5-2021

Assessing the Feasibility of a Biofilter in Medium-to-High Scale Industries

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ASSESING THE FEASIBILITY OF A BIOFILTER IN MEDIUM-TO-HIGH SCALE INDUSTRIES

A Thesis

by

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Submitted to the Graduate College of
The University of Texas Rio Grande Valley
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING

May 2021

Major Subject: Manufacturing Engineering

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May 2021

ABSTRACT

Garcia, Javier A., Assessing the Feasibility of a Biofilter in Medium-to-High Scale Industries. Master of Science in Engineering (MSE), May 2021, 67 pp, 10 tables, 16 figures, references, 56 titles.

The removal of volatile organic compounds, VOCs, from contaminated sources of air stream has become a major air pollution risk. Excessive amounts discharged to the atmosphere are highly risky to human health and to the environmental system. Demand for sustainable VOC control technologies has become crucial for the reduction of emissions. Biological treatments of waste gas streams, such as biofiltration, have proven to be cost effective and environmentally friendly compared to conventional pollution control technologies. The goal of this research is to simulate data for a given biofilter model, and to evaluate if it is economically and environmentally feasible to implement with a given set of conditions based on previous data. The model incorporates key parameters such as annual capital costs, investment costs, and annual operating costs. Results and observations show promise for developing a model that can reliably describe the effectiveness of a biofiltration system for medium scale industries.

DEDICATION

The completion of my master's studies would not have been possible without the love and support of my family, especially without the support of my father. My father inspired, motivated, and supported me by all means to accomplish this degree. Thank you for your devotion and patience. I love you dad; you are and will be my greatest inspiration in life.

ACKNOWLEDGEMENTS

I would like to thank my colleagues at UTRGV who helped me during my post-graduate career. Also, I would like to acknowledge the Manufacturing and Industrial Engineering Department, they treated me like family during these two and a half years.

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CHAPTER I

INTRODUCTION

Statement of the Problem

Every year, disproportionate amounts of VOCs, Volatile Organic Compounds, and waste gases are being discharged into the atmosphere which causes detrimental effects on human health, and to the environment. The main causes range from storage to transport, materials manufacture, printing industry, and several others (Zheng, Shen, Zhang, et al., 2017). Due to the Federal Air Act Amendment in the 1990's, and to the increasing amount of social awareness of removing these toxic compounds, this matter has gained importance over the past years.

Volatile Organic Compounds

VOCs are not only found in vehicles and industrial settings. There are many other sources that contribute to the formation of VOCs, this includes commercial applications, refrigerants, and burning of fuels such as gas, wood, and tobacco products. If all these sources are individually added, they account for unnecessary percentages of atmospheric VOC levels. These compounds undergo photochemical reactions which poses a toxic problem due to the creation of ozone, O_3, (Jeong, Suh, & Moskovits, 2000).

Biofiltration Technology

Although several control technologies exist to regulate and minimize the impact of these VOC compounds, biological methods have grown in the market due to their low operating costs, low-to-no secondary waste produced, and effectiveness when treating large volumes of pollutants (Bohn, 1992). When compared to conventional waste treatment technologies such as incineration, condensation, composting, bioprocesses have proved to be more environmentally viable (Malhautier, Khammar, Bayle, & Fanlo, 2005). Current application of biotechnologies techniques includes conventional bio filters, bio trickling filters, and bio reactors. Figure 1 shows the common biotechnology applications to lessen numerous pollutants.

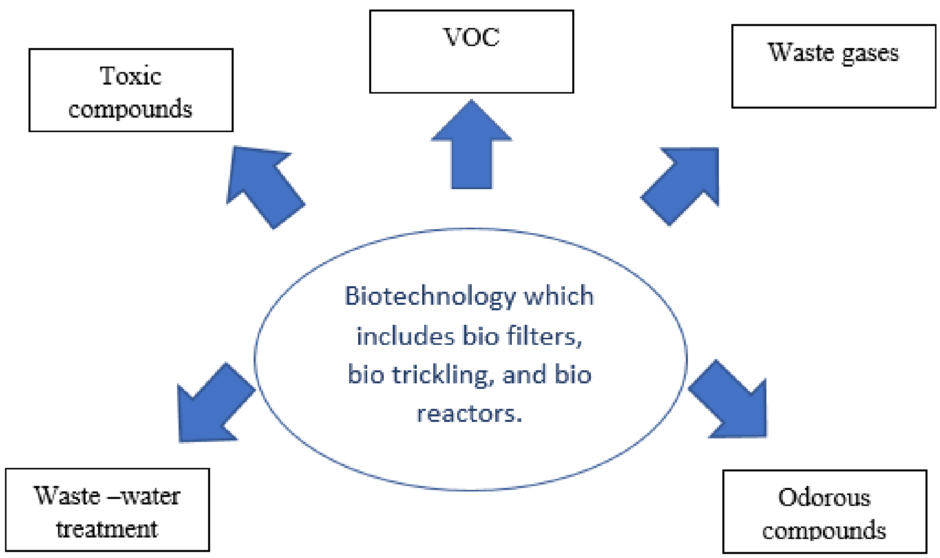

Figure 1 Application of biological waste treatment technologies to diminish air pollutants.

Even though biofiltration systems possess several advantages, it gained interest in the United States until the passage of the Clean Air Act amendments during the years of 1990. It first gained popularity mainly in Europe during the 1970's and 1980's as research and development took great progress in the refinement of this natural technology. After success of the control and removal of VOCs from contaminated air streams, (Wani, 1997) along with a spark of interest by the public revolving air pollution control issues, the United States started to take an interest into this technology through today.

Statement of the Purpose

Though there exist several biological methods, the overall procedure is very similar. The general process is to remove contaminants by degradation using microorganisms as the main source of removal. The microorganisms develop a biofilm on top of the media surface, which serves for growth and attachment purposes. Next, a stream of contaminated air passes and diffuses from the gas phase into the liquid phase, which the microorganisms use as their food source. (Ardjmand, Safekordi & Sima, 2005). Finally, under the correct set of conditions, the contaminated air is converted to carbon dioxide and water (Deshusses, Cox, 1999). Even though plenty of research has been conducted on big-scale bio processes, only a few studies on medium scale biological waste treatments have been conducted before. More importantly, few in-depth studies designed at assessing investment and operating costs of biological treatments have been published before. This research reviews the results of selected research on the different biological applications on the industry, experimental results are used to evaluate if a selected biological application would be feasible in a medium scale industry, such as a university. Due to the nature of biological systems, limitations such as reliable and data pose a problem to the research. To compensate this issue, simulation of data along with literature data was chosen and used. Feasibility of the biotechnology was placed on different measures such as process performance, environmental impact, economic costs, and efficiency at removing VOCs.

Ports of Entry

The United States-Mexico land POE are busy places where hundreds of vehicles cross every day, each with a different purpose, either tourism, shopping, commercial, or educational motives. Both sides benefit economically, especially by the crossing of goods and services, usually delivered in big quantities by heavy-duty diesel trucks. However, long waits at these ports, particularly in the northbound direction, due to idling have caused an increase in emission of gases by these vehicles. Carbon monoxides (CO), Volatile Organic Compounds (VOCs), and oxides of nitrogen (NO_x) are among the pollutant gases released to the atmosphere. VOCs and oxides of nitrogen are considered to be precursors of ozone(O_3), which chemically react with the atmosphere to cause ground-level ozone (United Stated Department of Agriculture, 2012) severely affecting the health of the drivers and pedestrians crossing the border, not to mention the detrimental effect on the environment. Several studies on pedestrians crossing at major lands ports of entry, such as San Ysidro, have shown levels of exposure to traffic-related air pollutants similar to busy roads (Quintana, Khlighi, Quinones, et al., 2018) (Galaviz, Yost, Simpson, et al., 2013). Average number of trucks in major land ports of entry in the South Texas region are shown in figure 2 (U.S. Department of Transportation, 2018). This figure shows that, for the past 15 years, average number of trucks, full and empty, at these ports have been increasing. Although idling is almost inevitable, a method of containing the emission of gases is achievable via several control technologies; catalytic converters are one of the most used control technologies nowadays, this is due to their capacity to reduce exhaust emissions to harmless CO_2, H_2O, and N_2. Nevertheless, automobile catalytic converters are a primary contributor of Platinum Group Elements (PGE) to the environment, a new source of environmental pollution (Yajun, Xiaozheng, 2012). Another control technology to treat VOCs is through the use of a biofiltration system.

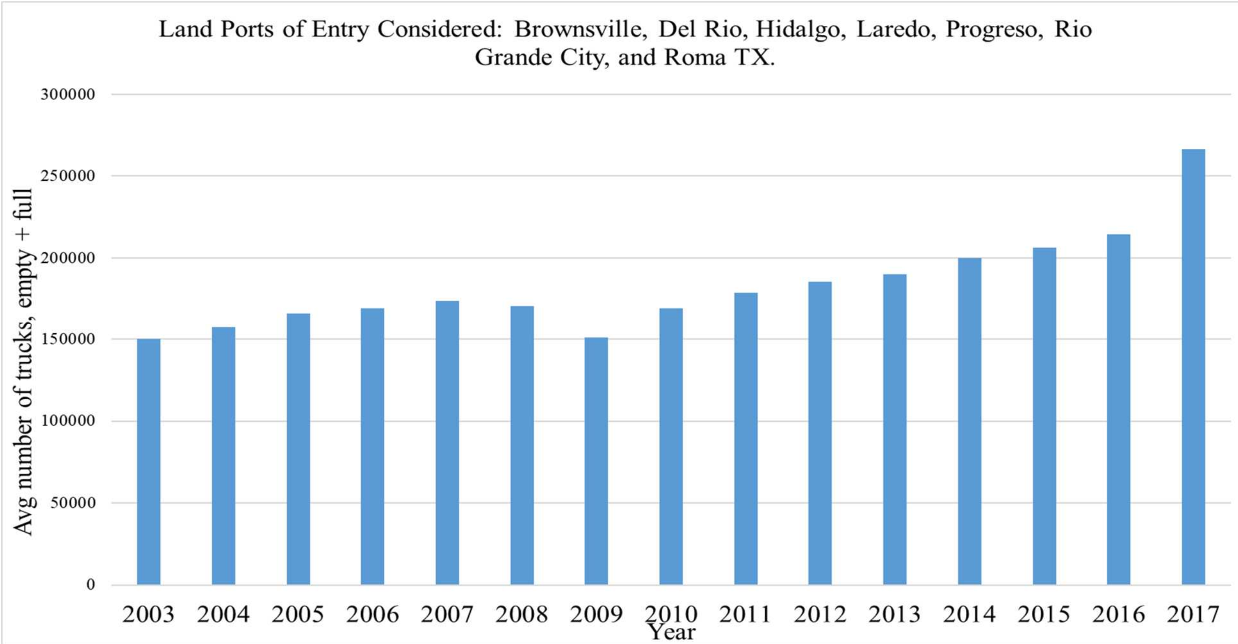

Figure 2 Average number of trucks in major land ports of entry in the South Texas Region.

Research Objectives / Questions

The purpose of this research was to determine if a medium-to-high industry can benefit both economically and environmentally from a bio filtration system for air pollution control rather than conventional methods. Research questions explored included:

1. Is it feasible and environmentally suitable method to implement a bio filtration system for reducing VOC release to the atmosphere?
2. What is the anticipated reduction in VOC emissions from a proof-of-concept conventional biofilter?
3. Will a biofiltration system be a cost-effective method for reducing Volatile organic compounds release to the atmosphere? Will a business model canvas show the economic benefits?

Methodology

A section of literature was reviewed for cases where biofilters were implemented successfully to treat similar emissions from comparable facilities. Two briefcase-studies were analyzed on two different facilities. From the literature collected, limitations and assumptions were obtained and further discussed for future research. As a result of the reviewed case-studies, a biofilter concept design was suggested following its basic principles and design equations outlined by several experts (Webster, Deshusses, & Devinny, 1999). Residence times, packing materials, pollution time, and other crucial parameters were determined from lab-scale studies also discussed in the literature. The correct sizing, material, and operation costs were determined to fit the adequate biofilter to certain cases, which fall under the medium-to high size. Also, the bio filter costs associated with the health and environment VOC control emissions were found using a net present value calculation.

