An Environmental Analysis of Recreational Cannabis Cultivation & Processing

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

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May 13, 2020

Abstract

The recreational cannabis industry has experienced rapid growth, yet the environmental impacts of the industry are still largely unknown. This may be attributed to the lack of available data and comprehensive studies. More fundamental and applied research is required in many areas of cannabis production. Our research provides an overview of current recreational cannabis regulations and an in-depth environmental analysis of five major concerns: water, pesticides, air, energy, and waste. For each category, common industry practices were evaluated to assess their environmental impacts. Based on our research, a series of recommendations were made to improve the sustainability of the cannabis industry.

Acknowledgements

We would like to thank our advisors, John Bergendahl and Stephen Kmiotek, for all of their help and guidance throughout this project.

Executive Summary

The recreational cannabis industry has experienced rapid growth, yet the environmental impacts of the industry are still largely unknown. This may be attributed to the lack of available data and comprehensive studies. More fundamental and applied research is required in many areas of cannabis cultivation and processing. Our research provides an overview of current recreational cannabis industry practices and current regulations, along with an in-depth environmental analysis of five major concerns: water, pesticides, air, energy, and waste. For each category, an evaluation of common industry practices was performed to assess their environmental impacts. Based on our research, a series of recommendations were made to improve the sustainability of the cannabis industry.

It is known in the industry that cannabis is a water-intensive crop. However, there is no current research documenting the details of water use of current industry practices. To address this gap, we calculated new values of water consumption based on more current growing practices and facility sizes. We determined that plants grown indoors and outdoors require 0.096-0.251 and 0.453-1.12 gallons per plant per day, respectively. Furthermore, the quantity and characteristics of wastewater produced by cannabis facilities has not been addressed in the literature. Constituents of concern for wastewater treatment plants include pesticides, nutrients, and certain biological agents, which may affect treatment processes. While the current loading rates are not a concern, wastewater treatment plants may experience greater than average loading rates if multiple facilities begin discharging to them at once.

The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) requires that all pesticides sold or distributed in the United States be registered by the EPA. Since cannabis cannot be legally grown or possessed under federal law, the EPA has not evaluated the safety of pesticides for the cannabis industry, or set tolerances for pesticide residues on cannabis products. If pesticides are not federally designated for use on cannabis, it is technically illegal to use them on cannabis. However, states can allow the use of pesticides exempt from FIFRA on cannabis. Of the states that have legalized recreational cannabis, none have established the same pesticide restrictions. Without federal oversight, the environment and consumer are left at risk. The environmental impacts of pesticides are somewhat documented, but it is unknown how pesticides transform when smoked or processed during extractions.

Through the use of temperature, pressure, and solvents (i.e. butane, ethanol, etc.), extraction techniques are used to produce cannabis concentrates with high concentrations of tetrahydrocannabinol (THC) and cannabidiol (CBD). Depending on the technique, extractions may be energy intensive. To estimate energy consumption, the energy required for the phase changes in each process was calculated. Butane, ethanol, supercritical CO_2, cold water, and food-based extractions require 4.34, 0.53, 14.91, 0.57, and 0.49 kWh/lb extract, respectively. In addition, solvent residuals in final products may pose a health concern. More research is needed in this area to determine the risk to consumers.

Air emissions from the cannabis industry have been the subject of many complaints and concerns. The emissions include odor, volatile organic compounds (VOC), and carbon dioxide. The characteristic odor and VOC emissions from cannabis is attributed to the release of terpenes by the plants. High levels of VOC in the atmosphere can increase ozone levels, which can have harmful health effects when present in high concentrations. VOC emissions are regulated on the state and local level to keep ozone levels below the federal requirement. However, these

regulations often omit agricultural contributors such as cannabis cultivation facilities. Air pollution control technologies are available to mitigate odors and VOC emissions, with activated carbon adsorbers being the most commonly recommended for the cannabis industry. In this work, a fixed-bed carbon adsorber for a typical indoor cannabis production facility was designed; it was determined that the scale required for effective odor and VOC treatment, as well as the cost, was not feasible for this typical cannabis facility. Improved air pollution control approaches need to be developed for this industry.

Cannabis cultivation uses a significant amount of energy primarily due to lighting needs, dehumidification demands, and HVAC systems. As the industry continues to grow, so will the energy demand and the associated CO_2 emissions. A widely-cited study estimated that 4,600 kg of CO_2 are emitted for every kg of final product produced (Mills, 2012). This value and the future industry sales were used to determine that approximately 7.4 billion kg of CO_2 will be emitted from recreational cannabis production in 2025. Research on energy efficient alternatives is required to reduce the energy demand for the cannabis industry.

Cannabis cultivators can generate large amounts of organic waste, which can be on the order of several tons per week. Most state regulations require cannabis plant waste to be disposed of in a 50/50 mix with other organic material or trash. This requirement can either double the amount of organic material ending up in a landfill or eliminates the option to compost organic material if it is mixed with trash. Furthermore, the federal status of cannabis hinders sustainable waste management, because many composting facilities are hesitant to accept a federally illegal waste. Cannabis cultivation and processing facilities are then forced to dispose of their waste with municipal waste (where it may be landfilled or incinerated depending on the practices of the local municipality) if they do not have space for onsite composting. Therefore, a significant amount of waste from the cannabis industry may be disposed of in non-sustainable practices.

The cannabis industry is projected to grow at a compound annual growth rate of 16%, and sales are expected to reach more than $29 billion by 2025. As the industry continues to grow, so will the environmental impacts. To mitigate these impacts, sustainable practices should be implemented in the industry. However, the full scope of the environmental impacts are unknown, and many known issues do not have practicable solutions. More fundamental and applied research is needed to address these gaps. Additionally, as more states legalize recreational cannabis, the gaps in knowledge will become greater due to the confusing state-by-state regulations.

Statement on Design

As the culmination of undergraduate studies in Environmental Engineering, Worcester Polytechnic Institute requires a Major Qualifying Project with a capstone design element to fulfill the Accreditation Board for Engineering and Technology (ABET) engineering requirements. Per the ABET General Criterion 5, students must be prepared for engineering practice through "a culminating major engineering design experience that incorporates appropriate engineering standards and multiple constraints, and is based on the knowledge and skills acquired in earlier course work." The major design portion of this project involved the design of a fixed-bed activated carbon adsorber, with the purpose of removing volatile organic compounds (VOCs) and odors, for the air emissions of a typical cannabis facility. The design for this project included the following constraints:

1. **Public Health, Safety, and Welfare:** The filter was designed to minimize the harmful health impacts of ozone and nuisance odors on surrounding communities.

2. **Social and Political:** In many regions, cannabis cultivation facilities are exempt from air emissions regulations, therefore there is limited pressure to install air pollution control technology. The purpose of this design was to determine if a fixed-bed carbon adsorber was practicable enough to encourage voluntary air emission control.

3. **Environmental:** As part of the design, regeneration of carbon was suggested, as opposed to one-time use, in order to reduce the amount of waste produced by the filter.

4. **Economic:** To determine if a fixed-bed carbon adsorber was an affordable air pollution control option for the cannabis facility, the total equipment cost was considered.

Statement on Professional Licensure

A century ago, anyone could work as an engineer. To ensure an engineer is competent and protect public health and safety, engineering licensure laws were enacted throughout the United States. Every state regulates the practice of engineering to ensure public welfare by granting Professional Engineers (PE) the authority to sign and seal engineering plans (NSPE, 2020).[1]

Engineers are licensed at the state level by professional licensing boards. To ensure an engineer is competent, he or she must meet a combination of requirements in education, exams, and experience. There are four main steps to become a licensed engineer. First, an engineer must complete a four-year college degree. Generally, engineering licensing boards require candidates to have an EAC/ABET-accredited bachelor's degree. Next, an engineer must pass the Fundamentals of Engineering (FE) exam. Then, four years of acceptable, progressive, and verifiable work experience in the industry under a licensed PE is required. Finally, an engineer must pass the Principles and Practice of Engineering (PE) exam (NSPE, 2020; NCEES, n.d.).[2]

To retain their licenses, PEs must continuously demonstrate their competency and maintain and improve their skills by fulfilling continuing education requirements depending on the state in which they are licensed. As a PE, an engineer may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients (NSPE, 2020). There are many benefits to becoming a licensed engineer. The title "PE" recognizes an engineer's experience, knowledge, and accountability. A PE provides ability for growth, as engineering positions at all levels of industry and government increasingly require licensure. As a PE, an engineer can establish a private practice. When an engineer earns a PE in one state, it is easier for them to apply for licensure in other states through a process known as comity licensure. Lastly, salary studies show that PE's earn significantly more throughout their career (NCEES, n.d.).

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[1] National Society of Professional Engineers (NSPE). (2020). What is a PE? Retrieved from https://www.nspe.org/resources/licensure/what-peStatement on Design

[2] National Council of Examiners for Engineering and Surveying (NCEES). (n.d.). Engineering licensure. Retrieved from https://ncees.org/engineering/engineering-licensure/

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Chapter 1: Introduction

The growing recreational cannabis market poses concerns for regulators, the public, engineers, and scientists alike. Currently, recreational cannabis has been legalized in 11 states and Washington D.C. Since it is not federally legal, federal agencies like the FDA and EPA are not able to regulate the industry with standardized laws. This leads to regulations that vary widely between states and leave gaps which have the potential to create environmental and public health hazards.

Regulators and the public are starting to engage in a discourse about the public health concerns of recreational cannabis, but the environmental impacts are still largely unknown or overlooked. This is in part due to the lack of research in the industry. It has been noted that more fundamental and applied research is required in many areas of cannabis production, specifically the environmental impacts (Ashworth & Vizuete, 2016).

This document is intended to provide an overview of current recreational cannabis regulations and an in-depth environmental analysis of five major concerns: water, pesticides, air, energy, and waste. The caregories are summarized below in Figure 1.1. To clarify, the term “recreational cannabis” in this document is used to describe any strain of *Cannabis sativa L.* with a THC level of 0.3% or greater by weight (Seltenrich, 2019). It should be noted that the information in this document could apply to other cannabis industries, such as hemp production or medical-use cannabis, but the industry practices can vary. The goal is to compile and analyze current research in these areas in one comprehensive document that can be used as a reference for future policy making.

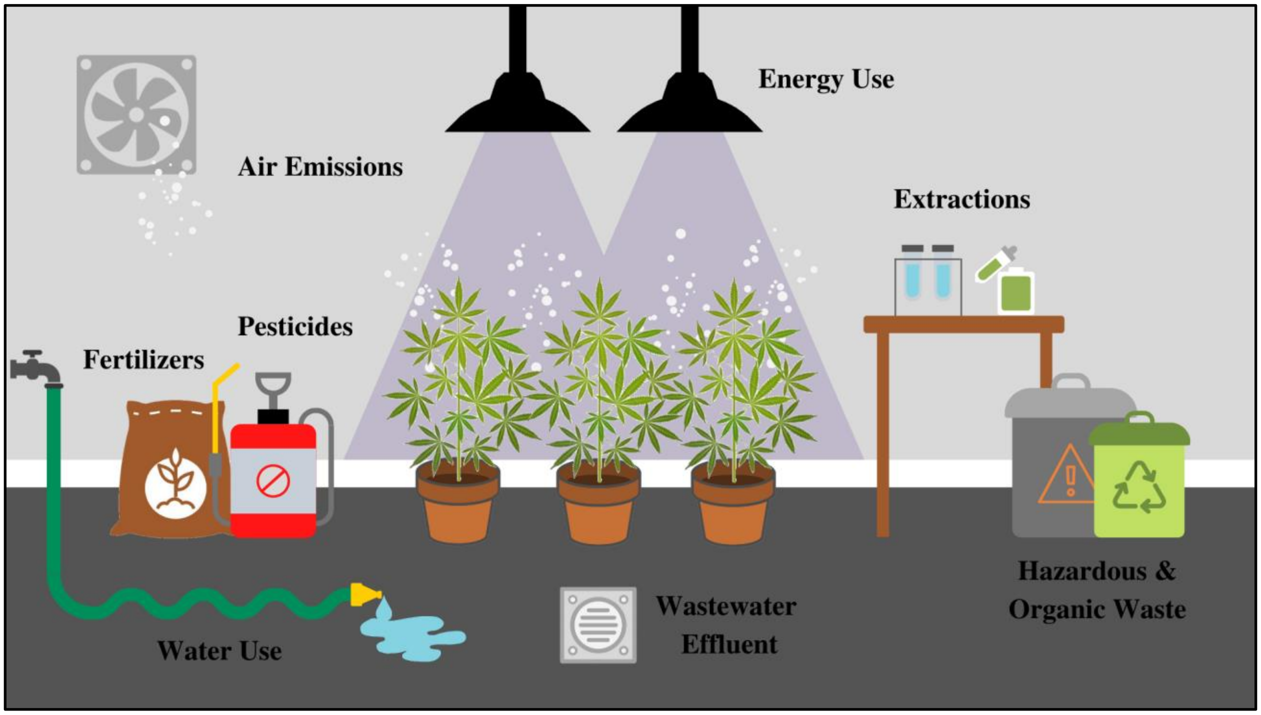

Figure 1.1. Overview of Environmental Analysis.

Chapter 2: Regulations

Of the 11 states and Washington D.C., that have legalized recreational cannabis in the United States, Colorado, California, Massachusetts, and Illinois have taken the most steps to ensure the industry is adequately regulated. Although recreational cannabis is legalized in 12 states, the regulations for the industry in a handful of states are still being constructed. In Maine, Vermont, and Washington D.C., there are currently no finalized regulations, resulting in a hold on the commercial market until they can be created. In Nevada, the industry is not regulated beyond taxation through the Department of Taxation (OHA, 2018). Oregon, Alaska, and Washington currently have state regulations, however they are lacking as many are non-specific to issues related cannabis production.

Colorado

As one of the first states to legalize recreational cannabis in 2014, regulations of the industry are comprehensive and innovative. Cannabis regulation in Colorado varies between municipalities. Colorado's state law dictates that local governments may regulate the industry based on the community's needs. Many counties have opted to ban recreational cannabis production and dispensaries. However, in the counties that allow production, base regulations include a disposal plan, proper ventilation to mitigate odor, proper waste management, and pesticide use that is in accordance with state statutes. In the case of Boulder, CO, the local code supports Colorado's Sustainability and Climate Action Plan goals by requiring renewable sources to grow recreational marijuana. Their local statutes state that, "a marijuana cultivation facility shall directly offset one hundred percent of its electricity consumption through a verified subscription in a Community Solar Garden, or renewable energy generated onsite, or an equivalent that is subject to approval by the city," (Boulder, CO Municipal Code § 6.16.8). Additionally, the county only allows cold-water extraction rather than using chemical solvents, (Boulder, CO Municipal Code § 6.16.8).

California

California first legalized medical marijuana in 1996. Most regulation was conducted by local governments until 2015, when the Medical Cannabis Regulation and Safety Act (MCRSA) established a state regulatory framework. Under MCRSA, three licensing authorities were established: the Bureau of Cannabis Control, CalCannabis Cultivation Licensing, and the Manufactured Cannabis Safety Branch. In November 2016, Californians voted to legalize recreational cannabis use and the regulated sale and distribution of cannabis. In June 2017, the Medical Cannabis Regulation and Safety Act and the Adult Use of Marijuana Act were integrated to create the Medicinal and Adult-Use Cannabis Regulation and Safety Act (MAUCRSA).

Under MAUCRSA, the BBC was established as the single regulatory system to govern the medical and adult-use cannabis industry in California. The BBC is responsible for licensing retailers, distributors, testing labs, microbusinesses, and temporary cannabis events. CalCannabis Cultivation Licensing (CalCannabis) is a division of the California Department of Food and Agriculture. It is responsible for public safety and environmental protection. CalCannabis is organized into a Licensing Branch and a Compliance and Enforcement Branch. Together, these two branches of CalCannabis license and regulate commercial cannabis cultivators and manages all commercial cannabis and cannabis products from cultivation to sale. The Manufactured

Cannabis Safety Branch (MCSB) of the California Department of Public Health is responsible for the regulation of all commercial cannabis manufacturing. The MCSB ensures that commercial cannabis manufacturers maintain safe workplaces and that products are free of contaminants, meet product guidelines, and are properly packaged and labeled. All three licensing authorities can accept and issue licenses for commercial cannabis activity in California (State of California, 2019).

With more than 10,000 cannabis operators, California is the largest cannabis market in the United States. California has arguably the most detailed cannabis regulations of any state, especially considering environmental protections. All licensed cannabis businesses must be in compliance with the California Environmental Quality Act, but many of the environmental regulations fall under the jurisdiction of other established laws. For example, each licensee must comply with the Water Code as implemented by the State Water Resources Control Board, Regional Water Quality Control Boards, or California Department of Fish and Wildlife (Cal. Code Regs. tit. 16, § 8307 (2018)). Licensed businesses must also comply with all pesticides laws and regulations established by the Department of Pesticide Regulation. Of all the states, California has the most comprehensive pesticide regulations. The regulations include pesticide application and storage protocols. The pesticides must be labeled properly, stored in secured areas, and leaks must be contained and immediately cleaned up. Producers are required to use the minimum amount of pesticide necessary to control the target pest and prevent offsite drift. Pesticides cannot be applied when pollinators are present or allow pesticide drift to plants that attract pollinators. Pesticides cannot be sprayed directly to surface water or allowed to drift to surface water. To ensure no drift occurs, pesticides may only be sprayed when the wind is blowing away from surface water bodies. Finally, pesticides are not to be applied when they may reach surface or groundwater (Cal. Code Regs. tit. 16, § 8307 (2018)).

In January 2019, new cannabis regulations were approved for cannabis businesses across the supply chain, from cultivation to retail. The new cannabis regulations included some key changes that further clarified and specified criteria for commercial cannabis businesses under MAUCRSA. One addition of note is an additional waste-management plan that allows cannabis waste to be reintroduced into the agricultural operation (CDFA, 2019).

Massachusetts

In Massachusetts, cannabis became legal for persons 21 years of age or older to grow and possess in December 2016. In July 2017, “An Act to Ensure the Safe Use of Marijuana” established the Massachusetts Cannabis Control Commission (CCC). The purpose of the CCC is to develop and enforce cannabis regulations and develop and execute a plan of public education. The most recent set of regulations was filed on October 18, 2019 under 935 CMR 500.000: Adult Use of Marijuana. Many of Massachusetts’ regulations are similar to states that have legalized recreational cannabis previously. For example, marijuana establishments are required to provide a plan to reduce energy demand and consider opportunities for renewable energy generation. In addition, organic waste disposal must render any marijuana unusable for its original purpose. However, the regulations are more explicit than others for liquid waste disposal, including a separate requirement stating that all liquid waste containing marijuana or by-products of marijuana processing “shall be disposed of in compliance with all applicable state and federal requirements, including but not limited to, for discharge of pollutants into surface water or groundwater.” Another unique regulation requires laboratory testing of environmental media, such as soil, growing media, and water, along with the testing for mold mildew, heavy metals, plant growth regulators, and the presence of pesticides.

Illinois

Despite being the 11th state to legalize recreational cannabis in 2019, Illinois has arguably the strictest regulations of the industry. As part of the application process for a production license, the grower has to include their waste management plan, total water needs, and total energy needs. The plan for each resource needs to include whether they have or will create a sustainable use plan in the future. The application also includes, "a commitment to use resources efficiently, including energy and water.... a cannabis cultivation facility commits to meet or exceed the technology standard identified: (i) lighting systems, including light bulbs; (ii) HVAC systems; (iii) water application system to the crop; and (iv) filtration system for removing contaminants from wastewater," (Ill. Admin. Code tit. 101-0027 (2019)).

Additionally, the law limits the amount of water and electricity that can be used during production. It also places limits on water runoff and wastewater (Schmid, 2019). It requires growers to collect and filter wastewater so that it could be used to water their plants in the future. In addition, a grower can use no more than 36 watts per square foot for lighting the plants. The lighting used must be high-efficiency lighting approved by the state (Schmid, 2019). This was passed in an attempt to prevent new large-scale environmental issues before they occur. The state government acknowledges how harmful the industry has the potential to be. Illinois is quickly becoming a leader in regulating the recreational cannabis industry and stands as a prime example for other states to follow.

Conclusions

Since recreational cannabis has not been federally legalized, there is no overhead authority to provide guidance for regulations. This leads to regulations varying greatly between states. Some states have opted to form specific agencies to focus on cannabis, such as the Massachusetts' Cannabis Control Commission, while others have chosen to regulate through already established departments. Furthermore, these agencies and regulations fall under different branches of government, from the state department of food and agriculture to the taxation department. This variance has left states to rely on their own intuition to create regulations. As a consequence, the regulators are often left playing catch up, trying to correct flaws in the regulations as the problems appear. Recently, many of these issues have involved public health, such as the rise of dabbing-related disease incidents. Because we have not seen the immediate effect of the lack of environmental regulation, environmental policy in regard to cannabis has been slow moving to nonexistent. For example, none of the states with legal recreational cannabis have any regulations in regard to specific cannabis pollutants. Research needs to be conducted to determine if regulations specific to the cannabis industry are needed.

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Chapter 3: Water Use and Wastewater

Introduction

Many of the environmental impacts of the cannabis industry are unknown, but there is great concern about the effects cannabis cultivation and processing facilities have on water quality. In certain parts of the United States, there is a lot of discussion regarding the demand these facilities will have on local water resources and infrastructure. More research needs to be conducted to determine the potential impacts cultivation facilities could have on local wastewater treatment plants. It is unknown what kind of effect pesticide residues, plant matter, nutrients, solvents, and other constituents have on the quality of a facility's wastewater.

There is little industry data available about the water use of cannabis cultivation. Some estimates suggest cannabis requires upwards of 22.7 liters (5.8 gallons) of water per plant per day,[3] while others estimate about 5,000 gallons per 1,000 plants per day (5 gallons) (U.S. National Drug Intelligence Center, 2007). The widely cited value of 22.7 liters includes estimates of both legal and illegal grow facilities in California. Including illegal facilities inflates the estimated water consumption of the industry, since they are known to engage in illegal management practices (California Council of Land Trusts, 2017; Everett, 2018; Bauer et al, 2015). It also assumes that cannabis plants grown indoors and outdoors use the same amount of water. However, research suggests that different cultivation methods require different amounts of water. There are many water-saving techniques that can be used in indoor environments to reduce consumption and cost. Additionally, the duration and number of growing seasons for indoor and outdoor can vary significantly depending on the location of the facilities. Ultimately, a more accurate number for both outdoors and indoors is required to properly assess the true impacts of the cannabis industry on water resources in the United States.

The goal of this chapter is to address some of these gaps in research by identifying sources and constituents of wastewater in the cannabis industry and by providing a better estimation of the amount of water used in cultivation. The production process of cannabis was broken down into two sections: cultivation and processing.

Cultivation

The stages of cannabis cultivation are summarized in Figure 3.1 below.

Figure 3.1. Cultivation stages for cannabis (Desjardins, 2018).

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[3] Ashworth & Vizuete, 2017; Bauer et al., 2015; Butsic & Brenner, 2016; Dillis et al, 2019; California Council of Land Trusts, 2017; ORIHIDTA, 2018; CA Department of Fish and Wildlife, 2018; Sawyer & Keeler-Wolf, 1995.

(2) *Seedling or Clone Stage*

The seedling or clone stage is the first stage in our analysis. Seedlings are cannabis plants grown directly from a seed, while clones are cuttings from a mother plant. Some research states that there is negligible water consumption for seedlings (Surna Technology, 2018). Other research states that seeds require less water than clones, since they are hardier and more resistant to disease. They may require more water initially, but the growth period overall is shorter for seeds than for clones (CCC, 2019). Clones are preferred by most grow facilities because the exact strain and properties of the mature plants are known. The tradeoff is increased nutrient consumption and reduced resistance to disease (CCC, 2019).

(3) Vegetative Growth Stage

The vegetative growth stage is recognized as the most water intensive portion of the growing process. The vegetative growth stage can last anywhere from 2 weeks to 2 months, lasts about 4 weeks on average (Griffith, 2019). During this stage, root zones and robust branches continue to develop. The humidity is usually kept around 50%, with temperatures around 20-24℃ (Royal Queen Seeds, n.d.). An estimation of total water consumption by square foot is shown below in Table 3.1.

