Devinny et al., 1999). When anaerobic conditions occur, the biotransformation process may produce less-desirable by-products that are toxic or odorous, such as methane, which is undesirable and leads to more frequent medium replacement (Tsang et al., 2017).

Contaminants consumed in the biotransformation process are converted into simpler compounds such as water and carbon dioxide and the energy used for this process is converted into heat (Devinny et al., 1999). Additionally, intermediates can form throughout the biotransformation process to create other by-products. Figure 4 below summarizes this process.

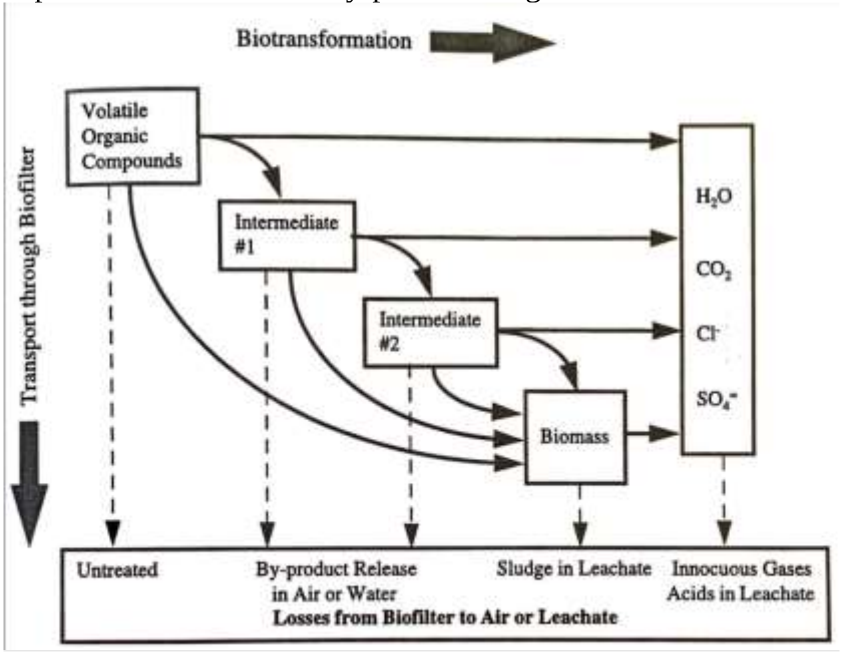

Figure 4 Biotransformation in biofilters (Devinny et al., 1999)

1.4.3 Biofilter Design

There are multiple factors to consider when designing a full-scale biofilter, and these decisions are dependent on what the characteristics of the waste gas are. Bench-scale experimentation is necessary to determine the most effective design and the operating conditions required to achieve a desired removal efficiency. There is an ordered experimental process recommended by Devinny et al. that begins with determining the contaminants and concentrations in the waste stream that requires filtration. The purpose of bench-scale testing is to determine the removal efficiency and elimination capacity of the biofilter. This could involve experimenting with various filter media and methods of nutrient delivery to achieve a desired removal efficiency.

With successful bench-scale testing, modeling programs can be used to predict sizing for a full-scale biofilter. The components required in the design of a full-scale model include air and water distribution systems, reactor media and a reactor, and controls to operate and monitor the system. The following sections will discuss important factors to consider in the process of designing a full-scale model.

1.4.3.1 Biofilter Media

Choosing a filter medium for a biofilter is the key decision in designing a biofilter that will impact the removal performance and operation costs. Filter media are typically categorized as organic, inorganic, or synthetic. Organic media is important to include in a compost biofilter because it provides nutrition to the microorganisms to increase the lifetime of the biofilter, especially during shutdown periods. Inorganic nutrient content is important to consider because elements such as nitrogen, phosphorous, potassium, and sulfates are required in excessive amounts to support the growth of microorganisms (Devinny et al, 1999). Typically, the nutrients are applied in granular form or mixed with water and sprayed over the medium before it’s loaded into the biofilter.

Chemical or inert materials are also commonly used in biofilter media and serve the purpose of preventing the media from compacting over time. Materials such as expanded polystyrene beads, wood chips, clay, perlite, etc. are considered bulking agents because their size provides negative space for air to pass through which minimizes pressure drop in a packed biofilter column. Other inert additives are included to serve the purpose of minimizing concentration changes. Granular activated carbon (GAC) is the most common example of this, as it can readily absorb unwanted materials and functions as a buffer to help control pH. A near neutral pH is considered an optimal condition for biofilter operation, so filter materials with a pH range of 6-8 are typically desired.

Possibly the most important factor to consider when choosing a filter medium is the sorption characteristics and porosity of that material. The ability of a pollutant to adsorb onto a packing material is a function of moisture content, the characteristics of the pollutant, and the nature of the filter medium (Devinny et al, 1999). The packing material should be able to provide a large surface area for sorption and pollutant immobilization. In a homogenous filter bed, the typical porosity for a packing material ranges from 40-80% and their diameter is quite small (1-5 cm). To promote bacterial attachment, the material should not only be porous, but have a rough surface and be hydrophilic.

The last parameters to consider when choosing filter media is the materials cost, lifetime and how it will be disposed of when it reaches its lifetime. Medium replacement is required when the removal performance exceeds the appropriate limit, or when there are no actions to change operating conditions that improve the removal performance. From experience with different filter materials, it is said that packing material should be able to withstand replacement for 2-4 years (Devinny et al, 1999). Disposing of the filter materials is a relatively simple process because none of the waste should be considered hazardous if the pollutants are biodegraded. The compost can be reused through land farming. In some cases, the bulking agent will need to be separated, but this should be a simple task if the packing hasn't been degraded.

1.4.3.2 Water Content

Water content is also an important design consideration as there is a specific water content required to nurture the microorganisms. This is a delicate balance because if the material becomes too saturated, it can use high back pressures and lower retention times if the pores are full of water. It can also be problematic if the media dries out because composts that are initially hydrophilic when wet can become hydrophobic when dry. Due to this, rewetting the compost can be a slow or even impossible process (Swanson, 1997). It is ideal to have a filter media that is about 40-80% water (by weight) when saturated (Devinny et al, 1999).

Controlling the moisture level over time can be a complex process because the appropriate amount of water is necessary to maintain the biofilm and therefore a consistent removal efficiency. To combat this, the waste stream is typically humidified before contacting the filter media. Humidification is typically utilized to keep the waste stream at a uniform temperature for the filter media. This is necessary to prevent condensation or evaporation from occurring because this would disrupt the mass transfer process from water to biofilm. Direct irrigation to the filter bed is also used in current biofilter processes. This can be done in multiple forms depending on the reactor configuration, but irrigation is typically applied through spray nozzles with a combination of water and nutrients.

1.4.3.3 Temperature

Temperature is crucial to keep microorganisms alive, which is why the ideal temperature for biofilter operation is the mesophilic temperature range (20-45ºC) (Devinny et al., 1999). The temperature of the waste gas is used to control the temperature of the filter media. Ideally, the entering gas stream must be uniform and the same temperature as the filter media. Insulation is utilized for outdoor units in areas with cold weather to prevent freezing or dramatic temperature changes. There is not a "perfect" temperature that has been discovered for biofilter operation. This is because phase transfer and sorption are more favorable at lower temperatures within the mesophilic range, while microbial activity significantly increases at temperatures above 35ºC.

1.4.3.4 Reactor Configuration

There are many ways that biofilters have been designed in previous research. One of the simplest configurations is an open bed system, which is usually built into the ground. Air is run underneath the system in a parallel manner along the biofilter so that air is distributed evenly. Air is loaded through the bottom of the system to force it through the medium so that the treated air can be released directly to the atmosphere. This design option typically requires a lot of space and is ideal for low cost and low performance projects such as odor control (Devinny et al, 1999). One disadvantage to this system is that it is sensitive to weather conditions and may require additional equipment to overcome weather constraints.

Another alternative is an enclosed biofilter system, which can be designed in many shapes, but provides better control over the operating parameters. Enclosed beds are typically 1-1.5 meters deep (to avoid compaction of filter material) and air can be sent through either the top or bottom (Devinny et al, 1999). The enclosure limits the effects of weather and makes it easier for the operator to control the temperature, humidity, pH, etc. and therefore increases the favorability for microbial content to live and thrive. Open and closed biofilter designs can be constructed as single beds, in parallel, or in series as a multi-level unit. (Devinny et al, 1999).

1.4.3.5 Computer Systems and Controls

Computer systems are used to monitor the performance parameters of a biofilter, and their price is dependent on the level of monitoring required and the size of the reactor. Manual operation is possible but can become expensive and extremely time consuming with larger reactors. The technology used to monitor biofiltration operations has advanced in the last few decades. The most common control system is a programmable logic controller computer which can measure various performance parameters including moisture content, temperature, air flow rate, relative humidity, pressure drop, and inlet and outlet concentrations (Devinny et al, 1999). The computer stores and displays data which simplifies monitoring changes over time. Some models also include a feedback control program to resolve any issues found. There are various technologies that can be used to take measurements, depending on the desired parameter. These systems require different amounts of electricity and vary in price.

1.4.3.6 Cost and Economic Considerations

One of the most important considerations in designing a biofilter is the budget. When designing a biofilter, the main requirement is that it meets a specified performance level. However, to have a feasible operation, you must also try to minimize capital investment and operating costs. Operating costs are also a factor of sustainability. Operating costs for biofiltration consist of water and energy consumption, monitoring, maintenance, and medium replacement (Devinny et al, 1999).

Capital costs include all equipment required to assemble the system, labor for installation, and any depreciation or interest costs. From existing biofilter systems, we can conclude that open-bed systems offer a simpler design and are therefore less expensive than closed-bed systems (Devinny et al, 1999). This is partially because the material that the reactor vessel is made from can have a significant impact on the capital cost. Purchasing filter media can also contribute to a significant amount of the capital cost, but these costs vary per unit volume. Devinny et al reported that small designs (around 100 ￼) are estimated at $1000-$3000 per ￼ of filter bed, while larger systems (around 3000 ￼) become more cost-effective at $300-$1000 per m^3 of filter bed.

Operating costs vary more between systems based on the design factors, the type of air stream you are working with, and the contaminant being treated. Some contaminants biodegrade easier than others, requiring a lower bed volume, which in turn minimizes the water and electric costs as well as the effort for maintenance and monitoring. Larger systems could be required for larger concentrations and/or more stubborn contaminants. Such systems have higher pressure drops and volumes of bed media. This increases the electrical demand, as well as the water consumption required to maintain the appropriate moisture content.

Media replacement is typically done every 3-7 years with organic media. The operating costs can vary as the media ages because the pressure drop increases as the media settles, which increases electric demand (Devinny et al, 1999). Replacing the filter medium is a complex process and requires a significant amount of time and labor but varies with the size of the reactor. This is one design consideration that can be crucial to simplifying media replacement and offering a substantial opportunity for saving money. Inorganic and/or synthetic mediums may extend the lifetime of the bed media but require a larger capital investment.

Monitoring and maintenance can also become more complicated with larger systems. Designs with automated control systems will require much less interaction with an operator, and would reduce labor costs, but would increase the initial capital investment. Obviously if problems arise, such as air channeling or insufficient removal, this will require a much higher level of maintenance and attention to attend to these problems.

All these trade-offs are what determine the overall financial impact of a biofilter. Therefore, it is necessary to perform a cost-benefit analysis before deciding to construct a full-scale biofilter. A preliminary assessment of the desired location, careful consideration of the system components and cost can prevent the eventual “failure” of a biofilter system.

1.4.4 Biofilter Applications

Biofilters are used to remove pollutants emitted from various industries such as wastewater treatment, pulp and paper, surface coating, food and beverage, and general chemical manufacturing facilities. The various pollutants that are present in these industries are classified as either VOCs or odorous compounds.

In some instances, biofiltration has been effective at removing other compounds such as hydrogen sulfide. One example of this was reported from a wastewater treatment plant in Ontario, Canada, where researchers designed a biofiltration system to treat the exhaust air from the clarifier and pumping station (Husain et al, 2012). The intent of their filtration system was to remove odors and hydrogen sulfide from their exhaust stream. They designed a combination of a biotrickling filter and a biofilter which was intended to replace the existing activated carbon filter. A biotrickling filter is a combination of a biofilter and bioscrubber, where excess water is pumped through the filter media to remove excess sludge, biofilm and/or decomposition products. This process used synthetic filter media and the unit had a total bed volume of 8.75 m^3 to treat a flow rate of 4000 m^3h^{-1}. The researchers had remarkable results with 95% removal of odor with an empty bed residence time (EBRT) of only 8 seconds. This system was designed to flow air horizontally through each chamber and they reported a 75% reduction of their footprint compared to a vertical design which would require a larger bed height (Husain et al, 2012). Figure 5 shows a diagram of their apparatus.

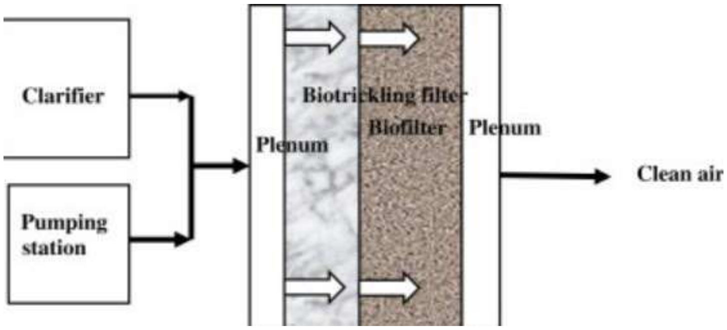

Figure 5. Diagram of Horizontal Biotrickling-Biofilter System (Husain et al, 2012)

Biofiltration can be beneficial in situations like these by reducing operating costs and offering a simple and sustainable method of air pollution control, but it has some limitations that make it unsuitable for other applications. Firstly, biofilters are only capable of removing VOCs and odorous compounds. As we know, these compounds have low Henry's Law constants, meaning that the solubility of the biofilm must be large enough to prevent any reaction limitations to prevent the removal of these contaminants (Shareefdeen, 2020). If there were other pollutants present in the air stream, pretreatment processes would need to be implemented to remove those contaminants prior to biofiltration.

Along with that, biofilter technology is only effective at removing low concentrations of pollutants from an air stream. If the concentration is too high, other methods can be implemented such as incineration or condensation, and the pretreated residue could then be run through a biofilter to completely remove the pollutants. Compared to other methods, biofiltration requires a larger reactor volume because the EBRT for most VOCs in a biofilter is 30 seconds, whereas incineration can remove VOCs from an air stream in less than 2 seconds (Shareefdeen, 2020).

The final limitation to biofiltration is due to the fact that the process is controlled by the biological oxidation process. Since there are living microbial components involved, biofilters require constant monitoring to make sure it is effectively removing contaminants. This also means that the unit should not be shut down for a prolonged period of time because the media may dry out and therefore cause those living organisms to die.

Aside from these limitations, it is becoming more apparent that biofiltration would be an effective method to remove terpenes from the exhaust stream coming from a *Cannabis* facility. Since *Cannabis* facilities are achieving 10-18 air changes per hour, there are smaller concentrations of terpenes in the air, so researchers are confident that biofiltration is an effective method to remove low concentration of terpenes from such large quantities of air (Jordan, n.d.). The biofilter design may require a larger unit to treat high quantities of air, but the trade-off of a higher capital cost with lower operating cost would be worth it in the long run. The biofiltration process is also seen as sustainable because there is no further waste generated during operation, and wastewater can be easily treated or recycled to provide additional nutrients for the microorganisms in the filter media.