In order to demonstrate the feasibility of the biofilter, a demonstration in principle to verify the concept was done to show the potential in a larger scale. This thesis reviews the levels of CO exhaust emissions as a result of idling, and the feasibility of a bench-scale biofilter as a control technology to capture contaminants produced by a Volkswagen Jetta 2017, and a dump truck, which served as the HHDV. This initial study was conducted using a smaller personal vehicle which does not operate using diesel as fuel, as a comparison for results. After acclimatization of the biofilter, input concentration, outlet concentration, and removal efficiency were determined. Final results are compared to those of a traditional catalytic converter to measure the removal capabilities of both technologies. Finally, an objective forecasting method was implemented to be more objective for nearer term forecasting horizons and for events where there is plenty of quantitative data available. A time series method was executed since it attempts to estimate future outcomes on the basis of historical data. This provided us with useful information onto whether a biofiltration systems was feasible or not.

Assumptions and Limitations

Due to the nature of the topic, limitations in the study were discussed. Only a few studies on medium scale biofilters have been conducted before, which pose a problem when performing the literature review on the topic. While VOCs do vary greatly with location, the process done by the biofilter is essentially the same, therefore maintenance processes and operational practices among the facilities do not vary greatly. However, differences in the parameters such as environmental regulations, infrastructure of the facility, workload do vary and exist. Hence, applying the results found in this research could become a potential challenge. Before trying to apply the results of this study to a similar facility, careful analysis of the processes, emissions, workload, capacity is necessary to prevent challenges.

One of the biggest limitations encountered was the absence of a facility adequate to conduct lab-scale experiments, and the lack of time involved with installing a pilot-scale system aimed for medium-to-high industries. Finally, research on common biofilters has shown that no data exists on biofilters built for heavy-diesel trucks, which was the vehicle chosen to conduct the proof-of-concept prototype. But, studies of bench and pilot scales have proven for biofilters to be cost effective, operate with low capital costs, effective because secondary waste streams are not produced, and convenient (Mudliar, Giri, Padoley, et al., 2010). Also, due to the vast dependency on biological parameters such as bed medium, pH, moisture, temperature, it is difficult to determine the exact performance for the desired bio filtration system. Fortunately, the results of this study showed that a biofiltration system could benefit areas such as the Rio Grande Valley and its surrounding communities. This can facilitate the adaptation of a biofiltration system to this area, and the benefits associated with it can be explained.

Significance

Despite the current limitations and circumstances, as predicted, biofiltration proves to be a cost-effective and appropriate solution to control air pollution and reduce the number of VOCs released to the environment. Now, from the environmental viewpoint, this control technology focuses on reducing secondary wastes produced by the reduction of pollution created by VOCs. Biofiltration enables the decrease of VOCs, hence it reduces the formation of ground level ozone as fewer chemical reactions are likely to occur.

CHAPTER II

REVIEW OF LITERAURE

Background

Biological waste treatment technologies are recent technologies practiced in the United States; however, they have proven to be effective at removing VOCs when concentrations are lower than 1000ppm. It consists of a stationary filter bed containing a porous media/packing material which serves as a host to a microbial population. These microorganisms, which either live in a biofilm on the surface of the packing material or are suspended in a liquid phase which surrounds the media, break down contaminants within a contaminated air stream as the air stream passes through the filter bed. The contaminants interested in this research are Volatile Organic Compounds.

Volatile Organic Compounds

Biological treatment has been found to be an idyllic treatment process for large quantities of exhaust air containing low concentrations of pollutants or contaminants (Wani, 1997). Compared to other control technologies, such as thermal oxidation, catalytic oxidation, and adsorption, the removal efficiency, and annual operating costs of a biofiltration technique has proven to have a lead due to the advantages that it carries. Table 1 shows some of the characteristics of several mentioned techniques along with the advantages and disadvantages. (Faisal, & Ghoshal, 2000).

Table 1 Several techniques to remove Volatile Organic Compounds, VOCs and their advantages and disadvantages.

Techniques	Annual Operating cost $/cfm	Removal Efficiency %	Secondary Waste Produced	Advantages	Disadvantages
Thermal Oxidation	15-90	95-99	Combustion products	Energy recovery is achievable	Halogenated and other compounds may require additional control equipment downstream
Catalytic oxidation	15-90	90-98	Combustion products	Energy recovery is achievable	Efficiency is sensitive to operating conditions. Certain compounds can poison the catalyst
Bio-filtration	15-75	60-95	Biomass	Requires less initial investment, less non-harmful secondary waste, non-hazardous	Slow, and selective microbes decompose selective organics, requires a mixed culture of microbes.
Condensation	20-100	70-85	Condensate	Product recovery can offset operating costs	Requires rigorous maintenance.
Absorption	25-120	90-98	Wastewater	Product recovery can offset operating costs	Requires rigorous maintenance. May require pretreatment of the VOCs
Adsorption Activated Carbon	10-35	80-90	Spent carbon and collected organics.	Recovery of compounds, which may offset annual	Susceptible to moisture and some compounds

				operating costs.	can clog the pores, thus decreasing the efficiency.

Volatile Organic Compounds (VOCs) include several or most solvent thinners, cleaners, liquid fuels, such as gasoline and diesel, lubricants, and degreasers. Some of the common VOCs are listed in table 2, which as seen, include methane's, ethane's, chlorohydrocarbons, etc. VOCs are the common air pollutants which are emitted by chemicals and most petrochemical industries. (Faisal, & Ghoshal, 2000).

Table 2 Some of the common Volatile Organic Compounds, VOCs.

Number	**Volatile Organic Compound**
1	Acetaldehyde
2	Acetone
3	Benzene
4	Carbon tetrachloride
5	Ethyl acetate
6	Ethylene glycol
7	Formaldehyde
8	Hexane
9	Isopropyl alcohol
10	Toluene
11	Xylene

They originate from a variety of sources, which include, storage tanks, venting of process vessels/container, leaks from waste-water treatment plants and heat exchange systems, not to mention ongoing car vehicles. Control of VOC emission has been a major concern of the industries to maintain a green and healthy environment. VOC react with nitrogen oxides and other airborne chemical particles, in conjunction with sunlight, to form ozone, a thread to the environment and public health. Removal of Volatile Organic Compounds from polluted air.

Ozone:

Ozone is a molecule which is composed of three oxygen molecules, O_3. Two atoms of oxygen form the basic oxygen molecule, which is the basic compound we breathe that is essential to life. However, once a third oxygen molecule attaches to two atoms of oxygen, it alters their chemical composition. This ability to bond with and react with other substances forms the basis of manufacture's claims. Tropospheric, another term for ground level ozone, is formed by the chemical reaction between oxides of nitrogen (NOx) and volatile compounds. The combination of Nitrogen Oxides, NOx, Volatile Organic Compounds, VOCs, and sunlight yield Ozone, O_3

How is Ozone Harmful?

The same basis, chemical properties, that allow high concentrations of ozone to react with organic material outside the body, possess the same ability to react with similar organic material inside the body, and can potentially cause detrimental health consequences. When ozone is inhaled, it can cause damage to the lungs, while low amounts can cause chest pain coughing, shortness of breath and throat irritation. Not only that, but relatively high amounts of ozone can also develop into chronic respiratory diseases such as asthma and can compromise the ability of the body to fight respiratory infections.

Ozone in the upper atmosphere can help filter out damaging ultraviolet radiation from the sun. However, ozone in the lower atmosphere can be harmful to the respiratory system. Ozone in the atmosphere can be produced by the interaction of sunlight with certain chemicals in the environment such as automobile emissions, and chemical emissions by industrial plants. Figure

3 shows a diagram of ozone formation due to several emissions, including VOCs (Lu, Zhang, & Shen, 2019).

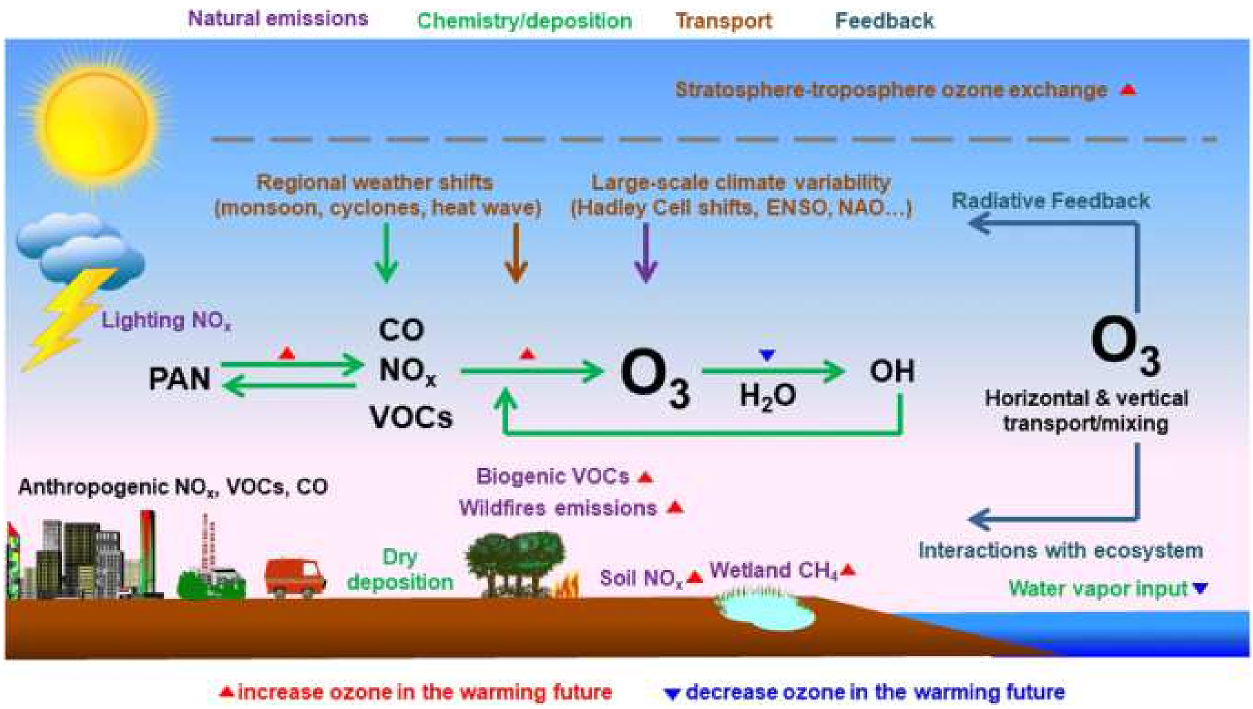

Figure 3 Pathways of interaction between meteorology/climate changes and tropospheric ozone.

OSHA guidelines for O_3 in the workplace are based on time-weighted averages. Ozone levels should never exceed the following average: 0.10 ppm (parts per million) for 8 hours per day exposure.

However, the OSHA (Occupational Safety and Health Administration) recommends certain guidelines for ozone in the workplace.

- 0.2ppm for no more than 2 hours exposure
- 0.1 ppm for 8 hours per day exposure doing light work.
- 0.08 ppm for 8 hours per day exposure doing moderate work.
- 0.05 ppm for 8 hours per day exposure doing heavy work.

Environmental Effects of Ozone

Ozone affects ecosystems and vegetation in general, this includes wilderness areas, forests, and national parks. During growing season, ozone can harm sensitive vegetation. The effects can cause serious negative impacts which include loss of species diversity, changes to the assortment of plants and quality, and it could change the cycles of nutrients in the ecosystem, disrupting the whole food chain.

Ozone Levels in the Manufacturing Operation Side

Although 0.08 ppm for 8 hours per day exposure when doing moderate work are considered safe, when performing manufacturing operations, many factors affect the indoor concentration of ozone, in which some conditions, these ozone levels may exceed public health standards. One of the studies by (Shaughnessy & Oatman, 1991), a large ozone generator was placed in a 350 square foot room and run at a moderate-to high setting. The ozone concentrations inside the room quickly escalated high, 0.50 to 0.80ppm, which is 5 to 10 times higher than public health standards and exceeding the OSHA guidelines. It is important, to mention that these concentrations excluded the portions brought in from the outdoors. Indoor concentrations of ozone brought in from the outside ranges from 0.01 to 0.02ppm, however, it could be as high as 0.03 to 0.05 ppm (Charles, Weschler, Shields, 1997). If these levels of ozone were included in the indoor concentrations generated in the manufacturing operations, clearly the indoor concentration would have been higher, hence increasing the risk of excessive ozone exposure.

Current Situation at the Border

The United States National Energy Policy 2001, emphasized on the need to reduce emissions from idling of long-haul trucks, most of the vehicles used for the transportation of goods between both sides of the border. The U.S. Environmental Protection Agency shows how much impact on road vehicles, including idling, have on VOC emissions across the U.S. Approximately, 28% of the VOCs are produced by on road vehicles (U.S. Environmental Protection Agency. EPA, 2005). During long waits, drivers idle their engines to provide the necessary cooling to their cargo because of the annual high temperatures experienced in the South Texas region (Rahman, Masjuki, Kalam, et. al., 2013). Because of these long waits, Cameron County requested and proposed an expansion of the bridge to show how these changes can reduce the idling waiting time, and therefore the emissions. Figures 4 and 5 show the idling of personal car vehicles and commercial trucks at different border sites.