Table 3.1. Vegetative Growth Stage[4]

	Indoor	**Outdoor**
Duration	4 weeks	
Quantity of water	0.096 - 0.48 $\frac{gal}{sq.ft\ x\ day}$	
Total Consumption	8.74 - 43.67$\frac{gal}{sq.ft}$	

(4) *Flowering Stage*

Harvesting takes place at the end of the flowering stage. The flowering stage typically lasts 6-12 weeks. Not all cannabis plants require the same amount of time for flowering, but most strains will not be ready before week 8 (Royal Queen Seeds, 2017). At this stage, the plants begin to indicate their sex and produce buds. The humidity is usually reduced to 40-50%, with temperatures around 20-28℃ (Royal Queen Seeds, n.d.). During this stage, a 12-12 (hour) light-dark cycle is used to artificially stimulate flower development. When grown outdoors, the flowering stage typically begins at the end of summer or beginning of autumn, when the daylight hours begin to decrease (Royal Queen Seeds, n.d.). Table 3.2 shows the quantity of water consumed by indoor flowering plants versus outdoor.

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[4] Data from: CCC, 2019; Surna Technology, 2018

Table 3.2. Flowering Stage[5]

	Indoor	**Outdoor**
Duration	10 weeks	
Quantity of water	0.096 - 0.16 $\frac{gal}{sq.ft\ x\ day}$	0.12 - 0.2 $\frac{gal}{sq.ft\ x\ day}$
Total Consumption	6.72 - 11.2$\frac{gal}{sq.ft}$	8.4 - 14.0 $\frac{gal}{sq.ft}$

The flowering stage consists of the early bloom, late bloom, and flush phases. The early bloom phase is about 4-5 weeks long. During this phase, the focus is to produce strong sturdy plants with heavy buds and a robust root system (Griffith, 2019). The late bloom phase is about 4 weeks long. During this phase, the plant has an intense, pungent odor and the plants' pistols may turn darker, into a brown or amber color (Royal Queen Seeds, 2017). The flush phase typically occurs 2 weeks before harvest. During this phase, the plants are "flushed"; they stop receiving nutrients and are given pure, pH-balanced water. The goal is to flush out any salts and minerals that may remain (Royal Queen Seeds, 2017).

(5) ***Harvest***

The time to harvest can be determined by the plant's physical appearance. At the beginning of flowering, the trichomes have a transparent color (Ryan, 2019). When it is time to harvest, 60% or more of the trichomes should be milky white. Some cultivators wait until 90% of the trichomes have changed color, which produces a product with a more sedative effect. Another indicator is the foliage. When the leaves turn yellow, it indicates that the buds are fully utilizing nutrients, signaling the optimum point of ripening of the plant (Royal Queen Seeds, 2017). Depending on the strain, the pistils may also turn an amber color (Ryan, 2019).

Cultivation Methods

There are many methods to grow cannabis plants indoors. The two core methods of indoor growing are soil growing and hydroponics. Hydroponics is a growing technique that involves the cultivation of plants without the use of a substrate. Hand watering is classified as a soil growing technique and hydroponic techniques include: aeroponics, drip watering, ebb and flow, nutrient film, water culture, and wick systems. The methods are briefly summarized below in Table 3.3.

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[5] Data from: CCC, 2019; Surna Technology, 2018

Table 3.3. Cultivation Methods

Irrigation Method	Automated	Recycle Potential	Difficulty
Aeroponics	Y	Y	Advanced
Drip Watering	Y	Y	Intermediate
Ebb and Flow	Y	Y	Beginner
Hand Watering	N	N	Beginner
NFT Systems	Y	Y	Advanced
Water Culture System	Y	Y	Beginner
Wick System	Y	Y	Beginner

Aeroponics

Aeroponic systems use spray nozzles to mist the stem or roots of the plants with nutrients. For large-scale systems, a channel system is often used, where the roots of the plants are enclosed in a channel lined with spray misters. Another method of aeroponics is the bucket system, in which nutrified water and air are maintained in buckets into which the roots grow (CCC, 2019; DEH-CSWG, 2017).

There are many environmental benefits to growing in aeroponic systems. Aeroponically grown plants require less pesticides. The lack of soil in the system means that the plants are not vulnerable to pests typically found in soil. Aeroponic systems are very efficient in terms of nutrients, water, and space. Any nutrient solution or water that is not absorbed by the roots of the plant can be recycled. Furthermore, aeroponic systems have a faster growth cycle than soil-based systems. Some aeroponic systems can reduce the average growth cycle from 90 to 60 days. Aeroponic systems take up less space because the roots of the plant are not constrained by a pot or the amount of available soil. This means that more plants can be grown closer together. An additional benefit to growers is that aeroponic systems offer a high degree of control for the grower. Plants grown in these systems also have the highest yield of trichomes (Kavanagh, 2018; Youngblood, 2017).

Aeroponic systems require a 24/7 supervision because the system is vulnerable. Minor problems in the setup such as power outages, poorly mixed nutrient solution, or clogged pipes, can result in compromised crops. If the roots do not receive a constant stream of water and nutrients, they can start to die within an hour. Due to the high level of supervision and expertise required, aeroponic systems are not recommended for beginners. There is also a risk of molds developing in an aeroponic system. The roots require darkness and moisture, which creates ideal conditions for molds to thrive (Kavanagh, 2018; Youngblood, 2017).

Drip Watering

Drip irrigation involves irrigation systems that feed directly to each plant through thin drip tubes. Nutrified water is pumped through irrigation tubes and drip emitters. This method is considered the most water efficient way of irrigating a crop. The amount of water can be controlled directly or on an automated schedule. Drip irrigation allows the grower to fine tune how much water is given to each plant, and drip emitters can be pressure compensated so that each plant gets the same amount of water. Drip irrigation systems allow growers to water several times per day to deliver the total desired volume of water over a longer period. This virtually eliminates excess water waste and runoff from the plants (CCC, 2019; DEH-CSWG, 2017).

The main benefits of drip watering, as discussed above, are automation and precision. Drip watering is also applicable for both small-scale and large-scale growers. One of the major drawbacks of drip irrigation is maintenance. Drip irrigation requires a monthly flush-out to ensure there is no algae or mineral build up. Build-up can prevent water flow, preventing plants from getting their required water and nutrients. If the drip irrigation is under the soil, a clog may go undetected until the plant exhibits signs of nutrient deficiency, which may be too late (Royal Queen Seeds, 2017; Worms, 2019).

Ebb and Flow (Flood Tables)

Ebb and flow (E&B) systems use large, shallow tables that flood periodically on an automated schedule. When the table floods, a layer of water and/or nutrients is provided to the plants. These tables are generally used with plants seed trays, plug trays or small pots that can wick up water or nutrient solution through drainage holes. With E&B systems, there is less of a chance of under-watering plants. These systems are also easy and inexpensive to build. However, E&B systems do require large amounts of water to be used at once. This can cause increased humidity if the table does not have a lid. E&B systems must also be maintained to ensure the system is clean, there is no mineral buildup, and enough water is available for the next flood cycle. To mitigate this impact, E&B systems are best used when the majority of the water will be absorbed or when the operator is prepared to sanitize, re-nutrify and re-use the water. Any water that is not taken up by the plants can be recycled. The recycled water is typically treated to kill any pathogens using chemicals or UV light prior to reuse (CCC, 2019; DEH-CSWG, 2017).

Nutrient Film Technique

The Nutrient Film Technique (NFT) consists of a very shallow nutrient solution that runs downward in a tube or tray towards a reservoir (CCC, 2019; DEH-CSWG, 2017). The plants sit on top of the angled channel, so that the nutrient solution runs over the roots. The reservoir collects excess nutrient solution to be reused (Tomoski, 2019). NFT is similar to ebb and flow in the sense that both methods use water pumps. However, ebb and flow systems flood the plants and then drain the water, while NFT uses a small, constant water stream. A typical flow rate for NFT is about one liter of water per minute (Royal Queen Seeds, 2018).

This method is normally used on smaller plants with a short crop cycle. This is so that large root systems do not block the pipes and flow of nutrient solution. The overcrowding or overgrowing of roots can also lead to disease and loss of crops (DEH-CSWG, 2017). NFT can be difficult to maintain since the roots need to receive a constant stream of water and nutrients to protect the roots from drying out (Tomoski, 2019).

Water Culture Systems

In water culture systems, the plants are suspended so the roots hang down into a nutrient solution. The nutrient solution is held in a reservoir. The reservoir is continuously aerated to prevent the roots from suffocating and ensure the plants receive an ideal amount of nutrients and oxygen (CCC, 2019; DEH-CSWG, 2017).

Water culture systems are good for water loving, rapid growing plants. They allow for flexible plant sizes, including large root masses. Water culture systems reuse water and provide a larger yield with fewer plants. However, plants in a water culture system can be prone to root diseases. The roots of the plants may also grow too large and clog the irrigation lines (Flo-n-Gro Grow Systems, 2020).

Wick System

Wick systems employ a reservoir that provides water and nutrients for a plant. The plants pull up the nutrient solution via capillary action through the wick material. This system is well-suited for small plants. In regard to cannabis plants, seedlings and newly vegetating plants are occasionally watered sing wick systems. However, the system can be insufficient for large plants with increased water needs. Plants with high water demands, such as cannabis, can lose weight and yield if the wicking process is too slow (CCC, 2019; DEH-CSWG, 2017). While this is considered one of the simplest systems, it is also one of the least efficient (Tomoski, 2019).

Hand Watering

Hand watering is one of the most common practices since it does not require expensive equipment or heavy maintenance. Watering by hand involves the use of hoses or watering cans. This method allows growers to get a “hands on” feel for mixing and feeding each plant. However, hand watering allows for a large margin of error. The amount of water applied to each plant can vary greatly, especially between applicators. The amount of nutrients can also vary by day or applicator. Therefore, there is much greater potential for water and nutrients to be wasted through either over application or by missing the plant root system. If hand watering is being used, the facility should have a good operating procedure on how to hand water (CCC, 2019; DEH-CSWG, 2017).

Water Use Analysis

In order to estimate the amount of water used by facility size, as well as by plant, an analysis was conducted using the water requirements of cannabis at each life stage, shown in Table 3.4.

Table 3.4. Water Use by Stage

Stage of Life	**Water Use** $(\frac{gal}{sq \cdot ft\ x\ day})$	
	Indoor	**Outdoor**
Vegetative Growth	0.096 - 0.48	
Flowering	0.096 - 0.16	0.12 - 0.20

These values were then multiplied by the duration of each stage to obtain the total lifetime water use of the plant. These values were calculated for both outdoor and indoor plants, shown in Tables 3.5 and 3.6, respectively.

Table 3.5. Outdoor Water Use

Stage	**Water Use** $(\frac{gal}{sq \cdot ft\ x\ day})$	**Duration (days)**	**Lifetime Consumption** $(\frac{gal}{sq \cdot ft})$
Vegetative Growth	0.096 - 0.48	28	2.69 - 13.44
Flowering	0.12 - 0.20	70	8.4 - 14.0

Table 3.6. Indoor Water Use

Stage	**Water Use** $(\frac{gal}{sq \cdot ft\ x\ day})$	**Duration (days)**	**Lifetime Consumption** $(\frac{gal}{sq \cdot ft})$
Vegetative Growth	0.096 - 0.48	28	2.69 - 13.44
Flowering	0.096 - 0.16	70	6.72 - 11.2

The total lifetime water consumption for indoor and outdoor are summarized below in Table 3.7.

Table 3.7. Lifetime Water Consumption

Facility Type	**Water Use** $(\frac{gal}{sq \cdot ft})$
Indoor	9.40 - 24.64
Outdoor	11.09 - 27.44

To determine the amount of water used by facility size, the total water use in gal/sq.ft was multiplied by the canopy size in sq.ft. The canopy size refers to the total size of the grow space within a facility. To determine the standard canopy sizes, a range of canopy sizes from the Massachusetts Cannabis Commission (CCC, 2018) were used. The results are summarized in Tables 3.8 and 3.9 for outdoor and indoor, respectively.

Table 3.8. Outdoor Water Use by Facility Size

Canopy Size (sq.ft)	**Water Use (gal)**
5,000	55,440 - 137,200
10,000	110,880 - 274,400
20,000	221,760 - 548,800
30,000	332,640 - 823,200
40,000	443,520 - 1,097,600
50,000	554,400 - 1,372,000
60,000	665,280 - 1,646,400
70,000	776,160 - 1,920,800
80,000	887,040 - 2,195,200
90,000	997,920 - 2,469,600
100,000	1,108,800 - 2,744,000

Table 3.9. Indoor Water Use by Facility Size

Canopy Size (sq.ft)	Water Use (gal)
5,000	47,040 - 123,200
10,000	94,080 - 246,400
20,000	188,160 - 492,800
30,000	282,240 - 739,200
40,000	376,320 - 985,600
50,000	470,400 - 1,232,000
60,000	564,480 - 1,478,400
70,000	658,560 - 1,724,800
80,000	752,640 - 1,971,200
90,000	846,720 - 2,217,600
100,000	940,800 - 2,464,000

In order to calculate the total water use per plant, the total water use in gallons per sq.ft was multiplied by the space requirement per plant. Indoor plants tend to be more densely packed than outdoors, so a value of 1 sq.ft per plant was used for the indoor analysis, and an average value of 3 sq.ft per plant was used for outdoor (Caulkins et al., 2013). These values are summarized in Table 3.10.

Table 3.10. Total Water Use Over Lifetime of Plant

Facility Type	Water Use Per Plant (gal/plant)
Indoor	9.408 - 24.64
Outdoor	44.352 - 109.76

Based on the estimation of the life cycle of a cannabis plant, indoor growers could harvest up to 4 times a year, which is on the low end of the typical range of 4-6 times (Caulkins et al., 2013). The average outdoor grower is only able to harvest cannabis once a year, unless they are located close to the equator and environmental conditions are conducive to year-round cannabis cultivation (Caulkins et al., 2013). Using these numbers, it can be estimated how much water will be used over the course of a year for both indoor and outdoor cultivation facilities. These numbers are displayed in Table 3.11.

Table 3.11. Water Use Over a Grow Year

Canopy Size (sq.ft)	**Indoor Water Use (gal) (4 Harvests)**	**Outdoor Water Use (gal) (1 Harvest)**
5,000	188,160 - 492,800	55,440 - 137,200
10,000	376,320 - 985,600	110,880 - 274,400
20,000	752,640 - 1,971,200	221,760 - 548,800
30,000	1,128,960 - 2,956,800	332,640 - 823,200
40,000	1,505,280 - 3,942,400	443,520 - 1,097,600
50,000	1,881,600 - 4,928,000	554,400 - 1,372,000
60,000	2,257,920 - 5,913,600	665,280 - 1,646,400
70,000	2,634,240 - 6,899,200	776,160 - 1,920,800
80,000	3,010,560 - 7,884,800	887,040 - 2,195,200
90,000	3,386,880 - 8,870,400	997,920 - 2,469,600
100,000	3,763,200 - 9,856,000	1,108,800 - 2,744,000

Water Use Discussion

Many researchers suggest that the amount of water used per plant per day is a much higher value of 22.7 L (5.8 gal) as compared to the calculated value of 0.096 - 0.251 gal per plant per day for indoor growing and 0.453 - 1.12 gal per plant per day for outdoor. This may be contributed to the fact that the calculations above were solely based on the estimated amount of water applied during the cultivation process over one harvest cycle. It does not include humidifiers, heating, processing, landscaping, or water for sanitary purposes. It was assumed based on research that the water required to clean processing machines would be negligible compared to the amount of water required for growing. Additionally, the use of humidifiers would be highly variable depending on the lighting to space requirements of individual facilities. It also did not account for the fact that growers may apply more water knowing that a certain amount may runoff or the effect leaks may have on total water consumption. The value calculated for outdoor plants may also vary depending on the climate the plants are grown in. This would lead to variability in numbers across the country. This estimation can be considered a conservative estimate based on the water-saving techniques many growers use and what the cannabis plant actually requires.

The numbers may vary for additional reasons. The first reason is that there is a lack of comprehensive research on cannabis growth in the United States. The numbers selected for this analysis were selected from Surna Technology, a company specializing in technology for the cannabis industry. These numbers were supported by Massachusetts' Best Management Practices for Water Use for Cannabis Cultivation and a study assessing the carbon footprint of indoor cannabis cultivation (CCC, 2019; Mills, 2012).

Secondly, the duration of growth cycles vary based on the strains that are being grown. Depending on the length of the growth cycle, the amount of water consumed per harvest may be higher. Some estimates put the growth cycle at 150 days, as compared to the value used in the analysis of 98 days (Butsic & Brenner, 2016). New strains and techniques are being developed by growers to shorten the duration of the growth cycle and increase yearly yields. In the future, this may further reduce the water consumption per harvest cycle, but may increase yearly water consumption.

Despite the fact that the above analysis is a conservative estimation, cannabis cultivation facilities still have a demand on local water treatment plants. For example, a mid-sized indoor canopy of 50,000 sq. ft requires 4,800 - 12,571 gal per day from cultivation operations alone. If this facility was located in a small municipality with a water treatment capacity of 650,000 gal/day, it could use anywhere from 0.7% to 2% of the town's daily water supply on irrigation. This does not take into account water required by the rest of the facility. This demand would be multiplied if more than one facility were to move into a municipality. This could strain a region's water supply in drought-prone states like California.

When comparing the water consumption to other crops, cannabis has a similar value to tobacco. Peak water consumption for tobacco plants reaches 3-5 liters of water per plant per day (0.79-1.32 gallons) in the seedling phase (FAO, n.d.). However, many articles compare cannabis to wine grapes, which use approximately 12.6 liters (3.32 gallons) of water per plant per day (Bauer et al., 2015).

Wastewater Sources

Water pollution can come in many different forms from many different sources. Sources of water pollution are often classified into two categories: point source and nonpoint source. Point and nonpoint sources are legally defined by the Clean Water Act. According to section 502(14) of the Clean Water Act, the term point source means 'any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged." The term nonpoint source is defined to mean any source of water pollution that does not meet the legal definition of a point source. Consequently, agricultural stormwater and return flows from irrigated agriculture are considered nonpoint sources (EPA, 2018).

Point Source Pollution

An indoor cultivation facility can be considered an industrial source and therefore a point source of pollution. Many regulations prohibit the dumping of cannabis wastewater. It is required to be stored and hauled to a wastewater treatment facility. California allows cannabis cultivation wastewater to be discharged to a community sewer system if the wastewater meets the sewer system requirements. California also allows cannabis cultivation facilities to be exempt from this requirement if they qualify. In this case, they are issued a permit to allow wastewater to be discharged to on-site treatment systems, like septic tanks and leach fields, to land, or surface water. There are multiple ways in which wastewater is produced in indoor facilities.

Disposal of Excess Irrigation Water

Hydroponic systems are designed to be open or closed. Open hydroponics systems discharge the water once it has gone through the system and do not recirculate it. Some growers look to reduce their wastewater by selecting closed systems. Closed systems may use less water by reusing the water once it passes through the system. The water is only discharged once the salinity and nutrient concentrations of the water reach a certain level and is no longer usable (Kumar & Cho, 2014).

Irrigation tail water is wastewater that is generated when excess water drains from the growth media (California Water Control Board, 2019). The water may contain excess macro and micronutrients such as phosphates, nitrates, calcium, magnesium, iron, and zinc. The water can have a high salinity or contain pesticide residue (California Water Control Board, 2019).

In cultivation facilities where water is recaptured, stored in tanks, and reused, the watering tanks have to be refreshed when the salinity and nutrient concentrations become too high. When there are too many nutrients present, nutrients will build up in the growth media and not be conducive to plant growth (Surna Technology, 2018). The constituents present in this wastewater are similar to irrigation tail water, but the concentrations vary due to varying nutrient requirements at different stages of growth.

Air Pollution Control Equipment

Blowdown from air pollution control equipment is another potential source of wastewater in a cannabis cultivation facility (EPA, 2006). Air pollution control equipment, like wet scrubbers, are used to remove contaminants and odor from a facility's air stream. They remove contaminants in the vapor by converting them to their liquid or condensate form or by trapping particulates in water droplets (EPA, 2002). The content of the air emissions will determine what ends up in the wastewater blowdown. Air pollution control equipment will be discussed further in Chapter 6.

Reverse Osmosis

Reverse osmosis (RO) is a common industry practice for growers who wish to control the amount of nutrients their plants receive. RO is the process of purifying municipal or well water by using a semipermeable membrane to remove ions and large particles. It is performed prior to the application of water to plants to allow the grower to start at the lowest possible concentrations of ions (Surna Technology, 2018). This also prevents excess salts from accumulating in the growing medium. The ions that are removed by RO include metals and salts such as iron, sodium, potassium, phosphorus, nitrate, and more. The RO process increases the amount of concentrated wastewater on site, producing approximately 0.5 to 5 gallons of RO brine (wastewater) for 1 gallon of usable water (Surna Technology, 2018; DEH-CSWG, 2017). For facilities that use thousands of gallons per day, this can create massive amounts of wastewater that is discarded to sanitary drains (DEH-CSWG, 2017). This is not accounted for in the amount of water usage per plant or sq. ft. Based on the numbers calculated in the water use analysis, an analysis of the wastewater produced by using RO was conducted.

Reverse Osmosis Analysis

To estimate the amount of wastewater produced in the RO process, the range 0.5 to 5 gallons of wastewater (WW) to 1 gallon of usable water was used. Using water use per one harvest cycle, the ranges of RO wastewater produced by canopy size were calculated using the equations below.

$$(Low\ or\ high)\ Water\ use\ (gal)\ *\ \frac{0.5\ gal\ of\ WW}{1\ gal\ of\ usable\ water} = gal\ of\ RO\ WW$$

$$(Low\ or\ high)\ Water\ use\ (gal)\ *\ \frac{5\ gal\ of\ WW}{1\ gal\ of\ usable\ water} = gal\ of\ RO\ WW$$

Using the canopy size of 5,000 sq.ft and the low water use value of 47,040 gal (Table 3.9), an example calculation is shown below.

$$47{,}040\ gal\ *\ \frac{0.5\ gal\ of\ WW}{1\ gal\ of\ usable\ water} = 23{,}520\ gal\ of\ RO\ WW$$

$$47{,}040\ gal\ *\ \frac{5\ gal\ of\ WW}{1\ gal\ of\ usable\ water} = 235{,}200\ gal\ of\ RO\ WW$$

The calculations were repeated for high water use (Table 3.9) and for each canopy size. The values are outlined below in Table 3.12. It should be noted that RO wastewater was calculated for only indoor water use.

Table 3.12. Reverse Osmosis Wastewater Quantity

Canopy Size (sq.ft)	RO WW produced by low water use (gal)	RO WW produced by high water use (gal)
5,000	23,520 - 235,200	61,600 - 616,000
10,000	47,040 - 470,400	123,200 - 1,232,000
20,000	94,080 - 940,800	246,400 - 2,464,000
30,000	141,120 - 1,411,200	369,600 - 3,696,000
40,000	188,160 - 1,881,600	492,800 - 4,928,000
50,000	235,200 - 2,352,000	616,000 - 6,160,000
60,000	282,240 - 2,822,400	739,200 - 7,392,000
70,000	329,280 - 3,292,800	862,400 - 8,624,000
80,000	376,320 - 3,763,200	985,600 - 9,856,000
90,000	423,360 - 4,233,600	1,108,800 - 11,088,000
100,000	470,400 - 4,704,000	1,232,000 - 12,320,000

Because of the large quantity of wastewater produced, states like Massachusetts and Colorado do not recommend the use of RO in their best management practices (CCC, 2019; DEH-CSWG, 2017). Additionally, the Denver Best Management Practices cautions against the use of RO due to the high concentration of salts and minerals in wastewater, since it can create difficulties in wastewater treatment plants (DEH-CSWG, 2017). The RO process also requires periodic flushing, which would lead to more cleaning solvents and descaling compounds in the wastewater (California Water Control Board, 2018) To reduce wastewater, some growers use their RO wastewater in humidifiers (California Water Control Board, 2018).

Nonpoint Source Pollution

Outdoor cultivation is considered a nonpoint source of pollution. The runoff cannot be collected or easily controlled. Nonpoint source pollution generally results from land runoff, precipitation, drainage, and seepage. The main concern for nutrients is runoff from rainfall or snowmelt. As the runoff moves, it washes away excess nutrients and deposits them into lakes, rivers, wetlands, coastal waters, and ground waters. Nonpoint source pollution is a leading cause of water quality issues since it is much more difficult to control than point sources. Excess runoff, particularly from nonpoint sources, can have significant impacts on water bodies (EPA, 2018). The main contaminants of concern in nonpoint cannabis cultivation runoff are the pesticides and nutrients in the water. It is necessary to quantify any potential nutrient runoff in order to meet the necessary water quality standards.

Cultivation Wastewater Constituents

The constituents of wastewater are a concern for facility owners and wastewater treatment plants (WWTPs) alike. Constituents of concern include pesticides, nutrients, and certain biological agents. These constituents can affect the biological oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS).