1.4.5 Alternatives to Biofiltration

There are many different options that an engineer could consider when designing a system to treat waste gas. The two forms of air emission control are considered source control and secondary control. Source control involves reducing the emissions by targeting the source through substituting a raw material, reduction, or recycling (Devinny et al, 1999). Secondary control consists of treating waste gas after it's produced, and these are the types of treatments that will be discussed in this section.

1.4.5.1 Condensation

In waste gas streams where the contents are highly concentrated and have a high boiling point, a technique of simultaneously compressing and cooling can be used to recover the materials back to their liquid form. This process is only economically feasible for highly concentrated vapor streams and where recycling or recovery can be implemented into the process. This technique often requires additional removal processes, and recycling is impossible if the waste gas is mixed with a pollutant stream (Devinny et al, 1999). While scrubber technology has been used for many years, condensation scrubbing is a more recent discovery in air treatment technology. To utilize a condensation scrubber, the gas stream needs to reach saturation conditions. Once the gas stream reaches saturation, steam is injected resulting in the gas being supersaturated and therefore condensation begins (United States Environmental Protection Agency, 2003).

Condensation, similar to most treatment processes, has advantages and disadvantages to be considered. Advantages include that the process can handle fine particulate matter and flammable or explosive particles with little risk. Many disadvantages with condensation are caused by the waste products being collected wet, in liquid form. This liquid waste, if not disposed of properly, can lead to issues with water pollution. With a liquid waste stream instead of a gaseous waste stream, it is important to consider steps to prevent freezing. This treatment may also cost a company or business more money as disposing the waste can be more expensive than other options. This can be due to condensation resulting in slurry as waste, which requires both solid waste removal and wastewater treatment. (United States Environmental Protection Agency, 2003).

1.4.5.2 Incineration

This widely used and efficient treatment process involves the combustion of waste gas streams at high temperatures. The process consists of oxidizing combustible organic materials by increasing the temperature of the material to reach above its auto-ignition point and maintaining the temperature for long enough so that the only remain products are carbon dioxide and water (Environmental Protection Agency[1]). Incineration is widely used as a secondary treatment technique, but it can become costly when treating pollutants in low concentrations because there is a large amount of fuel required to run the technology. This process is not necessarily sustainable or environmentally friendly because it can produce nitrogen oxides and some dioxins (Devinny et al, 1999). There are two types of incineration: thermal and catalytic.

Thermal incineration requires temperatures ranging from 700-1400°C (Devinny et al, 1999). This type of incineration is most beneficial when the stream is not a variable flow. Highly variable flows result in a lower residence time and overall poor mixing which can affect the combustion process. Poor combustion can result in a decrease in temperature in the chamber which lowers the efficiency of removal. The main disadvantage of thermal incinerators is the high operating costs due to fuel requirements, especially for high flow and low concentration streams (Environmental Protection Agency[1]).

Catalytic incineration requires temperatures ranging from 300-700°C because it involves a catalyst such as platinum, palladium, or rubidium (Devinny et al, 1999). This type of incineration offers many advantages compared to other types of incinerators, specifically thermal. Due to lower operating temperatures, there is little to no insulation required and also reduced fire hazard. A major advantage of catalytic incinerators is the lower fuel requirement and therefore lower operating costs. Although the operating cost is lower for catalytic incinerators, the initial cost is higher. If the catalyst is no longer able to be regenerated, the spent catalyst will need to be disposed of properly (Environmental Protection Agency[2]).

1.4.5.3 Membrane Separation

Membrane systems have a variety of applications for air purification including the transfer of VOCs from the gas phase to a water phase. To begin the process, the gas stream is compressed and condensed before moving through a packed bed containing a membrane that's meant to absorb the contaminant. Compression involves high pressures ranging from 310-1400 kPa because a higher-pressure differential is required to drive the membrane separation process (Devinny et al, 1999). Once the mixture is compressed, it can be processed through a condenser to recover organic vapors and then the remaining air stream passes across the surface of a porous hydrophobic membrane. Materials used for membrane separation are typically polyethylene or polypropylene. The pores of the membrane contain water and the differential pressure allows the organic vapors to transfer through the membrane where they attach to the water molecules (Devinny et al, 1999). The result of this process yields a permeate stream containing the residual compounds and a pure air stream. This process requires further treatment of the liquid permeate in order to dispose of the VOCs or recycle the liquid stream.

1.4.5.4 Adsorption

Adsorption occurs on a fixed or fluidized bed of material, typically activated carbon, and is effective at treating low concentration vapors. The effectiveness of this removal process is dependent on the flow rate of air, total VOC concentration and the individual components that are present in the VOC stream (Devinny et al, 1999). Activated carbon filters are highly popular in *Cannabis* facilities and is currently the most common form of treatment other than utilizing filtration technologies in existing HVAC systems.

Activated carbon is a highly porous substance with a significant surface area, making it ideal for adsorption applications. The particles or pollutants entering the media become trapped inside of the matrix of pores inside the carbon molecules, and the large surface area allows for a significant amount of pollutants to adsorb before the filter media is considered spent (Sorrels, 2018). Carbon filtration can be used for many designs including air filtration, water filtration, and other gas and liquid processing. These filters are even commercialized to provide filtration in respirator masks, fish tanks, and for vehicle emissions. For air filtration applications, carbon filters have been proven to effectively remove VOCs and odors from air streams (Metts & Batterman, 2006).

Carbon filters are relatively simple in design. They are easy to install, and up to 98% effective when properly maintained and replaced (Metts & Batterman, 2006). Currently, the Denver *Cannabis* Environmental Best Management Practices Guide recommends carbon filters as the best way to reduce VOC and odor emissions for indoor growing facilities.

While the microbes found in biofilters metabolize the pollutants, eliminating the need for frequent media replacements, carbon filters only adsorb the pollutants and trap them within the pores of the activated carbon molecules. This means that the activated bed material has an adsorptive capacity and would need to be replaced or recovered every 6-12 months in order to remain effective (Xiao, 2017). The most economical process to treat the material is by incineration. This is a disadvantage when compared to the biofilter, since biofilters only need to be replaced every 5-10 years. This process also increases the annual utility costs because steam is used to regenerate the spent filter media, and then recondensed and treated.

2.0 Materials and Methods

Since there is very little research on the removal of terpenes through biofiltration, bench-scale testing is required for proof of concept and to estimate the removal efficiency at different performance parameters. This project consisted of designing and building a bench-scale biofilter with three columns to experiment with different filter media and compost ratios. This section will discuss the bench-scale biofilter system and operating procedures conducted to determine the removal efficiency.

2.1 Experimental Setup

Figure 6 below shows the initial design of our bench-scale biofilter model. We constructed a terpene diffuser from an essential oil diffuser to humidify the air and create a synthetic waste stream from terpene oil. The dehumidifier was required to condense any water leftover in the samples before entering an enclosed box with a VOC sensor that was intended to measure the concentration of terpenes either initially or after exiting the biofilter. A pressure regulator and rotameter were used to control the airflow into the system. Figure 7 shows the final construction of the bench-scale model.

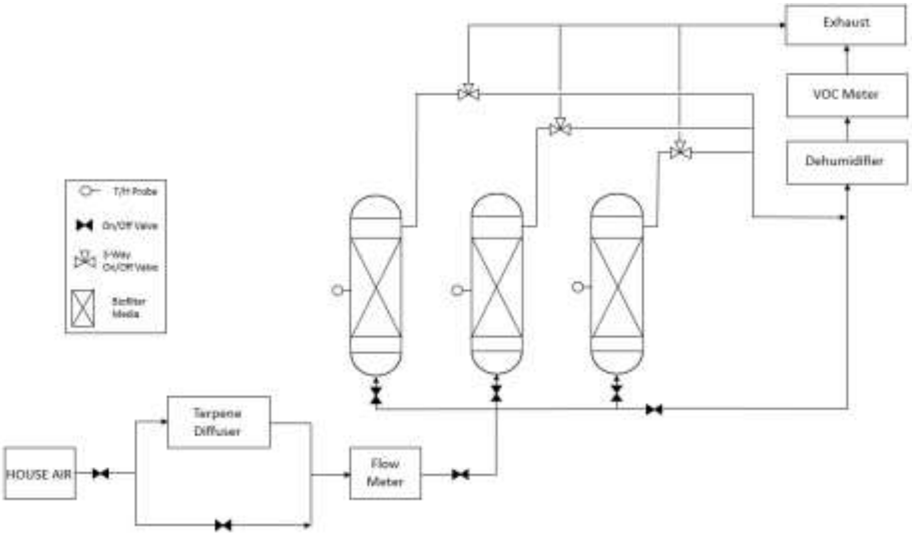

Figure 6 Schematic of Bench-Scale Biofilter Apparatus

Figure 7. Bench-Scale Biofilter Model. Pictured in Goddard Hall

2.2 Operating Procedures

2.2.1 Startup:

1. Take measurements of moisture level, pH, temperature from the top of each column by loosening the clamps and removing the end cap. Make sure to replace and secure all end caps before moving forward with the startup procedure.
2. Determine ratio of water to oil and add the appropriate contents to the diffuser. Turn the diffuser on by connecting the AC plug to the inlet at the bottom of the diffuser column and press the on/off button on the control box. Wait until you can see vapor rising from the diffuser column and then tightly seal the top using a wrench.
3. Check that regulator valve is completely open and set the valves to send air through the desired columns for experimentation or the bypass. Make sure the exit valves to allow air through either the exhaust or the dehumidifier to prevent pressure buildup.
4. Turn on the house air supply by turning the yellow valve to the on position.
5. Turn the gate valve to the “on” position and slowly begin turning the regulator until the pressure gauge reaches 3 psi.
6. Set the desired flow rate by rotating the red needle valve on the rotameter.

7. Connect the VOC analyzer to a computer using the USB connection. Download/open the "GasLab 2.1" program and set the input. Connect the sensor and begin logging data for desired time period by pressing the "Start Logging" button.

2.2.2 Shutdown:

1. Turn off the airflow by moving the gate valve before the pressure regulator to the "off" position.
2. Turn the valve at the house air inlet to the "off" position.
3. Turn off the diffuser by pressing the button on the control box twice.
4. Check the moisture level and temperature at both ports on each column. Add water to the top of the column(s) if necessary.

2.3 Methodology

The process of building a bench-scale biofilter began with intensive research on biofiltration. Through this gained knowledge, a schematic of the design was created, and equipment was ordered to begin building the apparatus. The filter bodies were made from clear PVC piping that was 2.5 inches in diameter and 36 inches long. Black vinyl pipe caps and clamps were used to create an air-tight seal on the filter columns. A wire mesh screen was installed approximately 3 inches from the bottom of each filter to prevent the filter media from clogging the air inlet and to allow excess liquid to drain. Approximately 30 feet of ¼ inch ID clear vinyl tubing was used for the piping. Ball valves were used to control which filter, or bypass stream the contaminated air flows through, a needle valve was used to control the air flowrate, and three-way diverting valves were used to direct the treated air flow to either the exhaust or to the VOC analyzer.

The biofilter media was comprised of compost, wood chips, and activated carbon pellets. Biofilter #1 was made from 4 parts compost, 1 part wood chips, and 2 parts activated carbon. Biofilter #2 was made from 4 parts compost, and 1 part wood chips. A third biofilter containing a different source of compost was intended to be created; however, the timeline of this project did not allow for additional experimenting. Mature compost was obtained from a family member and had been inoculating for over a year. This ensured that there was a high level of bioactivity present in the filter media. The wood chips acted as a bulking agent to prevent compacting within the filter, as well as an organic substrate for the biofilm layer to grow on. The activated carbon served the same purpose as the wood chips and was hypothesized to provide an increased amount of adsorption throughout the column due to its high porosity and surface area.

The waste air stream used to model the exhaust from a *Cannabis* facility contained an isolated terpene called terpinolene. Terpinolene is a common terpene found in many strains of *Cannabis sativa*, and is known for its pine and citrussy aroma. The terpene isolate oil was aerosolized into the stream using an ultra-sonic diffuser. This diffuser contained both terpene isolate and water, so it provided control of contaminant concentration and stream humidity.

Before beginning experimentation, the filters had to be primed to allow the biological components to acclimate and attach to the media. To accomplish this, clean air was run through the loaded filters multiple days a week for 5 or more hours each day to ensure that the biological activity in the compost would stay alive. The moisture content and temperature of each column frequently checked, and water was added as needed to maintain an appropriate moisture level.

Experimentation was performed utilizing gas chromatography (GC) analysis. GC analysis provided terpinolene concentrations for the contaminated and treated air streams. The data obtained was used to calculate the elimination capacity and removal efficiency of the biofilters. Additionally, GC was used to search for any other contaminants that might be present in the terpene isolate or created as a by-product of the biofiltration process. Evidence of a lower molecular weight contaminant was found in the terpene isolate, which is likely a solvent used in the extraction process. No evidence of contaminants created as a by-product of the biofiltration process was found.

3.0 Results and Discussion

The goal of this research was to demonstrate elimination capacity and removal efficiency of terpenes as a function of mass loading rate to determine the performance of a bench-scale biofilter at certain operating conditions. Through monitoring performance parameters such as air flow rate, pressure drop, and most importantly, the relative concentration of terpene in the air stream.

3.1 Empty Bed Residence Time

The first parameter that was monitored to characterize the biofilters was the empty bed residence time (EBRT). This value relates flow rate to the size of the biofilter, which is essential for scale-up design. EBRT is the most common way to classify a biofilter, as it is normalized term to discuss flow rate relative to the size of the unit. The actual residence time is more definitive of a biofilters performance, but it can fluctuate based on other factors such as media type, packing density, and water content. Packing density can fluctuate in a steady-state biofilter over time as gravity and air pressure compact the filter material. Water content also fluctuates constantly as water is added and removed from the system through evaporation and diffusion. EBRT was calculated as the filter bed volume (V_f) divided by the air flow rate (Q). The flow rate was kept relatively constant at 0.18 SCFM, which was standardized to be 0.3092 cubic meters per hour. The volume of one column of the bench scale biofilter was 0.00258 cubic meters, so the EBRT was calculated to be approximated 30 seconds.

3.2 Volumetric Mass Loading Rate

Next, the volumetric mass loading rate was calculated as this value represents the amount of contaminant being treated. The mass loading rate is also a normalized term which can be used in the scale-up design from bench- to full-scale modeling. The volumetric mass loading rate was calculated using equation 6 below, where C_{GI} is the inlet concentration of contaminant.

$$Mass\ loading\ rate\ (volumetric) = \frac{QC_{Gl}}{V_f} \tag{6}$$

There are two ways to experiment with the effects of changing mass loading rate. This can be accomplished by either adjust the flow rate or the concentration of terpenes in the inlet stream. This project experimented with the effects of loading rate by varying the concentration of terpenes. Relative concentrations were found through GC analysis and used to represent concentrations at the inlet and outlet of the biofilter columns. Using these concentrations, it was found that the volumetric loading rate ranged from 22.42-137.48 C*ft/min. These are essentially the limitations of contaminant removal for a biofilter at these conditions.

3.3 Overall Removal of Terpenes

Through testing the inlet contaminant concentration in comparison to the outlet concentration of treated air through GC analysis, it was found that both biofilter columns were successful at removing terpinolene from an air stream. This conclusion came from the determination that the average peak area of the treated air was smaller than the contaminated inlet stream. The figure below shows the relative inlet and outlet concentrations measured on the GC, which shows a significant decrease between trials.