Figure 4 Personal vehicles idling at the border of U.S.-Mexico.

Figure 5 Commercial truck vehicles idling at the border of U.S.-Mexico.

Benefits of the Proposed Expansion

The benefits of the proposed expansion relate to the increased capacity for the processing of passenger vehicles through the expanded primary and secondary areas; reduction in vehicle fuel consumed, reduction in emissions, and reduction in persons costs. Commercial vehicles will also benefit from the proposed expansion by removing the long queues of passenger cars into an increased storage space from four to eight lanes approaching the passenger vehicle primary stations. The peak hour capacity with increase from 260 vehicles per hour to 520 vehicles per hour. Based on the latest projections this will accommodate the demand to the year 2026. The northbound lanes of the bridge have surplus capacity to accommodate future volumes. The goal would be to maintain the waiting times to the minimum during peak hours and be able to staff the lanes to full capacity during those times. Table 3 reflects fuel consumed, fuel cost and person delay costs based on an hour wage rate of $22.90 per hour. The annual average waiting time was calculated for the peak for hours per day.

Table 3 Fuel and Person Delay Cost of Waiting.

Annual	**Annual Vol**	**Wait**	**Delay**	**Fuel**	**Fuel Cost**	**Person**	**Total Cost**
Volume	Pk 4 Hrs.	Min	Hours	Gallons	$3/gal	$22.90/hr.	
1,439,573	575,829	15	143,957	71,979	$215,936	$3,296,922	$3,512,558
1,439,573	575,829	20	191,943	95,972	$287,915	$4,395,496	$4,683,411
1,439,573	575,829	30	287,915	143,957	$431,872	$6,593,244	$7,025,116

The reduction of the average waiting time from 30 to 20 minutes during the peak four-hours per day results in an annual savings of $1,341,705. However, the important topic here is the primary pollutants and how this affects the emissions. The primary pollutants from motor vehicles trains unburned hydrocarbons (HC), oxides of nitrogen (NO_x), carbon monoxide (CO), and particulates. Hydrocarbons and NO_x can combine in a complex series of reactions catalyzed by sunlight to produce photochemical oxidants such as ozone (O_3) and NO_2. A reduction in emissions is achieved by reducing the idling or waiting times for passenger vehicles. The following is a summary of the emission analysis for the CO, HC, and NO_x for the various average waiting times. The annual volumes utilized only the peak for-hours on operation. The annual cost of the emissions for idling for an average delay of 30 minutes during a four-hour peak day is shown in table 4.

Table 4 Annual Emissions of Vehicles Idling.

	Emissions	**Unit Cost**	**Costs**

	Tons/Year	Costs/Year	
CO	13	$1,300	$16,586
VOCs	7	$1,300	$8,912
NO_x	704	$5,300	$3,732,574
Total			$3,758,072

Impact of COVID-19

The COVID-19 outbreak has completely disrupted the way of life of millions of citizens as it is a threat to health. It has provided an unparalleled opportunity to assess changes in the emissions and urban air quality due to a massive decrease in traffic and daily outside activities. The current reduced traffic activity presents an overview of the potential future of urban air quality, which would be reduce by less vehicles, and therefore reduce emissions of urban greenhouse gases, nitrogen oxides (NO_x), carbon monoxides (CO), and volatile organic compounds (VOCs). In return, we observed other sectors have a greater impact on air quality, such as volatile chemical products (VCPs), which are in rise due to the amount of cleaning products, disinfectants, and personal care products. These VCP's emissions have already begun to equal those emissions from the transportation sector, and it is another source which need to be considered in the main equation. Air quality changes during the COVID-19 outbreak will provide a unique insight into a potential future in which emissions reductions take place in U.S. cities to alleviate a climate change (Warneke, Frost, Williams, et al., 2020).

Due to the stay-at-home policies in response to the COVID-19 pandemic, has led to drops in various air pollutants, and an increase in chemical transformations in the atmosphere. Although research studies have indicated a reduction in air pollutants, such as Volatile Organic Compounds, as a measure to enforce quarantine and social distancing policies have suggested to believe there is cleaner air. Less travel reduces the emission of nitrogen oxides ($NO_x = NO + NO_2$), one of the major combustion by-products and considered as a primary pollutant, and a gas associated with adverse respiratory effects. The direct emissions by chemical products, are considered secondary pollutants, which are harmful to human health and contribute to the chemical processing and formation of ozone, O_3. Decreases, in emissions of air pollutants are critical for better air quality, however, because of the interdependences in chemistry in respect to the secondary pollutants observed in the past few months of 2020 due to Covid-19. Induced emissions changes are complex and uncertain. Further analyses of changes in the atmospheric composition over the past few months, and the months to come as the pandemic ends, will provide new understandings into the chemistry linking emissions and secondary air pollution (Kroll, Heald, Cappa, et al., 2020).

Forecasting

Objective forecasting methods are those in which the forecast is derived from an analysis of data. A time series method is one that uses only past values of the event we are predicting. This method allows a collection of observations of an economic or physical phenomenon, such as the evaluation of air quality data, drawn at discrete points in time, and the idea is to analyze the pattern of past observations which can be used to forecast future values. A time series forecast is obtained by applying some set of weights to past data (Nahmias, & Lennon, 2015).

$$Ft = \sum_{n=1}^{\infty}(a_n Dt - n) \text{ for some set of weights a1, a2, ...} \quad (1)$$

Evaluating the Forecast

Since forecasts possess the tendency of being wrong, we let e_1, e_2..., e_n be the forecast errors observed in *n* periods. Then, two common measures of forecast accuracy during the *n* periods, the mean absolute deviation (MAD) and the mean squared error (MSE), were applied to appreciate the errors.

$$\text{MAD} = (1/\text{n}) \sum_{\text{i}=1}^{\text{n}} |\text{ei}| \quad (2)$$

$$\text{MSE} = (1/n) \sum_{i=1}^{n} |e\text{^}2i| \quad (3)$$

The periods used, *n*, are further discussed in the methodology section.

Methods to Control Indoor Air Pollution

There are 3 common approaches to reducing indoor air pollution, which include source control, ventilation, and air cleaning. The third approach is not regarded as sufficient itself, but it is often used as a supplement source control and ventilation in order to reduce the amount of pollution formed in the environment. Control systems such as air filters, electronic particle air cleaners and ionizers are often used to remove airborne particles, and gas adsorbing material is also used to remove gaseous contaminants when ventilation systems are inadequate. Bio-filters are an innovative control technology which have become popular due to its benefits at removing clear components of ozone while reducing further waste.

Due to the increasing number of atmospheric emissions produced by VOCs, the environmental legislation has been enforcing the use of technologies which do not harm the environment by the processing of emissions in an effort to mitigate them. However, in order to be a feasible and viable alternative, these technologies must be efficient and cost-effective when it comes to operation costs. Traditional air pollution technologies require the additions of secondary chemicals, and a significant amount of energy in order to treat the target pollutants. This result in both high operating costs, and a release of secondary waste products. An appropriate solution to this matter is through the use of biological waste treatments. Figure 6 displays an illustration of the predicted number of industrial VOCs by the year of 2050, and how it has been increasing for the last years.

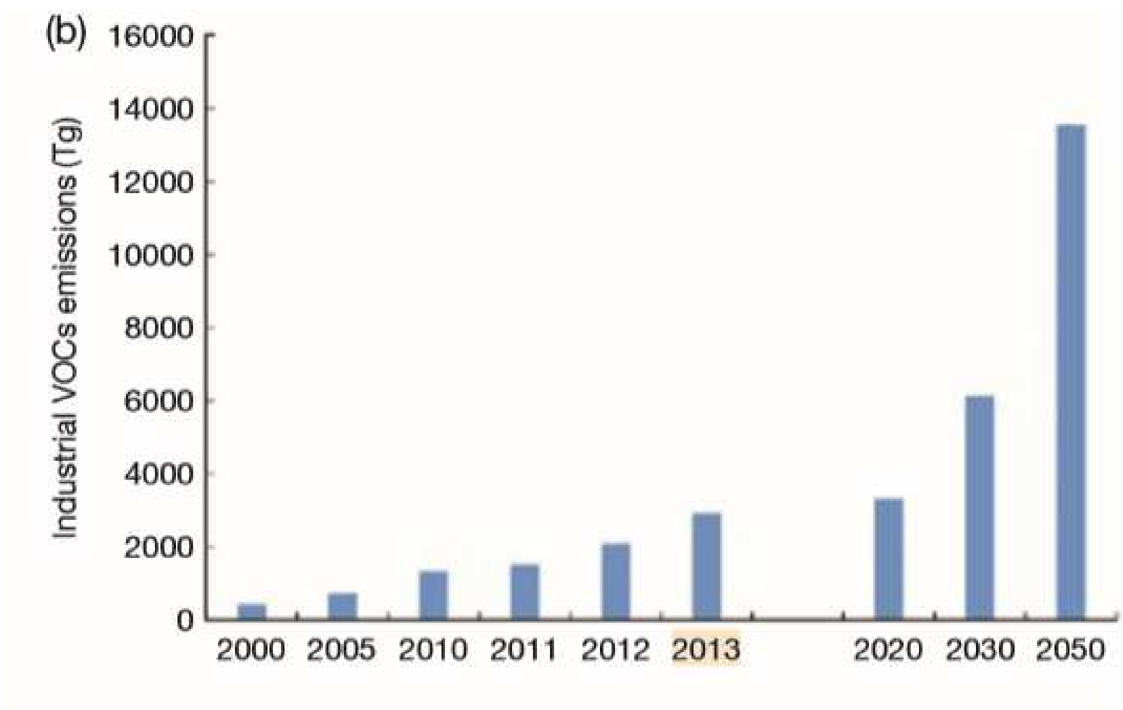

Figure 6 Projected industrial VOC emissions from 2000 to 2050.

Biological Waste Treatment Technologies

Biological waste treatment technologies are categorized by low operating costs, no secondary waste produced, and efficient when treating large volumes of pollutants containing low concentrations of VOCs. Several studies have been conducted which have pointed the advantages of biotechnologies in terms of reducing operating costs (Rajbir, & Ghaemi, 2014). Though, in several cases, industrial bioreactors run under no previous economic assessment at all, causing an increase in yearly operating costs. In the case of the biofiltration technique, investment costs are associated with the overall elimination capacity, which in turn depends on the removal efficiency and empty bed resistance, which is the amount of time the waste gas spends at the biofilter film before escaping. To maintain a fully operation biofiltration system, it is crucial to spend a substantial amount on the exchange of packing material since degradation of VOCs by microorganisms depend on the material media to sustain themselves. Therefore, the overall cost is directly inclined to the amount of packing material. The aim of this work is to find an optimal set of conditions that can process and eliminate VOCs, while being economically and environmentally feasible. Most of the parameters included in published models were not directly measured through experimentation, rather, they were obtained by fitting experimental data. This facilitated the analysis of the likelihood to implement a biofiltration system to a medium scale location such as the University of Texas Rio Grande Valley, UTRGV. The paper reviews and revises the results of current functional bio-waste treatments methods to treat selected pollutants (Webster, Deshusses, & Devinny, 1999). Then, a preliminary selection for choosing the adequate parameters in the method is proposed. The method and materials are reviewed in the next section.

As a result of the Federal Clean Air Act Amendment in the 1990 in the U.S., which brought strict regulations to air emissions, the biofilter market has grown, ranging from water treatment to modern and controlled units to remove waste gases from industrial processes. The Amendment also called to reduce the levels of ground-level ozone in the most contaminated areas by 15%. Although control technologies cannot completely eliminate waste gases, reduction is feasible and attainable. Among others, on the emergent control technologies is biofiltration via biofilters (Webster, Deshusses, & Devinny, 1999).

Biofilter

A biofiltration systems is considered to be one of the simplest technologies within the science of biological air purification. The effectiveness of any control technology depends on the concentration of VOCs of any desired pollutant. However, biofiltration has the advantage of effectively removing pollutants in low concentrations (<1000 ppm), making it an effective control technology for this study. Low operating and capital costs plus no further waste streams produced are another set of benefits by the application of a biofiltration system. The basic concept of biofiltration is to remove contaminants from an air stream via microbial degradation. A stream of humid air passes through microbial layers formed in a packed bed. Under the correct conditions, exhaust gases passing through the biofilter can be degraded to Carbon dioxide (CO_2), water, and residual mass. Aspects to consider when designing a bench –scale biofilter are media, moisture content, temperature, and pH. The degradation of VOCs by microorganisms is affected by these environmental factors and by the type of contaminant aimed to filter. Media can be any porous material which has adsorbing properties to capture chemical gases and supports biological growth of microorganisms (Yoon, & Park, 2002). One of the main key points to consider about biofilters is to maintain an adequate level of moisture or water. The correct amount of water level determines the efficiency of removal, and excess or insufficient levels could disrupt the performance. Optimal levels of water or moisture in biofilters are between 40-60% of capacity.