Biological Oxygen Demand

The biological oxygen demand is a measurement of how much oxygen is being consumed by microorganisms to decompose biodegradable material under aerobic conditions (Tchobanoglous et al., 2013). The COD test is used along with the BOD test to estimate the amount of nonbiodegradable organic material in a wastewater (Woodard & Curran, Inc., 2006). If the BOD is high, then a large quantity of dissolved oxygen is being consumed by microorganisms to break down the organic matter. Dissolved oxygen is required to sustain aquatic life, and if concentrations are too low the water body can become anoxic. These conditions are lethal for aquatic ecosystems. Additionally, excessively high BOD can lead to algal blooms. As part of a WWTPs' NPDES permit, they are required to reduce the BOD to a certain level. If high quantities of wastewater with high BOD are entering WWTPs, then it may cause the WWTPs to make extensive and expensive changes to accommodate this new influent. It may also interrupt or inhibit current processes within the treatment plant.

Total Suspended Solids

In addition to affecting the BOD, the organic material in the effluent of cannabis facilities affects the TSS of wastewater. Total suspended solids is the measure of solids that cannot pass through a 1.58 micron pore filter (Tchobanoglous et al., 2013). Essentially, it is the portion of solids in wastewater that are large enough to remain suspended in a waterbody. They are an important indicator for turbidity. The higher the amount of suspended, the lower the water clarity, and the higher the turbidity. Turbid waters have reduced light flow to the bottom of the waterbody and are not conducive to plant growth and can smother aquatic organisms. Cannabis wastewater has high levels of plant matter from rinsing, extractions, and runoff. Cannabis fibers are very rigid and difficult to break down. They are often found at high concentrations, which may inhibit a facility from being able to send their wastewater to municipal drains (Micron Waste Technologies, n.d.). They are also a problem for WWTPs, and may require additional processes to remove them.

Chemical Oxygen Demand

The COD is the amount of oxygen that is required to chemically oxidize organic and inorganic chemicals in the water. This test is typically performed using oxidizing agents including dichromate (Tchobanoglous et al., 2013). COD is classified by nonbiodegradable COD and biodegradable COD. Nonbiodegradable COD includes pharmaceuticals, persistent organic pollutants, industrial chemicals, pesticides, and organic pollutants. Biodegradable COD is used to estimate the BOD of a sample and includes fatty acids, nutrients, proteins, sugars, alcohols, and others (Arvia Technology, n.d.). High COD is generally caused by inorganic substances and organic substances that are difficult to oxidize biologically such as lignin (Tchobanoglous et al., 2013). Lignin is the compound in plants that gives them a rigid and woody texture. This may be the source of high COD experienced by WWTPs receiving effluent from cannabis facilities. Wastewater treatment plants are able to remove approximately 75-85% of COD through primary and secondary treatments, but recalcitrant compounds like pesticides, industrial chemicals, and other organic pollutants remain (Arvia Technology, n.d.).

Pesticides

Pesticides are one of the sources of high COD if large quantities end up in a facility's effluent. They are poorly removed in conventional WWTPs, since many are resistant to microbial degradation (Misra et al., 2013). Pesticides are toxic to certain microorganisms and can be metabolized or bioaccumulated by microorganisms (DeLorenzo, Scott, & Ross, 2001). This can inhibit photosynthesis and in turn limit process efficiency (Misra et al., 2013). Their concentrations are often higher in the effluent than the influent (Köck-Schulmeyer et al., 2013). This may be because transformation products of pesticides are converted back by WWTP processes or the desorption from particulates during treatment (Köck-Schulmeyer et al., 2013). This leads to high levels of pesticides entering surface waters from wastewater effluent. The environmental impacts of pesticides are discussed further in Chapter 4.

Biological Agents

The biological agents that are of concern in cannabis production are pathogens such as certain bacteria and fungus. Bacteria and other pathogens can be present in manure-based fertilizers, compost, biosolids, and soil amendments (California Water Control Board, 2018). If a facility is using any of the listed materials, there is the potential for salmonella or *E. coli* bacteria to be present. These pathogens may get caught in irrigation water and when the water is disposed, the pathogens may enter the wastewater. WWTPs have treatment processes in place to remove such contaminants, but should be aware that they are constituents of the WWTP influent.

Fungus such as *Trichothecium roseum* (pink mildew) and of the *Penicillium* genus are some of the most common fungus species found in cannabis grow facilities (Fundacion Canna, n.d.). Handling crops contaminated with these fungi can release up to 500,000 spores per square meter (Fundacion Canna, n.d.) These spores can end up in the runoff irrigation water or in the air ventilation systems. The fungus spores can then end up in the blowdown water from these air ventilation systems and exit in the facility's wastewater effluent.

Nutrients

When cultivating any type of plant, fertilization is a key component of success. Proper plant nutrition will determine if a plant thrives or struggles. In general, there are 17 essential nutrients for proper plant growth. Plants obtain hydrogen, oxygen, and carbon from water or the atmosphere. The remaining 14 nutrients must be provided by the grower (Whipker et al., 2019). The required nutrients are summarized below in Table 3.13.

Table 3.13. Types of Fertilizers

Macronutrients	Micronutrients
Nitrogen (N)	Boron (B)
Phosphorus (P)	Chlorine (Cl)
Potassium (K)	Copper (Cu)
Calcium (Ca)	Iron (Fe)
Magnesium (Mg)	Manganese (Mn)
Sulfur (S)	Molybdenum (Mo)
	Nickel (Ni)
	Zinc (Zn)

By providing all of the essential nutrients to plants, the plant growth is maximized. In addition to these nutrients, cobalt, selenium, silicon, and sodium also promote plant growth. However, they are not considered necessary to complete the plant life cycle. Some cannabis growers choose to apply silicon to their plants to promote overall plant health, but it is not required (Whipker et al., 2019).

The major component of optimizing plant growth is to provide a proper balance of nutrients. The proper balance of nutrients will vary depending on the specific growing situation. Table 3.14 provides general guidelines that have “produced many successful cannabis crops” (Griffith, 2019). These values assume that there are virtually no nutrients in the potting mix.

Table 3.14. Macronutrient Application

Stage of Life	Nitrogen[6,7] (ppm-N)	Phosphorus[6] (ppm P_2O_5)	Potassium[6] (ppm K_2O)	Calcium[8] (ppm Ca)	Magnesium[8] (ppm Mg)
Seedling/Clone	100	100	100	50	25
Vegetative Growth	200	120	200-250	100-125	50-62.5
Early Bloom	200-250	200-250	200-250	100-125	50-62.5
Late Bloom	100-150	“adequate”	187.5	93.75	46.875
Flush	0	0	0	0	0

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[6] Griffith, 2019. According to Cervantes (2006), nitrogen should be applied in equal amounts or higher to phosphorus and potassium during the vegetative stage. Cervantes (2006) also states that higher phosphorus quantities are meant for flowering plants. It was assumed that at minimum the phosphorus levels would need to be equal to the nitrogen levels.

[7] Whipker et al. (2019). How to Meet the Nitrogen Needs of Cannabis: Nutrient Matters.

[8] Whipker et al. (2019). Balancing the Nutrient Equation in Cannabis Cultivation.

One important distinction to make is that seedlings do not require as many nutrients as clones. During the early seedling stage, the plant can live off nutrients in the seed. Minimal or no fertilizer is required during the early seedling stage. On the other hand, clones are often deficient after propagation. After the early seedling stage or propagation, the plant should be fed very gently with the stated nutrients (Griffith, 2019).

The application of excess phosphorus appears to be a common trend among cannabis growers. Many cannabis cultivators believe that cannabis plants require high concentrations of phosphorus during the flowering process (CS Consulting, 2020). However, the scientific community is currently debating whether the phosphorus application needs to be increased just before flowering. Phosphorus fertilization strategies have been studied extensively over the past five years. One study led by Manitoba crop nutrition specialist John Heard on a dual-purpose hemp crop grown for seed and fiber suggests that extra P is not required by cannabis (Whipker et al., 2019). The research concluded that a scientifically-based trial is needed to determine the adequate phosphorus levels that should be provided to cannabis (Whipker et al., 2019). While the target level of phosphorus required by greenhouse-grown cannabis is not currently known, Whipker et al. (2019) speculate that based on the scientific data from other species that levels of 15 ppm to 20 ppm of phosphorus should be supplied on a constant basis. For continuous fertilization for plants grown in a soilless substrate, the target concentration is between 8 ppm and 15 ppm of phosphorus. Research is currently being conducted to determine the optimal phosphorus rates to supply at a constant level throughout the cannabis crop cycle (Whipker et al., 2019).

The phosphorus levels suggested by Whipker et al. are drastically lower than the levels suggested by Griffith (2019), as well Cervantes (2006). Since the research for optimal levels of phosphorus application are still ongoing, the following analysis utilizes the values provided by Griffith. It is expected that the values suggested by Griffith are more reflective of current growing practices and therefore would more accurately capture the current runoff potentials.

Nutrient Analysis

In order to assess the amount of nutrients that could potentially end up in a grow facility's wastewater, an analysis was performed based on the water and nutrient requirements of cannabis. To estimate this value, the potential for nutrient runoff over the lifetime of a plant was calculated. For the analysis, the assumption was made that because seedlings use is very minute compared to the other stages, so the runoff would be negligible. The nutrient requirement ranges were averaged for the calculations, shown in Table 3.15.

Table 3.15. Average Macronutrient Requirement

Stage of Life	Nitrogen (ppm-N)	Phosphorus (ppm P_2O_5)	Potassium (ppm K_2O)	Calcium (ppm Ca)	Magnesium (ppm Mg)
Vegetative Growth	200	120	225	112.5	56.25
Early Bloom	225	225	225	112.5	56.25
Late Bloom	125	125[9]	187.5	93.75	46.875
Flush	0	0	0	0	0

Table 3.16. Water Usage

Stage of Life	Water Use $\left(\frac{L}{sq.ft\ x\ day}\right)$	
	Indoor	Outdoor
Vegetative Growth	0.363 - 1.82	
Early Bloom	0.363 - 0.606	0.454 - 0.757
Late Bloom		
Flush		

To calculate the amount of nutrients applied at each stage, the average nutrient application (Table 3.15) was multiplied by the water used during each stage of growth (Table 3.16). Since the volume of water applied to the plants ranges throughout each growth phase, a range for the nutrients applied was determined. An example calculation is shown for the low range nitrogen requirement during outdoor vegetative growth:

$$Water\ Use\ *\ Nutrient\ Requirement\ = Nutrients\ Application$$

$$0.363\frac{L}{sq\cdot\ ft\ x\ d} * 200\frac{mg}{L} = 72.68\frac{mg}{sq\cdot ft\ x\ d}$$

Next, the value of nutrients applied was multiplied by the number of days per growth stage. The number of days per growth stage are summarized in Table 3.17.

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[9] Cervantes (2006) states that higher phosphorus quantities are meant for flowering plants. It was assumed that at minimum the phosphorus levels would need to be equal to the nitrogen levels. Therefore, "adequate" phosphorus (Griffith 2019) was established as 125 mg/L for the purposes of this analysis.

Table 3.17. Length of Growth Stage

Stage of Life	Number of Days
Vegetative Growth	28
Early Bloom	28
Late Bloom	28
Flush	14
Total	98

An example calculation is shown below for the low range nitrogen requirement during outdoor vegetative growth:

$$Nutrients\ Applied\ *\ Days\ of\ Growth\ Cycle\ =\ Nutrients\ Applied\ per\ Growth\ Stage$$

$$72.68\frac{mg}{sq\cdot ft\ x\ d}*28\ days=2{,}035.4\frac{mg}{sq\cdot ft}$$

Using these values for each stage, the total nutrients applied over the lifetime of the plant was determined. The values for applied nutrients during the vegetative, early bloom, late bloom, and flush were summed. An example calculation is shown below for the low range nitrogen requirement during outdoor growth:

$$2{,}035.4\frac{mg}{sq\cdot ft}+2{,}861.8\frac{mg}{sq\cdot ft}+1{,}589.9\frac{mg}{sq\cdot ft}+0.0\frac{mg}{sq\cdot ft}=6{,}486.7\frac{mg}{sq\cdot ft}$$

Plants are typically watered so that 10-20% of the water comes out as runoff (Cervantes, 2006; Botanicare, 2016; Coco, 2018; Haze, n.d.). This means 10-20% of the nutrients applied would runoff as well. Assuming an average runoff of 15%, the amount of nutrient runoff was calculated. An example calculation is shown below for the low range nitrogen requirement during outdoor growth:

$$Total\ Nutrients\ Applied*0.15\ =Nutrient\ Runoff$$

$$6{,}486.7\frac{mg}{sq\cdot ft}*0.15=973.0\frac{mg}{sq\cdot ft}$$

The nutrient runoff for outdoor and indoor grow facilities are summarized below in Table 3.18.

Table 3.18. Nutrient Runoff

Nutrient	Outdoor Runoff (g/sq.ft)	Indoor Runoff (g/sq.ft)
Nitrogen	0.97 - 2.64	0.84 - 2.42
Phosphorus	0.68 - 1.74	0.58 - 1.57
Potassium	0.87 - 2.59	0.76 - 2.42
Calcium	0.43 - 1.29	0.38 - 1.20
Magnesium	0.22 - 0.65	0.19 - 0.60

The total nutrient runoff was used two-fold. First, the total runoff over the lifetime of each plant was calculated. This is an estimate based on an average number of plants per square-foot. Outdoor grows usually require 2-4 square-feet per plant, so an average of 3 sq.ft per plant was used (Caulkins et al., 2013). The amount of space per plant is highly variable for indoor grows depending on growing technique. A value of 1 sq.ft per plant was used (Caulkins et al., 2013). The results are summarized in Table 3.19.

Table 3.19. Lifetime Requirements

Nutrient	Outdoor Runoff (g/plant)	Indoor Runoff (g/plant)
Nitrogen	3.89 - 10.56	0.84 - 2.42
Phosphorus	2.70 - 6.94	0.58 - 1.57
Potassium	3.47 - 10.36	0.76 - 2.42
Calcium	1.73 - 5.16	0.38 - 1.20
Magnesium	0.87 - 2.59	0.19 - 0.60

The total runoff was also used to predict the amount of runoff based on the canopy size of a facility. The canopy size refers to the total size of the grow space within a facility. To determine the standard canopy sizes, a range of canopy sizes from the Massachusetts Cannabis Control Commission were used (CCC, 2018). This estimation is calculated in grams per square foot in order to eliminate the variability in the amount of plants per square foot. The results for outdoor and indoor grow facilities are summarized in Tables 3.20 and 3.21, respectively.

Table 3.20. Outdoor Facility Nutrient Runoff (1 Harvest Cycle)

Canopy Size (sq.ft)	**Nitrogen (g/d)**	**Phosphorus (g/d)**	**Potassium (g/d)**	**Calcium (g/d)**	**Magnesium (g/d)**
5,000	49.6 - 134.7	34.5 - 88.6	44.2 - 132.1	22.0 - 65.8	11.1 - 33.0
10,000	99.3 - 269.3	68.9 - 177.2	88.5 - 264.3	44.1 - 131.6	22.1 - 66.1
20,000	198.6 - 538.6	137.8 - 354.3	177.0 -528.6	88.1 - 263.2	44.2 - 132.1
30,000	297.9 - 807.9	206.8 - 531.5	265.5 - 792.9	132.2 - 394.8	66.4 - 198.2
40,000	397.1 - 1,077.2	275.7 - 708.7	354.0 - 1,057.1	176.3 - 526.4	88.5 - 264.3
50,000	496.4 - 1,346.5	344.6 - 885.8	442.4 - 1,321.4	220.3 - 658.0	110.6 - 330.4
60,000	595.7 - 1,615.8	413.5 - 1,063.0	530.9 - 1,585.7	264.4 - 789.5	132.7 - 396.4
70,000	695.0 - 1,885.1	482.4 - 1,240.1	619.4 - 1,850.0	308.5 - 921.1	154.9 - 462.5
80,000	794.3 - 2,154.4	551.4 - 1,417.3	707.9 - 2,114.3	352.5 - 1,052.7	177.0 - 528.6
90,000	893.6 - 2,423.7	620.3 - 1,594.5	796.4 - 2378.6	396.6 - 1,184.3	199.1 - 594.6
100,000	992.9 - 2,693.0	689.2 - 1,771.6	884.9 - 2,642.9	440.7 - 1,315.9	221.2 - 660.7

Table 3.21. Indoor Facility Nutrient Runoff (1 Harvest Cycle)

Canopy Size (sq.ft)	Nitrogen (g/d)	Phosphorus (g/d)	Potassium (g/d)	Calcium (g/d)	Magnesium (g/d)
5,000	42.8 - 123.3	29.4 - 80.2	38.9 - 123.2	19.4 - 61.4	9.7 - 30.8
10,000	85.7 - 246.6	58.9 - 160.4	77.8 - 246.5	38.7 - 122.7	19.4 - 61.6
20,000	171.3 - 493.2	117.7 - 320.8	155.6 - 492.9	77.5 - 245.4	38.9 - 123.2
30,000	257.0 - 739.8	176.6 - 481.3	233.4 - 739.4	116.2 - 368.1	58.3 - 184.9
40,000	342.6 - 986.4	235.5 - 641.7	311.2 - 985.9	155.0 - 490.9	77.8 - 246.5
50,000	428.3 - 1,233.0	294.4 - 802.1	389.0 - 1,232.4	193.7 - 613.6	97.2 - 308.1
60,000	514.0 - 1,479.6	353.2 - 962.5	466.8 - 1,478.8	232.5 - 736.3	116.7 - 369.7
70,000	599.6 - 1,726.1	412.1 - 1,122.9	544.6 - 1,725.3	271.2 - 859.0	136.1 - 431.3
80,000	685.3 - 1,972.7	471.0 - 1,283.4	622.4 - 1,971.8	309.9 - 981.7	155.6 - 492.9
90,000	770.9 - 2,219.3	529.9 - 1,443.8	700.2 - 2,218.2	348.7 - 1,104.4	175.0 - 554.6
100,000	856.6 - 2,465.9	588.7 - 1,604.2	778.0 - 2,464.7	387.4 - 1,227.2	194.5 - 616.2

It should be noted that Tables 3.20 and 3.21 only account for one harvest cycle. As mentioned previously in the water consumption analysis, outdoor grow facilities typically have 1-3 harvest per year and indoor facilities typically have 4-6 (Caulkins et al., 2013).

It is important to quantify the amount of nutrients that may runoff from cannabis facilities in order to prevent adverse environmental effects such as eutrophication. The current rates of fertilizer application appear to follow standard fertilization practices used with floriculture production (Whipker et al., 2019). Therefore, it does not appear that the actual rate of fertilizer application will be the concern. Rather, the concern will be with how quickly the cannabis industry scales. Nutrient loadings at WWTPs will be greatly increased if multiple facilities are discharging to them at once.

Processing

There are both water and wastewater concerns specific to the processing of cannabis products. Cold water extraction is the only extraction process that relies on a large quantity of water to concentrate trichomes. This is briefly discussed in Chapter 5.

Wastewater Concerns in Extractions

It can be assumed that wastewater from the extraction process would be a main concern for WWTPs. However, most extractions are required to be closed loop and/or treated a hazardous waste by state regulations. In closed loop extractions, almost all of the solvent is collected at the end of the process to be reused. States like California, Colorado, and Washington have regulations that extractions involving the use of volatile organic solvents must be performed in a closed loop system (Al-Zouabi et al., 2018). Liquid solvents used in extractions such as hexane and ethanol, are considered hazardous waste due to their flammability and must be disposed of as such (City of Portland, 2007; EBMUD, n.d.). Assuming the industry is complying with these regulations, this eliminates the potential wastewater concerns of extraction solvents. Solvents used to the clean extraction machinery, like isopropyl alcohol, ethanol, and other VOCs, should be diluted and used according to the label to prevent high concentrations from entering municipal sewers (DEH-CSWG, 2017).

Wastewater Concerns in Edibles Production

Food service or production involving cannabis usually must meet requirements of food service establishments. The contaminants of concern are fats, oils, and grease (FOG), BOD, COD, and TSS. FOG are a main concern of the edibles process. When creating cannabis concentrates with oils and butter, there is the potential for FOG to be in wastewater. Excessive FOG can cause serious pipe and sewer blockages and greatly interrupt the wastewater treatment process (City of Portland, 2007). To mitigate these issues, facilities where foods containing cannabis are cooked, processed, or prepared are usually required to install a food-related oil and grease interceptor (City of Portland, 2007; ACRWC, n.d.). The issues with BOD, COD, and TSS are discussed prior.

Recommendations

THC in Water

THC (Δ9-tetrahydrocannabinol) is an emerging contaminant of concern with the increased legalization of cannabis. When cannabis is consumed, the THC is metabolized into THC carboxylic acid (THC-COOH). THC-COOH is a non-psychoactive metabolite eliminated by the body in urine and feces that is disposed of via sewers. The THC-COOH ends up at wastewater treatment facilities where it is ultimately released into freshwater bodies (Sharma, Murthy, & Bharath, 2012).

The presence of THC and THC-COOH has been shown to affect the health status of freshwater species. A study by Parolini and Binelli (2014) found that zebra mussels exposed to a THC concentration of 0.5 μg/L for 14 days exhibited significant oxidative stress. However, it should be noted that this concentration (0.5 μg/L) is greater than the highest reported THC concentration detected in sewer water (13.6 ng/L). It is also unlikely that unmetabolized THC would be found in these high concentrations due to its low solubility in water (Park, Mackie, & Gagnon, 2017). In another study by Parolini et al. (2017), the results showed that exposure to increasing concentrations of THC-COOH could represent a threat for the health status of the zebra mussel. The study was designed to mimic THC-COOH levels currently found in aquatic ecosystems and contractions that may be found in the future due to increased cannabis use. The zebra mussels showed increasing oxidative stress and damage to DNA when exposed to 3 concentrations of THC-COOH (100, 500, and 1000 ng/L) over 14 days (Parolini et al., 2017). Although many studies have detailed the analysis and detection of THC and THC-COOH in environmental waters, more studies are needed to determine the risk to aquatic ecosystems and clarify their true ecological hazard. Furthermore, research into the basic characteristics of THC, THC-COOH, and other THC metabolites and how they are transformed during water and wastewater treatment processes are needed (Park, Mackie, & Gagnon, 2017).

Currently, there are no specific regulations regarding THC and its metabolites in drinking water or effluent wastewater, except indirectly as a part of acute toxicity testing requirements for effluent wastewater (Park, Mackie, & Gagnon, 2017). Once THC and its metabolites are transported to WWTPs, they are subjected to various physical, chemical, and biological treatment processes that can remove them to varying extents (Yadav et al., 2017). Removal rates for THC and THC-OH (another THC metabolite) range from 8% to 100% and 38% to 100%, respectively (Park, Mackie, & Gagnon, 2017). The removal efficiency of THC-COOH in WWTPs has been reported to vary between 31% and 98% (Boix et al., 2014). Other reports have summarized THC-COOH removal rates in the range of -18.3% to 100%. THC-COOH sometimes has a negative removal rate that may be attributed to desorption from solids during treatment (Park, Mackie, & Gagnon, 2017). These removal rates may be reduced by increased chemical loads in the raw wastewater and insufficient hydraulic retention or contact times. They also vary depending on the technology used, such as trickling filters versus activated-sludge, and how the treatment process is operated (Yadav et al., 2017). Any remaining THC or THC metabolite is transferred in the final effluent into a receiving aquatic system, where they can bioaccumulate, affect water quality, or potentially reach drinking water sources. THC and its metabolites are continuously discharged from WWTPs (even states where it is not legal, due to medical use or illegal use) into the environment despite the fact that their effects on human and environmental health are essentially unknown (Yadav et al., 2017). More research into the treatment methods for the removal of THC and THC-COOH from wastewater is required.

Reduce Wastewater

Many facilities are not taking advantage of potential sources of reuse water (DEH-CSWG, 2017). When reuse water is captured, it can help save money and energy. There are a variety of different techniques to reduce a cannabis facility's water use. Systems can include ones that capture water from watering the plant and reusing and/or capturing water condensation from the HVAC system (CCC, 2019).