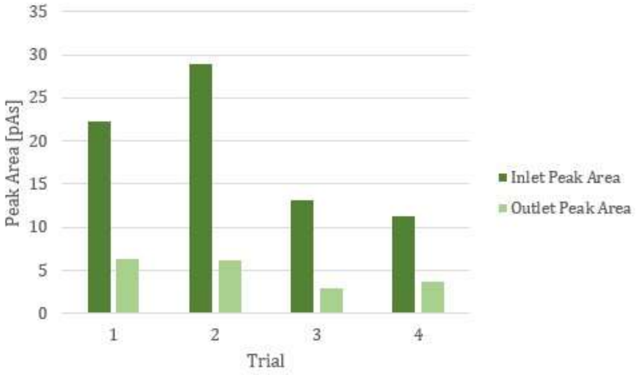

Figure 8. Graph of Relative Inlet and Outlet Concentrations

This data demonstrates that biofilters are capable of removing odorous terpenes. From initial observation, it was concludes that the outlet stream was far less odorous than the inlet stream. However, the outlet concentration was not below the odor threshold. This means that there was not a 100% removal efficiency from our biofilter but changing certain operating parameters could lead to achieving a higher removal efficiency.

3.4 Removal Efficiency

Removal efficiency (RE) is defined as the percentage of contaminants removed by the filter. This is a standard measurement of overall biofilter performance. The equation below was used to calculate removal efficiencies based on relative concentrations obtained through GC analysis.

$$RE = \left(\frac{C_{Gi} - C_{G0}}{C_{Gi}}\right) * 100 \qquad (7)$$

These measurements reflect removal efficiency at the specific operating conditions. This means it is an incomplete indicator of performance because removal efficiency varies with air flow, contaminant concentration/load, and biofilter size. The method used involved keeping the size and air flow constant, but the removal efficiencies shown in the table below vary by changing volumetric loads. The tables below display the varying volumetric load versus removal efficiency and the average removal efficiency for each column.

Table 2. Volumetric Load vs. Removal Efficiency for Biofilter Column #1

Trial	Volumetric Load	Removal Efficiency
1	44.66	42.54%
2	137.48	70.61%
3	26.22	77.27%
4	22.42	67.71%
Average		64.53% ± 7.60%

Table 3. Volumetric Load vs. Removal Efficiency for Biofilter Column #2

Trial	Volumetric Load	Removal Efficiency
1	89.32	27.56%
2	57.70	78.67%
3	137.48	80.47%
4	137.48	82.70%
Average		67.35% ± 13.30%

From this data it is shown that the removal efficiencies calculated for both columns are not statistically different. It was initially hypothesized that activated carbon would yield a higher removal efficiency because it is a porous material with satisfactory absorption properties. While the data does not support this hypothesis, it could still be proven that activated carbon leads to more effective removal due to that fact that the removal efficiencies calculated above are not statistically different, and overall performance is dependent on multiple factors other than what was measured.

3.5 Elimination Capacity

The next measurement used to determine effectiveness of the biofilters was elimination capacity (EC), which is the mass of contaminant degraded per unit volume of filter material per unit time. The equation below shows how this was calculated.

$$EC = \frac{(C_{Gi} - C_{G0}) * Q}{V_f} \qquad (8)$$

This calculation allows for a direct comparison between the results from the two columns because the volume and the flow rate are normalized. Elimination capacity was also measured as a function of concentration because the volumetric load was changing as a function of time. It can also be noted that the elimination capacity can only be equal to or less than the volumetric mass loading rate (Equation 6).

Theoretically, at low load conditions, the elimination capacity should reflect the load and the removal efficiency should be 100%. This means that at higher loads, it reaches a critical elimination capacity (EC_{max}) where the contaminant load is equal to EC at the highest possible removal efficiency. At any higher load, the RE would decrease as EC approaches EC_{max}.

In this case elimination capacity is independent of concentration and residence time for similar operating conditions, which allows for a useful comparison to determine the effectiveness at different operating conditions with a uniform contaminant load. A graph of load vs elimination capacity was created to create a visual of this concept in Figure 9.

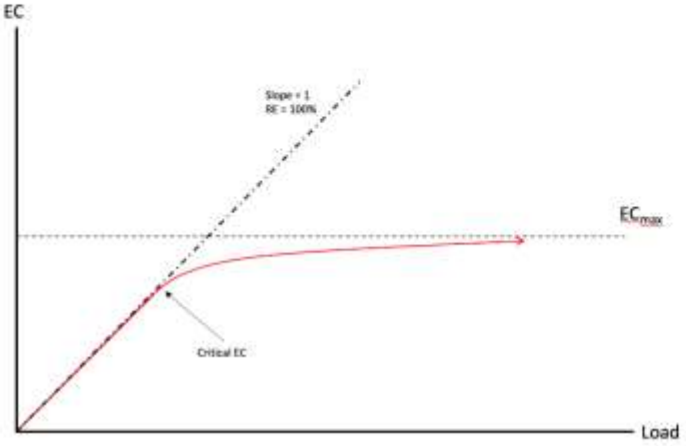

Figure 9. Load Versus Elimination Capacity

Figure 10 below shows our data of volumetric loading rate versus elimination capacity. This demonstrates a linear trend that is consistent through both biofilters and is similar to the trend Figure 9, besides the outlier from biofilter #2.

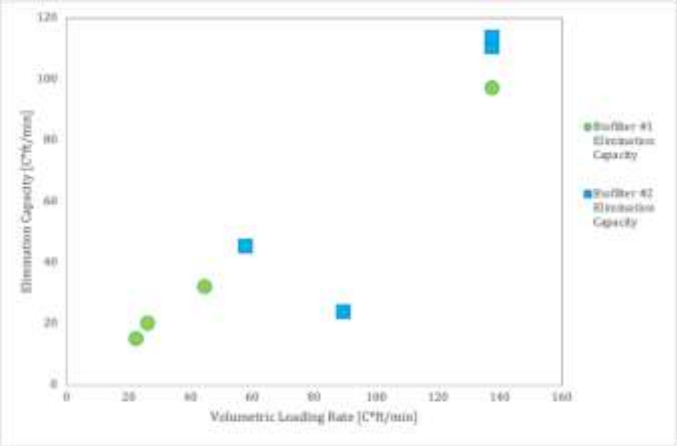

Figure 10. Volumetric Loading Rate Versus Elimination Capacity

The slope of this trend for biofilter column #1 was determined to be 0.7076 with an R^2 value of 0.9993. The slope of biofilter #2 was determined to be 1.005 with a slightly lower R^2 value of 0.7446, due to the presence of the outlier. This trend also does not support the hypothesis as the second column was found to perform better than the first. This could be due to many factors including the moisture content and/ or composition of the filter media. We believe that biofilter #1 did not perform as well because the activated carbon may have become spent faster than expected. Before GC data was collected, there was a long period of time where the biofilter was run daily to prime the filter material. During that time, the activated carbon may have reached its maximum adsorption capacity. To test this justification, the experiment could be repeated with fresh carbon. If it is the case that the activated carbon became spent in less than a year, the media would have to be replaced or regenerated more frequently than expected, which would not be economically or environmentally feasible, because the process requires energy to generate steam which removes the contaminant particles.

The linear trend found in Figure 10 also allows for the conclusion that this experimentation did not reach the maximum elimination capacity. This means that the biofilters can hypothetically handle loads much higher than what we subjected them to during experimentation. More experimentation using higher loading rates is needed to find the critical elimination capacity.

4.0 Future Research and Recommendations

With the knowledge that a biofiltration system can be used as an application for air filtration in *Cannabis* facilities, there are many areas that need further research to fully implement this. Future research will confirm the properties that provide the most effective system both economically and effectively. The recommended areas for future research include:

1. Characterization of the waste air stream that is exiting from an operating *Cannabis* facility and simulate the air stream. Utilize the information found to create an accurate model of the air dispersion of the determined pollutants. Test for different AVOCs such as butane.

2. Test different filter media compositions to determine the most effective media. Factors to be researched include moisture content, pH, and temperature. Determine if the spent media can be reused and how this could be accomplished. If the material cannot be reused ultimate disposal of the by-products from the process needs to be determined.
3. Find the critical elimination capacity of the bench-scale biofilter and terpenes to be used for a proper scale-up report. Determine a way to calibrate the GC system to retrieve measurable concentration data. Create a residence time distribution to determine the void volume and characterize the packing of media.
4. Conduct a Brunauer-Emmett-Teller (BET) surface analysis to characterize the media's adsorption area. This information can help to further the understanding of the kinetics and mass transfer mechanisms occurring within the biofilter media and associated biofilm.
5. Research newer innovations related to biofiltration systems that may be utilized in the *Cannabis* industry such as an active living wall of plants that simultaneously filters the air.

5.0 Full-Scale Biofilter Design

5.1 Introduction

The goal of the above research was to utilize information to scale-up the biofilter to create a full-scale model. The lack of information needed to determine actual concentrations prevented the successful design of a full-scale biofilter. However, the design below was created using estimated concentrations and considers the most probable and worst-case scenarios for an uncontrolled release of terpenes from a *Cannabis* facility. This was done to ensure there are minimal safety concerns to the general public and sensitive populations, including the nuisance of odor. A Process Flow Diagram (PFD) and a Piping and Instrumentation Diagram (P&ID) were created to model the process and detail all the components of the design. Applicable codes were considered when creating the layout diagrams, and an economic analysis was completed to understand the total investment and annualized costs to build and operate the biofilter. This cost analysis was compared to the cost of operating a full-scale activated carbon filter to determine which would be a better option. This chapter goes into detail on the entire process of modeling air emissions and designing the full-scale model.

5.1.1 Location

The selected location for the growing facility is 120 Brookline Avenue, Boston, Massachusetts. Boston is the capital of Massachusetts and is the most populous city in Massachusetts covering a total of 89.63 square miles. This building is specifically located in the Fenway Park area. Since this area contains a significant amount of foot traffic due to the many attractions and businesses, there is a concern of polluting the environment that would affect so many civilians. The area of the growing facility, shown as the yellow box in Figure 11, is 7,500 square feet.

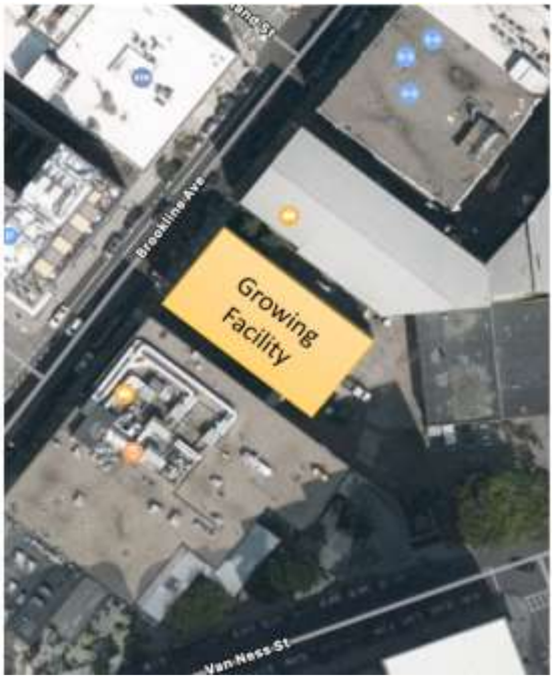

Figure 11. Growing Facility Location Area

Figure 12 shows a 1-mile radius around the growing facility. Within this radius are large buildings and attractions such as Fenway Park, Boston Children’s Hospital, Brigham and Women’s Hospital, Northeastern University, Boston University, and many more densely populated areas. The Charles River, which is connected to Boston Harbor, is one place of increased concern for environmental pollution within the radius. With so many important locations within a small radius of the growing facility, it is important to take all safety precautions and regulations into consideration.

Figure 12. Mile Radius Around Growing Facility

5.1.2 Climate

Boston, Massachusetts has warm summers, cold and snowy winters, and year-round is partly cloudy. The temperature at this location can range from -18°F to 104°F, with lows rarely dropping below 9°F and highs rarely climbing above 91°F. November, December, January, February, and March can be considered the winter months in Boston as the temperatures are colder on average. During these winter months, the minimum temperature typically ranges from 20°F to 40°F and the maximum temperature typically ranges from 35°F to 55°F. The average snowfall in Boston during the winter months ranges from 1 inch to 8.7 inches. Boston's summer season lasts from May to September with the hottest month being July with an average high of 82°F and low of 66°F. In Boston, the months of April and October receive the most rainfall with an average of 3.9 inches. The lowest average rainfall of 2.2 inches occurs in January followed by August with 3.1 inches. Humidity in Boston is the highest between the months of June and September with the level being muggy or oppressive from 10% to 39% of the time. From November to April the humidity level reaches muggy or oppressive 0% of the time.

5.2 Process Safety Management Specifications

5.2.1 Safety Information

Ozone is produced spontaneously in the troposphere when VOCs react with oxides of nitrogen and sunlight. Depending on where it's found in the atmosphere, ozone can be beneficial or harmful to humans and the environment. Ground-level ozone produced in the troposphere can pose a variety of health problems to humanity, while stratospheric ozone consists of the layer that protects all living things from the sun's UV rays (Environmental Protection Agency[6]). Since terpenes are considered VOCs, there is a level of concern over how much the exhaust from *Cannabis* cultivation and extraction facilities plays a role in the production of ozone globally.

The Clean Air Act, which was last amended in 1990, requires the EPA to review all National Ambient Air Quality Standards (NAAQS) and revise when necessary. The last amendment in relation to ozone was published in 2015, and the EPA made the decision to retain these standards in December of 2020 (Environmental Protection Agency[3]). The EPA has established NAAQS for six air pollutants, and each pollutant has primary and secondary standards. Primary standards are created for the purpose of protecting sensitive populations such as asthmatics, children, and the elderly. Secondary standards are intended to protect public welfare which includes the risk of decreased visibility from smog and potential damage to living beings other than humans (Environmental Protection Agency[3]). For ozone, the primary and secondary standards are the same, and were based on the annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years.

Other exposure guidelines include limits set by OSHA and NIOSH for workplace exposure. The regulations set by OSHA are usually in agreement with recommendations from NIOSH. These standards are typically given over a time-weighted average (TWA) of 8 hours or based on short-term exposure limits (STEL) with given times. Another important regulation included in Table 4 is the Immediately Dangerous to Life or Health (IDLH) concentration which was established by the NIOSH to classify an exposure that would result in death or permanent health impacts. The IDLH for ozone was originally set at 10 ppm by the NIOSH and lowered to 5.0 ppm in 1994 (CDC, 2014).

Table 4. Air Quality Standards for Ozone

Material	NAAQS (ppm)	PEL (ppm)	IDLH (ppm)
Ozone	0.07	0.10	5.00

There are other safety concerns to consider such as the hazards associated with filter media and issues that could arise during operation or maintenance. Many components of the filter media are flammable, such as wood products or activated carbon. However, these materials will be wet the entire time they are in use, which leaves no concern of flammability or combustibility. The pumps that operate the biofilter run on electricity and will be contained to avoid any risk of electrocution. The incoming air stream and compost within the biofilter may be noxious and odorous but are not considered hazardous materials.