Before the gas travels to the biofilm, it must pass through a humidifier to fully saturate it with moisture, this prevents stripping and removal of water from the biofilter. The waste gas must be heated or cooled depending on the source of emission, for optimal range in microbial activity, however, this step is often coupled with the humidification process. As the humidified gas travels to the biofilm chamber, the target gases undergo diffusion and biodegradation. The amount of time the gas spends at the biofilter biofilm is called Empty Bed Contact Time (EBCT) (Swanson, Loehr, 1997). Often, activated carbon is added to the media as an adsorption agent, enhancing the levels of adsorption by the biofilter, thus capturing more of the determined waste gas. Also, by increasing the adsorption capabilities, the residence time decreases as gas particles are trapped by the activated carbon. Pollutants are removed by activated carbon, acting as the adsorption medium to a subsequent biodegradation by the microbial population (Abumaizar, Kocher, & Smith, 1998).

Still, increasing engine speed with air conditioning resulted in increased emissions of CO, NO_x, and CO_2 emissions (Khan, Clark, Thompson, et al., 2006). More parameters are accounted during idling; vehicle class and weight, driving cycle, engine exhaust after treatment, vehicle age, etc. Although heavy duty diesel trucks are equipped with an after-treatment device such as a catalytic converter, which is effective in reducing HC and CO, levels of NO_x are still untreated after release (Clark, Kern, Atkinson, et al., 2002). As a consequence of past laws and current trends of pollution, a more biological solution is opted to minimize this pollution tendency.

A biofilter prototype was designed to suit the necessity of decreasing gas wastes of idling HDDV. The method and materials are reviewed in the next section.

Economics

Assigning dollar values to environmental quality is a difficult task which is a nonmarket valuation. Nonmarket valuation permits environmental benefits received by society to be compared monetarily to costs associated with certain regulations, policies, and programs aimed for pollution control (Loomis, 2005). One method used to measure nonmarket evaluation is determining how much society is willing to pay, WTP, for a certain environmental benefit. This monetary value theory is applied to the cost of an air pollution control technology to establish the economic benefits the system will have on the population. If the population decides to pay more for a cleaner air, then the air pollution control technology can be regarded as a cost-saver. An accurate measure of benefits of air quality typically contains WTP and cost of illness, COI. COI is a cost associated with medical expenditures and lost wages accumulated due to the illness caused by air pollution (Hall, 2006). However, a method in which these two values are tied together and can provide a present-day look at the cost of an air pollution control technology, is the net present value (NPV) method. This method compares the estimated value of money spent or earned in the future of today's dollar value over a predetermined period (Brigham, & Ehrhardt, 2005). Then, the economic and environmental benefits of biofiltration can be determined. With the NPV method, monetary expenditures or gains related with controlling air pollution over a determined time, can be shown in present-day dollars. Future costs of a biofiltration system over the same period of time in a similar or same region can also be calculated with this NPV method to present-day dollars. Successive analysis shows that in the long run, the cost of a biofiltration system compared to other control technologies mentioned, such as thermal oxidation and catalytic oxidation, is much cheaper and has a positive impact to the environment and most importantly, to the human element.

Summary

This literature review has given important insights about biofiltration technology and how it can serve as an air pollution control technology. From its formation in the early half of the twentieth century, through its implementation and enhancement in the United States after the passing of regulations which dictated better air quality, acceptance as a reliable method of controlling polluted air streams, and the benefits economically and environmentally have been discussed. Crucial design parameters of conventional biofilters have been detailed along with the importance of each in the designing process. The correct selection of appropriate parameters has shown to be the central component of the biofilter through the discussion of how it works. The relative cost of a biofiltration control technology to treat the emission of VOCs is shown to be advantageous over other conventional technologies discussed in this section, which are used today and are available in the market. Finally, the environmental and human health impact of VOCs have been demonstrated. This review has indicated that a biofilter is feasible and cost-effective method of controlling the release of dangerous VOCs to the earth’s atmosphere.

CHAPTER III

METHODOLOGY

Prototype Design

Based on the types of VOCs emitted by HDDV's, a biofilter was designed using essential principles such as cost, performance, processes, and effectiveness. The prototype mainly assessed the amount of Carbon Monoxide (CO) removed from an exhaust Volkswagen Jetta 2017 engine while idling, remaining stationary for long periods of time, and from a dump truck. Two prototypes were designed, both biofilters contained the same materials except for activated carbon in one of them. 2 cylindrical, 6-inches in diameter-x-2 feet in height, biofilters were constructed using PVC pipes. Both biofilters were filled with brown mulch, and natural pine bark mulch as the media. Before adding bacteria, Garden Magic Microorganisms, the media inside the biofilters was irrigated using de-chlorinated water to preserve the microorganisms. During the addition of the media, biofilter #2 was filled with activated carbon, Premium Laboratory Grade Super Activated Carbon, in order to assess the capabilities of adsorption by this chemical compound. Exhaust gas generated was collected by a garage exhaust hose, Continental Elite 54040/FLT250, and transported directly to the biofilter. As the waste gas traveled through one of the ends of the biofilter, a vacuum pump, ZENY 3,5CFM Single-Stage 5 Pa Rotary Vane Economy Vacuum Pump 3 CFM 1/4HP, was attached to the other hand to pull and collect exhaust gas containing CO. The exhaust gas had an average residence time of 3.5 minutes before collection. Inlet CO levels and Outlet CO levels were measured with a CO analyzer, Carbon Monoxide Detector CO Analyzer. To calculate the air flow and concentration of CO and airflow meter, ERAY Digital Anenometer Wind Speed Gauge Handheld Air Velocity Flow Volume Meter with Backlight LCD Display, was utilized (Tilley, & Ganeshan, 2005). The microorganisms had an acclimatization period of 72-96 hours, with temperatures ranging from 57 to 74 degrees Fahrenheit. De-chlorinated water was added with a spray water bottle every 24 hours to provide standard levels of moisture across the biofilter. Figure 7 displays the design of the prototype made.

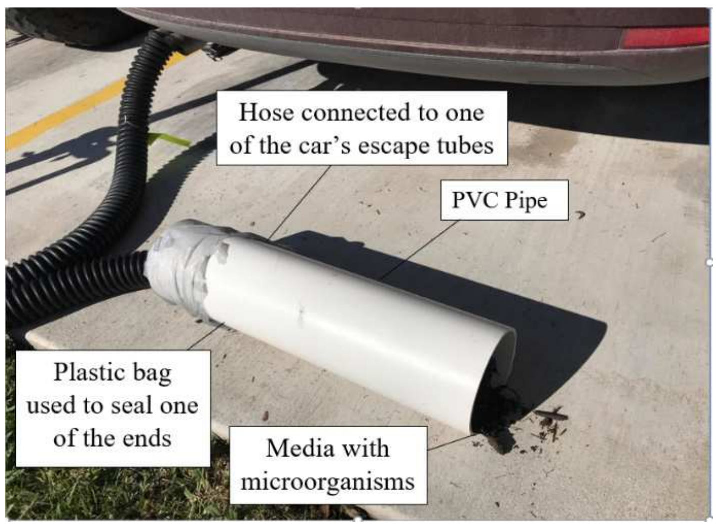

Figure 7 Illustration of the biofilter prototype.

Protocol

An in-depth cost estimation protocol is shown below. Several assumptions from (Kiared, Wu, Beerli, Rothenbühler, & Heitz, 1997), were established when the model was designed. Also, filter material composition was considered being homogenous, along with the biomass distribution and density. Carbon dioxide and water as by-products are considered as major assumptions as well. A major objective in the design of any protocol and pollution treatment technology is to minimize the overall treatment costs. Overall treatment depends on the sum of two associated factors, yearly capital, and operating costs. Aside from the associated costs, each model can include more complex parameters such as aimed reduction of pollutants, biomass growth, etc. However, final selection depends after the assessment of all possible options. Equations 1,2, and 3 describe the relationship between associated costs and defines the model approach to minimize these costs to find the most cost-effective reactor design and operational model (Deshusses, & Cox,1999). The model considers the flowrate of contaminated air, inlet concentration, and type of pollutant to deal with.

Equations for each of the three associated costs are shown below, represented by x, y, and z functions:

Annual capital costs, investment costs, and annual operating costs

$$x \text{ (Plant life, and investment cost)} + y \text{ (Reactor size and reactor type (not discussed in this research)} + z \text{ (packing material, water, labor, energy)} \tag{4}$$

Yearly treatment cost can be defined as the sum of annual capital costs and annual operating costs. In order to design the most cost-effective bio-treatment technology, it is crucial to minimize yearly treatment, which equivalates to minimize both annual capital and operating costs. The challenge in this model is to find the appropriate parameters which minimize cost-effectiveness. It is assumed that annual capital costs, which include, plant life and investment cost, is a unique event that is unlikely to happen again, and attention was placed on the annual operating costs. 4 parameters are considered within the annual operating costs which influenced final and total cost, these are packing material, water, labor, and energy cost. For a specific flow rate, each of the costs are added and the total result only consider the factors in the model described. Finally, investment costs are associated with removal efficiency and empty bed resistance.

Net Present Value Calculations

To demonstrate the final cost overt time in present-day-dollar- value of installing and operating a specific project or system, the net present value method is certainly used. The primordial reason to use such method is to provide the buyer of the system with an initiative of how fast they will receive their investment back, in other words, to determine at what point in the future the control technology/system installed will earn enough money to balance the initial cost of purchase and installation. This information is crucial to the buyer and it is often the deciding factor when a decision must be rendered regarding the acquisition or implementation of a biofiltration system in this case. The net present value technique is a concept easily shown visually using a cash flow diagram (Sullivan, Wicks, & Koelling 2019). Figure 8 shows and example of a cash flow diagram.

Figure 8 Example cash flow diagram representing $1,000 loan from a bank with 2% interest per year over four years and the amount of money per period. (Thusen, Fabrycky, & Thusen, 1971.)

Over the course of a project's expected life span, expenditures, and incomes, composed by outflows and inflows which are depicted by arrows pointed downward to show outflows and upwards to show inflows at the end of each assigned period (Fabrycky, 1991).

Investors are usually interested in knowing how long it will take to recover the initial amount of money invested in the system. An NPV calculation can be performed by first determining the present value of each cash inflow and outflow subtracted from the system's capital expenditure. By summing the discounted cash flows, the NPV can be determined, and if the result is positive, the NPV is satisfactory and in most cases accepted by the investor (Brigham and Ehrhardt, 2005). Equation 2 is a representation of how the NPV is calculated and how it is used in this research to perform all the desired calculations (Staff ,2020).

$$\text{NPV} = \frac{Cash\ flow}{(1+i)^t} - \text{initial investment} \tag{5}$$

Where:

i = Required return or discount rate

t = Number of time periods

However, if the work is expected to be a long-term project with multiple cash-flows, the formula for net present value is the following:

$$\text{NPV} = \sum_{t=0}^{n} \frac{Rt}{(1+i)^t} \tag{6}$$

Where:

R_t = net cash inflow-outflows during a single period t

i = discount rate or return that could be earned in alternative investments

t = number of time periods

In terms for the audience,

NPV = Today's value of the expected cash flow – Today's value of investment

Maintenance and operating costs of the designed biofilter in operation are also considered using the NPV method. The University of Texas Rio Grande Valley, UTRGV, does not have in disposition a biofilter to control its VOC emissions. An economic solution using NPV techniques to this issue is explored in this study. The first step to determine the cost of the biofiltration system in the UTRGV facility is to use concrete parameters in the first NPV calculation. These parameters include, cost of the system, installation cost, system maintenance, annual cost of operation. Figure 9 depicts the parameters included.

Figure 9 Schematic diagram showing the costs associated with annual operating cost of biological waste-treatment.

Deterministic Model

For the proposed deterministic model, and application of a bio-waste treatment to two case study and air data quality from the McAllen, Edinburg-Mission, TX was analyzed (U.S. Environmental Protection Agency. EPA, 2005). Both case studies had a bio-treatment operating continuously, 24 hours per day, 365 days per year, while the statistical pollutant O_3 was analyzed in the core based statistical area.

The first case involved a university, with an emission of 50,000 m3 h−1 (293 K, 1 bar, 40% relative humidity) with a composition based upon the characterization of the odor pollution from a WWTP located at Stuttgart University. The second, engaged a biotreatment aimed to treat an air flow rate of 10,000 m3 h−1. Table 5 shows the characteristics for each case study.