Depending on the system, the water could be captured through drain pipes and lines, ditches, dehumidifiers, or condensation recapture modules (CCC, 2019). The effectiveness of drain pipes and lines or ditches will depend on the cultivation method, as discussed above in the Cultivation Methods section. Dehumidifiers and condensation recapture modules collect the condensate water that is generated by a number of processes in a growing facility. These systems mainly re-condense the humidity produced from transpiration (Hanson, 2018). Often, growers will not reuse their dehumidifier water because they believe it is not clean. There are concerns with mold and fungus growing in and around drains, pans, and hoses, as well as concerns about heavy metals related to the copper tubing and soldered connections in the dehumidifiers (Steffes, 2018). However, studies have shown that there is no significant difference in plant growth between the use of recycled water versus the use of freshwater (CCC, 2019). The captured water can also be filtered and disinfected prior to application to address these concerns.

If the captured water is to be applied to plants, it needs to be treated to prevent the spread of microbial pathogens and to reduce the amount of ionic and toxic elements that may be present. Common practices include reverse osmosis and carbon filtration (CCC, 2019). While the main purpose of reverse osmosis (RO) is to improve the quality of the incoming water, some facilities have used RO to treat reuse water. RO allows for approximately 97% reuptake, but produces a brine that is difficult to dispose of (CCC, 2019). The process works the same as when filtering tap water, as discussed above in the Reverse Osmosis section. Carbon filters are less common in cannabis facilities (Manke, 2018), but carbon filtration is commonly used in drinking water and wastewater treatment. During water filtration, contaminants adhere to the activated carbon and become trapped in the small pores of the filter (Mazille & Spuhler, n.d.). Carbon filters can adsorb relatively small quantities of soluble organics and inorganic compounds such as nitrogen, sulfides, and heavy metals remaining in the wastewater (EPA, 2000). Unlike RO, carbon filters do not produce wastewater. However, the filters do need to be replaced periodically.

To ensure that the water does not contain any harmful bacteria, it is important to sanitize the water before reapplication. There are several sanitation options available, but the operator should know what they are trying to remove from their irrigation water. The technology should be able to kill waterborne pathogens such as pythium, phytophthora, fusarium and rhizoctonia (DEH-CSWG, 2017). Chemicals, such as hydrogen peroxide or iodine, may be added to clean the water before reapplication to reduce microbe levels (CCC. 2019; Manke, 2018). These chemicals must not be added in too high of a concentration, otherwise they can be toxic to the cannabis plants (Manke, 2018). Other sanitation techniques include pasteurization, ozonation, and UV disinfection. Pasteurization uses high temperatures to kill bacteria in the water. It involves using heat exchangers to rapidly heat the water (Manke, 2018; Royal Queen Seeds, 2018). Ozonation involves infusing water with ozone (O_3) to kill any contaminants. Ozonation is highly effective, but it is an expensive process and the equipment can be damaged if the system is not used properly (Royal Queen Seeds, 2018). UV radiation is a chemical-free disinfection method that exposes the water to high-intensity UV rays to inactivate bacteria and pathogens (Manke, 2018; Royal Queen Seeds, 2018).

Facilities may also employ the use of an aerobic treatment unit to reduce chemical and microbial levels in the returned water to a satisfactory level (CCC, 2019). One Canadian company, Aurora Cannabis, has set a goal to recycle 90% or more of the water they use. The company has implemented measures such as water recirculation, rainwater harvesting, and retaining ponds at several of its sites. In addition, the wastewater is treated onsite with an aerobic waste digester (Westcott, 2018). The system grinds down the cannabis waste with a blend of microbes and enzymes that denatures the cannabinoids. As an added benefit, effluent from the system is treated in order to generate clean, potable water that can be reused in growing operations (Micron Waste Technologies, n.d.). The use of onsite treatment methods should be encouraged to reduce the impact of the cannabis industry on wastewater treatment plants.

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Chapter 4: Pesticides

Introduction

The term pesticide covers a wide range of compounds. They can be classified by eight major groups based on use against specific pests: insecticides, fungicides, herbicides, rodenticides, plant growth regulators, acaricides, molluscicides, and nematocides (Birkett & Taylor, 2019; EPA, 2014). There are many benefits and consequences of using pesticides. The benefits include increased crop production, decreased crop cost, and disease control. Some of the drawbacks include the potential for contamination of soil, groundwater, surface water, and air, as well as possible human health risks and decline of non-target species (Aktar, Sengupta, & Chowdhury, 2009).

Pesticides are regulated by the EPA under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA). FIFRA requires that all pesticides sold or distributed in the United States be registered by the EPA. To register a pesticide, the EPA examines the ingredients, the site or crop where it will be used, the amount, frequency, and timing of its use, and the storage and disposal practices. The evaluation also includes an assessment of a variety of potential human health and environmental effects associated with the pesticide. FFDCA requires the EPA to set pesticide tolerances for all pesticides used in or on food or in a manner that will result in a residue in or on food or animal feed. A tolerance is the maximum permissible level for pesticide residues allowed in or on human food and animal feed (EPA, 2019). The pesticide tolerances are established by the EPA and enforced by the Food and Drug Administration (FDA).

Since cannabis is not a legal agricultural crop under federal law, the EPA has not evaluated the safety of any pesticide on cannabis plants. Therefore, there are no established tolerances or exemptions from tolerances for pesticide residue on cannabis. The use of a pesticide not registered by the EPA is illegal. Therefore, without federal regulations to govern pesticide use in cannabis production, the use of pesticides on cannabis plants is technically illegal (Beyond Pesticides, 2019).

Under FIFRA, states have the broad authority to regulate pesticides. However, it is unlawful for States to "impose or continue in effect any requirements for labeling of packaging in addition to or different from those required under FIFRA" (7 U.S.C. §136 v(b)). Due to this law, pesticide regulations and tolerances vary from state to state. Some states prohibit the use of all federally registered pesticides on cannabis. Other states have no pesticide regulations because a state regulation would be arbitrary since registered pesticide use on cannabis is illegal (Beyond Pesticides, 2019).

Current Pesticide Use

Of the states that have legalized recreational cannabis, none have established the same pesticide restrictions. Even in neighboring states, consumers may experience dramatically different levels of protection. For example, Oregon requires testing for a different set of pesticides and enforces different limits for residue levels on cannabis products than California. In some cases, Oregon's limits are stricter than California's and they are more lenient in others (Seltenrich, 2019). In Washington, the state regulations prohibit the use of certain pesticides on cannabis, but pesticide testing is not required for recreational cannabis (Beadle, 2019; Seltenrich, 2019).

In this chapter, two groups of pesticides were analyzed: restricted pesticides and unrestricted pesticides. The pesticides categorized as "restricted" were retrieved from the

California Department of Pesticide Regulation’s Category II pesticides list. The pesticides categorized as “unrestricted” were selected by combining the allowable pesticides lists from California and Colorado. The reasoning for each selection and categorization are explained in the respective sections.

Restricted Pesticides

The first list that was analyzed is California’s list of Category II pesticides. California’s pesticide regulations are considered the strictest in the United States. This can be attributed to California’s Department of Pesticide Regulation (DPR), which has significant expertise in toxicology and human-health risk assessment (Seltenrich, 2019). Since no pesticides are federally registered for use on cannabis, California law states that a pesticide can be used on cannabis only if meets two specific criteria: (1) the active ingredients found in the product are exempt from residue tolerance requirements and (2) the product is either exempt from registration requirements or registered for a use that’s broad enough to include use on cannabis (CDPR, n.d.).

The DPR acknowledged that many pesticides that do not satisfy the criteria stated above would be present in detectable levels in final cannabis products. Because of this, the DPR established appropriate residue limits, rather than ban the complete presence of these pesticides on final products. The DPR established these limits by first compiling a list of commonly used pesticides by growers in other states, like Colorado and Washington, which could be tested for in third-party laboratories. Based on these consultations, the DPR created a list of 66 pesticides that pose a risk to the environment or human health and could be used on cannabis, but do not meet California’s standards for allowable use on cannabis. A list of 66 pesticides was established. Twenty-one of these pesticides are classified as Category I and are outright banned because they are banned federally or pose significant risk to the environment or human health (Seltenrich, 2019). These pesticides may not be present at any residue concentration. The other 45 pesticides are classified as Category II pesticides. Category II pesticides are on California’s Groundwater Protection List (3CCR section 6800) or are considered a restricted use material federally and/or in California (California Cannabis Cultivation, n.d.). The DPR established separate action levels for both ingestible and inhalable products for these pesticides (Seltenrich, 2019). Despite the fact that these 45 pesticides are not allowed to be used on cannabis because they do not meet California regulations, “a grower may still be able to apply these pesticides under certain conditions,” according to David Chen, lab director at Sonoma Lab Works (Seltenrich, 2019). As long as residues do not exceed the limit, the product is considered safe enough for sale (Seltenrich, 2019).

Unrestricted Pesticides

The unrestricted pesticide list is an amalgamation of pesticides allowed in California and Colorado. Because they were one of the first states to legalize cannabis, Colorado has been developing regulations for the industry the longest. The Colorado Department of Agriculture (CDA) determined which pesticides may be used on cannabis based on three principles. The first two principles are the same basis California uses to select pesticides, however, the third principle is based on which pesticides are legal for use on tobacco. The CDA acknowledged that cannabis is typically smoked, whereas the products the pesticides and tolerances were set for are not. Because of this, “any pesticide product allowed for use on cannabis must also have active ingredients that are allowed for use on tobacco to ensure EPA has considered use on commodities intended to be smoked in their risk assessment,” (CDA, n.d.). Colorado’s list has 74 different active ingredients and California’s list has 37, 31 of which overlapped between the two states (Appendix

A). This provided a list of 80 pesticides to review (74 on Colorado's list in addition to the 6 on California's list that were not on Colorado's list). Of the 80, 11 were identified as having possible risk to human or environmental health if used improperly, shown below in Table 4.1 with their GHS Hazard Statements.

Table 4.1. Pesticides with Possible Harmful Effects

Pesticide/Pesticide Synergist	GHS Hazard
Ammonium Nonanoate	Moderately toxic to aquatic ecosystems
Azadirachtin	Very toxic to aquatic ecosystems and bees
Mono- and Dibasic Sodium, Potassium, and Ammonium Phosphates	Toxic to aquatic invertebrates
Piperonyl Butoxide[10]	Moderately toxic to fish; Moderately to highly toxic to aquatic invertebrates
Potassium Laurate	Toxic to aquatic invertebrates
Pyrethrins[10]	Highly toxic to bees; Highly to very highly toxic to fish
Rhamnolipid Biosurfactant	Toxic to aquatic invertebrates and bees
Sodium Lauryl Sulfate	Mildly to moderately toxic to aquatic ecosystems

Environmental Fate and Transportation

Before allowing a pesticide product to be sold on the market, the EPA ensures that the pesticide will not pose any unreasonable risks to wildlife and the environment. An ecological risk assessment is performed to determine what risks are posed by a pesticide and whether changes to the use or proposed use are necessary to protect the environment (EPA, 2019a). As part of an ecological risk assessment, the EPA considers the interaction of a pesticide with soils, air, sunlight, surface water, and groundwater. The EPA needs to know how the pesticide breaks down in water, soil, and light, how easily it evaporates in air, and how quickly it travels through soil. Important parameters to consider are how fast and by what means does a pesticide degrade, what are the breakdown chemicals, and how much of a pesticide or its breakdown chemicals will travel from the application site, and where will they accumulate in the environment (EPA, 2019a).

The transportation and fate of a pesticide includes how a pesticide is transported, transferred, or transformed in the environment. Transport involves the different mechanisms by which the pesticide moves, including diffusion or advection. Pesticides can transfer from one medium or storage site through a number of mechanisms, including sorption on soil. Pesticides

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[10] These compounds were listed on Colorado's Allowable Pesticide List and were listed on California's Category II Restricted Pesticide List. They were included here due to their toxicity and inconsistency in categorization between the two states.

can transform into other contaminants under different environmental conditions. A pesticide may break down into CO_2 and water or may degrade in products that are more toxic than the original chemical (LaGrega et al., 2010). Once a pesticide is applied, it can meet a variety of fates. Pesticides may be volatilized into the atmosphere, carried away into surface waters by runoff, or leach into groundwater. Pesticides may also be taken up by plants or break down in the soil.

The physical and chemical properties of a pesticide determines how it will interact in the environment. These properties control how the pesticide moves in the environment and how effectively it can be removed by various methods (LaGrega et al., 2010). The transportation and fate of a pesticide is dependent on various factors, including the pesticide's properties, the soil properties, climate conditions, and management practices. Once a pesticide is applied, it can meet a variety of fates, as summarized in Figure 4.1.

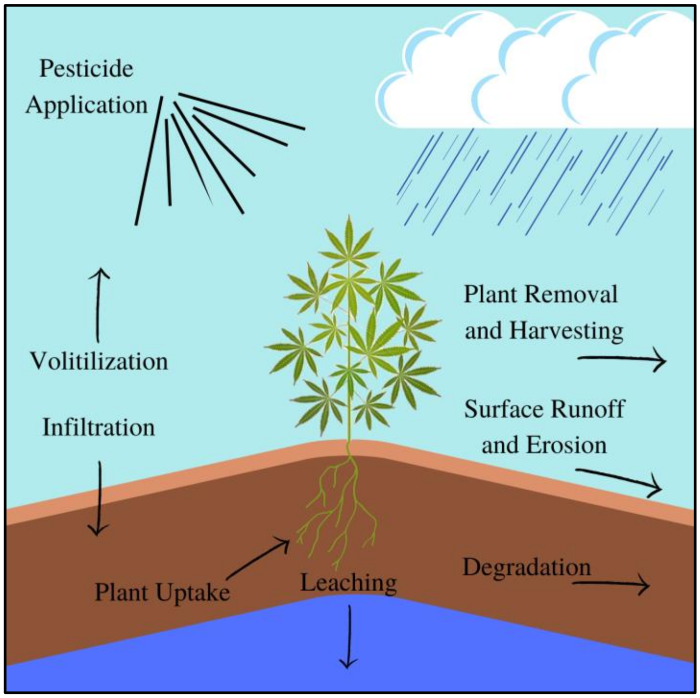

Figure 4.1. Pesticides in the Environment.

Soil Half-Life

The ability of a pesticide to remain present and active before degrading is called persistence. A pesticide's persistence is quantified by its half-life. A half-life is the time it takes an amount of pesticide to reduce by half. The longer a pesticide's half-life, the more persistent it is. If a persistent pesticide is applied to or spilled on soil, plants, or other surfaces, it can later harm the environment, including humans. They can also drift, leach, or runoff and contaminate other soils, surface water bodies, and groundwater. Since persistent pesticides do not break down quickly, they can remain on crops, resulting in the presence of illegal residue levels (Fishel, 2017).

The half-life of a pesticide is important because it characterizes the degradation process of that pesticide. Degradation processes break down pesticide compounds into simpler and often less-toxic chemicals (Fishel, 2017). Each pesticide can have many half-lives depending on the conditions in the environment. Pesticides can break down at different rates in soil, in water, on plants, and indoors. Environmental factors such as sunlight, temperature, oxygen, soil type, soil acidity, and microbe activity also affect the half-life. Since environmental conditions can change over time, it is impossible to establish a single, consistent half-life for pesticide. Therefore, pesticide half-lives are often given as a range. They are grouped into three groups in order to estimate persistence (Hanson et al., 2015). The ranges are shown below in Table 4.2.

Table 4.2. Half Life Rankings (Hanson et al., 2015).

Persistence	Soil Half-Life (days)
Low	Less than 16
Moderate	16 to 59
High	Greater than 60

The excessive application of pesticides has the potential for land degradation. Pesticides with a longer half-life are more likely to degrade soil. Pesticides can damage the biomass and microorganisms living in the soil, such as bacteria, fungi, and earthworms. These microorganisms are an important component of soil health (Joko et al., 2017). Furthermore, pesticides with a longer half-life are more likely to contaminate groundwater. If the pesticide does not readily degrade and moves freely with water, it can move downward through the soil. Since it does not degrade quickly, its likelihood of reaching groundwater is much higher than a pesticide that moves freely with water but degrades quickly. This scenario can be thought of as a race in time between their degradation into nontoxic by-products and their leaching into groundwater (Trautmann et al., 1989).

The soil half-life of a pesticide is greatly dependent on the type and conditions of soil, therefore the soil half-life is not as straightforward as other parameters. It can be difficult to estimate a value for the half-life due to the variability of soil conditions, including, pH, microbe populations, and several other factors (Harper et al., 2009). These factors range greatly between soil type and conditions (i.e. sandy loam, silty clay soil). For example, studies exploring the soil half-life of the pesticide diazinon, calculated a soil half-life of 21 to 103 days depending on the type of soil. Other studies showed half-lives of 1-5 weeks in non-sterile soils, and 6-12 weeks in sterile soils. Other research estimated the half-life of diazinon in sandy loam soils to be 37 days at pH 5.4 and 39 days at pH 7.8 (Harper et al., 2009).

Water Solubility

Solubility is the degree to which one substance, a solute (i.e. a pesticide), will dissolve into another, a solvent (i.e. water). The solubility of a pesticide in water is dependent on temperature and the particular pesticide (LaGrega, 2001). Pesticides that are highly soluble are more likely to be absorbed by the roots of plants. However, highly soluble pesticides dissolve in water more easily, making it more likely that the pesticide will move in surface runoff or move through the soil in water (Fishel, 2017).

Runoff occurs when irrigation, rain, or snow melt adds water to a surface faster than it can enter the soil. Pesticide movement in runoff occurs when a soluble or insoluble pesticide moves from the application site across the surface. It may be either dissolved or suspended in runoff waters that often enters surface water bodies such as canals, streams, rivers, and lakes (Gardner, n.d.). Leaching to groundwater occurs when soluble pesticides move downward through the soil to the groundwater. The more soluble a pesticide is, the more readily it will leach into groundwater (Gardner, n.d.). Often, groundwater contamination lasts for years and can be extremely difficult to clean up. Pesticide degradation in groundwater occurs more slowly than at the soil surface due to cold temperatures and low microbial activity. Groundwater also moves slowly, meaning it can take decades for the contaminated water to flow beyond the affected wells or aquifers (Trautmann et al., 1989).

Pesticide solubility is measured as the mass of pesticide that will dissolve in one liter of water (mg/L). The water solubility of pesticides can be categorized into three groups: low, moderate, and high (Ney, 1995). The ranges are shown below in Table 4.3.

Table 4.3. Solubility in Water (Ney, 1995).

Category	Solubility (mg/L or ppm)
Low	Less than 10
Moderate	10 to 1,000
High	Greater than 1,000

Vapor Pressure

Volatility is the tendency of a pesticide to evaporate. The potential for a pesticide to volatilize is measured by its vapor pressure. The higher the vapor pressure, the more volatile a pesticide is (Fishel, 2017). A pesticide's vapor pressure can be used to predict if the pesticide will volatilize, how long it will stay in water, on plants, and in soil, how much of the pesticide will enter the air, and whether people and animals are at risk of breathing in the pesticide (Hanson et al., 2016). When a pesticide volatizes, it can be carried off-site by the wind and settle in unintended areas (Fishel, 2017).

This can be an issue for outdoor cannabis growers. In large agricultural areas, such as California, pesticides can easily drift from one farm to another. Therefore, if a neighboring farm is using pesticides, an outdoor cannabis crop can become contaminated with pesticides the cannabis grower never applied. Sometimes, the contamination levels are at high enough levels that a cannabis crop will fail residue testing. One solution to this issue is to move cannabis cultivation indoors to avoid incidental pesticide contamination. In Canada, legal cannabis comes solely from greenhouse and indoor growers, due to its zero-tolerance policy on pesticide residues. However, indoor cannabis cultivation requires more energy and water consumption than outdoor cultivation. It should be noted that outdoor cultivation is legal in Canada, but the government has yet to approve any outdoor cultivation projects (Seltenrich, 2019). While indoor cultivation would reduce the environmental impacts of pesticides, air controls would need to be installed to protect the indoor growers.

The vapor pressure of a pesticide is affected by various environmental conditions. Temperature, wind conditions, humidity, and soil type each affect volatility. Of these, temperature can have the largest effect In general, pesticides have a lower vapor pressure at lower temperatures, and vice versa (Hanson et al., 2016). If the vapor pressure of a pesticide is known, it is easier to predict how it will act indoors and outdoors. This can help lower risk to people and the environment. For example, plastic row covers could be used to prevent a highly volatile pesticide from escaping the soil and drifting to nearby areas. If a highly volatile pesticide is used indoors, the employees can wear respirators and other protective equipment (Hanson et al., 2016). The volatility of a pesticide can be categorized into three groups: nonvolatile, low, and intermediate to high (EPA, 2019b). The ranges are shown below in Table 4.4.

Table 4.4. Vapor Pressure Ranges (EPA, 2019b).

Category	Vapor Pressure (atm)
Nonvolatile	$\leq 1.32 \times 10^{-9}$
Low Volatility	1.32×10^{-9} - 5.13×10^{-8}
Intermediate to High Volatility	$\geq 5.13 \times 10^{-8}$

Partition Coefficients

Partition coefficients are empirically derived constants that describe how a chemical distributes itself between two phases. They are expressed as a concentration ratio, assuming that dissolution is the only interaction between the two phases. Partition coefficients are used to describe the environmental fate of organic compounds, particular regarding the sorption of organics in the subsurface. Sorption is the process by which a component (a pesticide) moves from one phase to another across a boundary (LaGrega et al., 2010).

Octanol-water Partition Coefficient (K_{OW})

The octanol-water partition coefficient (K_{ow}) is the ratio of a pesticide's concentration in the octanol phase to its concentration in the aqueous phase. K_{ow} is a dimensionless constant. It provides an indication of how much of a pesticide will be taken up by aquatic organisms. K_{ow} is also related to the soil adsorption coefficients and the water solubility (LaGrega et al., 2010).

Values of K_{ow} can range from 10-3 to 107 and are often reported as log K_{ow}, which can range from -3 to 7. Pesticides with high values of K_{ow} tend to be hydrophobic and are more likely to sorb. Pesticides with low values of K_{ow} tend to be hydrophilic. Hydrophilic pesticides are less likely to sorb, remain in the aqueous phase, and are generally more mobile in the environment (LaGrega et al., 2010).

Sorption Coefficients (K_{SW} and K_{OC})

The physical binding of pesticide molecules to soil particles is called adsorption. The stronger a pesticide bonds to the soil, the less likely it is to leach or runoff. The strength of these bonds depends on the pesticide's chemical properties, the pesticide concentration in the soil water, the soil pH, and the composition of the soil. For example, the more clay particles and organic matter that are in the soil, the more the pesticide is held by the soil and becomes immobile. A strongly adsorbed pesticide will not leach or move unless the soil particles which they are bonded to move, usually due to erosion. The longer the pesticide molecules are held, the more likely that microbiological degradation will occur, which reduces the risk of leaching and runoff (Gardner, n.d.).

The soil-water partition coefficient (K_{sw}) is the tendency of a pesticide to be adsorbed by soil or sediment in an aqueous suspension. Pesticides with high values of K_{sw} tend to adsorb to soil. Pesticides with low values of K_{sw} tend to stay in solution (LaGrega et al., 2010). Almost all of the sorption of a pesticide by a soil is due to the organic carbon component of the soil. The organic carbon partition coefficient (K_{oc}) is the ratio of the concentration of pesticide in organic carbon component of soil to the concentration of pesticide in water (LaGrega et al., 2010). K_{sw} is estimated by multiplying K_{oc} by the fraction of organic carbon in the soil.

K_{sw} and K_{oc} are commonly used to model the fate and transport of chemicals in rivers, stormwater runoff, and soil/groundwater transport. The values of K_{sw} and K_{oc} are relatively independent of soil type, but can vary greatly depending on other environmental factors. Temperature, pH, particle size distribution and surface area, salinity, and the presence of dissolved organic matter or suspended particulate matter can all influence K_{sw} and K_{oc} values (LaGrega et al., 2010).

Best Management Practices

States have established best management practices (BMPs) to ensure the proper use and control of pesticides. The Central Valley Regional Water Quality Control Board issued best management practices for the application of pesticides in general agricultural facilities. To avoid surface and groundwater contamination, these BMPs recommend the mixing and loading of pesticides take place, "more than 50 feet away from any wells, streams, canals, irrigation ditches, riparian areas or sinkholes, and more than 200 feet away from any potable water supply wells" (Zhang & Goodhue, 2010). Mixing and loading should also take place on a containment pad, which is a concrete slab that drains to a central sump. If this type of structure is unable to be constructed, mixing and loading pesticides should be conducted on a tilled site, rather than hard packed or paved, where runoff can occur. In addition, sites should be rotated in order to prevent concentrating pesticide runoff in one location.