5.2.2 Emergency Releases

In order to determine any potential threats of a release from the biofilter, ALOHA software was used. As previously discussed, the location for the *Cannabis* facility is Boston, Massachusetts. Specifically, our location is in the heart of Boston at an existing *Cannabis* dispensary near Fenway Park. While the MedMen facility does not contain actual *Cannabis* plants, we chose this location since the impact of terpenes is minor to humans, it would be possible to have a growing facility in such a populated area. Also, the location of most growing facilities is typically undisclosed, and the industry is still expanding from smaller operations. In Figure 13, the two closest locations to the facility with sensitive populations are shown. Boston Children's Hospital is shown 0.8 miles from the MedMen facility and Brigham, and Women's Hospital is 1 mile away. To determine any threats to the population, the most probable case was calculated, and the worst-case scenario was considered. Simulations were run to determine the distance of impact for the maximum continuous and immediate accidental releases.

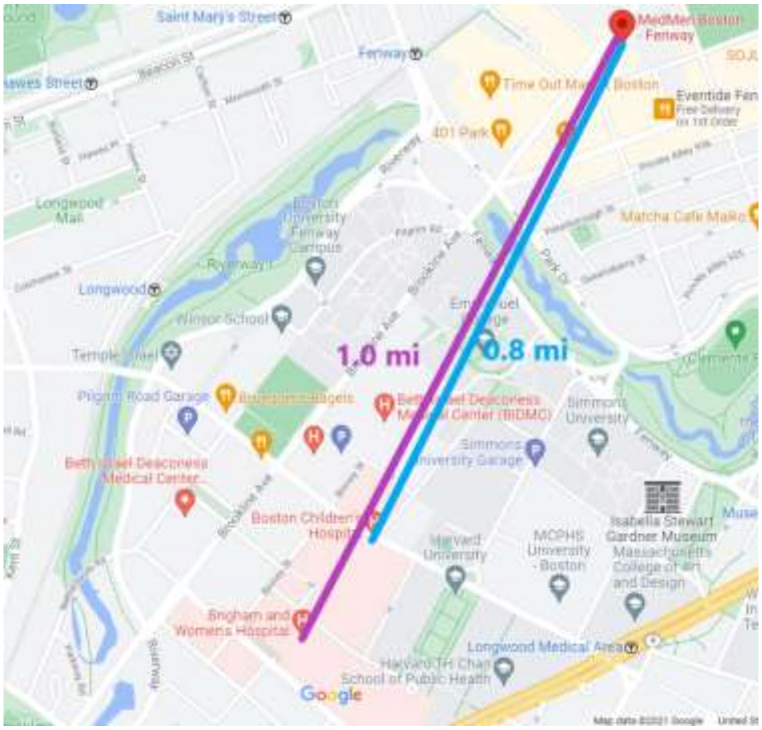

Figure 13. Distance of Sensitive Populations from Cannabis Facility

5.2.2.1 Most Probable Release

First the most probable release was considered. This would be the expected release on a normal production day without a biofilter. It is estimated that 744 mg of terpenes are released per day for each plant during the growing process (Samburova, 2019). Assuming a maximum value of 1000 plants, the release of terpenes in grams per minute was calculated to be 0.5167 g/min, as seen in Appendix A. This concentration is considered a small release because terpenes aren't life-threatening. In fact, this value was so small that it couldn't be modeled in ALOHA. Considering this is the expected release on a day-to-day basis without a biofilter, release with a biofilter would be even less. Therefore, the facility shouldn't expect to cause any harm to the surrounding area assuming the biofilter is working efficiently.

5.2.2.2 Worst Case Release

It is also important to model the worst-case scenario, to be prepared if there are ever unusual amounts of exhaust released. As discussed previously, the typical release of terpenes is 0.5167 g/min. This concentration is considered a small release since terpenes aren't life-threatening. Therefore, the worst-case scenario for terpene release needs to be a value in which people start to smell them which could cause discomfort. This value was estimated to involve a 60-minute release of a specific terpene at 25 g/min. This value is significantly higher than the value calculated above so it is highly unlikely that this would occur. However, this value is simply the worst-case scenario. It could exemplify multiple growing facilities or a future scenario of an expanded operation. A release at this level would pose a threat to humans in terms of odor and could negatively impact the environment due to the large concentrations of VOCs going into the atmosphere. For the threat zone, which is the model of the toxic vapor cloud, the red zone was chosen to be the odor threshold for terpinolene. This value represents the minimum concentration that would disturb humans and was found to be 0.041 ppm (Niu, 2020).

Since terpenes convert to ozone in the atmosphere, it was assumed that the worst-case scenario would involve a complete conversion to ozone from the terpene release. This is also highly unlikely because the conditions required to cause this reaction are not always present. However, recent expansions in the *Cannabis* industry without federal regulation have caused significant contributions to ground-level ozone concentration. The results from a study that visited four *Cannabis* facilities concluded that VOCs emitted by individual plants could cause a ground-level ozone production rate of about 2.6 grams per plant per day (DRI, 2019). For the ALOHA simulation, we calculated an ozone release of 20 g/min for 60 minutes, assuming that most of the terpinolene in the previous example converts to ozone.

5.2.2.3 Maximum Continuous Accidental Release

The ALOHA program was used to simulate the maximum continuous release of terpenes from a hypothetical *Cannabis* facility. The atmospheric data inputs were determined using typical weather in Boston, Massachusetts. The source strength was assumed to be the worst case of 25 grams per minute for a duration of 60 minutes with a release rate of 0.0551 pounds per minute. This resulted in a total release of 3.31 pounds of terpinolene over an hour. The threat zone for terpinolene release, as seen in Figure 14, was estimated to be 275 yards or 0.16 miles, which does not come close to any sensitive population locations.

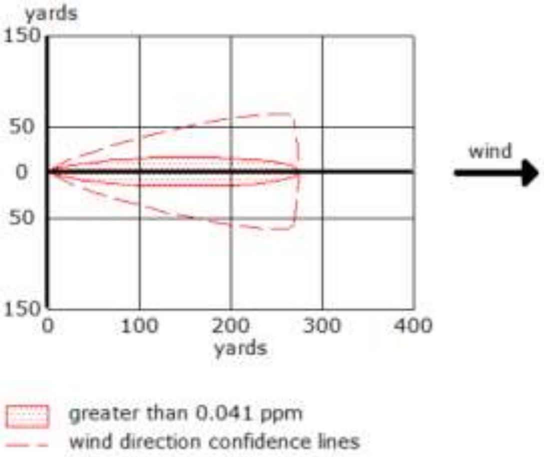

Figure 14. Toxic Threat Zone Diagram of Maximum Continuous Release of Terpinolene

This threat area is shown below in Figure 15. Based on the Aloha model, we would not expect anyone to be sickened or hospitalized from inhaling the exhaust. The only issue this would pose to humans is odor complaints. The release would reach Fenway Park, the Harvard Vanguard buildings, a Target, many restaurants, hotels and businesses, and a large portion of Brookline Ave and may travel to the Mass Pike. Foot traffic is dense in these areas, especially on game days and during the warmer months, so depending on these factors, there could be thousands of people impacted by the emission.

Figure 15. Map of Hypothetical Threat Zone

As previously mentioned, we also simulated the release of ozone from the facility. Assuming most of the terpinolene in the previous example converts to ozone we calculated a release of ozone at 20 g/min for 60 minutes as seen in Appendix B. The ALOHA simulation can be seen below in Figure 16. This simulation showed very little threat as the maximum distance from the facility was 85 yards or 0.05 miles, with a maximum concentration of 0.24 ppm. Similar to the release of terpinolene, ozone release at this concentration isn't harmful to humans but people in the area may complain of an "irritating" smell (McConnell, et. al). Therefore, this release has minor effects and will only affect the area directly surrounding the facility.

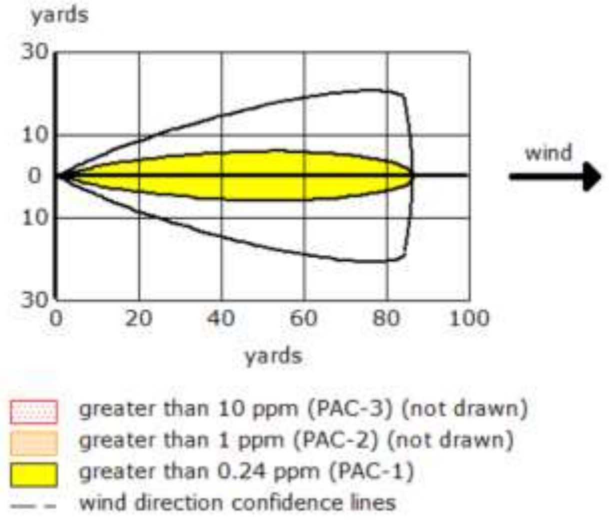

Figure 16. Toxic Threat Zone Diagram of Maximum Continuous Release of Ozone

5.2.2.4 Maximum Instantaneous Accidental Release

We modeled the maximum instantaneous release to provide the minimum disturbance to people in the surrounding area while being able to produce a diagram on ALOHA. This simulation was determined to have a direct source of 4 grams of terpinolene over 1 minute giving a total release of 0.0088 pounds of terpinolene. Since no harm is being posed to humans, to begin with, we thought this model would give a good idea of what the current releases are like from growing facilities. This scenario was modeled on Aloha and is shown in Figure 17. Since the maximum continuous release case is unrealistic, this case is considered to be the maximum impact that could occur on the surrounding community.

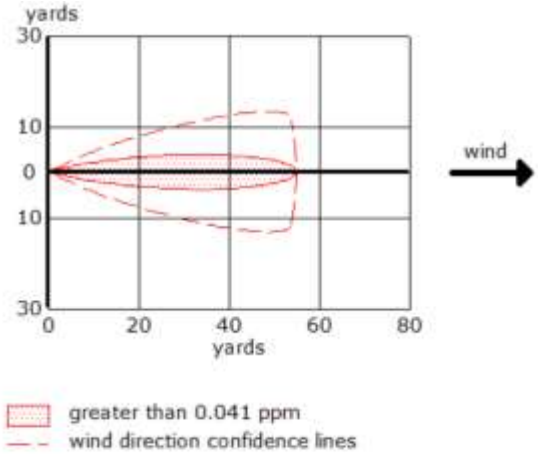

Figure 17. Toxic Threat Diagram of Scenario with Maximum Instantaneous Release

5.2.3 Applicable Codes

This section will detail the codes that are applicable to the treatment of the terpene exhaust presented in this report.

5.2.3.1 International Building Codes (IBC)

The following International Building Codes sections were analyzed to help design the utility closet where part of the design is located.

Means of Egress

The following codes were taken from the IBC to design the utility closet with safe and accessible entry and exit points.

Code 1003.2 Ceiling height

The means of egress shall have a ceiling height of not less than 7 feet 6 inches (2286 mm) above the finished floor.

Code 1005.7.1 Doors

Doors, when fully opened, shall not reduce the required width by more than 7 inches (178 mm). Doors in any position shall not reduce the required width by more than one-half.

Code 1006.33 Single exits

A single exit or access to a single exit shall be permitted from any story or occupied roof where one of the following conditions exits:

1. The occupant load, number of dwelling units and common path of egress travel distance do not exceed the values in Table 1006.3.3(1) or 1006.3.3(2)

Code 1008.2 Illumination required

The means of egress serving a room or space shall be illuminated at all times that the room or space is occupied

Code 1008.3 Emergency power for illumination

The power supply for means of egress illumination shall normally be provided by the premises' electrical supply

Code 1010.1.1 Size of doors

The required capacity of each door opening shall be sufficient for the occupant load thereof and shall provide a minimum clear opening width of 32 inches (813 mm)

5.2.3.2 National Fire Protection Association (NFPA)

The following National Fire Protection Association sections were analyzed to help design the utility closet where part of the design is located.

Standard for Portable Fire Extinguishers

The following codes were taken from the NFPA in order to design the utilities closet with fire extinguishers in case of fire.

Code 4.1.2

Each fire extinguisher shall be marked with the following:

1. Identification of the listing and labeling organization
2. Product category indicating the type of extinguisher
3. Extinguisher classification
4. Performance and fire test standards that the extinguisher meets or exceeds

Code 5.1.1

Portable fire extinguishers shall be installed as a first line of defense to cope with fires of limited size.

Standard for the Installation of Sprinkler Systems

The following codes were taken from the NFPA in order to design the utilities closet with sprinkler systems in case of fire.

Code 9.1.1

The requirements for spacing, location, and position of sprinklers shall be based on the following principles:

1. Sprinklers shall be installed throughout the premises.

2. Sprinklers shall be located so as not to exceed the maximum protection area per sprinkler.
3. Sprinklers shall be positioned and located so as to provide satisfactory performance with respect to activation time and distribution.

Recommended Practice for Handling Releases of Flammable Gases

The following codes were taken from NFPA to protect the *Cannabis* facility and environment against flammable gases.

Code 4.1.1

Releases of flammable and combustible gases can result from leaks in tanks, containers, or pipelines, from surface spills, or from human error.

Code 5.1 Indicators of a Release

The release of a flammable or combustible gas can be indicated by physical discovery of an actual release or by indication of a potential release.

Code 5.2.1

Depending on the circumstances of physical discovery, conditions might exist where a potential hazard to life or property exists, in which case immediate steps should be taken to protect the public from the danger of an explosion or fire.

Code 5.4.5.1

Where gas or vapor concentrations are above 50 percent of the LFL, everyone in the affected area should be evacuated.

5.2.3.3 National Standard Plumbing Code

The following National Plumbing Code sections were analyzed to help design the plumbing needed in the utility closet and throughout the process.

Joints and Connections

The following codes were taken from the National Standard Plumbing Code to help design the plumbing needed throughout the process.

Code 4.1.1 Tightness

Joints and connections in water supply, sanitary drain and vent, and storm drain piping shall be watertight when the piping is leak tested.

5.3 Basic Design

The following section details the basic design of the biofilter set up to control an exhaust air stream from a *Cannabis* growing facility. This includes a process flow diagram, a layout diagram, a piping and instrumentation diagram, as well as additional specifications on the equipment featured in this design.

5.3.1 Process Flow Diagram (PFD)

Figure 18 shows the process flow diagram (PFD) of the biofilter system. A PFD is a flowchart that illustrates the major components found in an industrial process. Our design features two vessels, two centrifugal pumps, an air blower, a humidity controlling pump, and finally a biofilter reactor. Additional details on the equipment are shown in Table 5 in the equipment specifications section. The purpose of this process flow diagram is to give a simplified visual of the entire process.