Table 5 Characteristics for each case study.

	Case Study 1	**Case Study 2**
Air flow rate	10,000 m^3h^{-1}	50,000 m^3h^{-1}
Pollutant / inlet concentration	Toluene / 1.5 g m^{-3}	Methyl mercaptan /2 mg m^{-3}
Operation time	24 hours, 365 days per year	24 hours, 365 days per year
Pollutant removal efficiency	100 % removal	100% removal

When evaluating the investment costs of both studies, removal efficiency and empty bed resistance were the factors selected to have the greatest impact in this category. Both parameters measure the degree of the removal of pollutant compounds from the air and reveal information about the rate of the process based on the airflow rate and the size of the bioreactor. It is important to mention that values of both calculations were taken from literature data.

Where:

Cin = inlet concentration of pollutant

Cout = outlet concentration of pollutant

V = Volume of filter bed

Q = Inlet gas flow rate

Table 6 shows the parameters considered for the evaluation of investment cost of the biotechnology waste treatment to consider.

Table 6 Parameters and definitions for a biological technology (Vikrant, Ki-Hyun, Szulejko, et al., 2017).

Parameter	Definition
Inlet load (g m $^{-3}$ h)	$IL = \frac{C1Q}{V}$

Removal efficiency (%)	$X = (\frac{C1-CO}{C1})$ x 100
Empty bed resistance time (s)	$EC = \frac{V}{Q}$

Air quality fluctuates differently depending on the region, however, the following climatically region, the Rio Grande Valley located in the south region, within the continuous United States provides an overview of how levels of ozone, O_3, have been throughout the years. Figure 10 shows the trend of O_3 across the past 18 years. As observed, it shows a decreasing trend along the years. However, the average amount of year was crucial to determine the feasibility of a biotechnology treatment in this region.

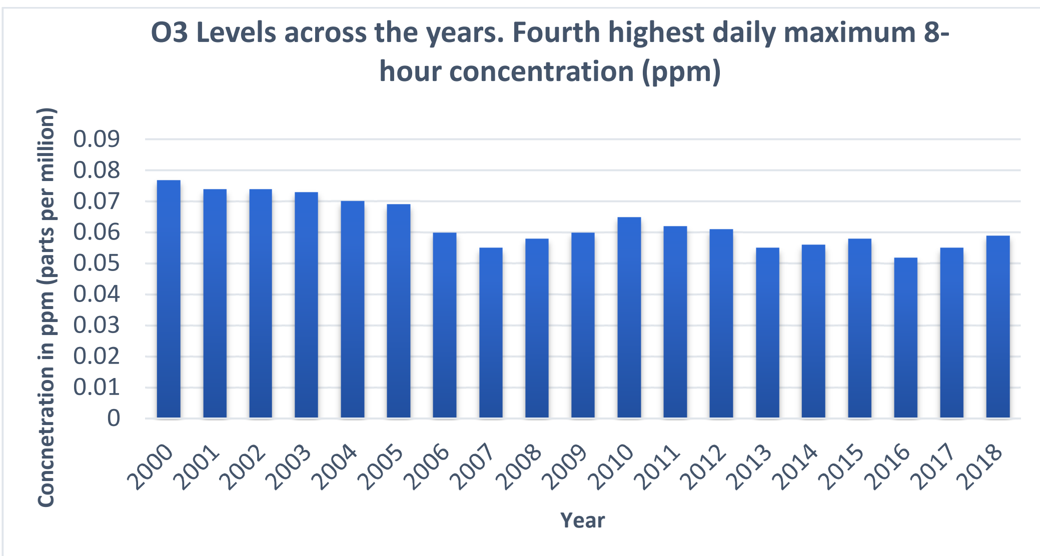

Figure 10 Fourth highest daily maximum 8-hour concentration (ppm) of O3.

Business Canvas Model

The Business Canvas Model, BMC, is one of the most widely adopted academic framework for business model innovation among students and practitioners (Blank, 2013). The

BMC is basically a strategic management technique and lean startup template for developing new or authenticating existing business models. The BMC is constituted by nine building blocks derived from in-depth literature review performed by (Alexander Osterwalder, 2004). Figure shows the framework of the template used. The right side of the canvas highlights choosing, delivering, and capturing value using five building blocks which are, customer segments, value proposition, channels, customer relations, and revenue streams. The left side is focused on value creating through internal and external processes and logistics techniques using four blocks: key activities, key sources, key partnerships and costs (Lima, & Baudier, 2017).The goal of implementing a BMC in this study is to: make it easy to visualize, evidently explain the cognitive and functional benefits of using the tool, in this case a biofiltration system, and make it easy to learn by creating user-friendly lessons that can be effortlessly appropriated by practitioners and self-teaching adopters. Figure 11 shows the typical representation of Business Canvas Model.

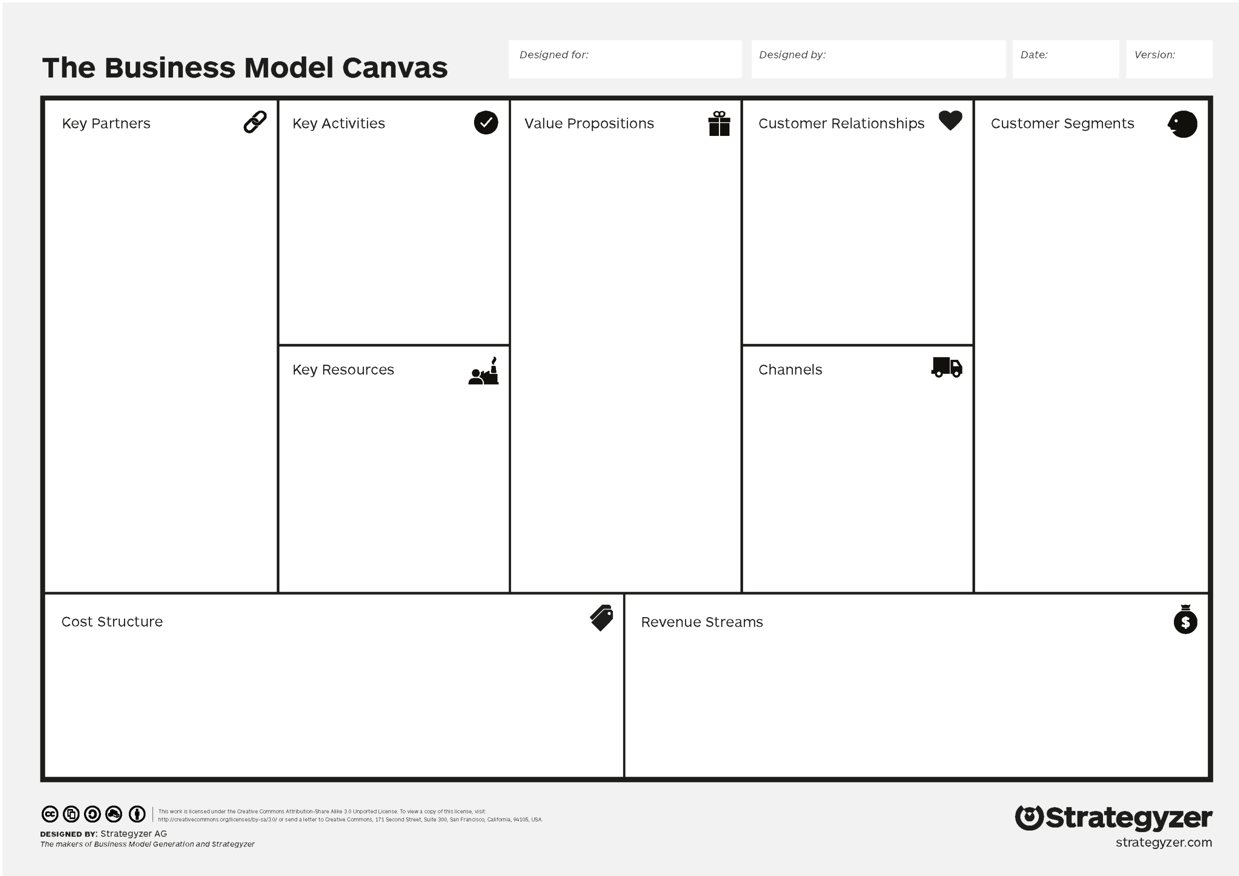

Figure 11 The Business Model Canvas.

CHAPTER IV

RESULTS AND FINDINGS

This chapter reviews the results and predicted performance of the biofiltration system designed for a medium-to-high scale industry or facility. First, the results of the prototype as a proof of concept are presented. Then, the focus is given to the expected performance of a similar design to a medium-to-scale facility, extracted from case studies, is explored in depth, and compared to potential cases with similar characteristics. The performance, costs to install, operate and maintain the design is explored and analyzed. Two case studies regarding biofilters in operation are reviewed as a basis for the offered designs. The material in this chapter is introduced into the following sections:

4.1: Feasibility of Biofilters to Reduce Pollutant Emissions in Diesel Engines

4.2: Case study 1

4.3 Case study 2

4.4 Operating costs

4.5 Design results

4.6 NPV Results

4.7: Business Model Canvas

Feasibility of Biofilters to Reduce Pollutant Emissions in Diesel Engines

Studies compared both biofilters based on removal performance per unit time. Table 7 shows the results for both biofilters. Rate of removal was calculated using the following formula:

$$\frac{\text{Inlet concentration} - \text{Outlet Concentration}}{\text{Inlet Concentration}} \text{ x } 100 \qquad \textbf{(7)}$$

Table 7 Experimental data for biofilters.

	Biofilter with activated carbon on personal vehicle	Biofilter with no activated carbon on personal vehicle	Biofilter with activated carbon on HDDV	Biofilter with no activated carbon on HDDV
Inlet concentration (ppm)	420	420	95	95
Outlet Concentration (ppm)	270	325	42	53
Air flow rate (m/s)	1.69	1.69	9.25	9.25
Temperature (°C)	42.7	42.7	44.0	44.0
Rate of removal	35.71%	22.62%	55.79%	44.2%

The prototypes contained a mix of brown mulch, and natural pine bark mulch, plus approximately 79 mL of Garden Magic Microorganisms. Both biofilters treated Carbon monoxide emitted from a Volkswagen Jetta 2017 personal vehicle, and from a dump truck provided by the University, after idling 10 minutes with the a/c turned off. The first biofilter contained activated carbon while the second biofilter contained no activated carbon. After the hose was connected to one of the car's escape tubes, air flow rate from the exhaust gas was measured to average 1.69 m/s for the personal vehicle, and 9.25m/s for the HDDV.

Biofilter with Activated Carbon:

After 10 minutes of idling passed, CO inlet concentration was measured using a Carbon Monoxide analyzer and it averaged 420 ppm, parts per measure. Since biofilters are designed to operate with large volumes of air stream containing low concentrations of VOC, in this case Carbon Monoxide, the vehicle's emitted Carbon Monoxide was viable for our designed biofilter. The other end of the hose was connected to one of the ends of the biofilter, completely sealed off with a plastic accessory to prevent gas from dissipating. The biofilter operated with a retention time of 2 minutes and 30 seconds, and a temperature of 42.7 and 44 degrees Celsius for the personal vehicle and HDDV, respectively. The other end of the biofilter was connected to a vacuum pump for collection of gas as it traveled the biofilter. After gas collection, outlet CO concentration was measured to be 270 ppm for the personal vehicle, and 42 ppm for the HDDV. Finally, after applying the rate of removal formula, the rate of removal for our biofilter containing activated was equivalent to 35.71% and 55.79% respectively.

Biofilter with no Activated Carbon:

The second biofilter contained the exact components as those of the biofilter with activated carbon except for the activated carbon. After gas collection, outlet concentration was measured to be 325 ppm for the personal vehicle, and 53 ppm for the HHDV. Since inlet concentration was constant after a 10-minute period of idling, after applying the rate of removal formula, the rate of removal for the biofilter with no activated carbon was equivalent to 22.62% and 44.2% respectively.

According to (Sharma, Goyal, & Tyagi, 2015), it was observed that the use of new catalytic converter on diesel engines gives a minimum of 40% reduction and a maximum of 81% reduction in CO emissions at the wide range of engine revolution per minute, figure 12.