These BMPs also include recommendations to properly time the application of pesticides. By timing the application of pesticides to not coincide with a rainfall or irrigation event, the risk of runoff or leaching can be mitigated. However, this may not apply to pesticides with long half-lives (Zhang & Goodhue, 2010). Furthermore, the wind speed is another important consideration to take into account when applying pesticides. It is recommended that pesticides be applied at wind speeds of 2 to 10 mph. At wind speeds less than 2 mph, small droplets may remain suspended in the air and be carried offsite. At wind speeds above 10 mph, small droplets of pesticides may be carried long distances (Zhang & Goodhue, 2010).

Certain equipment can also alleviate the transportation of pesticides. Certain sprayer and nozzle designs can provide a more targeted approach to prevent pesticides from being caught in a wind gust. Nozzles can be selected to produce large or small droplets; it is generally thought that although large droplets fall straight down rather than drift, they are less effective and might require higher doses (Zhang & Goodhue, 2010). Protective equipment and clothing may also be utilized to ensure worker safety and equipment should be checked regularly to check for leaks.

These management practices also include recommendations on proper storage, disposal, and more application techniques for pesticides. These recommendations are generally accepted standards that agricultural facilities should follow. In most cases, when best management practices are followed, the harmful effects of certain pesticides can be greatly mitigated. For example, the pesticide and the synergist, pyrethrins and piperonyl butoxide, are used in various states including Massachusetts and California for mosquito control (Orth, 2019; CDPH, 2014).

States like Massachusetts and Colorado have issued BMPs specifically for pesticide use in cannabis cultivation facilities. These BMPs encourage the use of Integrated Pest Management (IPM) to avoid the use of pesticides altogether. This will be discussed in the Recommendations section.

Health Concerns

The health concerns associated with pesticide use on cannabis result from the gap in regulations between the EPA and state governments. These concerns are related to the consumption of cannabis, through smoking and extracts, and the safety of the facility workers.

Smoking

The health hazard created when cannabis with pesticide residue is burned is one of the largest health concerns associated with cannabis consumption. When smoked, the pesticide residue directly reaches the bloodstream through lung gas exchange, which results in a much higher bioavailability than if the product was ingested orally (Taylor & Birkett, 2019). Additionally, cannabis smokers have a much higher risk of inhaling smoke contaminated with pesticides and plant growth regulators than tobacco smokers. Common cannabis smoking methods, such as bongs and joints, do not have included filters like most cigarettes. The exact health impacts of inhaling pesticides are unknown (Seltenrich, 2019).

A study was conducted in 2013 that measured the pesticide residue in the smoke from cannabis contaminated with insecticides, bifenthrin, diazinon, and permethrin, and paclobutrazol, a plant growth regulator (Sullivan et al., 2013). The study found that 60% to 70% of the residue was recovered in the smoke condensate of water pipes and glass pipes (Sullivan et al., 2013). These devices did not include a cotton filter. When the smoking device had an incorporated filter, the pesticide recovery in the smoke was much lower at 10% to 13% (Sullivan et al., 2013).

The compounds that pesticides break down into when burned are also largely unknown (Seltenrich, 2019). It is reported that the metabolites of many pesticides are more toxic than their parent compounds and it is unknown how they may react with each other (Taylor & Birkett, 2019). For example, the fungicide myclobutanil breaks down into hydrogen cyanide when heated. Hydrogen cyanide is associated with neurological, respiratory, cardiovascular, and thyroid problems (Craven et al., 2019). Additionally, it is unknown how pesticides react with the terpenes and cannabinoids in the matrix structure of cannabis (Taylor & Birkett, 2019).

The problem of pesticide residues on cannabis is similar to the problem of pesticide residues on tobacco, since both plants are consumed but are not considered a food crop. Because tobacco is not a food crop, the EPA has not set tolerances for the residue levels (Sullivan et al., 2013). Additionally, there have been actions taken to prevent overtreatment to reduce the exposure of tobacco consumers to high residue levels, but they are not federally enforced (Sullivan et al., 2013). It can be assumed that when cannabis is federally legal, the same problem with pesticides will occur. However, cannabis consumers will be at a higher risk than tobacco smokers, since most cannabis is smoked without filters. This problem may be corrected by a stronger set of regulations for products that are not classified as food but are still consumed.

Extractions

There is scarce information about how pesticide residues are altered during the extraction process (Stone, 2014). It may result in decomposition or increased bioavailability of the compounds. Based on current research, it may be expected that lipophilic compounds remain in oil-based extraction products, posing a risk to consumers (Stone, 2014).

Worker Safety

Workers at cannabis growing facilities mainly face hazards related to inhalation and dermal contact exposure, although ingestion is a risk as well. Workers can be exposed during spills, mixing and loading the chemicals, misapplication, and entering treated areas (Stone, 2014). A study conducted in Oregon found that pesticide residue levels on cannabis products were so high that the proper safety pesticide practices were not followed (Evoy & Kincl, 2019). This means that pesticide label laws were not followed, and may indicate that workers are involved in the use of restricted-use pesticides without knowing the laws for safe pesticide application (Evoy & Kincl, 2019). Another study in Colorado found that 35% of the workers experienced "adverse health symptoms" after handling pesticides (Walters et al., 2018). These examples suggest a need for more research into proper pesticide use and practices to protect the safety of workers.

Recommendations

Tobacco's Pesticide Regulations

Many researchers and regulators are looking to the tobacco industry for guidance on how to regulate cannabis. In theory this would be the appropriate method of regulating pesticides for cannabis, however, there are major issues with tobacco pesticide regulations. Tobacco regulations were determined based on a report by the U.S. General Accounting Office (GAO) which included an analysis by the EPA (GAO, 2003). The EPA concluded that pesticide residues declined on tobacco as it was stored, cured, manufactured, and burned (Stone, 2014). The report also includes pyrolysis studies conducted by manufacturers that determined how much residue was collected from combustion smoke (Stone, 2014). The EPA determined these values were low enough to not warrant tolerance levels, since they did not cause short-term health concerns (Stone, 2014). While the EPA regulates the specific pesticides that may be used on tobacco crops, it does regulate pesticide residues on tobacco (GAO, 2003). However, pesticide residues are regulated by the U.S. Department of Agriculture (USDA). Under the Dairy and Tobacco Adjustment Act, the USDA tests imported and domestic tobacco for residues of pesticides not approved by EPA for use on tobacco that federal officials believe are used in other countries (GAO, 2003).

Based on cannabis research, pesticide residues are much higher in concentration in cannabis smoke than tobacco smoke (Sullivan et al., 2013). As stated previously, this is of major concern considering very little is known about how pesticides transform when burned and cannabis users inhale greater amounts of smoke than tobacco users (Sullivan et al., 2013). Cannabis regulations should not be strictly modeled after tobacco regulations due to the different concerns associated with the products. Additionally, cannabis is ingested orally through edibles while tobacco is not. The edibles market is the largest sector of the cannabis industry (New Frontier Data, 2019). Because of this, cannabis should be classified as a food crop, and pesticide residues should be tested by the EPA. Stricter regulations are needed to ensure the safety of consumers and the environment. Canada serves as an example for more well-defined pesticide regulations.

Canada's Pesticide Regulations

As of July 30, 2019, Canada has registered 29 pesticides for lawful use on cannabis plants. The majority of them are biological fungicides and herbicides. The pesticides pose minimal risk to humans and most of them do not contain any chemicals found in many popular pesticides. If any cannabis pesticides do contain dangerous ingredients, such as sulfur, the concentration is too small to harm human health (Chem Service, 2019). Canada also has a list of pesticides not entirely banned for use on cannabis similar to California's restricted use pesticides. However, the residue limits for these pesticides are generally, and in some cases significantly, stricter than the limits set by California (Health Canada, 2018).

In 2017, there were multiple large-scale recalls of medical cannabis due to illegal pesticide use.[11] After these findings, Health Canada began enforcing strict pesticide testing requirements. Prior to this, the specific regulations regarding pesticide use were not strictly enforced. Health Canada began to suspend or terminate cannabis licenses for those who did not conduct mandatory testing. In November 2018, Health Canada enhanced the existing pesticide testing regulations. Cannabis cultivators are required to deliver samples of their products to products to independent laboratories for testing that tests for approximately 100 different chemicals (Chem Service, 2019). Before Canada enhanced its pesticide regulations, the specifications as to how the testing was implemented were not clear. By strictly defining and enforcing the regulations, there is little leniency for unauthorized pesticide use on cannabis. This forces cultivators to make sure their growth and processing practices are up to code (Chem Service, 2019).

There are many takeaways from the example set by Canada. First, the pesticide limits should be lowered until acceptable tolerance limits can be established and studied for effectiveness. Second, a national regulatory body should be established to ensure an equal level of regulation across the States. If recreational cannabis is federally legalized, this responsibility would fall to the EPA. However, the industry should not wait for this possibility and take initiative to self-regulate. Lastly, recreational cannabis regulations need to be clearly defined and easily accessible. Some requirements are vaguely defined and difficult to understand what is legal or not. The exact regulations can also be difficult to locate. This can make it more difficult for well-intentioned cultivators to ensure their practice is legal.

Integrated Pest Management

Both the Massachusetts and Denver Best Management Practices recommend the use of an Integrated Pest Management (IPM) program, "to prevent, reduce, or maintain pest populations at non-damaging levels by utilizing a variety of mechanical, physical, and biological controls" (DDPHE, 2018; CCC, 2019). IPM plans are structured to include the following approach: prevention, suppression, and eradication. Prevention of pests includes: spacing out the plants; sealing cultivation areas; maintaining a controlled environment; removing pest habitats; trap setting; pest scouting; and applying natural oils to deter pests. Any new plants or products that enter the facility must be quarantined for 21 days to prevent the introduction of a pest to the closed system. IPM also relies on extensive documentation of pest populations, treatment methods, and treatment results. Grow media must always be replaced with sterile media and never reused. The facility must also be maintained to ensure a dry, clean, and trash-free environment. Windows and

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[11] In the U.S, medical and recreational cannabis are regulated under two separate systems. In Canada, medical and recreational cannabis are regulated under the same system. Therefore, medical cannabis laws apply to recreational cannabis.

doors must be free of cracks and remain sealed at all times. Additionally, eradication of pests surrounding the facility should be done in order to minimize the risk of infiltration (DDPHE, 2018). If a pest problem does arise, biological control agents, including the pest’s natural predator or parasites, are applied. The only time synthetic controls (pesticides) are used is if they are approved by the appropriate regulatory agency. In the case of Denver and Massachusetts, 25b Minimum Risk Pesticides may be applied (DDPHE 2018; CCC, 2019; C.F.R. 40 § 152.25, 2013).

Future Research

There is extensive research about the harmful effects of pesticides on the environment; however, there is much uncertainty about the health risks of pesticide use on cannabis. Little research has been conducted to determine the risk posed by smoking cannabis with pesticide residue and even less research has been conducted to explore how pesticides may transform during the extraction process. If cannabis becomes federally legal, these concerns will need to be brought to the forefront of the discussion when determining which pesticides are suitable for use on cannabis.

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Appendix A: Cross-Referenced List of Pesticides Allowed in CA and CO

Colorado	California	California but not Colorado
Acetic Acid		Bacillus thuringiensis sub. israelensis
Ammoniated soap of fatty acids		Horticultural oils (petroleum oil)
Ammonium Nonanoate		Iron phosphate
Auxin		Potassium bicarbonate
Azadirachtin	Azadirachtin	Sodium bicarbonate
Bacillus amyloliquefaciens Strain D747	Bacillus amyloliquefaciens strain D747	
Bacillus pumilus Strain GHA 180		
Bacillus subtilis MBI 600		
Bacillus subtilis QST713 Strain		
Bacillus thuringiensis SSP. Aizawai		
Bacillus thuringiensis SSP. Kurstaki	Bacillus thuringiensis sub. kurstaki	
Beauveria bassiana Strain GHA	Beauveria bassiana	
Burkholderia sp strain A396	Burkholderia spp. strain A396	
Canola Oil		
Capric Acid/Caprylic Acid		
Capsicum Oleoresin Extract	Capsaicin	
Castor Oil	Castor oil	
Cedar Oil		
Chromobacterium Sub Strain PRAA4-1 Cells		
Cinnamon Oil	Cinnamon oil	
Citric Acid	Citric acid	
Clarified Hydrophobic Extract of Neem Oil	Neem oil	
Clove Oil	Clove oil	

Complex polymeric polyhydroxy acid (CPPA)		
Copper Octanoate		
Corn Oil	Corn oil	
Cottonseed Oil	Cottonseed oil	
Cytokinin (Kinetin)		
Diatomaceous Earth		
Eugenol		
Garlic Oil	Garlic oil	
Geraniol	Geraniol	
Gibberellins (Gibberellic Acid)		
Gliocladium catenulatum strain J1446	Gliocladium virens	
GS-omega/kappa-Hxtx-Hv1a		
Harpin Alpha Beta		
Helicoverpa armigera nucleopolyhedrovirus strain BV-0003		
Hydrogen Peroxide		
IBA (Indole-3-Butyric Acid)		
Indole-3-butyric acid		
Isaria fumosorosea	Isaria fumosorosea	
Kaolin		
Lemon Grass Oil		
Linseed Oil		
Mineral Oil		
Mono- and Dibasic Sodium, Potassium, and Ammonium Phosphites		
Monopotassium Phosphate		
Myrothecium verrucaria		
Peppermint Oil	Peppermint oil	
Peroxyacetic Acid		

Phosphorous Acid, Mono- and Di-Potassium Salts of		
Piperonyl Butoxide		
Potassium Laurate		
Potassium Salts of Fatty Acids	Insecticidal soaps (potassium salts of fatty acids)	
Potassium Silicate	Potassium silicate	
Potassium Sorbate	Potassium sorbate	
Pseudomonas chlororaphis strain AFS009		
Pyrethrins		
Reynoutria sachalinensis	Reynoutria sachalinensis extract	
Rhamnolipid Biosurfactant		
Rosemary Oil	Rosemary oil	
Sesame Oil	Sesame oil	
Sodium Chloride	Sodium Chloride	
Sodium Ferric EDTA	Sodium Ferric EDTA	
Sodium Lauryl Sulfate		
Soybean Oil	Soybean oil	
Streptomyces sp. Strain K61		
Streptomyces Strain K61		
Sulfur	Sulfur	
Thyme oil	Thyme oil	
Trichoderma asperellum Strain ICC 012		
Trichoderma gamsii Strain ICC 080		
Trichoderma harzianum Rifai Strain KRL-AG2	Trichoderma harzianum	
Trichoderma virens Strain G-41		
Total 74	**31**	**6**

Data Sources

[12]California Department of Pesticide Regulation. Cannabis Pesticides That are Legal to Use. [PDF File]. https://www.cdpr.ca.gov/docs/cannabis/can_use_pesticide.pdf

[13]Colorado Department of Agriculture. Colorado pesticides allowed for use in cannabis production. [PDF File]. Retrieved from https://drive.google.com/file/d/1JLP-Z2-88TLpShucZ4bowA38cuqBaM8A/view

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[12] This is not an exhaustive list of active ingredients that may fit the legal use criteria.

[13] Pesticides allowed for use in Cannabis production in accordance with the PAA Rule: Effective February 14th, 2020. Accessed on April 21, 2020. List was filtered by “YES” for Commercial Use.

Appendix B: California's Restricted Category II Pesticide List

Pesticide	Type	Half-life (days)	Water Solubility (mg/L)	K_{oc}	Vapor Pressure (mm Hg)	log K_{ow}
Abamectin	Insecticide	33.50	1.21 at 25 °C	12,388	1.5E-9 at 20 °C	4.4
Acephate	Insecticide	3.00	818,000	4.7	1.7E-6 at 25 °C	-0.85
Acequinocyl	Acaricide	0.10	0.00669 at 20 °C	56000	1.27E-8 at 25 °C	6.2
Acetamiprid	Insecticide	16.00	4250 at 25 °C	199.5	4.36E-5 at 25 °C	0.8
Azoxystrobin	Fungicide	226.50	6	400.5	8.3E-13 at 25 °C	2.5
Bifenazate	Acaricide	0.30	3.76	3984.5	7.5E-8 at 25 °C	3.4
Bifenthrin	Insecticide	173.50	0.001 at 20 °C	11,360	1.335E-8 at 20 °C	6
Boscalid	Fungicide	337.00	4.6	9500	5.4E-10 at 20 °C	2.96
Captan	Fungicide	10.00	5.1	316.5	9E-8 at 25 °C	2.8
Carbaryl	Insecticide	10.00	50 at 20 °C	296.7	1.36E-6 at 25 °C	2.36
Chlorantraniliprole	Insecticide	211.00	0.95 at 20 °C	354	1.2E-14 at 25 °C	2.76
Clofentezine	Acaricide	40.00	0	11,000	9.75E-10	4.09
Cyfluthrin	Insecticide	116.00	0.003	30,000	1.50E-10	---
Cypermethrin	Insecticide	15.50	0.004 at 20 °C	261,900	1.7E-9 at 20 °C	6.6
Diazinon	Insecticide	4.60	60	1,017	9.01E-5 at 25 °C	3.81
Dimethomorph	Fungicide	91.50	49.2 at 20 °C	5690	7.39E-6 at 25 °C	2.68
Etoxazole	Acaricide	20.50	0.0754	5000	1.64E-8 at 25 °C	5.59

Fenhexamid	Fungicide	1.00	20	4100	3E-9 at 20 °C	3.51
Fenpyroximate	Miticide	36.50	0.0231 at 25 °C	12000	5.58E-8 at 25 °C	5.01
Flonicamid	Insecticide	12.75	5200	25	7.073E-9 at 20 °C	0.3
Fludioxonil	Fungicide	246.50	1.8 at 25 °C	3388	2.93E-9 at 25 °C	4.12
Hexythiazox	Ovacide (miticide)	23.20	0.5	6,200	2.55E-8 at 20 °C	5.57
Imidacloprid	Insecticide	119.00	610	478	7E-12 at 25 °C	0.57
Kresoxim-methyl	Fungicide	1.00	2	1700	1.72E-8 at 20 °C	3.4
Malathion	Insecticide	2.74	143 at 20 °C	9,274	3.97E-5 at 30 °C	2.36
Metalaxyl	Fungicide	55.00	8,400	157	5.62E-6 at 25 °C	1.71
Methomyl	Insecticide	30.00	58,000	160	5.4E-6 at 25 °C	0.6
Myclobutanil	Fungicide	66.00	142	950	1.6E-6 at 25 °C	2.94
Naled	Insecticide, Acaricide, Fungicide	0.25	1.5	242	2.0E-4 at 20 °C	1.38
Oxamyl	Insecticide	34.50	282,000	8	0.00023 at 20-25 °C	-0.47
Pentachloronitrobenzene	Fungicide	468.00	0.44	20000	5E-5 at 20 °C	4.22
Permethrin	Insecticide, Acaricide	42.00	0.0111	48,236	5.18E-8 at 25 °C	6.5
Phosmet	Insecticide	12.00	25	660	4.9E-7 at 20-25 °C	2.95
Piperonylbutoxide	Insecticide synergist	14.00	0	614.5	5.2E-6 at 25 °C	4.75
Prallethrin	Insecticide	25.85	8	3082	3.5E-5 at 20 °C	4.49
Propiconazole	Fungicide	110.00	110	650	10^{-6} at 25 °C	3.72

Pyrethrins	Insecticide	12.00	0	100,000	2.03E-5 at 25 °C	6.15
Pyridaben	Acaricide	13.00	0.012	5000	1.18E-6 at 20 °C	6.37
Spinetoram	Insecticide	18.40	29 at 20 °C	22836	4275.351 at 20 °C	4.2
Spinosad	Insecticide	13.00	89.4	1000	2.25E-9 at 25 °C	4.1
Spiromesifen	Insecticide	10.25	0.13	34,000	1.5E-4 at 20 °C	4.55
Spirotetramat	Incesticide	0.20	29.9	4.55	4.20E-11 at 20 °C, 1.13E-10 at 25 °C	2.5
Tebuconazole	Fungicide	400.00	36	1023	1.28E-8 at 20 °C	3.7
Thiamethoxam	Insecticide	50.50	4,100	60	4.95E-11 at 25 °C	-0.13
Trifloxystrobin	Fungicide	3.00	0.61	4504.5	2.55E-8 at 25 °C	4.5

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Chapter 5: Extraction Methods

Introduction

One of the leading concerns in cannabis production is the type of solvent used during extraction. Extraction is the process of purifying and concentrating cannabinoids, flavonoids, and terpenes from the cannabis plants. Through the use of temperature, pressure, and solvents, the purpose of extraction is to make cannabinoids and other beneficial components available in a highly concentrated form (Romano & Hazekamp, 2013; The Valens Company, 2019). Cannabis concentrates are created to contain high amounts of desired compounds, such as tetrahydrocannabinol (THC) and cannabidiol (CBD). These concentrates can be grouped into categories, seen in Figure 5.1. Recent advances in high-level THC extractions have led to an increase in the number of concentrate products in the United States.

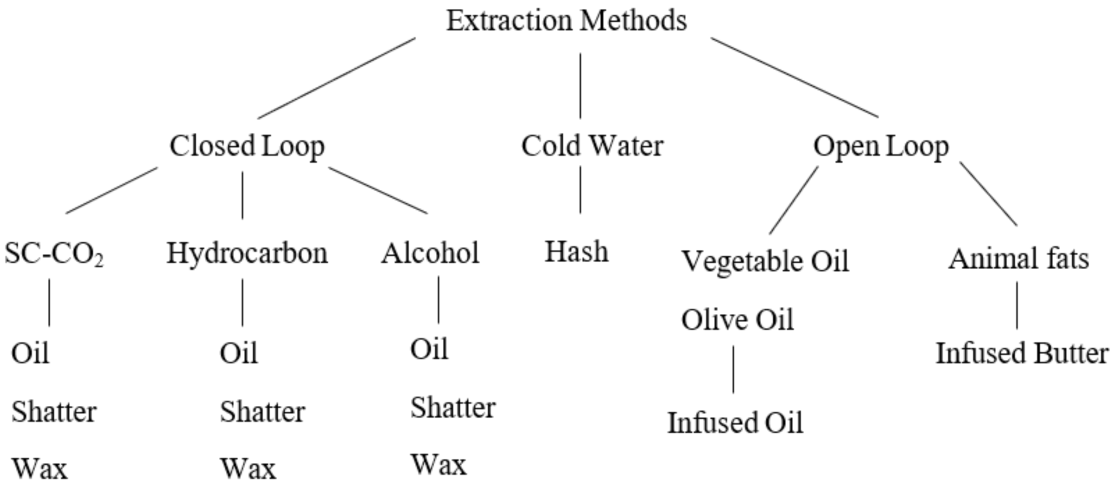

Figure 5.1. Categories of Products and Extraction Methods.

There are several methods and solvents used to extract compounds from the cannabis plant. Mechanical methods rely on temperature and pressure to force cannabis compounds out of the plant, whereas solvent-based methods rely on a solvent to extract the compounds from the plant. The mixture is then processed, in a variety of ways, to separate the solvent from the desired product (The Valens Company, 2019). Non-polar solvents are commonly used for extraction, such as petroleum ether, naphtha, alcohol and olive oil (Romano & Hazekamp, 2013). Table 5.1 displays the different categories of solvents allowed by states.

Table 5.1. Categories of Solvents

CATEGORY	SOLVENT	CATEGORY	SOLVENT
Hydrocarbons	Butane Propane Heptane	Alcohol	Ethanol Isopropanol Propylene glycol
Food	Glycerin Butter Olive oil Animal fats Vegetable oils	Misc.	Acetone Chlorofluorocarbons Carbon dioxide Water

Each state has a different list of allowable solvents, ranging in specificity; these are displayed in Table 5.2.

Table 5.2. Allowable Solvent by State[14]

SOLVENT	AK	CA	CO	IL	ME	MA	MI	NV	OR	VT	WA	DC
Hydrocarbons		●			○		●	⦸	⊗	⦸		
Butane	●	○	●	●	○	●	●	⦸		⦸	●	
Propane	●	○	●	●	○	●	●	⦸		⦸	●	
Heptane	●	○	●		○		●	⦸		⦸	●	
Alcohols		○			○			⦸		⦸		
Ethanol			●	●	○			⦸	●	⦸	●	●
Isopropanol			●	●	○			⦸	●	⦸		●
Propylene glycol	●		●	●	○			⦸		⦸	●	
Fats	●	●	●	●	○			⦸		⦸		
Vegetable/Olive Oils		●	●	●	○			⦸	●	⦸		●
Butter/Animal Fats	●	●	●		○			⦸	●	⦸	●	●
Glycerol	●		●	●	○			⦸		⦸	●	●
Water	●	●	●	●	○	○	○	⦸	●	⦸	●	●
Carbon dioxide		●	●	●	○	●	●	⦸	●	⦸		●
Acetone			●		○			⦸		⦸		
Fluorinated gases		●			○			⦸		⦸		

Legend:
● Specifically allowed
○ Non-specifically allowed
⊗ Specifically banned
⦸ Unknown

California allows chloroform and other fluorinated gases to be used for extraction, however, this is an outdated process that has become obsolete. Additionally, Colorado allows the use of acetone as a solvent, but most producers do not use it as the process produces unwanted byproducts.