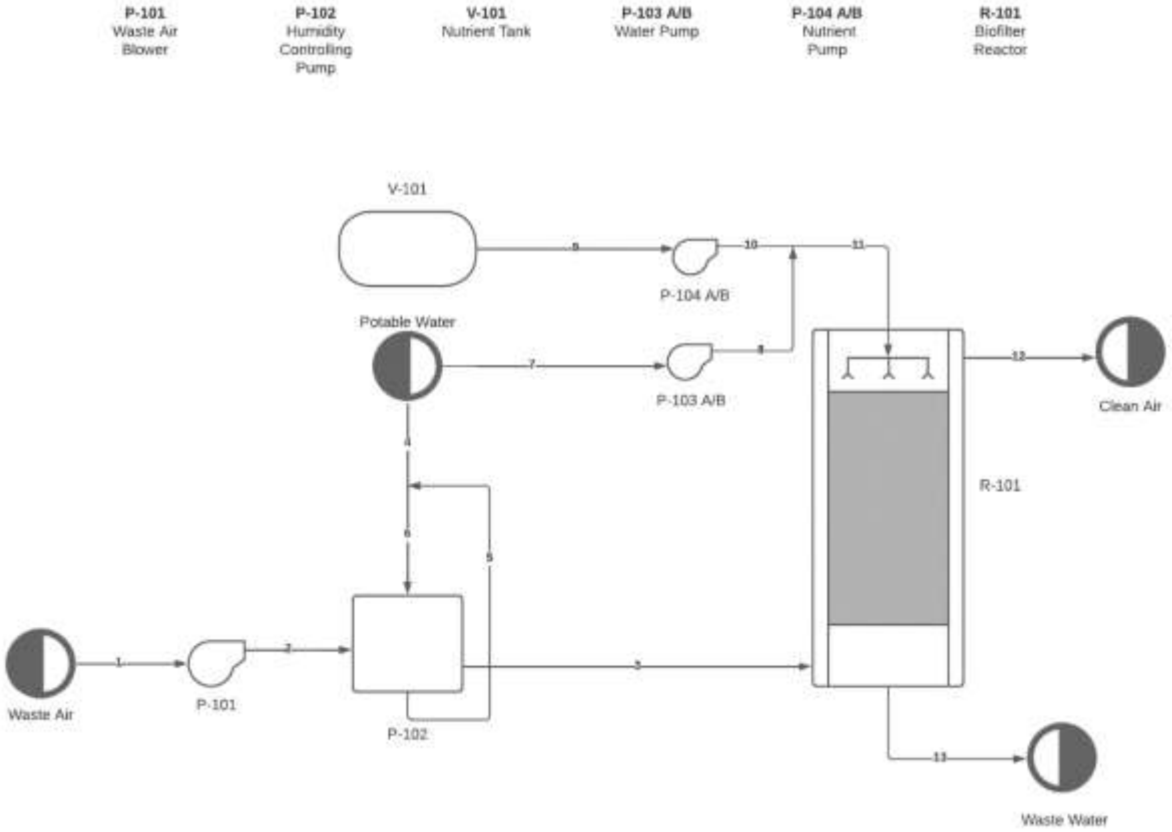

Figure 18. Process Flow Diagram of Biofilter System

5.3.2 Layout

Figures 19, 20, & 21 show layout diagrams of the biofilter process. Most of this process takes place outdoors due to the large footprint of the biofilter. Larger equipment including the biofilter reactor, the water tank, and the nutrient tank will be housed outside of the building, while smaller equipment including the blower, humidity pump, and the controller system will be located inside the growing facility. There will be a small room built off of the growing facility that serves as the control room for the biofilter. This room will hold the humidity pump, as well as any extra supplies or maintenance materials that the biofilter might need in its lifetime. The control panel in this room will show the flow rates and temperatures of all the process streams, the humidity of the air stream, the liquid levels in the water and nutrient tanks, the flowrates of the exiting treated air and wastewater streams, and finally the temperature and moisture level of the biofilter reactor.

The floor plan of the control room shows that the room is 10x12 ft. This room has two exits, one leading inside to the growing room, and the other leading outside to the biofilters location. The rooms' dimensions and exits both follow the International Building Code. Since equipment is in operation inside of this room, the room must have good ventilation, as well as carbon dioxide and carbon monoxide detectors. To ensure the exhaust air stream is relatively consistent and constantly flowing, a blower is used to control the exhaust airflow. This will result in the building being slightly negatively pressured, meaning outside air will likely be pulled through any doors, windows, or other areas where there are leaks in the building. The exhaust air blower is located in the exhaust vent as a fan that is 12x12 in. It is important that this fan can generate enough power to handle the air flow of the entire building.

The humidity controlling pump is connected to the water source through ¼ in copper piping which is approximately 6 ft long. It creates humidity using an electrical heater to boil water and generate steam. There is a built-in system that collects excess water and recycles it to reduce water consumption. This pump is 13 by 18 ½” and is 19” tall. The exhaust stream enters through a square duct that is 12x12 in. The humidified stream exits the building in an insulated schedule 40 PVC pipe that is 8 inches diameter. This pipe leads directly to the biofilter, which is approximately 8 ft away from the building.

Outside, the nutrient vessel has a diameter of 0.797 m and a height of 1.67 m. The tank is insulated to avoid freezing in the winter. Outside of the tank and water supply is two centrifugal pumps that control the flow of the water and nutrients entering the biofilter. The flows run through an insulated schedule 40 PVC pipe that has a 2” diameter and are approximately 5 ft long. Inside the biofilter, the liquid stream connects to an irrigation system that sprays over the filter media.

The biofilter reactor is the largest piece of equipment in this design, with a height of 2 m and diameter of 1 m. It is also insulted to avoid heat loss. The clean air exits the top of the reactor through an exhaust duct that is 12x12 in. The wastewater build up is drained at the bottom of the reactor straight to the building’s sewage.

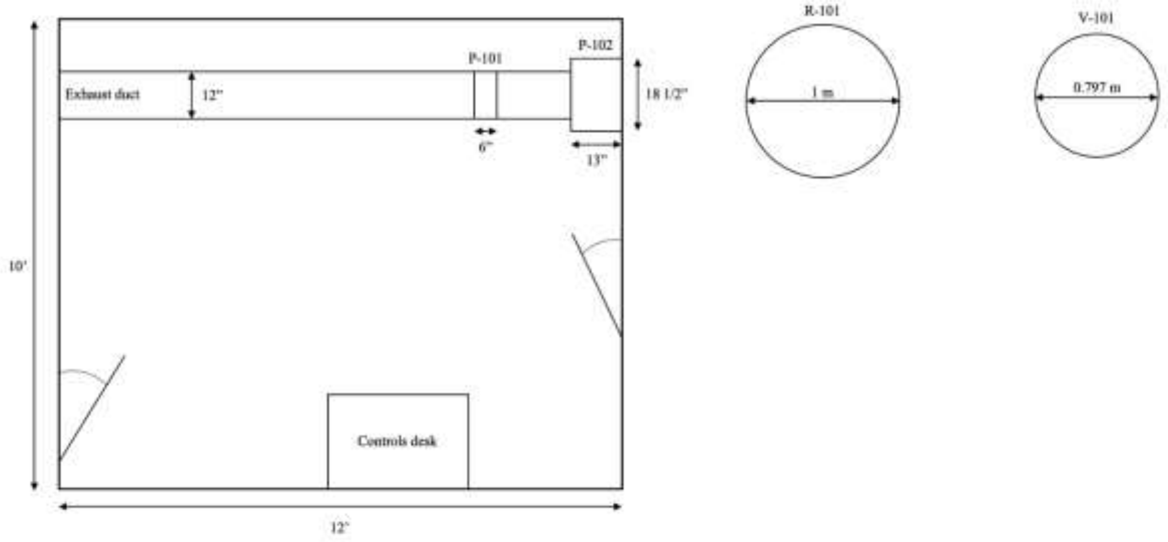

Figure 19. Layout Diagram of Biofilter Design (Top)

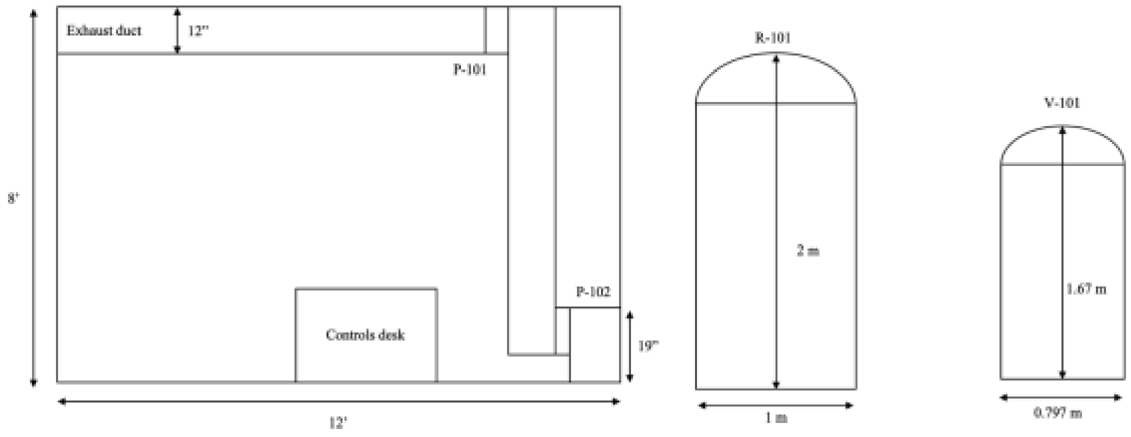

Figure 20. Layout Diagram of Biofilter Design (Side)

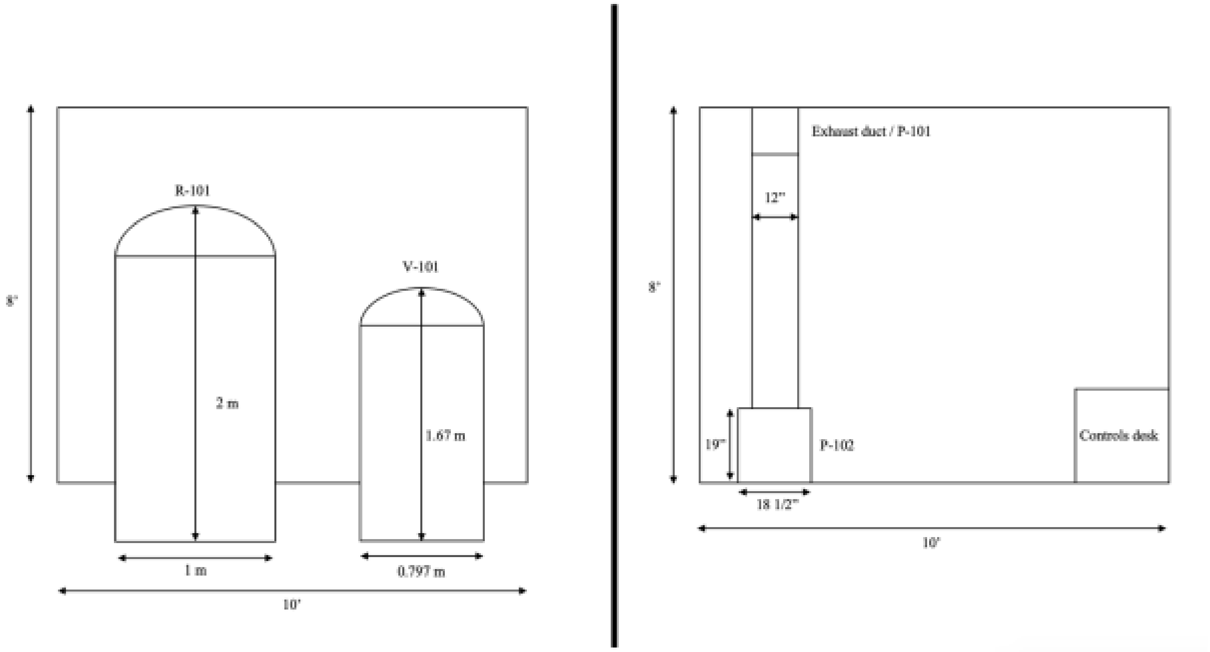

Figure 21. Layout Diagrams of Biofilter Design. The left is the front view from the outside perspective, while right is the front view from the inside perspective.

5.3.3 Piping and Instrumentation Diagram (P&ID)

Figure 22 below shows a P&ID for the biofilter set up. A P&ID is a more detailed diagram than the PFD that shows all the process equipment, the piping, and the control systems in place. Details on the sizing of the equipment can be found previously in the layout section of this report and in the equipment specifications section.

There are control systems in place that regulate the humidity of the air stream and the moisture level inside the biofilter media. There are flowrate and temperature indicators on the inlet and outlet air streams. There is also a level indicating controller on the bottom of the biofilter to manage the wastewater build-up. More details about the control units can be found in the controls section of this report.

Piping dimensions were determined from the layout diagram and specific equipment needs. Details on the piping sizes, material of construction, and insulation can be found in the layout section of this report.

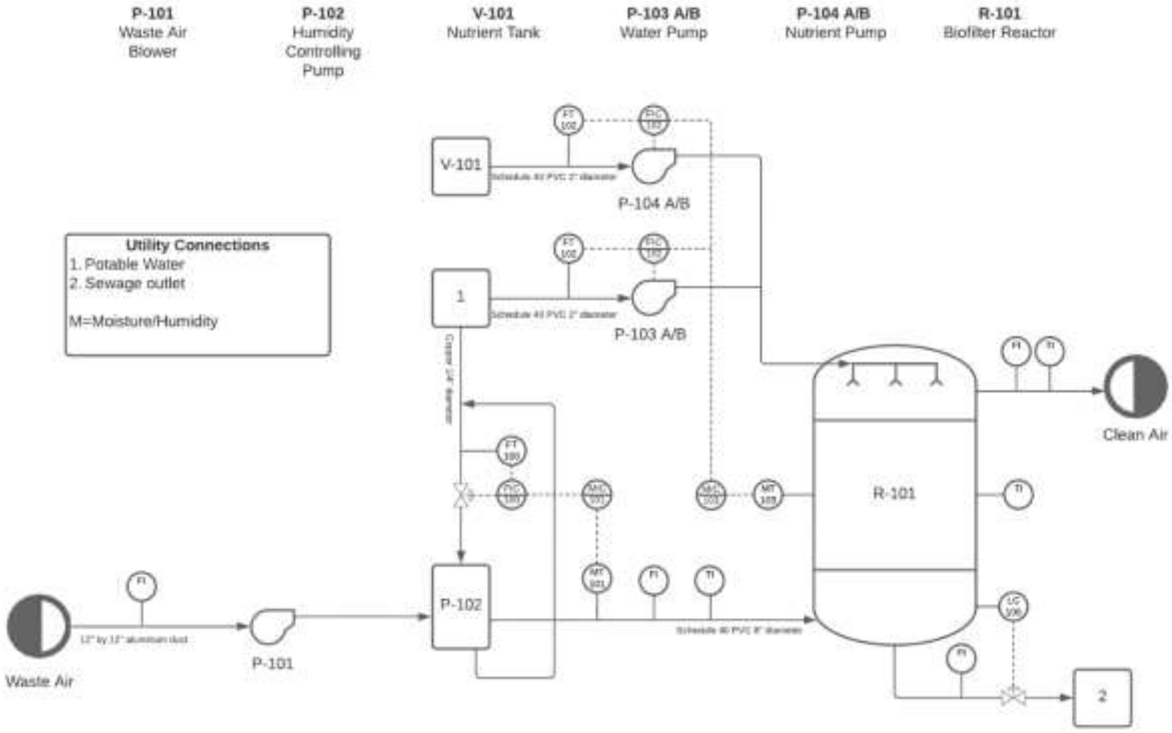

Figure 22. Piping and Instrumentation Diagram of Process

5.3.4 Equipment Specifications

The following table shows details of all major equipment in the biofilter process. Information on the pricing of these materials can be found in the economics section of this report.

Table 5. Major Equipment Specifications

	V-101	P-101	P-102	P-103	P-104	R-101
MOC	SS	Aluminum & steel	SS	CS	CS	SS
Diameter	0.797 m	-	-	-	-	1m
Height	1.67 m	12 in	19 in	-	-	2 m
Type	Insulated	Blower	Humidity Pump	Centrifugal	Centrifugal	Insulated
Volume	0.833 m^3	-	-	-	-	6.28 m^3

Pressure In	1 barg	1 barg	1 barg	1 barg	1 barg	
Pressure Out	-	1 barg	1 barg	1 barg	1 barg	1 barg
Temp In	25°C	35°C	35°C	25°C	25°C	40°C
Temp Out	25°C	35°C	40°C	25°C	25°C	40°C
Efficiency	-	-	-	0.86	0.86	-
Power	-	120 V	115 V	1.16 kW	1.16 kW	-
Length	-	12 in	13 in	-	-	-

5.3.5 Containment

The major equipment P-101 and P-102 are kept in a separate room within the growing facility. All other major equipment, V-101, P-103, P-104, and R-101 are kept outside the growing facility to prevent any potential risks that could be present if the equipment was kept inside. Extra ventilation is not necessary as the exhaust from the growing facility will replace ventilation.