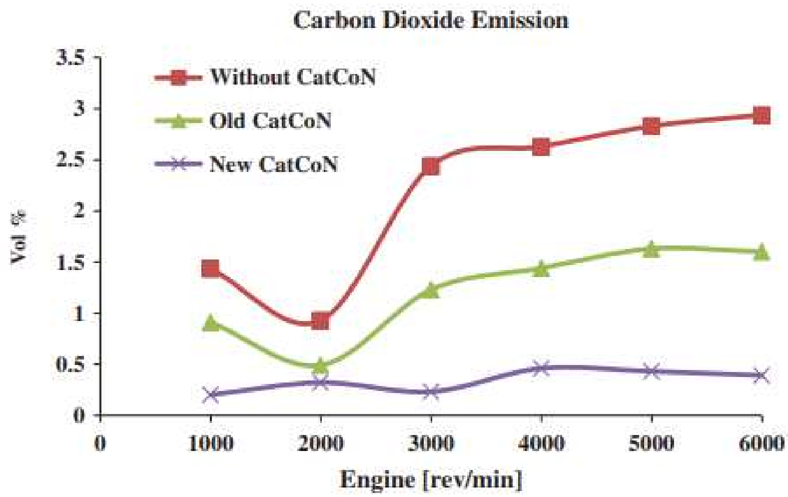

Figure 12 CO2 emission vs engine speed [with CatCoN, without CatCoN and new CatCoN].

Nevertheless, the secondary waste produced by this type of control technology is of great importance, even though reduction of CO is viable, the production and release of PGE to the environment poses a threat. Biofilters are designed to filter high levels of air streams at low concentrations, typically <1000ppm, and produce no secondary waste.

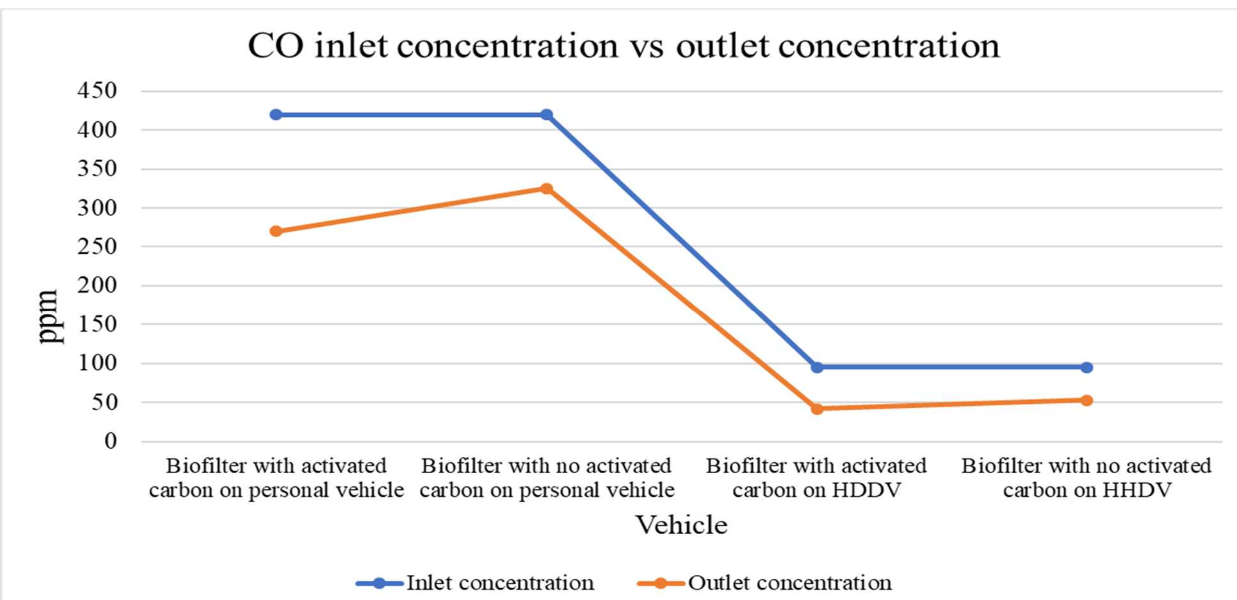

Figure 13 Carbon monoxide inlet and outlet concentrations on both vehicles.

Both tests revealed that the biofilter containing activated indeed enhanced the performance of the biofilter. Due to the adsorbing capabilities, it functioned better than the biofilter with no activated carbon at same retention times, figure 13. However, the prototype removed more than 1/3 third of the Carbon Monoxide emitted by the personal vehicle, and almost 60% on the dump truck. When compared to the conventional catalytic converter, the biofilter falls on rate of removal. While the minimum reduction of CO on a catalytic converter is 40% of the gas, the biofilter achieved a maximum removal of 55.79%. Several factors must be considered. Figure 14 shows a graphical representation of the Carbon monoxide inlet and outlet concentration of the two biofilters with and without activated carbon.

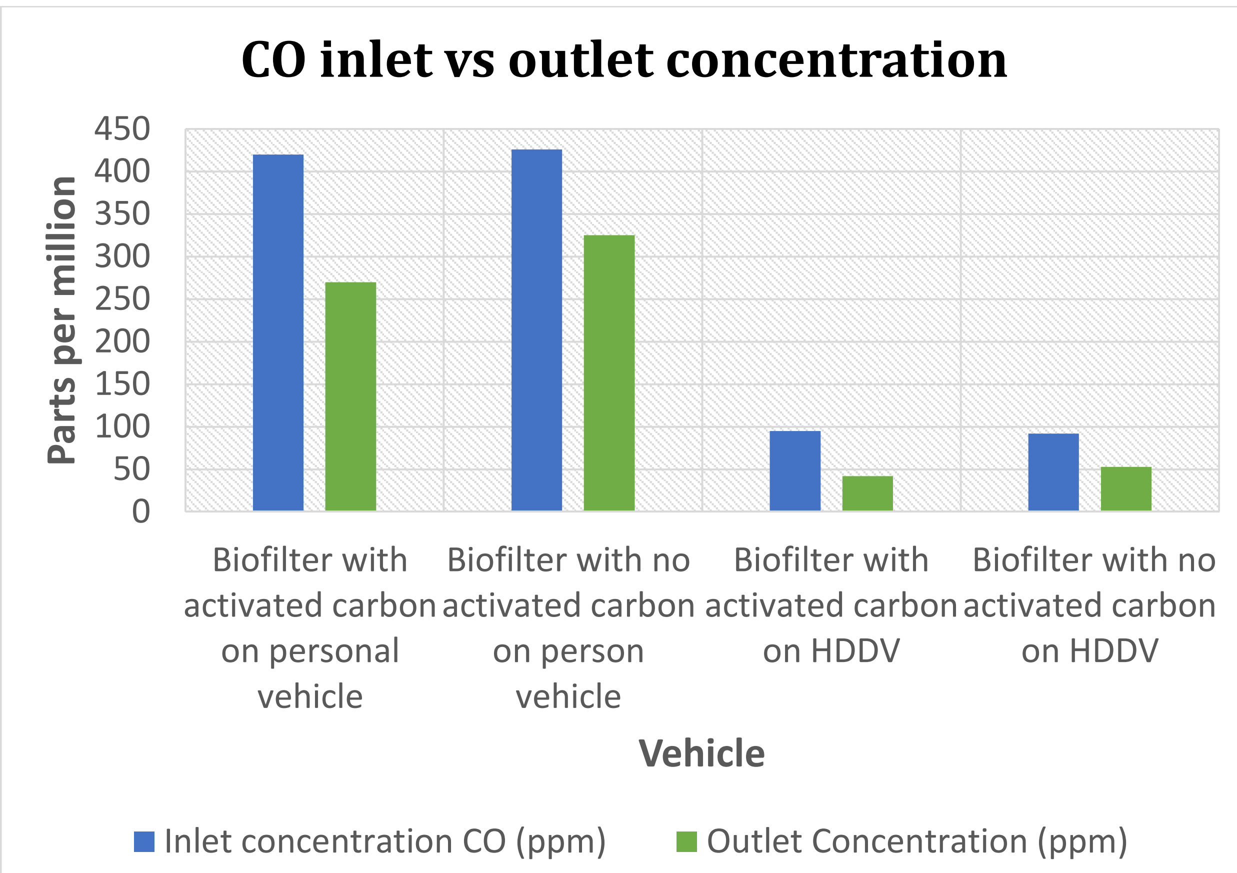

Figure 14 Graph representation of both results of biofilters

Even though both biofilters were constantly irrigated, once every 24 hours before testing, the exhausted gas was being directly transported to the biofilter without any sort of pre-humidification. Hence, by implementing a chamber where the gas can be 100% humidified before going to the biofilter can potentially increase the removal of Carbon Monoxide. Also, studies have indicated temperature affects removal efficiency. Maximum removal rate has been found to be at 35°C, thus, temperatures above 35 °C can cause for removal efficiencies to decrease as seen in the experiment (Bishop, & Govind, 2008). On the other hand, temperatures below 25°C decrease the removal efficiency on a linear basis, but such constraint was not involved in the experiment. Improvement in biofilter performance could be achieved by decreasing the temperature before it enters the biofilter chamber. This process could be coupled with the humification step to save on costs and processes. Another method is heat exchangers to cool hot off gases. Most industrial sources of air pollutants do not operate in a continuous manner, and biological activity could suffer due to extended periods of shutdown. However, vehicles are constantly being used, providing fuel sources to microorganisms and extended periods of shutdown are not sources of constraint (Leson, & Winer, 1991). As previously mentioned, one the advantages of the biofiltration system over conventional VOCs control technologies are the costs involved. The budget involved in the creation of both prototypes was under $500. Although results were not as expected, by implementing several changes to improve the system and considering other factors such as humidification and a cool system, biofilters can increase the removal capacity and eventually match the reduction capabilities of those of the catalytic converter. Figure 15 shows the process of a biofiltration system. As the raw gas travels through the system, a scrubber of humidifier is required to be able to humidify the gas in order to saturate the air as it enters the biofilter. Finally, the air stream travels to the biofilter chamber where the microorganisms are found the biodegradation process takes place. Finally, the clean gas escapes the chamber.

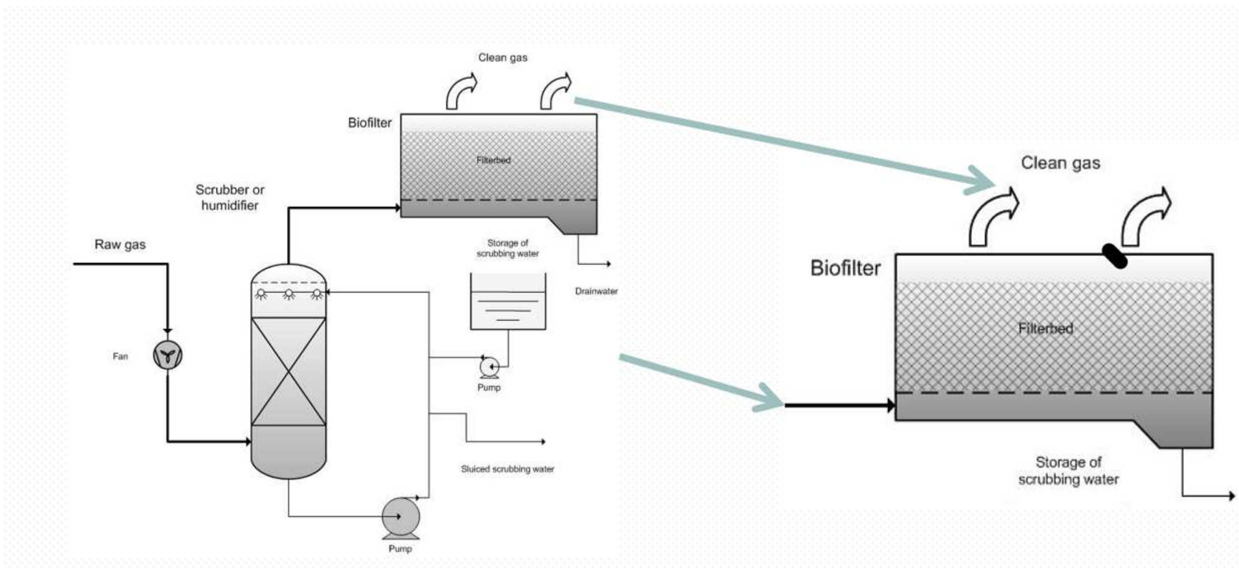

Figure 15 Process of biofiltration.

Case Study 1

Model VOC emission. An emission of 50,000 m^3h^{-1}, 293 K, 1 bar, 40 % relative humidity, and with a composition based upon the characterization of the odour pollution from a Wastewater Treatment Plant located at Stuttgart University (Germany) was the first case study selected for this research. Methyl mercaptan, 2mg m^{-3}, and hydrogen sulfide, 21 mg m^{-3}, were the pollutants included in the emission. In the biofiltration technology used, it consisted of a bio-tricking filter with an EBRT of 9s, packing height of 2 m, backed up by an AC filtration using activated carbon with an EBRT of 2.5 s, packing height of 0.5 m, pressure of 1750 Pa. and a 2-year lifespan.