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[14] Boulder, CO Municipal Code § 6.16.8; Ill. Admin. Code tit. 101-0027 (2019); Cal. Code Regs. tit. 16, § 8307 (2018); Mass. Gen. Laws ch. 935, § 500.000 (2019); AS 03.306 (2014); Me. Stat. tit. 28-B (2016); MCL 333.27951-333.27967 (2018); NRS 453D.130 (2017); ORS 475B (2014); VT H.511 Act 86 (2019); RCW 69.50.325 (2014); DC Safe Cannabis Sales Act of 2019.

Closed-Loop Systems

A closed-loop system is a type of extraction process in which, theoretically, all the solvent is removed from the concentrate and reused. Closed-loop systems are used for solvents that are either dangerous to leave in the product or for the solvent to be recycled completely. In practice, the system loses small amounts of solvent through the machinery or remain in the concentrate. A process flow diagram for a generic closed-loop extraction is shown in Figure 5.2.

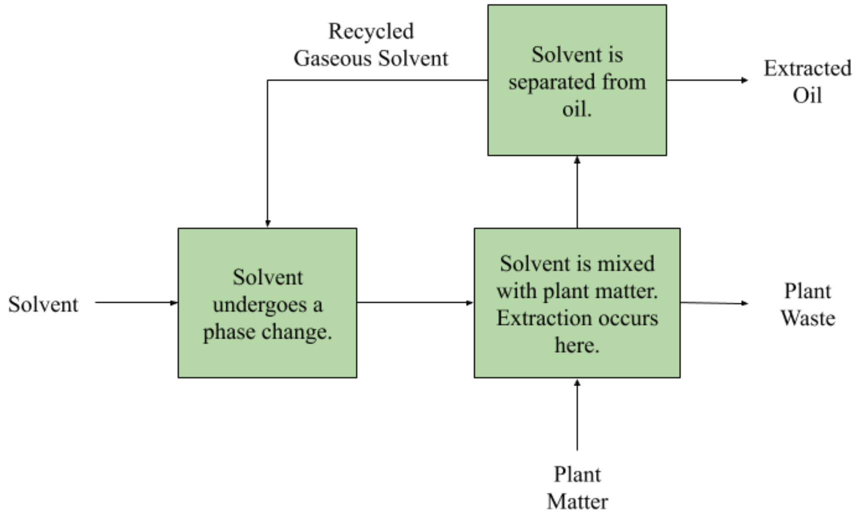

Figure 5.2. Closed-loop Extraction Process.

Hydrocarbon Extractions

Hydrocarbon extractions involve the use of butane, propane, heptane, or a mixture, to extract cannabinoids and terpenes from plant material. Many extraction techniques use a mixture of butane and propane to strip additional terpenes than butane alone (June-Wells, 2018). Hydrocarbons require a low pressure system where extractions can be conducted between 0 to 30 psi. The extraction process works by washing plant material with cold butane to dissolve the terpenes and cannabinoids. The concentrate-solvent mixture then passes through an in-line dewaxing process, to separate the concentrate from the waxes. Lastly, the hydrocarbon solvent is evaporated off and collected to be reused (June-Wells, 2018). Hydrocarbon extraction results in many different types of products that can be produced through different solvent-purging methods. These purging methods include whipping the concentrate solution, spreading it thin and placing it in a vacuum oven, or placing the concentrate under high heat to separate it from the butane (June-Wells, 2018).

The main problem with hydrocarbon-based extraction is the high potential for residual solvent, even after using a purging method. In the current regulations of the states that have legalized recreational cannabis, all eleven permit the use of butane and propane as an extraction solvent. However, there is a wide disparity in the limits of residual butane and propane allowed. California has a residue limit of 5,000 ppm in the final product of both butane and propane. Colorado initially set a residue limit of 800 ppm, then increased it to 5,000 ppm, and lowered it to 1,000 ppm in 2018. On the contrary, Massachusetts has set a residue limit of 12 ppm (Seltenrich, 2019). The reason for this large disparity can be attributed, in part, to the fact that many states rely on guidance from the U.S. Pharmacopeial Convention (USP), "a nonprofit scientific organization...that develops and disseminates public compendial quality standards for medicines and other articles" for setting these limits (USP, n.d.). The USP guidelines categorize 59 solvents that can be used to manufacture herbal medicines and other drug products into three different classes: solvents to be avoided, solvents to be limited, and solvents with low toxic potential (USP, 2007). The USP suggests specific residual concentration limits for each of the 59 solvents that are considered safe. The limit of 5,000 ppm, the California residue limit and previous Colorado limit, is a standard limit that the USP has assigned for all 26 of its "less toxic" solvents, which notably does not include butane or propane. Butane and propane are not commonly used to manufacture herbal medicines and other drug products, therefore they are not included in the USP guidelines (Seltenrich, 2019). There are numerous risks of butane inhalation, including convulsions, hallucinations, cardiac damage, arrhythmias, organ failure, respiratory depression, vagal inhibition, and anoxia. Solvent inhalation can also be associated with "chronic problems such as cardiomyopathy, renal damage, liver damage, and a variety of psychiatric syndromes," (Al-Zouabi et al., 2018). Due to the health risks associated with butane, stricter regulations with scientific backing need to be established.

These arbitrary regulations are of particular concern due to the growing problems surrounding butane hash oil (BHO). BHO products are highly potent cannabis concentrates that are produced using butane extraction. Due to the high concentration of THC that can be acquired using this method, butane extraction "is perceived as the more efficient alternative for amateur production" in the cannabis industry (Al-Zouabi et al., 2018). However, butane extraction can be extremely dangerous if not performed correctly. This is especially a concern in regard to home producers where butane extraction is often performed in garages, tool sheds, and vacant homes. Butane can accumulate in confined spaces such as these and cause an explosion if ignited by a spark or static electricity. Explosions and flash fires most often occur during the process of purging the remaining butane from the final product. On the contrary, these problems rarely occur in the commercial production of extracts. Commercial production utilizes closed-loop systems that recycle the solvent (i.e. butane), preventing the butane from being released into an area where it could be ignited (Al-Zouabi et al., 2018).

Alcohols Extraction

Extraction of cannabinoids through the use of alcohol is primarily performed using ethanol or isopropanol. The most commonly used alcohol is ethanol. Ethanol extraction is a single-stream process that may be conducted at hot or cold temperatures (June-Wells, 2018). Warm processes tend to extract more plant pigments and waxes, whereas supercooled ethanol processes are more time consuming and less efficient (June-Wells, 2018). In addition to the cannabinoid extraction steps, additional dewaxing steps are required for both temperatures. Extraction by warm ethanol also results in a green extract that has an unpleasant odor (Hazekamp and Romano, 2013). The Food and Drug Administration (FDA) classifies both isopropanol and ethanol as Class 3 solvents that should be limited to 5,000 ppm residual solvent.

The major problem with ethanol extraction is downstream handling (June-Wells, 2018). Ethanol extraction processes require 0.6-1 gallon of ethanol per pound of plant material in order to fully saturate the flowers (June-Wells, 2018). To fully extract the ethanol, rotary evaporators or falling film evaporators are needed to remove the ethanol from the plant material (June-Wells, 2018). These systems are expensive to operate for small-scale growers.

Propylene glycol is a diol that is legal in most states. It is classified as "generally recognized as safe" by the FDA when ingested orally (He et al., 2017). The extraction process functions similar to that of other alcohols however, there is a concern for residual propylene glycol. When heated, propylene glycol can transform into carbonyls and respiratory irritants like formaldehyde, a known carcinogen (He et al., 2017).

Supercritical CO_2 Extraction

Supercritical fluid extraction is a commonly used technique in large scale extraction of essential oils and other compounds. The most commonly used supercritical solvent is carbon dioxide (CO_2). CO_2 is inexpensive, generally recognized as safe, and has well-known physicochemical properties (Rovetto & Aieta, 2017). Supercritical CO_2 is also nontoxic, nonflammable, and has excellent operational safety (Raber et al., 2015).

Supercritical CO_2 is an effective solvent due to its density, diffusivity, and viscosity properties. Supercritical CO_2 can dissolve a large amount of the desired compound(s), penetrate into small spaces of the plant material, and has very little flow resistance. Most notably, supercritical CO_2 can be used to target more specific compounds than hydrocarbons or ethanol by manipulating its density and polarity. This is possible because the extractive properties of supercritical CO_2 are controlled by temperature and pressure. An advantage of supercritical CO_2 is that each compound has a unique solubility profile related to the density of supercritical CO_2. Therefore if the critical density is known for the target compound, the compound can be individually extracted, removed, and/or separated. The solubility profiles can also be used to separate multiple components of supercritical CO_2 extraction. By altering the temperature and pressure downstream of the extraction site, certain compounds will “fall out” of the solution as the density of the supercritical CO_2 is decreased (June-Wells, 2018).

In an industrial supercritical CO_2 process, the CO_2 is recycled, with most units reusing up to 95% of the initial CO_2. Therefore, the only solvent waste involved in this method is the CO_2 that leaks from the system or is contained in the extract (Attard et al., 2015). The most beneficial aspect of this technique is that it produces a “solvent-free extract,” (Aladić et al., 2015). CO_2 reaches a supercritical state at 31.1℃ and 7.39 MPa and will return to a gas state under ambient conditions. This allows for any residual CO_2 to be removed fairly simply, resulting in a solvent-free product (Rovetto & Aieta, 2017).

Cold Water Extraction

Cold water extraction, as the name implies, utilizes cold water to produce cannabis concentrates. Cold-water extraction is performed using ice water to make the trichomes on the cannabis plant brittle. The ice water and plant mixture are agitated to break the trichomes off of the plant. The ice water, plant, and trichome mixture is then repeatedly sifted through increasingly smaller mesh filters until the desired product is made (Raber et al., 2015). Due to the use of purely water, this extraction technique produces a solvent-free product. It should be noted that Boulder County, CO only allows cold water extraction at cultivation sites within its jurisdiction (Boulder, CO Municipal Code § 6.16.8).

Food-based Extraction

Food-based extractions use vegetable and olive oils as well as animal fats to extract cannabinoids for food products. The process is not closed-loop, since the resulting products are cannabinoids mixed in a solvent (i.e. oil, butter). Solvents used for food processing are required by law to be food-grade purity.

Food-based extraction solvents are cost effective, nonflammable, and nontoxic. The energy requirement is also relatively low, as the solvent only needs to be heated up to its boiling point.

After cooling and filtering, the product is ready for consumption. However, the extract produced by this technique cannot be concentrated by evaporation, therefore customers will need to consume a larger volume in order to get similar effects of more concentrated products (Romano & Hazekamp, 2013).

Extraction Method Analysis

In order to compare to the environmental impact of each extraction method, the total energy, in kilowatt hours (kWh), required to produce one pound (lb) of extract was calculated. Extract is defined as the product of the extraction process. The results are summarized in Table 5.3. Compared to the energy needed for the required phase changes, the energy used by the pumps and other equipment was negligible. Since the extraction methods can vary greatly between producers, there is currently no standard method for quantifying the amount of energy used in the extraction process. If the model of machinery used is known, the energy requirements can be directly calculated. To conduct a general analysis, a phase change analysis was conducted. This involved calculating the energy needed to cool, condense, heat, and evaporate each extraction solvent to its required temperatures. Since cold water extraction is based on different parameters than the other extractions, the amount of energy required to transport and treat the amount of water consumed in the process was also included. The total amount of energy required to perform all the necessary temperature and phase changes was then converted to kWh. The full calculations and list of assumptions for each method can be found in Appendix A.

Table 5.3. Total Energy of Extraction Methods

Extraction Method	**Extraction Process Energy** $(\frac{kWh}{lb\ extract})$	**Winterization Energy** $(\frac{kWh}{lb\ extract})$	**Total Energy Required** $(\frac{kWh}{lb\ extract})$
Pure Butane	4.34	N/A	4.34
Cooled Ethanol	0.22	0.31	0.53
Supercritical CO_2	14.60	0.31	14.91
Cold Water	0.57	N/A	0.57
Food-based*	0.49	N/A	0.49

*This extraction method was evaluated using vegetable and olive oil.

To better assess how this would affect the environment, kWh was converted to equivalent CO_2 emissions. The equivalent CO_2 emissions of each process were calculated using the value 1.559 lb CO_2/ kWh, as shown in Table 5.4 (EPA, n.d.).

Table 5.4. CO_2 Emissions of Extraction Methods

Extraction Method	**Total Energy Required** $(\frac{kWh}{lb\ extract})$	**Equivalent CO_2 Emissions** $(\frac{lb\ CO_2}{lb\ extract})$
Pure Butane	4.34	6.77
Cooled Ethanol	0.53	0.83
Supercritical CO_2	14.91	23.24
Cold Water	0.57	0.89
Food-based	0.49	0.77

Recommendations

Supercritical CO_2,

While many people claim that butane is the superior solvent because it results in a higher concentrated extract, according to a study conducted by Hazekamp and Romano, "the more concentrated an extract becomes, the more difficult it will be to remove the residual solvent," (Romano & Hazekamp, 2013). Applying more heat to evaporate the solvent will increase the amounts of terpenes that are lost (Romano & Hazekamp, 2013). This creates a trade-off between residual solvents and terpene content. Therefore, solvents that are not harmful to health should be used. Supercritical CO_2 extraction does not leave harmful solvent residuals in the concentrate, making this process the most conducive to preserving human health.

When considering the environmental impact of supercritical CO_2 extraction, the commercial production of CO_2 is arguably less of an environmental burden than that of butane. Butane is extracted from Liquefied Petroleum Gas (LPG) at stripper plants. Carbon dioxide is produced commercially as a byproduct of other reactions, such as in the production of ammonia or at coal-fired power plants. It is harvested to be reused in other processes, rather than released into the atmosphere. Additionally, CO_2 is obtained through a variety of carbon sequestration practices, which further improves the viability of the solvent.

Currently, several state governments are taking action to reduce energy consumption of cannabis producers by including suggestions and requirements in their regulations. While Illinois does not have permanent regulations yet, the state's temporary rules require the permit holder to notify the state, "if it has or will adopt a sustainable energy use and energy conservation policy," (Ill. Admin. Code tit. 101-0027 (2019)). Additionally, in Massachusetts, the regulations require the producers "demonstrate consideration" of efficiency requirements and development of an energy conservation plan (Mass. Gen. Laws. ch. 935, §500.000 (2019)). Both states have taken preliminary action to reduce energy consumption, but the industry requires stricter guidelines. However, in Boulder, CO, cannabis producers are required to use renewable energy sources (Boulder, CO Municipal Code § 6.16.8). Since states are starting to require renewable energy plans and efficiency requirements, CO_2 extraction could be the most viable environmentally friendly solvent, if the regulations continue to significantly improve.

Dimethyl Ether

Recently, dimethyl ether (DME) has been studied as an alternative extraction solvent. The technique uses liquefied DME to target compounds and remove water from wet materials. DME is a non-toxic and cost-efficient alternative (Li & Makino, 2014). It is also derived from biomaterial and easy to transport (Subratti et al., 2019). Furthermore, the European Food Safety Authority has determined that there are no health concerns with regard to the use of DME as an extraction solvent in food processing (Li & Makino, 2014).

DME is the simplest ether, with a chemical formula that is identical to ethanol (CH_3OCH_3). It is a gas at standard room temperature and pressure. The boiling point of DME is -24.8°C, which is lower than the boiling point of butane (-0.5°C). This means the DME is easier to remove from the final product than butane (Li & Makino, 2014). DME is also more polar than butane, which generates extractions with higher concentrations of terpenes. Since DME requires a lower pressure, DME extraction would require less energy than supercritical CO_2 extraction. To perform a DME extraction, a temperature of 40°C is desirable for solvent evaporation at a pressure of 0.51 MPa (Li & Makino, 2014); supercritical CO_2 requires a temperature of 31.1°C and a pressure of 7.39 MPa.

DME solvent extraction needs to be studied more before it is implemented on the industrial scale. One study by Subratti et al. (2019) explored the use of DME as a method for obtaining hemp seed oil from hulled hemp seeds. The results were promising in regard to oil yield, purity, and recyclability. In comparison to conventional organic solvents, DME had a higher yield and less chlorophyll contamination. The use of DME resulted in 25% and 31% yields for unground and ground seeds, respectively (Subratti et al., 2019). In another study by Rapinel et al. (2018), DME had the best efficiency with the highest yields for orange peel and lavender extractions compared to other common solvents. The hemp seed oil study also concluded that nearly 100% of the DME could be reused after each extraction cycle if implemented on the industrial scale with suitable equipment (Subratti et al., 2019). Further studies evaluating the feasibility of DME extraction for cannabis extraction need to be performed. It has not yet been determined if DME is suitable to extract CBD or THC.

Water Reuse

Most of the environmental footprint of a cold water extraction comes from the water use and the energy required to transport and treat the water. It is the only extraction process that directly consumes water. An industrial cold water extraction requires approximately 7.87 gallons of water to process one pound of plant mass. Assuming a cold water extractor is fed one pound of plant per hour, eight hours a day for one year, the cold water extraction would require approximately 22,980 gallons per year. That is equivalent to 63 years' worth of clean drinking water for an average person.

It is unclear if the water used in this process is reused or disposed of. From the research, it appears that the water is often reused by at-home producers, but each time the same water is reused, a smaller yield is produced. Therefore, it is assumed that the water would not be reused on the industrial scale. One potential way to reuse the extraction water is to recycle the nutrients in the water by pouring it directly onto the cannabis plant or creating a foliar plant spray. Cold water extraction water, commonly referred to as hash water, is rich in active enzymes, nutrients, and minerals that are beneficial for cannabis plant growth (High Times, 2015).

Another option is to purify the water and reuse it for cold water extraction. Activated carbon is a widely used adsorbent for water and wastewater treatment. It is an effective treatment for removing organic and inorganic pollutants (Bhatnagar et al., 2013). Small-scale carbon filters could be implemented in the cold water extraction process to recycle the water. Using an activated carbon filter, the cold water extraction process could be designed as a closed-loop system, where the water is continuously evaporated, condensed, and purified. Activated charcoal has already been shown to remove large portions of chlorophyll, cannabinoids, and terpenes from extracts (Hazekamp, & Romano, 2013). Activated carbon filters should be evaluated further for potential water reuse applications.

Additional Considerations

Research should be conducted on potential uses for the chlorophyll and waxes produced during the extraction process. Many of these byproducts are produced and disposed of. If a use for the excess chlorophyll and/or waxes can be found, there may be a more sustainable disposal method than sending it to landfills. However, the extraction method used to produce the byproducts must be considered. Depending on the application of the byproducts, different extraction methods may be preferred. Extraction methods that result in a high residual solvent concentration may not be applicable for certain post-processing techniques of the chlorophyll and/or waxes.

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Appendix A: Extraction Calculations

Butane Extraction

Assumptions[15]

1. 0.15 lb extract/lb of plant mass
2. The equipment must be able to keep 25 kilograms of butane at -40°F
3. "Typical" extractor input of 4,500 g
4. In-line dewaxing requires a minimum temperature of -30°C (243.15 K)
5. Butane starts at STP

Knowns[16]

1. Butane has boiling point of -0.5°C (272.65 K)
2. C_v of butane is $1.57\frac{kJ}{kg\cdot K}$
3. $H_{condensation}$ of butane = $H_{vaporization}$ of butane = $386\frac{kJ}{kg}$

Calculations

$$\frac{25\ butane\ mass}{4.5\ \ plant\ mass} \times \frac{1\ lb\ plant\ mass}{0.15\ lb\ extract} = \frac{25\ butane\ mass}{0.675\ lb\ extract}$$

Gaseous butane is cooled from 298 K to 272.65 K

$$Q = mC_v \triangle T$$

$$Q = \frac{25\ lb\ butane}{0.675\ lb\ extract} \times 1.57\frac{kJ}{kg \cdot K} \times (272.65\ K - 298\ K) \times \frac{0.436\ kg}{1\ lb}$$

$$Q\ = 642.68\frac{kJ}{lb\ extract}$$

Gaseous butane is condensed at 272.65 K

$$Q = m \times H_{condensation}$$

$$Q = \frac{25\ lb\ butane}{0.675\ lb\ extract} \times 386\frac{kJ}{kg} \times \frac{0.436\ kg}{1\ lb}$$

$$\mathrm{Q} = 6233.19\frac{kJ}{lb\ extract}$$

Liquid butane is cooled from 272.65 K to 223.15 K (includes in-line dewaxing)

$$Q = mC_v \triangle T$$

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[15] June-Wells, M. (May 2018). Your Guide To Hydrocarbon Extraction. Retrieved from https://www.cannabisbusinesstimes.com/article/your-guide- to-hydrocarbon-extraction

[16] Engineering Toolbox (n.d.). Retrieved from https://www.engineeringtoolbox.com/

$$Q = \frac{25\ lb\ butane}{0.675\ lb\ extract} \times 1.57 \frac{kJ}{kg \cdot K} \times (223.15\ K - 272.65\ K) \times \frac{0.436\ kg}{1\ lb}$$

$$Q\ = 1254.95 \frac{kJ}{lb\ extract}$$

Liquid butane is heated from 233.15 K to 272.65 K

$$Q = mC_v \triangle T$$

$$Q = \frac{25\ lb\ butane}{0.675\ lb\ extract} \times 1.57 \frac{kJ}{kg \cdot K} \times (272.65\ K - 223.15\ K) \times \frac{0.436\ kg}{1\ lb}$$

$$Q\ = 1254.95 \frac{kJ}{lb\ extract}$$

Liquid butane is evaporated at 272.65 K

$$Q = m \times H_{vaporization}$$

$$Q = \frac{25\ lb\ butane}{0.675\ lb\ extract} \times 386 \frac{kJ}{kg} \times \frac{0.436\ kg}{1\ lb} = 6233.19 \frac{kJ}{lb\ extract}$$

Total energy required

$$Q_{total} = 642.68 + 6233.19 + 1254.95 + 1254.95 + 6233.19 = 15618.96 \frac{kJ}{lb\ extract}$$

$$Energy\ required = 15618.96 \frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = 4.34 \frac{kWh}{lb\ extract}$$

Butane extractions typically do not undergo winterization. Rather, in-line dewaxing is performed, where the temperature of the mixture is brought to a minimum of -30°C (243.15 K), which is accounted for in the calculations.

Ethanol Extraction

Assumptions[17]

1. 1 g THC/1 mL of ethanol
2. 0.6 gal ethanol/lb of plant mass
3. 1 g THC = 1 g of extract
4. Ethanol starts at STP

Knowns[16]

4. Ethanol has a boiling point of 78.39 °C (351.539 K)
5. C_v of ethanol is $2.18\frac{kJ}{kg \cdot K}$

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[17] June-Wells, M. (July 2018). Your Guide to Ethanol Extraction. Cannabis Business Times. Retrieved from https://www.cannabisbusinesstimes.com/article/your-guide-to-ethanol-extraction/

6. H

Calculations:

$$\frac{1\ g\ extract}{1\ mL\ ethanol}\times\frac{0.6\ gal\ ethanol}{1\ lb\ plant\ mass}\times\frac{3785.412\ mL}{1\ gal}\times\frac{1\ lb}{453.592\ g}$$

$$=\ \frac{1\ lb\ extract}{5.0007247041\ lb\ plant\ mass}=0.1997\frac{lb\ plant\ mass}{lb\ extract}$$

$$\frac{0.6\ gal\ ethanol}{1\ lb\ plant\ mass}\times\frac{6.59\ lb\ ethanol}{1\ gal\ ethanol}=3.954\frac{lb\ ethanol}{lb\ plant\ mass}$$

$$\frac{3.954\ lb\ ethanol}{1\ lb\ plant\ mass}\times\frac{0.1997\ lb\ plant\ mass}{lb\ extract}=0.7896\frac{lb\ ethanol}{lb\ extract}$$

Ethanol extraction can be performed at STP or under cooled conditions. STP ethanol extraction does not require any energy due to the lack of temperature or phase change, therefore the only energy required for STP ethanol extraction is the energy required to remove the residual ethanol. Ethanol extractions are not typically performed at STP on an industrial scale, therefore this analysis focuses on cooled ethanol extraction.