5.3.6 Controls

5.3.6.1 Indicators, Transmitters, and Controllers

The first control system is a humidity/moisture control on stream 3, which exits the humidifier P-101. There is a moisture transmitter (MT) connected to a moisture indicating controller (MIC), that connects to a flow indicator and control (FIC) and a flow transmitter (FT) on stream 6. Stream 6 is the water that is supplied to the humidifier. Humidity is important in a biofilter because water content in a biofilter is an indirect index of availability, as water is the primary contact between the pollutant and the microbes that metabolize it. The MT reads the moisture content in stream 3, the FT reads the flow rate of water in stream 6. The MIC and FIC adjust the flow rate of the water in stream 6 through a valve based on the desired moisture content for the exiting stream.

The last controller for the air stream entering the biofilter is a flow controller on P-102. This pump will control the flow rate of the contaminated air based off of the load requirements for the biofilter. There is a FT that reads the flow rate of stream 3. The stream exiting the pump (stream 4) now has controlled temperature, humidity, and flow rate.

In addition to the air condition controls, the biofilter needs a controlled moisture content within the filter media. There is a MT located in the biofilter media that is connected to a MIC and two FIC that controls the flow rates of streams 8 and 10 through a pump. A FT on streams 7 and 9 reads the flow rate of this stream. Stream 11 consists of water as well as nutrients that will maintain the moisture level in the biofilter and feed the microbes in the biofilter. Stream 11 leads to an irrigation system inside of the biofilter that distributes the water and nutrients evenly.

There are multiple flow indicators (FI) and temperature indicators (TI) throughout the system. There is a FI on streams 3, 12, and 13 and TI on streams 3 and 12. There is also a TI located within the reactor itself.

Lastly, there is a level controller (LC) located at the bottom of the biofilter, below the bed media. As water and nutrients are added to the biofilter, some of the liquid is bound to drain out. Since the reactor is a closed system, this water build-up can clog the contaminated air entering, which may lead to water backing up the pipes. The LC on the filter connects to a valve that will drain the filter when the level reaches a certain height, this will drain to wastewater sewage or can be recycled to water and fertilize plants in the facility.

5.3.6.1 Operators and Security Measures

To prevent the system from sabotage, there is security within the growing facility. There will be fencing and cameras around the perimeter of the building so the equipment outside can be monitored. Also, there will be cameras within the control room inside the growing facility that holds the control panel, pumps, and other equipment. The door to the room inside the growing facility will have a lock on it to allow only approved employees to have access to the control panel. An employee must check the control room every day of operation to monitor the control panel, equipment, and overall process. There will be alarms set in place to notify the staff if anything reaches a dangerous level so that the problem can be resolved immediately.

5.4 Economics

For this design it was important to know the total capital cost and the total annualized cost of the project. Any calculations that were done to determine these prices can be found in Appendix B.

5.4.1 Base Cost

First, the capital cost was calculated by determining the equipment and material costs. CAPCOST was utilized to price most of the equipment. Exceptions were the humidifier and the blower which were based on equipment found on the McMaster-Carr website, and the biofilter which was priced using *Biofiltration for Air Pollution Control* (Devinny et al, 1999). Information from a cost-estimate of a full-scale biofilter was also used to price the materials needed including the medium and its installation as well as the biofilter liner. These prices were researched to confirm their accuracy and can be seen in Table 6 below.

Table 6. Summary of Equipment and Material Costs

Equipment	
Name	**Cost**
Biofilter (R-101)	$6,283.20
Nutrient Tank (V-102)	$12,300
Blower (P-101)	$800
Humidifier (P-102)	$1,100
Pump 1 (P-103 A/B)	$15,300
Pump 2 (P-104 A/B)	$15,300
Medium	
Name	**Cost**
Compost	$193.51
Install	$13.08
Other	
Name	**Cost**
Liner	$348.70
Capital Cost	
TOTAL	**$51,638.49**

After obtaining the capital cost above, the total capital cost was able to be calculated by taking the piping, electrical, equipment installation, and engineering design costs into account. The breakdown of these costs can be seen in Table 7 below, where the total capital cost was determined to be $66,097.27.

Table 7. Total Capital Cost Breakdown

Contributions	**Cost**
Capital Cost	$51,638.49
Piping (10% of Capital Cost)	$5,163.85
Electrical (4% of Capital Cost)	$2,065.54
Equipment Installation (4% of Capital Cost)	$2,065.54
Engineering Design (10% of Capital Cost)	$5,163.85
TOTAL CAPITAL COST	**$66,097.27**

5.4.2 Annualized Costs

Next the annual cost was calculated to determine the cost per year for the next 12 years. The total annualized cost is a combination of the annual capital, operating, and medium replacement costs. These annualized costs are evaluated based on the present value of each component and then taking the inflation and interest rates into account. The capital cost was already known from previous calculations, but the operating cost had to be determined. As for the cost of the medium replacement, that includes the cost of the compost and installation which can be seen in Table 9 as well as the medium removal cost which is $37.13.

As mentioned previously, before calculating the total annual cost, the total operating cost had to be determined. This price is based on the water consumption of the system as well as the electricity used by the pumps, humidifier, and blower. The water consumption cost was determined by estimating the amount of water required annually to keep the system in operation, the electricity cost of the three pumps were determined in CAPCOST, and the electricity costs of the humidifier and blower were determined based on their electricity output detailed on the McMaster-Carr website. A summary of these costs can be found in Table 8 below.

Table 8. Summary of Operating Costs

Electricity	
Equipment	**Cost**
Blower (P-101)	$5,256
Humidifier (P-402)	$84.56
Pump 1 (P-403)	$652
Pump 2 (P-404)	$652
Water Consumption	
Equipment	**Cost**
Water Supply	$1,300
Operating Cost	
TOTAL	$7944.56

Once the operating cost was found the annualized cost could be calculated. First, for the annualized capital cost we assumed a 3.75% interest rate over 12 years and using Equation 1 it was found to be $6941.03 yr^{-1}.

$$Annualized\ Capital\ Cost = Initial\ Capital\ Cost \times (A/P, 3.75\%, 12) \tag{1}$$

For the annualized operating costs, we assumed a 3.5% rate of inflation over a 12-year period which was then plugged into Equation 2 to find the total cost over 12 years. This number was then divided by 12 to get $10,005.53 yr^{-1}.

$$Total\ Cost\ Over\ 12\ Years = \sum_{1}^{n} Annual\ Op\ Cost \times (F/P, 3.5\%, 12) \tag{2}$$

The annualized medium replacement cost was a more difficult calculation as it only needs to be replaced every 5 years. So, in the 12-year lifetime of the project it will only be replaced in years 5 and 10. To solve this, Equation 3 was used, and we assumed a 3.5% inflation rate as well as a 3.75% interest rate over 12 years. This value was found to be \$39.16 yr^{-1}.

$$\begin{aligned} &\mathit{Annualized\ Medium\ Replacement\ Cost} \\ &\quad = \mathit{Medium\ Replacement\ Cost} \times (F/P, 3.5\%, 5) \times (P/F, 3.75\%, 5) \times (A/P, 3.75\%, 12) \\ &\quad + \mathit{Medium\ Replacement\ Cost} \times (F/P, 3.5\%, 10) \times (P/F, 3.75\%, 10) \times (A/P, 3.75\%, 12) \end{aligned} \tag{3}$$

Finally, these three costs were added together to get a total annualized cost of \$19,042.28 yr^{-1}. A summary of these costs can be seen in Table 9.

Table 9. Summary of Annualized Costs

Contributions	**Annualized Costs**
Capital Costs	\$6,941.03 yr^{-1}
Operating Costs	\$10,005.53 yr^{-1}
Medium Replacement Costs	\$39.16 yr^{-1}
TOTAL ANNUALIZED COST	**\$16,985.71 yr^{-1}**

5.4.3 Base Liability

The biofilter being designed is intended to reduce the environmental impact of *Cannabis* growth by greatly reducing the release of terpenes and therefore reducing ground level ozone pollution from VOCs. Since this system is a safety system meant to protect both the environment and humans from ground level ozone pollution it eliminates the liability of the *Cannabis* grower's environmental impact. Since this system is required to control emissions based on federal and/or state regulations, there is no possible base case with no safety systems in place.

Additionally, there is no scenario that would result in the injury or death of a worker. Based on the ALOHA simulations, even the maximum possible release would not contain enough terpenes to cause significant damage. If a worker or bystander were to experience health effects from ground-level ozone pollution the company would not be liable for such an impact as there is no way to determine when this occurred. Also, it most likely would have had to happen over time since an instant release would not contain enough to affect anyone. Since the system is a mandated safety system and there are no potential accidents that could cause significant damage, the base liability for this design is zero.

5.5 Alternate Design

While a biofilter is one solution to this air emission concern, there are multiple viable ways to reduce air pollution in an indoor *Cannabis* growing facility. This section is aimed to critically analyze an alternative design of a carbon air filtration system that will accomplish the same job as the biofilter. Carbon filtration is a widely used process and can be applied to odorous systems such as terpene removal. This report will detail the critical information of the carbon filter design, as well as compare the advantages and disadvantages of the two unique systems.

5.5.1 The Disadvantages of Biofilters

The biofilter design has many advantages and disadvantages. Some advantages include its minimal maintenance, its effectiveness on multiple pollutants, its use of common and organic materials, and its relative ease of construction (Devinny et al., 1999). Potential disadvantages are its large footprint, its potential impact on the building's ventilation system, its moisture maintenance requirements, and its large initial cost (Chen, L. 2009). It is important to consider these advantages and disadvantages when designing any system so that the most practical decisions are made for this particular process.

The large footprint associated with biofilters is a major disadvantage for indoor *Cannabis* growing facilities, especially those that are located in tight quarters. For example, the proposed biofilter design is located in the Fenway neighborhood of Boston, Massachusetts. The design requires the use of three outdoor vessels to treat the contaminated air. Two of the tanks are for liquid storage, and one larger vessel is the biofilter reactor unit. These units are located approximately 8 feet away from the building, where the facility has empty outdoor space. If an alternative, more compact filter was used, this space could be used as extra parking, a delivery loading dock or in many other useful ways.

The proposed biofilter design uses multiple pumps and blowers to ensure the functionality of the building's ventilation system. Additionally, the design incorporates sensors and automated pumps to maintain the proper moisture requirements needed for an efficient removal. The large initial capital investment of a biofilter can potentially be reduced by using house sourced compost and filter media. While the equipment is expensive, the appeal is minimal maintenance and replacement.

5.5.2 Carbon Filtration

Carbon filtration utilizes a bed of activated carbon to remove pollutants through adsorption. Activated carbon is a highly porous substance with a significant surface area, making it ideal for adsorption applications. The particles or pollutants entering the media become trapped inside of the matrix of pores inside the carbon molecules, and the large surface area allows for a significant amount of pollutants to adsorb before the filter media is considered spent (Sorrels, 2018). Carbon filtration can be used for many designs including air filtration, water filtration, and other gas and liquid processing. These filters are even commercialized for the use of respirator masks, fish tank filters, and even vehicle emission filters. For air filtration applications, carbon filters have been proven to effectively remove VOCs and odors from air streams (Metts & Batterman, 2006).

Carbon filters are relatively simple in design. They are easy to install, and up to 98% effective when properly maintained and replaced (Metts & Batterman, 2006). Currently, the Denver *Cannabis* Environmental Best Management Practices Guide recommends carbon filters as the best way to reduce VOC and odor emissions for indoor growing facilities.

While the microbes found in biofilters metabolize the pollutants, eliminating the need for frequent media replacements, carbon filters only adsorb the pollutants and trap them within the pores of the activated carbon molecules. This means that the filter will need to be replaced or recovered every 6-12 months in order to remain effective (Xiao, 2017). This is a disadvantage when compared to the biofilter, since biofilters only need to be replaced every 5-10 years. Similarly to biofilters, carbon filters have multiple advantages and disadvantages; therefore, it is hard to say that one is clearly better than the other.

5.5.3 Basic Design

The following section details the basic design of the carbon filter set up to control an exhaust air stream from a *Cannabis* growing facility. This includes a process flow diagram, a layout diagram, a piping and instrumentation diagram, as well as additional specifications on the equipment featured in this design.

5.5.3.1 PFD

Figure 19 shows a process flow diagram for the activated carbon filter design. This design features one blower, two vessels, and one condenser. The blower ensures proper air ventilation inside the building. The two vessels are fixed bed activated carbon filters. There are two of them because as one is active, the other is regenerating through the use of steam. This allows one filter to be active at all times. Steam desorbs the VOCs from the carbon and the impurities and exits through the water waste stream. The condenser ensures that the steam is in liquid form when being processed for waste.

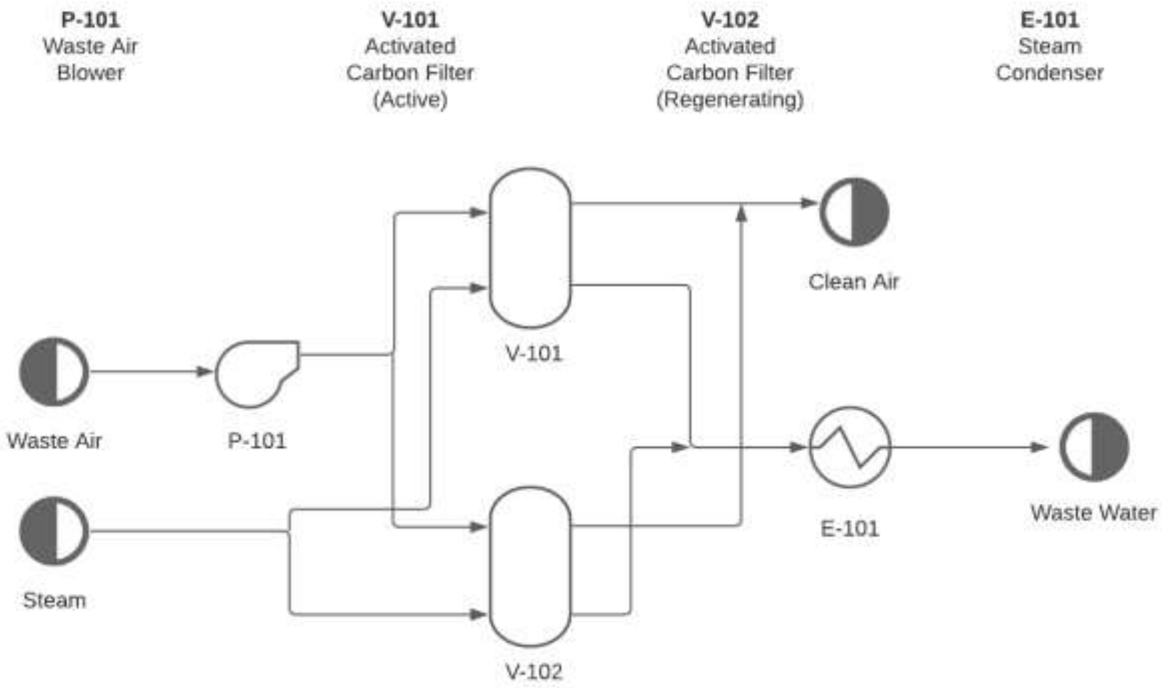

Figure 19. PFD of Activated Carbon Filter

5.5.3.2 P&ID

Figure 20 shows the P&ID for the activated carbon filter design. The utility connections needed for this design are a steam generator and a cold-water source. Details on the sizing of the equipment can be found in the layout section of this chapter. Additionally, information on the controls of this system can be found in the controls section of this chapter.