Case Study 2

This case study represents a medium air flow rate, a moderately high inlet concentration. An emission of 10,000 m^3h^{-1}, 293 K, 1 bar, 40 % relative humidity, and with a composition based upon the characterization of the odour pollution from a plant in California was the second case study selected for this research. Toluene, 1.5g m^{-3}, was the pollutant included in the emission. This concentration was chosen since it matches experiments done on biomass accumulation and toluene elimination at various nutrient loadings. Also, for this reactor/biofilter, nitrate was the limiting nutrient since it had shown in previous studies it affects the rate of biomass accumulation and the performance of the system (Deshusses & Cox, 1999).

Two very assumptions were made for the proposed protocol. First, the elimination capacity is constant over the height of the biofiltration system. Secondly, the elimination capacity is not affected by the growth of mass over time.

Labor costs was determined to be of the main factors to influence the annual operating costs in bio filters with a capacity below 50,000 m^3h^{-1} according to (Prado-Rubianes, David, & Lafuente, 2009). However, for bigger bioreactors, this cost is minimized.

Operating Costs

Previously mentioned, biotechnology offers low operating and investment costs. However, one of the parameters which impacts the most in terms of annual operating costs is the replacement of the packing material (Miller, Sówka, Grzelka, etal., 2018). According to Deshusses and Cox, 1999, a simple relationship to estimate the capital cost of a bio-tricking filter based on bed volume can be evaluated. The cost estimated by this relationship has a 20 +- % accuracy for volumes ranging from 5 to 1000 m^3. Equation (4) shows the relationship between capital cost and reactor volume.

$$\text{Fixed capital cost} = 13{,}000 \times \text{Bed Volume}^{0.757} \quad (8)$$

However, it must be noted this is the fixed capital cost of 1999, we converted the amount to today's present dollars using the following formula, (Staff, U. 2020)

$$FV = PV\,(1+i)^{n} \quad (9)$$

Where:

- FV: Future value
- PV: Present Value
- i: Interest rate (inflation)
- n: Number of times the interest is compounded (for example, number of years)

For example, the FV, future value, represents the final amount acquired after applying the inflation rate to our initial cost. In the next example, 21 years between 1999 and 2020, the average inflation rate has been of 2.072%, the formula can be worked out like this:

$$FV = PV\,(1+i)^{n} = (\text{Fixed capital cost obtained}) * (1+0.02072)^{21} \quad (10)$$

Assuming that a reactor volume can be found from knowing the pollutant concentration, air flow rate, and the desired removal efficiency, a reactor with an emission of 50,000 m3 h−1, would require a bed volume of 200 m^3. After doing calculations, the resultant fixed capital cost was determined to be around 720k.

$$FV = PV\,(1+i)^{n} = (720{,}000) * (1+0.02072)^{21} = \$1{,}107{,}571.1 \quad (11)$$

In today's present dollars, the resultant of $1,107,571.1 was obtained after applying the FV formula. An empty bed resistance time was found using formula 3, giving a resultant of 60 seconds. For case # 2, an emission of 10,000 m^3h^{-1}, would require a bed volume of 40m^3, with a resultant fixed capital cost of around 210k.

$$FV = PV\,(1+i)^{n} = (210{,}000) * (1+0.02072)^{21} = \$323{,}041.6 \quad (12)$$

In today's present dollars, the resultant of $323,041.6 was obtained after applying the FV formula. Volumes between 200 m^3 and 40m^3 would be efficient at removing the concentrations released in this region. Biofilter and bio-trickling filters have the advantage of effectively remove pollutants in low concentrations, typically less than 1000 ppm.

Yearly operating costs were composed of the following: nutrient, water, electricity, labor, and costs of biomass control. However, a simple relationship dictated by equation 5 was used which considered all the parameters mentioned and the fixed capital cost which we obtained for each both case studies.

$$\text{Yearly capital costs} = / \ 10.75 \ (\$/\text{year}) \quad (13)$$

When applying the yearly capital costs for case study one, the resultant was a total of $1,107,571.1.

$$\text{Yearly capital costs case study 1} = \$1,107,571.1 / \ 10.75 \ (\$/\text{year}) = \$103,029.87 \quad (14)$$

When applying the yearly capital costs for case study two, the resultant was a total of $30,050.3814.

$$\text{Yearly capital costs case study 2} = \$323,041.6 \ / \ 10.75 \ (\$/\text{year}) = \$30,050.3814 \quad (15)$$

Both technical and economic factors were considered to describe a model which can predict the advantages in terms of costs and durability for a given bio-waste treatment. For the cases described in this research, a gas flow rate of 50,000 m3 h−1 and 10,000 m^3h^{-1} running 365 days per year, 24 hours a day, would result in a total of $1,107,571.1 and $323,041.6. Removal rate and capacity were increased by the input gas/pollutant rate. The volume of the bioreactor is directly determined by the empty bed residence time, which, depends on the total amount of target pollutant targeted, and their respective concentrations. A widespread application of biotechnology for the treatment of VOC in the south Texas region seems to be feasible and relatively priced, based on the parameters of known studies, and to the data retrieved from the area, reduction in O_3 is attainable.

Design Results

However, to reduce costs, as mentioned, attention should be placed in the type and amount of packing material, as it was found to have the biggest impact on operating costs (Estrada, Kraakman, Lebrero, et al., 2011). Usually, packing material used for its organic and nutrient content, large surfaces, air permeability, inexpensive cost, and low maintenance is a compos of wood chips mixture, which was also used in the prototype designed (Delhomenie, & Heitz, 2005). Optimal empty bed resistance time, EBRT, from several studies, for a compost using wood chips is between 30s and 60s, which were the times used in both case studies (Mann, & Garlinski, 2002). Using the parameters discussed, a filter bed size can be determined using the airflow rate and average time of EBRT, which is 45 seconds:

$$V_f = \text{EBRT x Q (airflow rate)} \tag{16}$$

$$V_f = 45\text{s x Q } (\frac{m^3}{hr}) \tag{17}$$

$$V_f \text{(case study 1)} = 45\text{s x } 50{,}000 \text{ m}^3\text{h}^{-1} = 625 \text{ m}^3 \tag{18}$$

$$V_f \text{(case study 2)} = 45\text{s x } 10{,}000 \text{ m}^3\text{h}^{-1} = 125 \text{ m}^3 \tag{19}$$

Bed volume is used to establish the measurements of the filter bed. These measurements are set as the parameters for the protocol. After getting these parameters, the removal efficiencies were set to control 90%. To determine the elimination capacity at the 90% RE rate, the volumetric mass loading rate was calculated in the following approach:

$$\text{VML} = \frac{Qx\ Cgi}{Vf} \tag{20}$$

Where:

Q = Air flow rate

Cg_i = Inlet concentration

V_f = Filter bed size

$$\text{VML (case study 1)} = \frac{Qx\,Cgi}{Vf} = \frac{50{,}000\ \mathrm{m^3h^{-1}}\ x\ 0.002\ \ g\,m^{-3}}{625\ m^3} \quad (21)$$

$$\text{VML (case study 1)} = \frac{0.16g}{m^3h} \quad (22)$$

$$\text{VML (case study 2)} = \frac{Qx\,Cgi}{Vf} = \frac{10{,}000\ \mathrm{m^3h^{-1}}\ x\ 1.5\ \ g\,m^{-3}}{125\ m^3} \quad (23)$$

$$\text{VML (case study 2)} = \frac{Qx\,Cgi}{Vf} = \frac{120g}{m^3h} \quad (24)$$

Finally, after the volumetric mass loading, VLM, is obtained from both case studies is then used to determine the elimination capacity, EC, for the biofilter:

$$\text{EC} = \text{VML X RE} \quad (25)$$

$$\text{EC (Case study 1)} = \text{VML X RE} = \frac{0.16g}{m^3h}\ \text{x}\ 90\% = \frac{0.144g}{m^3h} \quad (26)$$

$$\text{EC (Case study 1)} = \text{VML X RE} = \frac{0.16g}{m^3h}\ \text{x}\ 90\% = \frac{0.144g}{m^3h} \quad (27)$$

$$\text{EC (Case Study 2)} = \text{VML X RE} = \frac{120g}{m^3h}\ \text{x}\ 90\% = \frac{108\ g}{m^3h} \quad (28)$$

Loading rates which surpass the elimination capacity become less efficient and experience lower removal efficiencies. Thus, the contaminant waste-gas/pollutant stream must not load the filter bed at a larger rate than the obtained EC's, which were 0.144 g m^{-3} h and 108 g m^{-3} h. Table 8 and 9 show the characteristics of both biofilters studied in this research.

Table 8 Characteristics of case study #1 biofilter.

Location	Stuttgart, Germany
Type of airstream	Exhaust air

Year of installation	2008
Volume	625 m^3
Humidification	40 % relative humidity
Air flow rate	50,000 m^3h^{-1}
Empty bed resistance time	45 seconds
Pollutants treated	Methyl mercaptan and hydrogen sulfide, 2 mg m^{-3} or 0.002 g m^{-3}
Approximate capital cost	$103,029.87
Approximate operating cost	$1,107,571.1
Performance	90%

Table 9 Characteristics of case study #2 biofilter.

Location	California
Type of airstream	Exhaust air
Year of installation	1999
Volume	125 m^3
Humidification	40 % relative humidity
Air flow rate	10,000 m^3h^{-1}
Empty bed resistance time	45 seconds
Pollutants treated	Toluene; inlet concentration: 1.5 g m^{-3}
Approximate capital cost	$30,050.3814
Approximate operating cost	$323,041.6
Performance	90%

Due to the nature of the biological characteristics of the reactor, microorganisms need to be taken care of in a special manner. Since the packing material contributes for growth and attachment purposes, routinely exchange and placement is crucial. Also, if the pollutant flow rate value is set to a certain value, the EBRT influence on the operating costs is directly correlated to the permitted surface area and volume of the bioreactor (Gospodarek, Rybarczyk, Szulczynski, et al., 2019). Affordable, and accessible solutions are needed to enable countries to change to a cleaner economy. Even though people are turning into solutions which have more environmental benefits, such as electric vehicles, the transition will certainly not take place from day to the other. It is crucial to mitigate the effects of high-carbon economy to smoothen the transition to a cleaner economy and reduce the number of pollutants released to the environment.

According to the information retrieved from the EPA on the current air quality trends in the South Texas region, the maximum 8-hour concentration recorded of O3 was of 0.077 ppm in the year 2000. Based on the resultant calculations on current treatment technologies, the treatment in this area is attainable and feasible.

NPV Results

The formula used to arrive to the total cost of the treatment technology is shown in equation 6. Also, NPV calculations are shown in the spreadsheet in Appendix B.

$$\mathbf{NPV} = \sum_{t=0}^{5} \frac{CFt}{(1+r)^t} \qquad (29)$$

Where:

Cf_t = Total operating cost

i = Required return or discount rate

t = Number of time periods

$$\text{NPV(Case Study 1)} = \sum_{t=1}^{5} \frac{\$1{,}107{,}571.1}{(1+0.0275)^1} + \ldots + \text{NPV} = \sum_{t=5}^{5} \frac{1{,}107{,}571.1}{(1+0.0275)^5} = \$5{,}238{,}386.94 \quad (30)$$

$$\text{NPV(Case Study 2)} = \sum_{t=1}^{5} \frac{\$323{,}041.6}{(1+0.0275)^1} + \ldots + \text{NPV} = \sum_{t=5}^{5} \frac{\$323{,}041.6}{(1+0.0275)^5} = \$1{,}527{,}863.00 \quad (31)$$

The study assumed a 5-year project due to the necessity of replacing organic media between 5 to 7 years. At the same time, for the calculations, a 2.5% discount rate was used as the applicable rate established by the USDA (USDA, 2020). It is important to mention the costs calculated can vary depending on the aimed facility and whether it can support the monetary investment by itself. The probable savings to a medium to high scale industry which desires to introduce a biofiltration system to reduce the amount of pollutant released to the atmosphere, is presented in appendix A. Over a 5-year span, which is the amount of time decided due to the conditions of the chosen organic media, it is evident the high cost of installing a biofilter. Consequently, there is an environmental benefit of having such a system installed. With a VOC reduction of more than 90% for both cases, after the cost of installing the biofilter and the costs associated with its operation and maintenance for five years is shown in table 10. Therefore, the aimed design would fall between the ranges of $5,238,386.94 and $1,527,863.00.

Table 10 Operation and maintenance cost for the next 5 years.