Liquid ethanol is cooled from 298 K to 253 K

$$Q=mC_v\bigtriangleup T$$

$$Q\ =0.7896\frac{lb\ ethanol}{lb\ extract}\times 2.18\frac{kJ}{kg\cdot K}\times(253\ K-298\ K)\times\frac{0.436\ kg}{1\ lb}=33.77\frac{kJ}{lb\ extract}$$

Liquid ethanol is heated from 253 K to 351.539 K

$$Q=mC_v\bigtriangleup T$$

$$Q\ =0.7896\frac{lb\ ethanol}{lb\ extract}\frac{lb\ ethanol}{lb\ extract}\times 2.18\frac{kJ}{kg\cdot K}\times(253\ K-351.539\ K)\times\frac{0.436\ kg}{1\ lb}$$

$$Q\ \ =73.95\frac{kJ}{lb\ extract}$$

Liquid ethanol is evaporated at 351.539 K

$$Q=m\times H_{vaporization}$$

$$Q=0.7896\frac{lb\ ethanol}{lb\ extract}\times 919\frac{kJ}{kg}\times\frac{0.436\ kg}{1\ lb}=316.38\frac{kJ}{lb\ extract}$$

Gaseous ethanol is condensed at 351.539 K

$$Q = m \times H_{condensation}$$

$$Q = 0.7896 \frac{lb\ ethanol}{lb\ extract} \times 919 \frac{kJ}{kg} \times \frac{0.436\ kg}{1\ lb} = 316.38 \frac{kJ}{lb\ extract}$$

Liquid ethanol is cooled from 357.539 K to 298 K

$$Q = mC_v \triangle T$$

$$Q = 0.7896 \frac{lb\ ethanol}{lb\ extract} \times 2.18 \frac{kJ}{kg \cdot K} \times (298\ K - 351.539\ K) \times \frac{0.436\ kg}{1\ lb}$$

$$Q\ = 40.18 \frac{kJ}{lb\ extract}$$

Total energy required

$$Q_{total} = 33.77 + 73.95 + 316.38 + 316.38 + 40.18 = 780.66 \frac{kJ}{lb\ extract}$$

$$Energy\ required = 780.66 \frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = 0.22 \frac{kWh}{lb\ extract}$$

Product Winterization

To purge the excess ethanol from the final product, additional ethanol is used. The process requires the product to be soaked in or mixed with ethanol. The ethanol is then brought as close to the freezing point of ethanol as possible, which precipitates out waxes and chlorophyll.

Assumptions[17]

1. 10 lb ethanol/1 lb of extract
2. The ethanol mixture is cooled to as close to the freezing point of pure ethanol as possible, -76℃ (197.15 K).

Ethanol is cooled from 298 K to as close to 197.15 K as possible.

$$Q = mC_v \triangle T$$

$$Q = \frac{10\ lb\ ethanol}{1\ lb\ extract} \times 2.57 \frac{kJ}{kg \cdot K} \times (197.15\ K\ -\ 298\ K) \times \frac{0.436\ kg}{1\ lb} = 1130.04 \frac{kJ}{lb\ extract}$$

$$Energy\ required = 1130.04 \frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = \ 0.31 \frac{kWh}{lb\ extract}$$

CO_2 Extraction

Assumptions[18]

1. 50 CO_2 mass/plant mass
2. 0.18 lb extract/lb of plant mass
3. Carbon dioxide starts at STP.

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[18] June-Wells, M. (March 2018). Your Guide to Supercritical Extraction. Cannabis Business Times. Retrieved from https://www.cann abisbusinesstimes.com/article/your-guide-to-supercritical- extraction/

Knowns[16,19]

1. Carbon dioxide is supercritical at 304.25 K, 7.89 MPa
2. C_v of CO_2 is $0.658\frac{kJ}{kg\cdot K}$
3. C_p of CO_2 is $0.939\frac{\boldsymbol{kJ}}{\boldsymbol{kg\cdot K}}$
4. $H_{critical}$ of CO_2 is $110\frac{BTU}{lbm}$

Calculations:

$$\frac{50\ CO_2\ mass}{1\ plant\ mass} \times \frac{1\ lb\ plant\ mass}{0.18\ lb\ extract} = \frac{50\ CO_2\ mass}{0.18\ lb\ extract}$$

Gaseous CO_2 is compressed, increasing the pressure and temperature. Assume the temperature will increase up to 130 °C (403.15 K).

$$Q = mC_v \triangle T$$

$$Q = \frac{50\ CO_2\ mass}{0.18\ lb\ extract} \times 0.658\frac{kJ}{kg\cdot K} \times (403.15\ K\ -\ 298\ K) \times \frac{0.436\ kg}{1\ lb}$$

$$Q = 8379.52\frac{kJ}{lb\ extract}$$

CO_2 is cooled from 403.15 K to 304.25 K (critical point).

$$Q = mC_p \triangle T$$

$$Q = \frac{50\ CO_2\ mass}{0.18\ lb\ extract} \times 0.939\frac{kJ}{kg\cdot K} \times (304.25\ K - 403.15\ K) \times \frac{0.436\ kg}{1\ lb}$$

$$Q\ = 11247.24\frac{kJ}{lb\ extract}$$

The supercritical CO_2 is held at a constant pressure and temperature, which occurs at constant specific enthalpy.

$$Q = m \times H_{critical}$$

$$Q = \frac{50\ CO_2\ mass}{0.18\ lb\ extract} \times (110\frac{BTU}{lbm}) \times \frac{1.055\ kJ}{1\ BTU} = 32236.11\frac{kJ}{lb\ extract}$$

Evaporation of the CO_2 occurs at a constant pressure and temperature. Assume the CO_2 returns to STP (298 K).

$$Q = mC_v \triangle T$$

$$Q = \frac{50\ CO_2\ mass}{0.18\ lb\ extract} \times 0.939\frac{kJ}{kg\cdot K} \times (304.25\ K - 298\ K) \times \frac{0.436\ kg}{1\ lb} = 710.77\frac{kJ}{lb\ extract}$$

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[19] Massachusetts Institute of Technology (n.d.) Mollier Diagram of CO2. Retrieved from http://web.mit.edu/10.213/oldpages/f99/supp/tablediag/co2/index.html.

Total energy required:

$$Q_{total} = 8379.52 + 11247.24 + 32236.11 + 710.77 = 52573.64 \frac{kJ}{lb\ extract}$$

$$Energy\ required = 52573.64 \frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = 14.60 \frac{kWh}{lb\ extract}$$

Product Winterization

To purge the excess CO_2 from the final product, ethanol is used. The process requires the product to be soaked in or mixed with ethanol. The ethanol is then brought as close to the freezing point of ethanol as possible, which precipitates out waxes.

Assumptions[4]

3. 10 lb ethanol/1 lb of extract
4. The ethanol mixture is cooled to as close to the freezing point of pure ethanol as possible, -76 °C (197.15 K).

Ethanol is cooled from 298 K to as close to 197.15 K as possible.

$$Q = mC_v \triangle T$$

$$Q = \frac{10\ lb\ ethanol}{1\ lb\ extract} \times 2.57 \frac{kJ}{kg \cdot K} \times (197.15\ K\ -\ 298\ K) \times \frac{0.436\ kg}{1\ lb} = 1130.04 \frac{kJ}{lb\ extract}$$

$$Energy\ required = 1130.04 \frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = 0.31 \frac{kWh}{lb\ extract}$$

Cold Water Extraction

Assumptions[20,21]

1. 1 lb of plant/0.15 lb of extract
2. 6-8 gallons of water per 1.5 lb of plant mass
3. 40 lbs of ice per 6-8 gallons of water
4. Each pound of ice produces about 0.12 gallons of water = 4.8 gal of water
5. Water begins at STP.
6. Ice begins at 0 °C (273.15 K) and standard pressure.

Knowns[16,22]

1. 3300-3600 kWh to treat and transport a million gallons of water
2. The temperature the an ice-water mixture is 14.8 °C (287.95 K)

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[20] Fourside, S. (n.d.). Solventless Extraction Showdown- Bubble Hash vs. Dry-Ice Hash. Retrieved from https://www.growweedeasy.com/bubble-hash-vs-dry-ice-hash

[21] Eberbach Corporation. (n.d.). E5703.IWE Ice Water Extractor. Retrieved from https://www.eberbachlabtools.com/Lab-Apparatus/E5703-Ice-Water-Extractor.html

[22] Copeland, C. & Carter, N. (January 2017). Energy-Water Nexus: The Water Sector’s Energy Use. Retrieved from https://fas.org/sgp/crs/misc/R43200.pdf

Calculations:

$$\frac{11.8\ gal\ water}{1.5\ lb\ plant\ mass} \times \frac{1\ lb\ plant\ mass}{0.15\ lb\ extract} = 52.44\frac{gal\ water}{lb\ extract}$$

The ice-water mixture is cooled from 287.95 K to 273.15 K.

$$Q = mC_p \triangle T$$

$$Q = 52.44\frac{gal\ water}{lb\ extract} \times 4.19\frac{kJ}{kg \cdot K} \times (273.15\ K - 287.95\ K) \times \frac{0.436\ kg}{1\ lb}$$
$$= 1417.83\frac{kJ}{lb\ extract}$$

Energy required to cool the ice-water mixture.

$$1417.83\frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = 0.39\frac{kWh}{lb\ extract}$$

Energy required to transport and treat water needed for extraction process.

$$52.44\frac{gal\ water}{lb\ extract} \times 3450\frac{kWh}{million\ gal\ of\ water} \times \frac{1\ million\ gal}{10^6\ gal} = 0.18\frac{kWh}{lb\ extract}$$

Total energy required.

$$Energy\ required = 0.39\frac{kWh}{lb\ extract} + 0.18\frac{kWh}{lb\ extract} = 0.57\ \frac{kWh}{lb\ extract}$$

Food Extractions

Assumptions[23]

1. 0.48 lb/0.02 lb plant

Knowns[16, 23]

1. C_p of vegetable oil is $1.67\frac{kJ}{kg \cdot K}$
2. C_p of olive oil is $1.97\frac{kJ}{kg \cdot K}$
3. The average C_p is $1.82\frac{kJ}{kg \cdot K}$
4. 1 cup of vegetable oil is 218 grams (0.48 lbs)
5. 1 cup of cannabis is 7 grams (0.02 lbs)
6. The temperature cannot exceed 118 °C (391.15 K). This is the temperature at which THC burns.

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[23] CannaConection. (February 2019). How to Make Cannabis Infused Olive Oil. Retrieved from https://www.cannaconnection.com/blog/17441-how-make-cannabis-infused-olive-oil

Calculations:

$$\frac{0.48\ lb\ oil}{0.02\ lb\ plant} \times \frac{1 lb\ extract}{1\ lb\ oil} = 24 \frac{lb\ oil}{lb\ extract}$$

Energy required to heat the oil from STP to 391.15 K.

$$Q = mC_p \triangle T$$

$$Q = 24 \frac{lb\ of\ oil}{lb\ extract} \times 1.82 \frac{kJ}{kg \cdot K} \times (391.15\ K - 298\ K) \times \frac{0.436\ kg}{1\ lb} = 1773.99 \frac{kJ}{lb\ extract}$$

Total energy required.

$$Energy\ required = 1773.99 \frac{kJ}{lb\ extract} \times \frac{1\ kWh}{3600\ kJ} = 0.49 \frac{kWh}{lb\ extract}$$

Note: This is the amount of energy required to produce one pound of extract. In this scenario, one pound of "extract" is equivalent to one pound of product. One pound of product is considered one pound of infused oil.

Chapter 6: Air Emissions

Introduction

The regulations for air emissions from the cannabis industry vary widely across the country. Since some states exempt agricultural activities from air emission standards, the cultivation portion of the industry is not regulated while the extraction process is. Cannabis plants naturally emit odors and volatile organic compounds as they grow (Wang et al., 2019a; Wang et al., 2019b). Volatile organic compounds are also emitted during solvent-based extraction processes (Urso, 2019). Research shows that both the cultivation process and extraction process contribute to decreased air quality. Air emissions from the cannabis industry can be categorized by odor, volatile organic compounds, and carbon dioxide. A series of air pollution control technologies can be used to mitigate the effects of the cannabis industry on air quality.

Odor

Across the country, the cannabis industry is facing challenges due to odor complaints. When recreational cannabis was legalized in California, odor was not a main concern for lawmakers. However, as the amount of cannabis facilities has increased, so has the number of odor complaints. For example, residents in Sonoma County are suing to ban cannabis operations from their neighborhoods. Residents in Mendocino County established zones where cannabis cultivation is banned (Fuller, 2018). In Yamhill County, OR, cannabis growers are being sued by a vineyard that claims the "odors would damage wine grapes with 'foul-smelling particles'" (The Associated Press, 2017a). In Carbondale, CO, a cannabis business was summoned for a permit revocation hearing after numerous odor complaints were filed over the course of a year (Summerlin, 2018). As a response to odor complaints in Spokane County, WA, cannabis farms have to register with an air pollution agency (The Associated Press, 2017b).

The characteristic odor associated with cannabis is attributed to the release of chemical compounds into the air known as terpenes. Terpenes are fragrant oils secreted by plants, and some insects, to ward off predators and attract pollinators (Marinho et al., 2014). Cannabis plants produce over 150 different terpenes. Terpenes are a group of highly reactive volatile organic compounds that contribute to the formation of ozone and particulate matter in the atmosphere (Booth & Bohlmann, 2019). Terpenes are naturally emitted by the cannabis plants during cultivation.

Despite attempts to regulate it, odors remain one of the top air pollution complaints to regulators and government bodies (McGinley et al., 2000). A major problem for local governments trying to legislate cannabis odors is that there is no objective standard for scents. Odor is a subjective experience that varies from person to person, but regulating odor requires objective and reproducible measurement techniques (SRF Consulting Group, 2004). Furthermore, there are no federal regulations for odor. Odors are classified as non-criteria pollutants by the EPA. Therefore, odor control regulations are set by state and local air pollution control agencies (Leonardos, 1974). Odor regulations, or "odor laws," vary from state to state. To establish odor laws, one or several criteria are utilized. Common criteria that are used are: annoyance criteria, complaint criteria, ambient odor detection threshold criteria, ambient odor intensity criteria, episode duration-frequency criteria, source emission criteria, and best available control technology criteria (McGinley et al., 2000).

Regulations for odor related to cannabis production vary on the state, regional, and local level. In Santa Barbara County Air Pollution Control District, under Section 41705 of the California Health and Safety Code, District Rule 30, the discharge of air contaminants, including odors, does not apply to odors emitted from agricultural operations. Since cannabis cultivation is considered an agricultural operation, it is exempt from odor regulations. However, the rule still applies to all other cannabis operations that are not related to agricultural operations. This includes cannabis oil extraction manufacturing operations, retail storefronts, and smoking lounges (APCD, 2019). In Colorado, cannabis cultivation is exempt from the state Air Pollution Emission Notice and permitting requirements because it is an agricultural activity (DDPHE-CSWG, 2018). Some states and municipalities are addressing these inconsistent or lacking regulations for odor related to cannabis production. The City and County of Denver chose to update its odor ordinance in order to require cannabis cultivation facilities to control their odor emissions (DDEH, n.d.). Additionally, Denver has implemented fines if "five or more complaints from individual residents representing separate households within a 12-hour period and the complaints are related to a single odor source," which range from $150 to $2000 (Bender, 2020). Many regulators are choosing to impose hefty fines for companies that transmit perceptible odors to reduce the risk of odor complaints. Other states, including Oregon, Washington, and Iowa, require odor control plans or clean air permits as part of the licensing process to reduce odor emissions (Hammon, 2018).

As the number of cannabis facilities continues to increase, it is expected that the number of odor complaints will increase as well. To avoid the controversy surrounding odor and cannabis production, regulators need to establish consistent and clear guidelines. Facilities need to be aware of the standards that must be followed. Clear and consistent regulations will provide a baseline for cannabis facilities to follow and prevent heavy fines. Furthermore, a feasible odor control standard may help mitigate community complaints and help ease tension between the industry and surrounding communities.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are defined by the EPA 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" (EPA, 2017). They are more generally recognized as "organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure" (EPA, 2017). VOCs react with other urban air constituents (nitrogen oxides NO_x, hydroxyl radicals) to create ozone (O_3), particulate matter, and secondary VOCs (e.g., formaldehyde and acrolein) at the tropospheric level and negatively impact air quality (Samburova et al., 2019). The speed of these reactions is increased by UV radiation and therefore ozone concentrations tend to be higher on hot days (EPA, 2019a). Tropospheric ozone can irritate the respiratory tract, reduce lung function, and aggravate asthma (EPA, 2019b). At the stratospheric level, VOCs have the opposite effect, where they can deplete the ozone layer and contribute to climate change (Aldrich, 2005).

VOCs from the cannabis industry are categorized by biogenic and anthropogenic VOCs. Biogenic VOCs (BVOCs) are emitted by the cannabis plants, which include terpenes like β-myrcene, D-limonene, and α-pinene (Samburova et al., 2019). Anthropogenic VOCs are emitted from the use of hydrocarbon and alcohol solvents in extraction facilities. Cannabis cultivation and extraction facilities are largely constructed in urbanized areas, where they are located close to sources of nitrogen oxides (Samburova et al., 2019). This contributes to the creation of tropospheric ozone. There have been several studies researching the potential impacts cannabis facilities have on air quality (Samburova et al., 2019; Wang et al., 2019b; Mills, 2012; Wang et al., 2019a). One study conducted in cannabis facilities in California and Nevada determined that the VOCs emitted by cannabis plants could produce tropospheric ozone at a rate of approximately 2.6 grams per plant per day (Samburova et al., 2019).

Tropospheric ozone is regulated under the National Ambient Air Quality Standards (NAAQS) under the Clean Air Act (CAA). It is classified as both a primary and secondary standard, meaning that it protects both public health and welfare. NAAQS requires that the annual fourth-highest daily maximum tropospheric ozone 8-hour concentration must not exceed 0.070 ppm when averaged over 3 years (40 CFR Part 50). The EPA set this limit to prevent the harmful health effects associated with high concentrations of ozone.

The EPA directly regulates VOC emissions for some industries under 40 CFR 59, the National Volatile Organic Compound Emission Standards for Consumer and Commercial Products. However, these regulations target the largest contributors of VOC emissions: aerosol coatings, architectural coatings, automobile refinish coatings, and consumer products. With the exception of these industries, VOCs are not regulated on the federal level. States and local governments have established VOC regulations in order to meet federal ozone requirements. However, these regulations often omit agricultural contributors such as cannabis cultivation facilities.

Regions or counties that fail to meet the federal standards are then classified as nonattainment zones under the CAA (P.L. 91-604, Sec. 109). When a region is classified as a nonattainment zone, the state and local governments are required to develop a plan that details how the region will identify the sources of air pollution and how they will meet NAAQS (EPA, 2019a). In 2008 and 2015, the Denver Metro/North Front Range and Denver-Boulder-Greeley-Ft. Collins-Loveland regions in Colorado both failed the 8-Hour Ozone concentrations. These regions are designated as marginal and serious nonattainment zones, respectively (EPA, 2020).

Case Study: Colorado

Research suggests that the concentrated presence of cannabis facilities in Denver are producing rates of BVOCs and VOCs that are high enough to affect the local air quality. As of January 1, 2020, there are 685 recreational cannabis cultivation facilities and 288 recreational cannabis product manufacturers in Colorado (Colorado Department of Revenue, 2020). In 2018, 41% of all cannabis cultivation facilities are located in Denver County, CO (Wang et al., 2019b). The distribution of facilities can be seen in Figure 6.1.

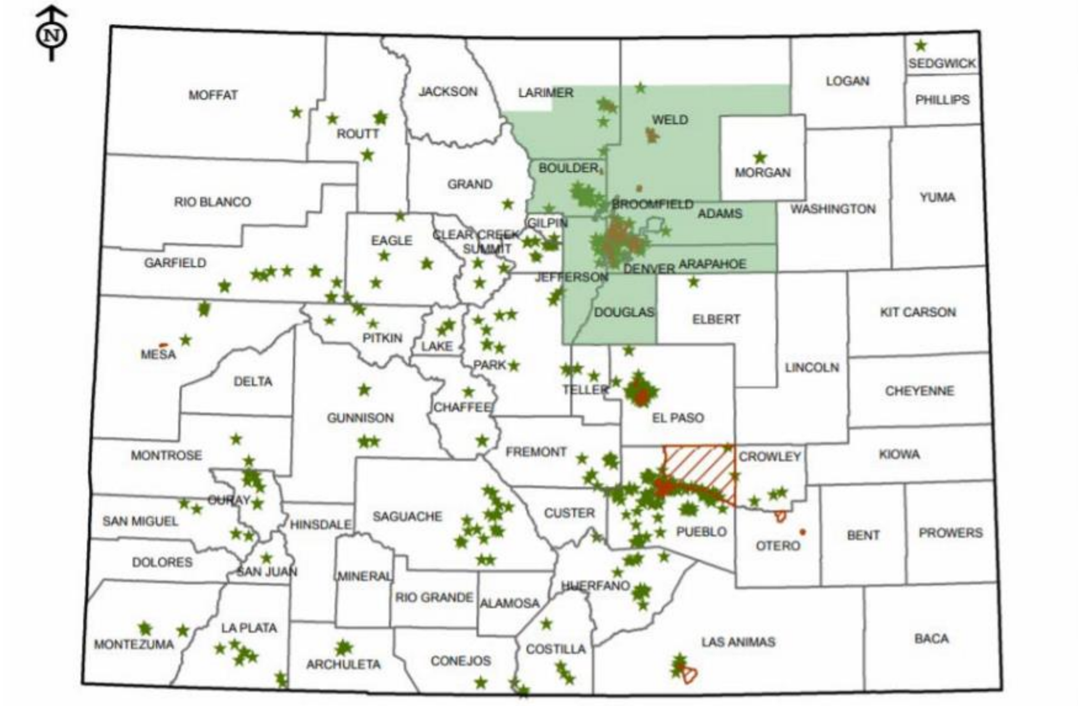

Figure 6.1. Cannabis Cultivation Facilities in Colorado 2017 (Urso, 2019)[24].

In Colorado, agricultural facilities are exempt from air emissions standards, which include both indoor and outdoor cannabis cultivation facilities (CRS Title 25. Health § 25-7-109: 8a). The regulations do not account for the fact that indoor cannabis cultivation facilities are considered point-sources of air pollution. However, cannabis extraction facilities are regulated under 5 CCR 1001-9 Regulation 7 (Control of ozone via ozone precursors and control of hydrocarbons via oil and gas emissions). The regulations vary based on a facility's annual emissions levels and detail how to minimize the amount of VOCs that escape from a facility. According to the Colorado Department of Health and Environment, many of the cannabis extraction facilities in Colorado are unaware of the standards they must follow and are in noncompliance (Urso, 2019). Under state regulations, it is the responsibility of the business to calculate an estimation of their VOC emissions from solvent extraction (Denver Department of Public Health, 2018).

Several studies have researched the extent the cannabis industry contributes to poor air quality in Colorado. A study was conducted in Denver to estimate the extent of air quality impacts from cannabis cultivation facilities by using an air quality model to predict regional ozone impacts. They determined that the range of possible emissions in Colorado from terpenes was 66–657 t yr^{-1}, half of which came from Denver County (Wang et al., 2019b). Model predictions suggest that an increase in 1,000 metric tons of terpenes a year results in a 130 ppb increase in daytime hourly ozone concentrations and a maximum daily 8-hour ozone average of 0.30 ppb (Wang et al., 2019b). Another study in Denver found that there was large variability between the BVOC emissions of different cannabis strains, with some emitting almost twice as much as others. (Wang et al., 2019a).

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[24] In this figure, the green stars are cannabis cultivation facilities, the reddish brown outlined regions are the state's environmental justice priority areas, and the green shaded region is the Denver nonattainment zone.

The Denver models show that the levels of ozone in the atmosphere are correlated with the emission rates from cannabis facilities (Wang et al., 2019b). However, the rate of emissions from the facilities are too uncertain to fully understand the impacts of cannabis facilities on air quality. Although several studies have researched the impacts of cultivation facilities on air quality, there has been little documented research on the impacts from extraction activities. Since edibles are the largest growing sector of the cannabis industry (New Frontier Data, 2019), more research needs to be conducted to determine the impact of extraction facilities on VOC emissions. As the entire cannabis industry continues to grow, so will the emission rates of VOCs. If the emissions rates continue to increase without regulations, there may be significant ramifications on air quality (Wang et al., 2019b). More research is required to determine the VOC emission rates from cannabis cultivation facilities and extraction facilities, as well as the impacts on ozone levels and public health.