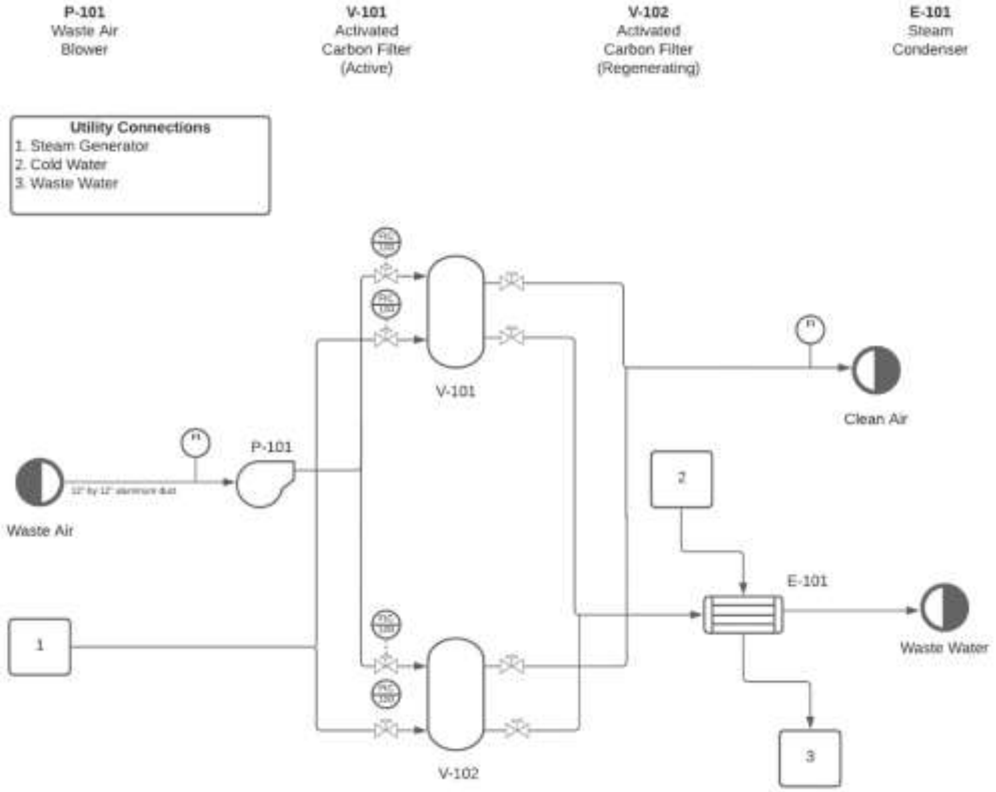

Figure 20. P&ID of Activated Carbon Filter

5.5.3.3 Layout

Figures 21, 22, 23 show the layout diagrams for the carbon filtration process. Here, we can see that none of the equipment needs to be housed outdoors, which is one benefit to the carbon filter design. Similarly to the biofilter, the carbon filter will need a 10 ft by 12 ft room which will have the filters, other equipment, and the controls desk.

The floor plan of the control room shows that the room is 10x12 ft. This room has two exits, one leading inside to the growing room, and the other leading outside. The rooms' dimensions and exits both follow the International Building Code. Since equipment is in operation inside of this room, the room must have good ventilation, as well as carbon dioxide and carbon monoxide detectors. To ensure the exhaust air stream is relatively consistent and constantly flowing, a blower is used to control the exhaust airflow. This will result in the building being slightly negatively pressurized, meaning outside air will likely be pulled through any doors, windows, or other areas where there are leaks in the building. The exhaust air blower is located in the exhaust vent as a fan that is 12x12 in. It is important that this fan can generate enough power to handle the air flow of the entire building. The vessels which are used as the filter beds are 3.6 ft in diameter and 5.3 ft tall. Each vessel is designed to hold 1000 lbs of carbon, which is assumed to be enough carbon to filter all VOCs out of the exhaust stream.

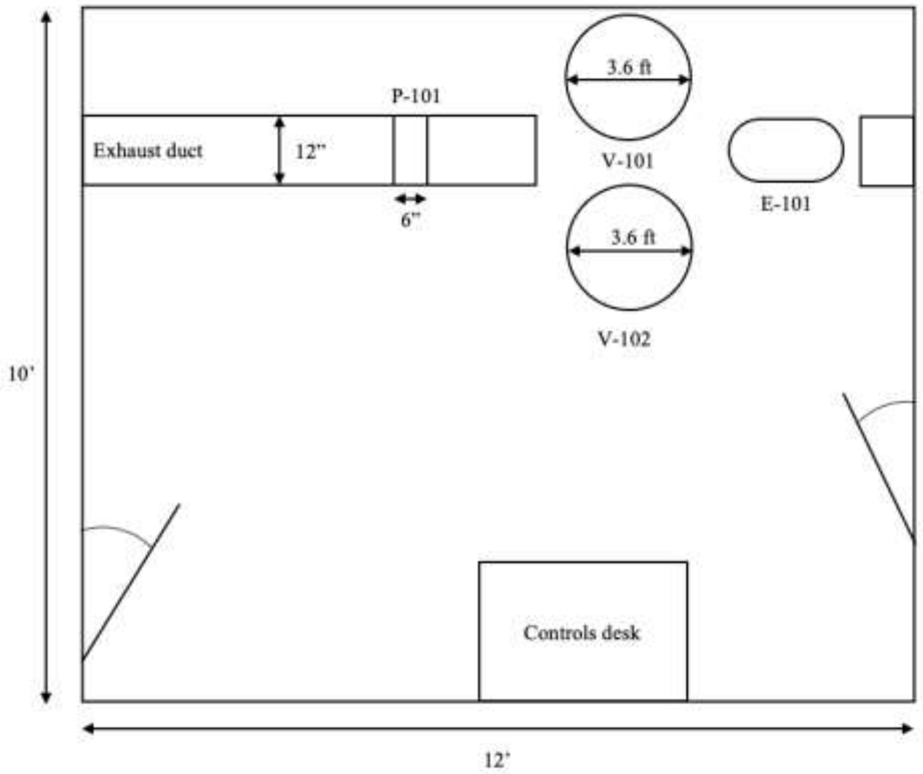

Figure 21. Top-view Layout Diagram of Activated Carbon Filter

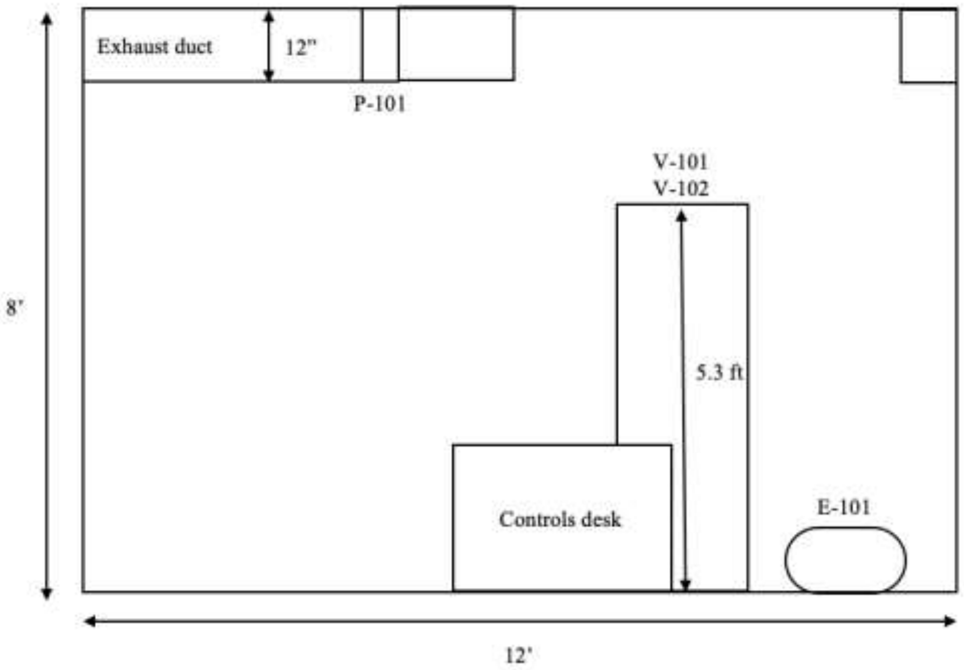

Figure 22. Side-view Layout Diagram of Activated Carbon Filter

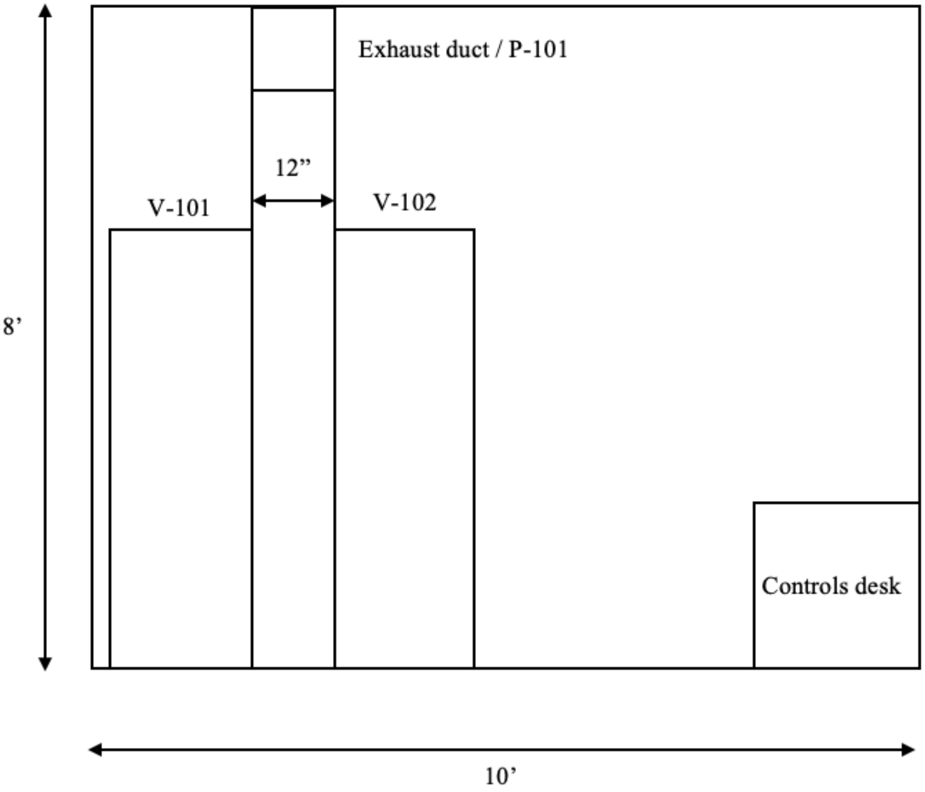

Figure 23. Front-view Layout Diagram of Activated Carbon Filter

5.5.3.4 Controls

The carbon filter is much simpler than the biofilter in terms of equipment and control systems. During the filter process, one bed is actively acting as the filter, while the other bed is regenerating using steam. There is only one control system needed per stream, which is connected to the inlet valves of each filter bed. These flow indicating controllers are set on a timer and alternate which bed is treating the contaminated air, and which bed is regenerating with steam.

5.5.4 Economics of Activated Carbon Filtration

For this design, an economic analysis was performed to determine the base cost as well as the annualized cost of operating the activated carbon filter. While this analysis is complete, it is more basic than the analysis from the previous report on the biofilter, therefore some cost variables are left out. This base cost analysis includes the total cost of all equipment needed for the design. This base cost does not include the installation, electrical components, and design costs. The annualized cost includes the annualized capital cost, utilities (steam, cold water, and electricity) and the cost of medium replacements.

5.5.4.1 Base Cost

This base cost is determined using the cost of the major equipment needed as well as an estimation of the cost of other supplies based on the systems operation parameters. The cost of the vessels was found through CAPCOST, and the cost of the carbon was assumed to be $1.90 per pound of carbon. The rest of the equipment cost was estimated using the following relationship (Sorrels, 2018).

$$C_A = R_c\left[C_c + C_v\left(N_A + N_D\right)\right]$$

Here, C_A is the total adsorber equipment cost, C_C is the cost of carbon, C_V is the cost of the vessels, and N_A and N_D are the number of adsorbers and number of desorbers respectively. The ratio R is assumed to be 2.24 (Sorrels, 2018). Calculations for the pricing of the carbon and the vessels can be found in Appendix B.

After computing this estimation, the total equipment cost of the adsorber was found to be \$31,942.

5.5.4.2 Annualized Cost

The annualized cost was used to determine how much this design would cost to operate per year over a twelve-year life. First, the utility costs were estimated using operating parameters of the system. The calculation of the utility costs for steam, cold water, and electricity were computed through CAPCOST and relationship estimations, which can be found in the appendix.

The total utility cost was found to be \$24,104 yr^{-1}. Next the medium replacement cost was found. It is assumed that the carbon needs to be replaced every 5 years. This totals to \$3,800 per replacement, which is twice in the plant's lifetime. Finally, the capital cost, utility cost, and medium replacement cost were annualized to determine the total annualized cost of the carbon filter operation. These calculations can be found in the appendix. The total annualized cost of the carbon filter was found to be \$34,146 yr^{-1}.

6.0 Conclusion

Throughout the course of this project, there has been minimal research provided on biofiltration specifically with an application in the *Cannabis* industry. Instead, we collected research on other applications of biofiltration and designed a bench-scale model to determine the effectiveness of using biofiltration to remove terpenes from the air. The research conducted aided in the design of the bench-scale model and helped to understand the mechanisms driving the biological removal of contaminants. This led to the characterization of a waste stream similar to that of a *Cannabis* facility, as well as gained knowledge on the ideal performance parameters and operating conditions. This research also involved understanding the advantages and disadvantages to biofiltration, as well as other air purification technologies.

This research led to the design and creation of a bench-scale biofilter. There were some setbacks with the design that opened opportunities for problem solving and revision of the initial design. These setbacks only increased the value of this hands-on learning experience and provided a better end result in the long run. With the successful construction of the bench-scale biofilter, and experimentation involving GC analysis, the group was able to determine some of the key performance parameters and provide a proof of concept.

For the first biofilter, containing the compost and woodchip mix along with activated carbon, was found to be less effective at removing terpenes than the second biofilter which did not contain activated carbon. While this goes against our initial hypothesis, both filters resulted in an average removal efficiency that was more effective than expected. Biofilter #1 had an average removal efficiency of 64.53%. By calculating the volumetric mass loading rate and plotting against the elimination capacity, there was a linear trend discovered where the slope was equal to 0.7076.

The second biofilter was found to be more effective, with an average removal efficiency of 67.35%. The trend associated with loading rate and elimination capacity was also found to be linear, giving a slope of 1.005. With this data, we expect that both biofilter columns could handle a higher loading rate and would eventually reach a maximum elimination capacity. It can also be determined from this data that the removal was driven by mass transfer processes rather than kinetics.