System	Biofilter case study 1	Aimed Biofilter	Biofilter case study 2
VOC Reduction	>90%	> 90%	>90%
Five-year NPV cost	$5,238,386.94	Value in between would be optimal	$1,527,863.00

Business Model Canvas

A business model canvas was created to define quickly, easily, and communicate the idea of implementing a biofiltration system to medium-to-high scale industries. In the next one-page summary, it describes the high-level strategic details needed for this service to successfully grow in the market. The categories contained in the canvas are the following:

- Product’s value proposition (promise and role of the product)
- Customer segments (who it is for)
- Key activities (the steps to make the product/service successful)
- Key resources (Tools, personnel, and budget)
- Channels (manners the organization/company will market it and sell it)
- Customer relationships (customer base)
- Key partners (how third parties will play a role in marketing this product)
- Cost structure (cost to build the product, as well as to sell and maintain it)
- Revenue streams (how the product will produce revenue)

It important to mention once the BMC is completed, it must be revisited to ensure that it is relevant, updated, and accurate with the latest information. The business model canvas is shown in figure 16.

Business Model Canvas

Designed for: Thesis

Designed by: Javier Garcia

Date: 11/18/2020

Key Partners

A key in the biotechnology business, and using biofilters to clean VOCs, is the advantages to attract other companies to share and support your business by implementing more similar methods. The support from biotech companies will becomes useful as the world changes directions to more of these approaches.

Key Activities

As biofilters have proven to release no secondary waste as a side product, companies inclined to a healthier and cleaner environment, will benefit the most from this technology.

Key Resources

By implementing this emission control technology to your company, you will create awareness and more people will be attracted due to the mission of reducing VOCs pollutants.

Value Propositions

The cost of a biofiltration system compared to other control technologies, such as thermal oxidation and catalytic oxidation, is much cheaper and has a positive impact to the environment.

This same technology has proven to be cost effective, operate with low capital costs, effective because secondary waste streams are not produced, and convenient.

Customer Relationships

The relationship involves dedicating the customer representative specifically to the individual client. This relationship will be established on a personal level, as the project presented is derived from academic research.

Channels

Distribution through the publication of the University thesis.

Customer Segments

Companies who operate a medium to high scale industry facility.
A medium to high scale industry can be classified as any firm/business which is composed with 50 and less than 200 employees. Several of those industries are found in the Rio Grande Valley.

Cost Structure

The first step to determine the cost of the biofiltration system in the desired facility is to use concrete parameters in the first NPV calculation. These parameters include, cost of the system, installation cost, system maintenance, annual cost of operation.

Maintenance and operating costs of the designed biofilter in operation are also considered using the NPV method.

Revenue Streams

Fixed capital cost = 13,000 x Bed Volume $^{0.757}$

Labor costs was determined to be of the main factors to influence the annual operating costs in bio filters with a capacity below 50,000 m^3h^{-1}

Figure 16 Biofilter Business Model Canvas.

CHAPTER V

SUMMARY AND CONCLUSION

The purpose of this research was to determine if a medium-to-high scale industry, like the University of Texas Rio Grande Valley, and its surrounding area can benefit both environmentally and economically from the implementation of a biofiltration system to control air pollution rather than the use of other conventional methods, which contaminate with an equal or greater amount due to their secondary waste. The questions answered by this research were the following:

1. Is it feasible and environmentally suitable method to implement a bio filtration system for reducing VOC release to the atmosphere?
2. What is the anticipated reduction in VOC emissions from a proof-of-concept conventional biofilter?
3. Will a biofiltration system be a cost-effective method for reducing Volatile organic compounds release to the atmosphere? Will a business model canvas/ economic model can show the benefits?

Each of these questions were answered during this research. This section shows a summary of those answers to each question, with the limitations encountered, and improvements which can be made in any follow-on research.

Research Question Answered

Our studies indicated that the designed biofilter, with activated carbon, performed under the conventional catalytic converter in terms of removal efficiency. One of the key constraints found was the high temperature of the gas produced by the vehicle, which can cause unfavorable conditions to the bacteria, thus decreasing the biodegradation chemical process to remove waste gases. Also, the humidification process was not implemented due to availability circumstances. As increasingly HDDV cross the United States-Mexico Land Ports of Entry, more VOCs and chemical waste gases are emitted, causing detrimental effects on both humans and the environment. Although catalytic converters are still one of the top technologies to reduce the amount of chemical gas wastes, the amount of secondary waste produced has opted to search for more natural methods to perform the same task with less risks. It is important to mention microorganisms withing the filter medium responsible of the degradation of pollutants, are capable to survive for as long as several weeks without a contaminated air stream, given the optimal set of conditions within the filter medium. Therefore, it is crucial for the filter medium to be closely monitored during its operation to guarantee optimal conditions to ensure maximum removal of the contaminants, and for the survival of the microbial population. Conventional biofiltration systems will be an acceptable method to reduce the emissions caused by different sources such as motor vehicles, power plants, and industrial activities.

Both technical and economic factors were considered to describe a model which can predict the advantages in terms of costs and durability for a given bio-waste treatment. For the cases described in this research, a gas flow rate of 50,000 m3 h−1 and 10,000 m^3h^{-1} running 365 days per year, 24 hours a day, would result in a total of $5,238,386.94 and $1,527,863.00, projected to a 5-year period. Removal rate and capacity were increased by the input gas/pollutant rate. The volume of the bioreactor is directly determined by the empty bed residence time, which, depends on the total amount of target pollutant targeted, and their respective concentrations. A widespread application of biotechnology for the treatment of VOC in the south Texas region seems to be feasible, based on the parameters of known studies, and to the data retrieved from the area, reduction in O_3 is attainable.

However, in order to reduce costs, as mentioned, attention should be placed in the type and amount of packing material, as it was found to have the biggest impact on operating costs (Estrada, Kraakman, Lebrero, Muñoz, 2012). Due to the nature of the biological characteristics of the reactor, microorganisms need to be taken care of in a special manner. Since the packing material contributes for growth and attachment purposes, routinely exchange and placement is crucial. Also, if the pollutant flow rate value is set to a certain value, the EBRT influence on the operating costs is directly correlated to the permitted surface area and volume of the bioreactor (Gospodarek, Rybarczyk, Szulczynski, Gebicki, 2019). Affordable, and accessible solutions are needed to enable countries to change to a cleaner economy. Even though people are turning into solutions which have more environmental benefits, such as electric vehicles, the transition will certainly not take place from day to the other. It is crucial to mitigate the effects of high-carbon economy to smoothen the transition to a cleaner economy and reduce the number of pollutants released to the environment. Thanks to the business model canvas, it helped to visualize the key elements which described the biofilter value proposition, infrastructure, customers, and finances. It also assisted in associating their activities by showing potential trade-offs.
Further expansion of the model needs to be developed, which includes more complex data and extra parameters which give an even detailed economic analysis.

Research Limitations

This research was limited by various factors which halted further elaboration of the topic. This study was not demanded by the University, but rather, the author approached this topic and offered his research services to conduct an investigation in an effort to bring interest to the field of biotechnology to cleanse air pollution. The main constraint was the inability to conduct lab and pilot scale experiments considering all the parameters mentioned throughout the discussion, as a result of this, the majority of the results were strictly theoretical as opposed to empirical. Additionally, due to the reduced amount of research on medium-to-high scale industries, the number of case studies was also limited. Finally, due to the COVID-19 pandemic, access to data was limited and prevented the author from examining further studies and potential experiments.

Proposed Improvements

Future research in the biological treatment of VOCs at medium-to-high industries should have an emphasis on more facilities which generate an air flow rate discussed in this research, this will bring more reports and assessments in which other researchers can base their research from. Some studies of this particular have been conducted, such as the ones studied in this study, but further research is necessary to provide more evidence of the concept's success. Most of the research found has been done on full-scale production industries and pilot-scale experiments treating a single contaminant, future research will have to assess methods of treating multiple sources of contaminants at a medium scale facility. Because of the different production processes of each industry, along with the standards, the likelihood of the annual and operating costs will vary from company to company, an economical study of this notion is also needed.

A closer assessment to the parameters accountable to the design of a biofiltration system to reduce the overall costs and increase in reduction of gaseous pollutants is necessary. A greater gas residence time equates to an increased filter bed size, equating a larger biofilter. Still, a medium sized filter medium can be designed which can treat the same amount and type of contaminants in an identical-sized air stream, similar to a large conventional biofilter can perform in much less space, then medium size facilities can benefit. Finally, it is important to inspect the area in which a potential biofiltration system can be implemented. A survey of a representative sample of a population to determine if there are any trends in adverse health that could cause negative effects amongst the population as a direct result of contaminated air.

Prototype

In regard to the prototype built, it is of sum importance to consider the air flow rate resistance as it goes through the packing material. As it is expressed as the ratio of pressure gradient in a material to airflow linear velocity in steady airflow conditions. Another point to tackle is the position of the biofilter prototype, horizontal and vertical positions .Since the cost of treatment by a biofiltration system is primarily correlated with filter construction and filter operation and maintenance, a crucial part of the operation cost is the energy consumption to surmount the air flow resistance of the bio filter. As the cost is directly proportional to the air flow rate and the pressure drops across the biofilter, for future research purposes, the reduction of energy consumption associated with air flow resistance can be through the choice of a proper biofilter material.

Also, according to the Central Limit Theorem, a sample size of approximately 30 can yield significant results and will be close to achieve a normal distribution. The accuracy for the analysis part stays almost the same as the sample size increases more than 30. Also, to save money, and be efficient , 30 samples would be needed to perform a more accurate assessment.

However, different situations and environments would also be of importance, such as stationary, and operational vehicles.. Controlled experiments under controlled conditions and changing one, or a few factors, such as time and temperature, are also required to follow a standardized step by step procedure and allow replication of the study.

Significance

This research has shown opportunities to finding solutions and a practical look at an inexpensive and effective method of mitigating Volatile Organic Compounds emissions released to the atmosphere. Based on the data collected, prototype designed, and case studies analyzed, a rough estimate of $50,000 and $75,000 would be needed to incorporate a small scale biofilter into the HDDV. However, to develop design specifications and recommendations, future research is required to determine air flow resistance for various types of biofilter media, and recommended operating and management purposes.

Also, this thesis may encourage similar studies to be performed in the future to research more possible solutions to confront Volatile Organic Compounds.

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APPENDIX A

APPENDIX A

NPV CALCULATIONS

Biofilter Case Study 1						
Study Biofilter;Net Present Value over 5-year period						
Discount rate	0.0275					
Year	0	1	2	3	4	5
Capital cost	$ 103,029.87					
Operation and Maintanance cost	$ -	$ 1,107,571.10	$ 1,107,571.10	$1,107,571.10	$1,107,571.10	$1,107,571.10
NPV per Year	$103,029.87	$1,077,928.08	$1,049,078.42	$1,021,000.90	$ 993,674.84	$ 993,674.84
	=NPV(B3/12,B6)+B5	=(C6)/(1+$B$3)^1	=(D6)/(1+$B$3)^2	=(E6)/(1+B3)^3	=(F6)/(1+B3)^4	=(G6)/(1+B3)^4
Total NPV	$5,238,386.94					
	=SUM(B7:G7)					

Biofilter Case Study 2						
Study Biofilter;Net Present Value over 5-year period						
Discount rate	0.0275					
Year	0	1	2	3	4	5
Capital cost	$ 30,050.38					
Operation and Maintanance cost	$ -	$ 323,041.60	$ 323,041.60	$ 323,041.60	$ 323,041.60	$ 323,041.60
NPV per Year	$30,050.38	$314,395.72	$305,981.23	$ 297,791.96	$ 289,821.85	$ 289,821.85
	=NPV(B3/12,B6)+B5	=(C6)/(1+$B$3)^1	=(D6)/(1+$B$3)^2	=(E6)/(1+B3)^3	=(F6)/(1+B3)^4	=(G6)/(1+B3)^4
Total NPV	$1,527,863.00					
	=SUM(B7:G7)					

BIOGRAPHICAL SKETCH

Javier Alejandro Garcia was born in McAllen, Texas. After completing his schoolwork at Roma High School in Roma in 2013, Javier entered the University of Texas at Austin in Austin, Texas. He received a Bachelor of Science with a major in Biology and a minor in Spanish from the University of Texas at Austin in May 2017. During the following three years, he enrolled in the University of Texas Rio Grande Valley to pursue his Master of Science in Manufacturing Engineering. During the summer of 2019, he interned with IACMI, Institute of Advanced Composites Manufacturing Innovation where gained technical experience in composites. He was awarded a Master of Science in Engineering, in Manufacturing & Industrial Engineering from the University of Texas Rio Grande Valley in May of 2021. Javier Garcia's email is javigarcia9404@gmail.com