By obtaining relative concentrations of contaminant in the inlet and outlet streams, and estimating the terpene concentration from a *Cannabis* facility, the bench-scale design was partially scaled-up to a full-scale model. This design allows the reader to visualize what a full-scale model would look like and all equipment specifications necessary to construct the model. This information allowed the group to conduct an economic analysis and compare costs to that of an activated carbon filter, which proved that biofiltration would be the economically and environmentally feasible option.

Finally, all this information has created vast opportunities for continued research and experimentation. Further analysis to characterize the waste stream and compare it to air emissions from an actual *Cannabis* facility could help to create a more accurate full-scale model. This would allow for more accurate experimentation with contaminant load per unit of filter volume. There are also many opportunities for experimentation to determine the ideal performance parameters such as temperature, water content, filter media and general operating conditions. This issue is only going to worsen as the *Cannabis* industry expands across the United States, and this research could contribute to finding a sustainable solution to control odor and VOC emissions.

7.0 References

Bureau of Waste Prevention. (2003). Responding to Local Noise, Odor, and Dust Complaints [Fact sheet]. Massachusetts Department of Environmental Protection. https://www.mass.gov/doc/how-municipalities-should-respond-to-noise-odor-dust-complaints-0/download

Climate and Clean Air Association. (n.d.) Tropospheric Ozone. CCAC. https://www.ccacoalition.org/en/slcps/tropospheric-ozone

County of Santa Barbara. (2017). Final Environmental Impact Report (EIR) for the *Cannabis* Land Use Ordinance and Licensing Program. Vol 2. SCH No. 2017071016. http://*Cannabis*.countyofsb.org/uploadedFiles/*Cannabis*/Documents/Final_PEIR/Santa%20Barbara_*Cannabis*_FEIR-Volume%202.pdf

Cox-Georgian D., Ramadoss N., Dona C., Basu C. (2019) Therapeutic and Medicinal Uses of Terpenes. In: Joshee N., Dhekney S., Parajuli P. (eds) Medicinal Plants. Springer, Cham. DOI: 10.1007

Devinny, J.S., Dushusses, M.A. & Webster, T.S. (1999). Biofiltration for Air Pollution Control. Lewis Publishers.

Devinny, J.S. & Ramesh, J. (2005) A Phenomenological Review of Biofilter Models. Chemical Engineering Journal, 113, 187-196. DOI: 10.1016

(1) Environmental Protection Agency. (n.d.). Air Pollution Control Technology Fact Sheet – Catalytic Incinerator. EPA. https://www3.epa.gov/ttncatc1/dir1/fcataly.pdf

(2) Environmental Protection Agency. (n.d.). Air Pollution Control Technology Fact Sheet – Thermal Incinerator. EPA. https://www3.epa.gov/ttnchie1/mkb/documents/fthermal.pdf

(3) Environmental Protection Agency. (n.d.). Clean Air Act Overview. EPA. https://www.epa.gov/clean-air-act-overview/clean-air-act-text#toc

(4) Environmental Protection Agency. (n.d.). Consumer Products: National Volatile Organic Compound Emission Standards. EPA. https://www.epa.gov/stationary-sources-air-pollution/consumer-products-national-volatile-organic-compound-emission

(5) Environmental Protection Agency. (n.d.). NAAQS Table. EPA. https://www.epa.gov/criteria-air-pollutants/naaqs-table

(6) Environmental Protection Agency. (n.d.). Technical Overview of Volatile Organic Compounds. EPA. https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds

Fricke, W., Goddeeris, L. (2018). *Local Impacts of Commercial Cannabis*. International City/County Management Association. ICMA. https://icma.org/sites/default/files/Local%20Impacts%20of%20Commercial%20*Cannabis*%20Final%20Report_0.pdf

Gu, S., Guenther, A., & Faiola C. (2021). Effects of Anthropogenic and Biogenic Volatile Organic Compounds on Los Angeles Air Quality Environmental Science & Technology. 2021 *55* (18), 12191-12201 DOI: 10.1021

Helmer, Jodi. (2019). The Environmental Downside of *Cannabis* Cultivation. *JSTOR*. https://daily.jstor.org/the-environmental-downside-of-*Cannabis*-cultivation/.

Hodzic, A. (2004). 12 - Re-use, recycling and degradation of composites. https://www.sciencedirect.com/science/article/pii/B9781855737396500154

Husain, H. Verhaeghe, L., Webb. D. (2012). A case study of a high rate biological odour control system Influents, 8, pp. 34-35.

Jordan, K. (n.d.) *Cannabis* Facilities: Air Filtration, UV-C Air Disinfection and Odor Removal. National Air Filtration Association. https://www.nafahq.org/*Cannabis*-facilities-air-filtration-uv-c-air-disinfection-and-odor-removal/#:~:text=Currently%2C%20the%20most%20efficient%20and,18%20air%20changes%20per%20hour.

Kraakman, N. J., Rocha-Rios, J., & van Loosdrecht, M. C. (2011). Review of mass transfer aspects for biological gas treatment. *Applied microbiology and biotechnology*, *91*(4), 873–886, DOI: 10.1007.

Li, Y., Barth, M. C., Chen, G., Patton, E. G., Kim, S.-W., Wisthaler, A., Mikoviny, T., Fried, A., Clark, R., and Steiner, A. L. (2016), Large-eddy simulation of biogenic VOC chemistry during the DISCOVER-AQ 2011 campaign, *J. Geophys. Res. Atmos.*, 121, 8083– 8105, DOI: 10.1002.

National Conference of State Legislature. (2022). State Medical *Cannabis* Law. NCSL. https://www.ncsl.org/research/health/state-medical-marijuana-laws.aspx

Samburova V., McDaniel M., Campbell D., Wolf M., Stockwell W. R. & Khlystov A. (2019). Dominant volatile organic compounds (VOCs) measured at four *Cannabis* growing facilities: Pilot study results, Journal of the Air & Waste Management Association, 69:11, 1267-1276, DOI: 10.1080/10962247.2019.1654038

Shareefdeen, Zarook. (2020). Chapter 9 - Industrial Biofilter Case Studies. *Biofiltration to Promising Options in Gaseous Fluxes Biotreatment*. p.p 177-192. DOI: 10.1016

Sommano SR, Chittasupho C, Ruksiriwanich W, Jantrawut P. (2020) The *Cannabis* Terpenes. *Molecules*. 25(24):5792. DOI: 10.3390

Swanson, W.J., Loehr, W.J. (June 1997). Biofiltration: Fundamentals, Design and Operations Principles, and Applications. *Journal of Environmental Engineering*. 123(6). DOI: 10.1061

Tsang, Y. F. , Wang, Y., Wang, H., Yang, Y., YuanhuiZhang, Y., & Chua, H. (2017). Biodegradation of Ammonia in Biofiltration Systems: Changes of Metabolic Products and Microbial Communities. In (Ed.), Nitrification and Denitrification. IntechOpen. DOI: 10.5772

United States Environmental Protection Agency. (2003). Air Pollution Control Technology Fact Sheet. [PDF]. *EPA. https://nepis.epa.gov/condensationscrubberfactsheet*

Wartenberg A. C., Holden P. A., Bodwitch H., Parker-Shames P., Novotny T., Harmon T. C., Hart S. C., Beutel M., Gilmore M., Hoh E., and Butsic V. (2021). *Cannabis* and the Environment: What Science Tells Us and What We Still Need to Know. Environmental Science & Technology Letters. *8* (2), 98-107 DOI: 10.1021

Zhu, X., Suidan, M.T., Pruden, A., Yang, C., & Alonso, C. (2004). Effect of Substrate Henry's Constant on Biofilter Performance. *Air & Waste Manage. Assoc. 54:409–418.* DOI: 10.1.1.611.5191

8.0 Appendices

Appendix A: OAP from *Cannabis* Land Use Ordinance and Licensing Program

The following list includes the elements required for a *Cannabis* cultivation facility's OAP:

- Odor abatement strategies within the *Cannabis* activity site that would be implemented to prevent persistent, intrusive or pervasive odors outside the property boundary, particularly within any nearby residential neighborhoods, including, but not limited to, the following:
    - Activated carbon filtration systems, such as:
        - Ventilation systems, in which odor-causing agents are adsorbed and filtered through activated carbon
        - Canisters, in which activated carbon ventilation systems are supported by activated carbon gas canisters
    - Vapor-phase systems, in which deodorizing liquids are vaporized and dispersed where necessary within the *Cannabis* site, altering the chemical composition of *Cannabis* terpenes into a neutralized chemical odor.
        - The resulting odors must be odor-neutralizing, not odor-masking
        - The technology must not be utilized in excessive amounts to produce a differing scent (such as pine or citrus)
        - Use of these systems must have supporting documentation which meet USEPA's Acute Exposure Guideline Levels (AEGLs) or similar public health threshold
    - Other odor controls systems or agricultural practices that can be shown to be effective in controlling odors.
    - Adequate distance from residentially-zoned neighborhoods, and the permitting official shall have the discretion to determine the necessity of the system.
- The name and telephone number of a designated individual who is responsible for logging in and responding to odor complaints, 24 hours a day, 7 days a week;
- Providing property owners and residents of property within a 1,000-foot radius of the *Cannabis* facility with the contact information of the individual responsible for responding to odor complaints;
- Policies and procedures describing the actions to be taken when an odor complaint is received, including the training provided to the staff on how to respond;
- Description of potential methods for reducing odors, including feasible addon air pollution control equipment;
- Contingency measures to curtail odor emissions in the event of a continuous public nuisance;
- Require the designated individual to report all odor complaints to the appropriate County department within a reasonable time frame and to record and report the steps they took to resolve the issue; and
- For sites that generate recurring odor emissions that have been documented to be persistent, intrusive, or pervasive in nearby residential neighborhoods include an enforceable process to require additional control equipment or operational changes to mitigate odors.

Appendix B: Economic Analysis Calculations

Total Capital Cost Calculation

Initial Site Preparation Calculation:

Filter bed volume (V) = Q x EBRT

$$V = 5.23\ m^3 = 184 ft^3; Q = 600\ cfm;\ therefore\ EBRT = 0.3067\ min$$

Assuming 20% safety factor

$$V_{safety} = V \times 1.2 = 6.26\ m^3$$

Reactor Cost Calculation:

\$1000 per m^3 filter bed (D=1 m, H=2 m)

$$Volume = \pi r^2 h = 6.28\ m^3$$
$$Reactor\ Cost = \$1000 m^{-3} \times 6.28 m^3 = \$6283.20$$

Medium Costs:

Compost: Assume \$37 per m^3 for compost

$$Compost\ Cost = \$37 m^{-3} \times 5.23 m^3 = \$193.51$$

Installation: Assume \$0.7 m^3 to rent equipment, \$1.1 m^3 for labor, \$0.7 m^3 profit/overhead

$$Installation\ Cost = \$2.5 m^{-3} \times 5.23 m^3 = \$13.08$$

Total Medium Cost:

$$Medium\ Cost = \$193.51 + \$13.08 = \$206.59$$

Liner Cost:

Assume liner cost \$22 per m^2

$$Liner\ Required = A_{Liner} = 7.85 m^2 + (1m \times 2m) + 2(1m \times 2m) = 15.85 m^2$$
$$Liner\ Cost = \$22 m^{-2} \times 15.85 m^2 = \$348.70$$

Annualized Cost Calculations

Operating Calculations

Electricity Use:

Humidifier: 13 gal/day output, 120 V = 0.161 hp

$$Annual\ Humidifier\ Electrical\ Consumption = C_{Humidifier}$$
$$= 0.161 hp \times \frac{0.75 kW}{hp} \times \frac{365 days}{yr} \times \frac{24 hr}{day} = 1057\ kWh$$

Blower: 10 hp

$$Annual\ Blower\ Electrical\ Consumption = C_{Blower} = 10hp \times \frac{0.75kW}{hp} \times \frac{365days}{yr} \times \frac{24hr}{day}$$
$$= 65700\ kWh$$

Pumps: \$652/yr

$$Annual\ Pump\ Cost = 2 \times \$652yr^{-1} = \$1304yr^{-1}$$

$$Electrical\ Cost = \left[\left(C_{Blower} + C_{Humidifier}\right) \times \$0.08kWh^{-1}\right] + C_{Pumps} = \$6{,}644.56yr^{-1}$$

Water Consumption:
Assume cost of water is \$0.70 m^{-3}
Assuming inlet air from the process stream is 50% saturated, it is estimated that 36 (m^3 wk^{-1}) will be used

$$Water\ Cost = 36m^3wk^{-1} \times 52\ wk\ yr^{-1} \times \$0.7m^{-3} = \$1300\ yr^{-1}$$

<u>Medium Replacement Costs</u>
Medium removal

Excavation, transportation, disposal = \$7.1 m^{-3} (multiply by volume of filter media)

$$Medium\ Removal\ Cost = \$7.1m^{-3} \times 5.23m^3 = \$37.13$$

$$Replacement\ Cost = \$37.13 + \$206.59 = \$243.72$$

<u>Annualized Costs:</u>
Capital Costs

Assume 3.75% interest rt over 12 yrs

$$Annualized\ Capital\ Cost = Initial\ Capital\ Cost \times (A/P, 3.75\%, 12)$$

$$Annualized\ Capital\ Cost = \$66{,}097.27\left[\frac{0.0375(1+0.0375)^{12}}{(1+0.0375)^{12}-1}\right] = \$\mathbf{6,941.03\ yr^{-1}}$$

Operating Costs

Assume 3.5% rate of inflation over a 12 yr time frame

$$Total\ Cost\ Over\ 12\ Years = \sum_1^n Annual\ Op\ Cost \times (F/P, 3.5\%, 12)$$

$$Annualized\ Operating\ Cost = \frac{\$6644.56(1+0.035)^1 + \cdots + 6646.56(1+0.035)^{12}}{12}$$
$$= \$\mathbf{10,005.53\ yr^{-1}}$$

Medium Replacement Costs

Assume 3.5% rate of inflation and 3.75% interest rt over a 12 yr time frame (only changing medium at 5 and 10 yrs)

$$
\begin{aligned}
&\mathit{Annualized\ Medium\ Replacement\ Cost}\\
&\quad = \mathit{Medium\ Replacement\ Cost} \times (F/P, 3.5\%, 5) \times (P/F, 3.75\%, 5)\\
&\quad \times (A/P, 3.75\%, 12)\\
&\quad + \mathit{Medium\ Replacement\ Cost} \times (F/P, 3.5\%, 10) \times (P/F, 3.75\%, 10)\\
&\quad \times (A/P, 3.75\%, 12)
\end{aligned}
$$

$$
\begin{aligned}
&\mathit{Annualized\ Medium\ Replacement\ Cost}\\
&\quad = \left(\$243.72(1+0.035)^{5} \times \left(\frac{1}{1+0.0375}\right) \times \left(0.0375(1+0.0375)^{12}\right)\right)\\
&\quad + \left(\$243.72(1+0.035)^{10} \times \left(\frac{1}{(1+0.0375)^{10}}\right)\right.\\
&\quad \left.\times \left(0.0375(1+0.0375)^{12}\right)\right) = \$\mathbf{39.16\ \boldsymbol{yr}^{-1}}
\end{aligned}
$$

$$
\begin{aligned}
&\mathit{Annualized\ Cost}\\
&\quad = \mathit{Annualized\ Capital\ Cost} + \mathit{Annualized\ Op\ Cost}\\
&\quad + \mathit{Annualized\ Medium\ Replacement\ Cost}
\end{aligned}
$$

$$
\mathit{Annualized\ Cost} = \$6{,}941.03 + \$10{,}005.53 + \$39.16 = \$\mathbf{16{,}985.71\ \boldsymbol{yr}^{-1}}
$$