Carbon Dioxide

The amount of electricity used to power indoor cannabis cultivation facilities can be costly, especially when compared to outdoor cultivation. There are many benefits to indoor cultivation, including control over the environment, continuous harvest cycles, and increased security. However, the greenhouse gas emissions from the large amount of electricity generation is a cause for concern (Arnold, 2013).

Growing cannabis indoors requires lighting, ventilation, and cooling in order to replicate ideal outdoor conditions. The specific amount of energy required to produce these conditions will vary with different production practices (O'Hare et al., 2013). The overall carbon footprint will also depend on the power source. For example, illicit growers that rely on generators produce more than three times the CO_2 than facilities powered by the grid (Ashworth & Vizuete, 2017).

As recreational cannabis production increases, particularly in states with colder climates, an increase in greenhouse gas emissions can be expected. Currently, indoor-grown cannabis uses approximately 2,000 kWh per pound of product produced (O'Hare et al., 2013). Research also estimates that one kilogram of product is associated with 4,600 kg of CO_2 emitted to the atmosphere (Mills, 2012). The full impact of the cannabis industry on energy use and the consequent CO_2 emissions is discussed in depth in Chapter 7.

Indoor Air Quality

The indoor air quality of cannabis facilities is not well documented. Because of its federal status, little research has been done to assess what types of conditions workers may be exposed to (Davidson et al., 2018). Workers may be exposed to a variety of air contaminants including: organic dusts, bioaerosols, pollen, VOCs, and THC. Inhalation of such contaminants can lead to a variety of respiratory diseases and occupational asthma (Davidson et al., 2018). Furthermore, it is unknown what levels of THC workers are being exposed to. In studies, THC was below the limit of detection in air samples suggesting that THC is not an inhalation concern (Davidson et al., 2018). However, the impacts of long-term exposure to THC are unknown and there are no exposure limits for aerosols or surfaces contaminated with THC (Davidson et al., 2018). Since many terpenes emitted by cannabis plants are lipophilic and are therefore readily bioavailable, there are concerns of occupational health implications (Davidson et al., 2018). There have been documented terpene-related occupational illnesses in the hop and timber production industry. These workers exhibited occupational asthma, lung function deficits, and skin symptoms, which were suspected to be caused by irritation from terpenes (Hessel et al., 1995; Spiewak et al., 2001).

Butane is a growing concern in the cannabis industry; it is a highly ignitable VOC solvent used to create cannabis extracts. It has a lifetime of 2.5 days and leads to the creation of ozone in photochemical reactions with nitrogen oxides under atmospheric conditions (Samburova et al., 2019). Exposure to high concentrations of butane can lead to nausea, respiratory tract and mucous membrane irritation, as well as headaches and fatigue (OSHA, n.d.). Although hydrocarbon extractions are required to be closed loop in most states, a percentage of butane has the potential to escape the extraction system if a facility is not stringent enough. A study in California and Nevada found high concentrations of butane in cannabis extraction facilities ranging from 1,080 to 43,000 ppm. These concentrations were 0.9 to 49 times higher than the concentrations of BVOCs found in these facilities (Samburova et al., 2019). The researchers concluded that these levels of butane were high enough to potentially contribute to the formation of a significant amount of ozone and other harmful compounds (Samburova et al., 2019).

The health concerns associated with hemp production have been well documented (Zuskin et al., 1990; Zuskin et al., 1994; Fishwick et al., 2001). Research shows that there are high levels of airborne dust, contaminated with bacterial and fungal growth, at hemp production facilities that causes a range of health problems (Fishwick et al., 2001). Long-term inhalation of dust at hemp production facilities causes "hemp worker's disease," otherwise known as byssinosis. Byssinosis can be avoided by preventing direct worker exposure to airborne dust by keeping proper industrial hygiene. The occupational hazards associated with hemp demonstrate a need to further research the occupational health hazards of recreational cannabis production. In recent years, states like Washington and Colorado have taken steps to develop formal guidance on occupational hazards and indoor air quality for the industry (Spokane County, 2015; Colorado Department of Public Health and Environment, 2017).

Air Pollution Control Technology

Carbon Filtration

The Denver Cannabis Environmental Best Management Practices Guide currently recommends carbon filtration as "the best control technology for reducing VOC emissions" and odors (2018). Activated carbon filters have been used for odor control and to remove VOCs for many years across multiple applications (Metts & Batterman, 2006). Carbon filters work by adsorption. The carbon surface of the filter attracts VOCs and other air contaminants (DDPHE-CSWG, 2018). The contaminants adhere to the activated carbon and become trapped in the small pores of the filter (Mazille & Spuhler, n.d.). Carbon filtration can remove 50-98% of VOCs, depending on the filter system used, the environmental conditions, and the life of the filter (DDPHE-CSWG, 2018; Metts & Batterman, 2006; Sidheswaran et al., 2012).

Carbon filters are simple to install, inexpensive, effective and reliable when properly maintained and replaced. Depending on the air quality and size, the filter will need to be replaced every 6-12 months or according to the manufacturer's recommendations (DDPHE-CSWG, 2018). Currently, can or tube carbon filters are the most commonly used type. A constant supply of carbon cans or tubes are typically needed, especially if a facility has potent odors or high VOC levels (Jordan, n.d.)

Carbon filters can be stand-alone units or can be incorporated into an HVAC system. To be most effective, the filtration system must be properly sized based on contaminant volume and airflow requirements. In some cases, this may require multiple filters. Carbon filters can also be used in conjunction with other air pollution control technologies (DDPHE-CSWG, 2018).

Ozone Generators

Typically, ozone generators are used in industrial settings for sanitation purposes, but they have also been used to control strong odors (DDPHE-CSWG, 2018). An ozone generator produces ozone by disassociating oxygen molecules (O_2) through the use of UV light or a strong electrical charge. The dissociated oxygen atoms then reassociate as ozone (O_3) (Bishop et al., 1984). The ozone oxidizes evaporated terpene molecules to deodorize the air (Royal Queen Seeds, 2019). However, ozone is harmful to human health and can damage cannabis plants. Therefore, ozone generators are not recommended as an air pollution control technology (DDPHE-CSWG, 2018).

Odor Absorbing Neutralizers

Odor absorbing neutralizers use oils and liquids derived from plant compounds to eliminate odors. The neutralizer is sprayed as a mist into the exhaust air (DDPHE-CSWG, 2018). Odor neutralizers for cannabis need to be effective on the common compounds found in cannabis, including cannabinoids, terpenes and sesquiterpenes groups (Ecosorb, 2017). The effectiveness of a neutralizer can vary from 20-90% VOC reduction (DDPHE-CSWG, 2018).

Masking and Counteractive Agents

Masking agents, like odor absorbing neutralizers, are sprayed as a mist at the exhaust air. The difference is that masking agents are chemically derived, whereas odor absorbing neutralizers are naturally derived from plants. The use of masking agents may be subject to air quality regulations, depending on the state. Masking agents control odor, but not VOCs. Therefore, masking agents do not mitigate the impacts of VOCs on air quality. Masking and counteractive agents are not recommended in urban areas as an air pollution control technology (DDPHE-CSWG, 2018).

Fog Systems

Fog systems, also called high pressure misting systems, are an established technology that has been used in agricultural environments to treat odor (Hammon, 2018). Fog systems work by forcing water through a specialized nozzle to create microdroplets. These microdroplets are released into the air, where they attract particles and sink them to the ground to be removed. Prior to entering the nozzle, the water is mixed with chemicals or essential oils to create a neutralizing solution to eliminate odors (Wintering, 2016). For cannabis applications, the water is mixed with essential oils to prevent risks to the plants (Hammon, 2018).

The odor control process is the same for both indoor and outdoor facilities, but the set-up and system requirements differ (Wintering, 2016). For an indoor facility, the air is pulled across the plants and into an intake vent. When the air exits from exhaust vents, it is mixed with the fog. The external side of the exhaust vent is equipped with a nozzle (Hammon, 2018). For outdoor facilities, high-pressure fog lines are placed around the exterior of the facility. A perimeter defense is formed that utilizes the same fog (Wintering, 2016).

Negative Ion Generators/ Electrostatic Precipitators

Negative ion generators, also known as electrostatic precipitators, use a metal filter to emit a negative charge to attract positively charged particles in the air (DDPHE-CSWG, 2018).The filters need to be cleaned with water once they become concentrated with particles. They are typically powered by a single wall outlet and can run 24 hours a day. The energy consumption of this technology is dependent on its size and length of use. Overall they require little maintenance and require less energy than other technology (DDPHE-CSWG, 2018).

Industrial Scrubbers

Industrial scrubbers are typically used for landfills or wastewater treatment plants to reduce odor and emissions from facilities. However, scrubbers are also used to remove VOCs and particulate matter in gas streams exiting cannabis facilities. Wet scrubbers are the most common and use absorption to remove contaminants in the vapor by converting them to their liquid or condensate form or by trapping particulates in liquid droplets (EPA, 2002). Most wet scrubbers have efficiencies of approximately 90%, depending on the type of contaminant absorbed (EPA, 2019c). The most common liquid used in wet scrubbers is water, however some wet scrubbers use amines to absorb gases with low water solubility such as hydrocarbons (EPA, 2019c). They can be used with electrostatic precipitators to remove particles from the waste stream. Some common problems include: low gas flow rate, condensation of aerosols in the system, air leakage, freezing/plugging of lines, and scaling (EPA, 2019c).

Outdoor Grow Facilities

Outdoor cultivation has the greatest potential to expose sensitive receptors to odor. The predictability and degree to which the odors can travel is highly variable depending on climatic and topographic conditions near a cultivation site (County of Santa Cruz, 2017). Location and natural buffers can most easily be used to mitigate odors from outdoor cultivation facilities. Cannabis farms located in rural areas may be surrounded by other agricultural farms who raise animals or hay. Odors are a more acceptable part of living in these rural communities (Hammon, 2018). In urban areas, zoning laws may help with both odors and VOC concentrations. Natural buffers can be planted to surround cannabis plants to disperse odors and obscure crop visibility. This strategy has been used successfully by poultry and swine operations, but more research into the viability for cannabis facilities needs to be researched (Hammon, 2018).

Future Research

While there are many options for air pollution control, there is a lack of research in the application of these technologies in the cannabis industry. The efficacy and efficiency of each technology should be analyzed in regard to VOC emissions and odor control specific to the cannabis industry, such as the high levels of terpenes. In addition, the interactions between terpenes and solvent vapors are unknown, as are the potential effects on the removal efficiency.

Fixed-bed Carbon Adsorption Design

In air pollution control, adsorption is utilized to remove VOCs from low to medium concentration exhaust streams. During adsorption, a VOC molecule attaches to an absorbent and is removed from the air stream. Carbon is a commonly used adsorbent for VOC removal. Furthermore, the most commonly used types of adsorption equipment in air pollution control are fixed-bed systems and canister types (Vatavuk et al., 1999).

Due to the high volume of emissions produced by cannabis facilities, a canister type system would not be practical. Therefore, the design is focused on a fixed-bed system. Fixed-bed systems can be used to control continuous VOC streams at varying concentrations, in flow rates ranging from several hundred to several hundred thousand cubic feet per minute. In continuous operation, a carbon bed is always available for adsorption, so the system can operate continuously without shut-down. When the carbon in the active adsorption vessel reaches a certain VOC concentration, it shuts-down so the carbon can be regenerated and the other vessel comes online. In a system with 2 beds, each bed is sized to handle the entire emission stream so that one is always adsorbing while the other is regenerating/desorbing (Vatavuk et al., 1999). A typical fixed bed carbon adsorber is shown in Figure 6.2.

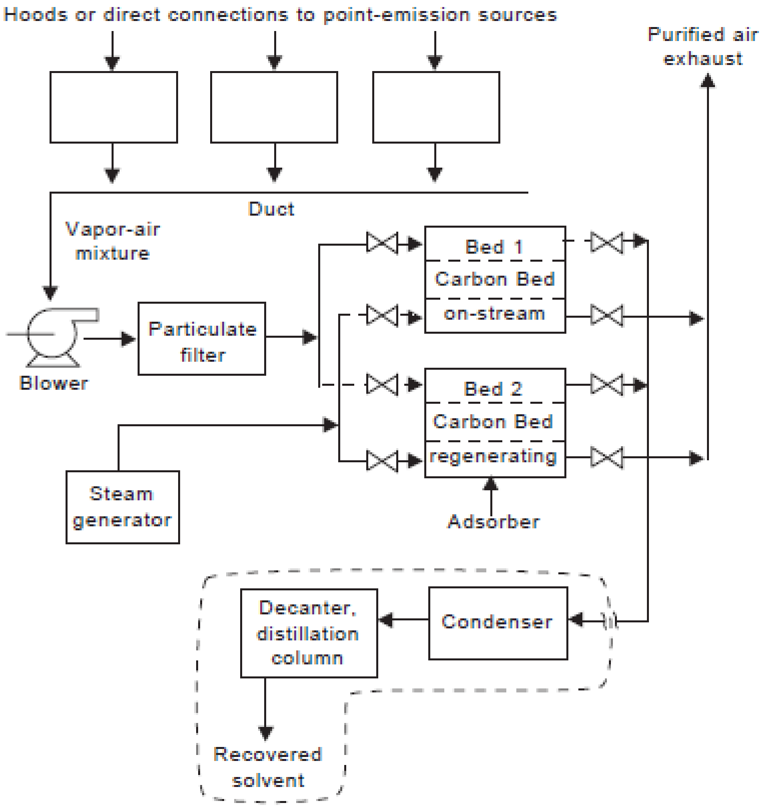

Figure 6.2. A Typical Two-bed Continuously Operated Fixed Bed Carbon Adsorber System (Vatavuk et al., 1999).

The terpene emission rate can vary depending on the strain of cannabis that is grown. For example, Rockstar Kush has a terpene emission capacity of 4.9 μgC g^{-1} hr^{-1}. The terpene emission capacity of 8.7 μgC g^{-1} hr^{-1} is measured for the strain Critical Mass. It was the highest terpene emission capacity measured in the study by Wang et al. (2019b). The terpene emission rate will also vary based on the growth phase of the plant. For example, Critical Mass produced 1.4 μgC dwg^{-1} hr^{-1} and 8.7 μgC g^{-1} hr^{-1} after 30 and 46 days of growth, respectively (Wang et al., 2019b).

The terpene emissions produced by different strains of cannabis contain different concentrations of individual terpenes. The individual terpenes in the emissions will also vary depending on how old the plant is. The concentration of individual terpenes for Critical Mass at 46 days of growth, when the highest terpene emission rate was measured, is shown in Figure 6.3.

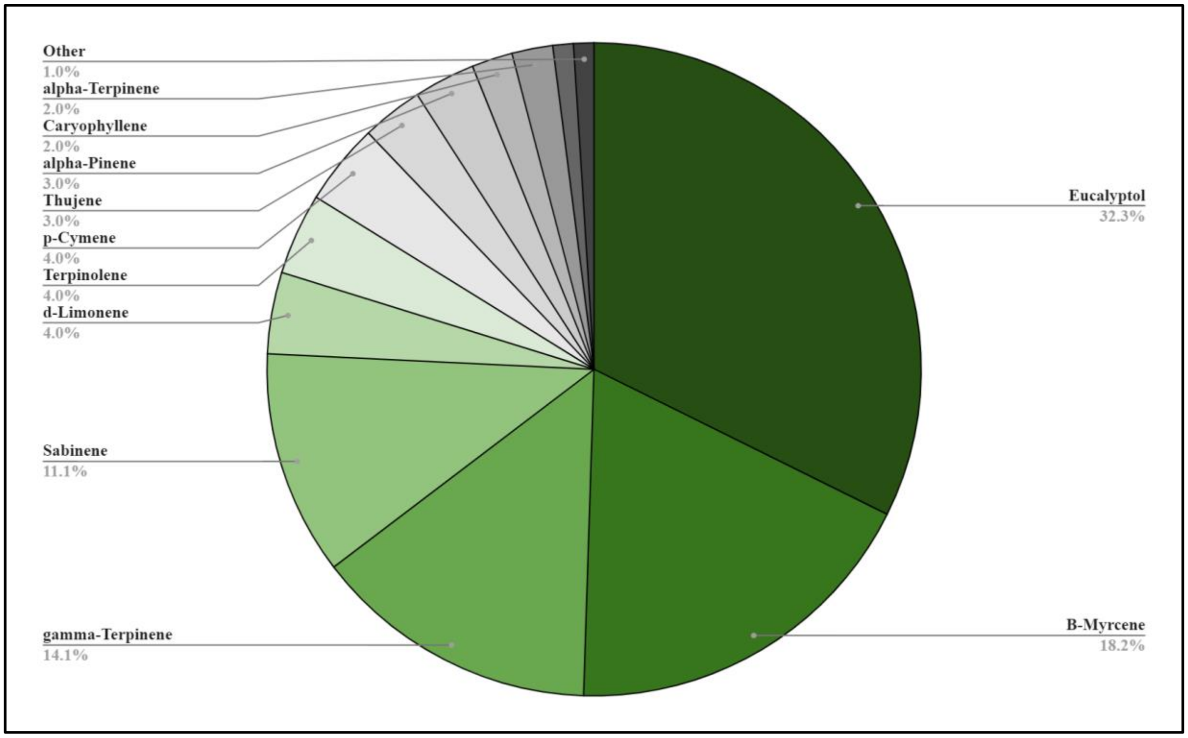

Figure 6.3. Percent Composition of Critical Mass Terpene Emissions (Wang et al., 2019b).

Terpene Volumetric Flow Rate

Wang et al. (2019a) calculated an average of 905 plants per facility in Denver County, CO. Based on this average, the adsorber was designed for a 1,000 plant facility. Assuming 1 sq.ft per plant (Caulkins et al., 2013), the design is for a 1,000 sq.ft facility.

The mass flow rate of total terpene emissions for a 1,000 sq.ft facility was calculated using a terpene emission capacity of 8.7 µgC g^{-1} hr^{-1} (Wang et al., 2019b). This emission capacity was measured by Wang et al. (2019b) based on the dry weight of the plant. It was converted to terpene emission capacity per plant using the value of 750 dwg $plant^{-1}$ (Wang et al., 2019b). This yielded a terpene emission rate of 0.006525 g $plant^{-1}$ hr^{-1}.

The terpene emission rate of 0.006525 g $plant^{-1}$ hr^{-1} for a 1,000 plant facility was calculated to be 6.525 g/hr. Using the percent composition of Critical Mass seen in Figure 1, the individual mass flows of the terpenes were calculated. An example calculation for the individual mass flow of eucalyptol (32% of the terpene composition) is shown below.

$$6.525\ \frac{g}{hr} * 0.32 = 2.088\ \frac{g\ eucalyptol}{hr}$$

The individual mass flow rates were calculated for each of the terpene constituents, except for the 1% labelled “others.” These mass flow rates were summed to determine a total molar flow rate of 0.0449 moles hr^{-1}. These calculations can be found in Appendix A. The total molar flow rate was then used to calculate the volumetric flow rate of the terpenes as shown below:

$$Q_{terpenes} = \frac{nRT}{P}$$

$$Q_{terpenes} = \frac{(0.0449 mol/hr)(0.0000821\ atm - m^3/mol - K)(298K)}{1\ atm}$$

$$Q_{terpenes}\ =\ 0.00110 \frac{m^3}{hr}$$

The volumetric flow rate of the facility was determined assuming a 10-foot ceiling height and 15 air changes per hour (UMASS Amherst, 2018; Walker & Duncan, 1973; Jordan, n.d.). The calculation is shown below:

$$Q_{room} = 1000\ ft^2 * 10\ ft^2 * 15 \frac{air\ changes}{hour} =\ 150{,}000\ \frac{ft^3}{hour}$$

$$Q_{room} = 4{,}247\ \frac{m^3}{hour} = 2{,}559\ \frac{ft^3}{min}$$

Vessel Dimensions

To determine the vessel dimensions, typical values for superficial velocity (V_b), bulk density of carbon ($P_{b,carbon}$), and the maximum bed depth to diameter ratio (H/D) were used. Typical values for these parameters are summarized in Table 6.1.

Table 6.1. Typical Values for Design (Vatavuk et al., 1999).

Parameter	Value
V_b	$60\ \frac{ft}{min}$
H/D	$\frac{\pi}{12}$
$P_{b,carbon}$	$30\ \frac{lbs}{ft^3}$

To calculate the diameter of the vessel, the following equation was used:

$$D\ = \sqrt{\frac{4 * Q_{room}}{V_b * \pi}}$$

$$D\ = \sqrt{\frac{4 * 2559 \frac{ft^3}{min}}{60 \frac{ft}{min} * \pi}}$$

$$D = 7.4\ ft$$

The diameter was rounded to 7.5 ft. Next, the bed depth was calculated using the H/D ratio as shown below:

$$Bed\ Depth\ = \frac{H}{D} * D$$

$$Bed\ Depth\ = \frac{\pi}{12} * 7.5\ ft$$

$$Bed\ Depth\ = 2.0\ ft$$

The length of the vessel was then calculated, using the assumption that the bed depth is one-third of the length (Vatavuk et al., 1999).

$$L = 2.0\ ft * 3$$

$$L = 6.0\ ft$$

The quantity of carbon per vessel ($M_{c,\ vessel}$) was then calculated using the following equation:

$$M_{c,vessel} = \frac{\pi * L * D^2}{4} * P_{b,carbon}$$

$$M_{c,vessel} = \frac{\pi * 6\ ft * (7.4\ ft)^2}{4} * 30\frac{lb}{ft^3}$$

$$M_{c,vessel} = 2650.72\frac{lbs\ carbon}{vessel}$$

It was determined that one active absorbing bed would be sufficient to treat the amount of terpenes in the exhaust emissions. Since the design is for a continuous, regenerative fixed-bed carbon adsorber, a desorbing bed is also required. Therefore, the total number of vessels is 2 and the total amount of carbon needed for 2 vessels was calculated as shown below:

$$M_{c,total} = \frac{M_c}{vessel} * number\ of\ vessels$$

$$M_{c,total} = 2650.72\frac{lbs\ carbon}{vessel} * 2\ vessels$$

$$M_{c,total} = 5301.44\ lbs\ carbon$$

Carbon Replacement

To determine the replacement frequency of the carbon, the equilibrium mass loading (w_e) was first calculated using the equation shown below. In the equation, G is the carbon loading at equilibrium (cm^3 liquid adsorbate per 100 g carbon) and V_m is the weighted fraction of the liquid molar volume (cm^3 mol^{-1}) calculated in Appendix B.

$$w_e = \frac{0.01G}{V_m} * MW$$

$$w_e = \frac{0.01(31.81\ \frac{cm^3}{100\ g\ C})}{162.0\frac{cm^3}{mole}} * 140.6\frac{g}{mole}$$

$$w_e = 0.28\frac{g\ terpenes}{g\ carbon}$$

Using the equilibrium mass loading of 0.28, the working capacity (w_c) was calculated assuming 50% efficiency (Vatavuk et al., 1999):

$$w_c\ =\ w_e\ *\ 0.5$$

$$w_c\ =\ 0.28\ *\ 0.5$$

$$w_c =\ 0.138\frac{g\ terpenes}{g\ carbon}$$

The working capacity was used to calculate the carbon usage rate, as shown below.

$$Carbon\ Usage\ Rate = \frac{Q_{terpenes}}{Working\ Capacity}$$

$$Carbon\ Usage\ Rate = \frac{2.056\ lbs\ terpenes/hr}{0.138\ lbs\ carbon/lbs\ terpenes}$$

$$Carbon\ Usage\ Rate = 14.9\frac{lbs}{hr}$$

The carbon usage rate was then used to calculate the amount of time before the carbon would have to be regenerated, based on the following equation:

$$Time = \frac{M_{c,vessel}}{Carbon\ Usage\ Rate}$$

$$Time = \frac{2650.72\ lbs}{14.90\ \frac{lbs}{hr}}$$

$$Time = 7.41\ days$$

Cost Analysis

Carbon Cost

The cost of carbon (C_c) to fill both the adsorbing vessel and desorbing vessel was calculated based on the following equation (Vatavuk et al., 1999):

$$C_c = 1.00M_{c,total}$$

$$C_c = \$5301.44$$

Vessel Cost

In order to calculate the cost per vessel based on the quantity of steel used, the surface area of each vessel was calculated as shown below.

$$S.A. = \pi * \ D \ * (L + \frac{D}{2})$$

$$S.A. = \pi * 7.5\ ft * (6.0\ ft + \frac{7.5\ ft}{2})$$

$$S.A. = 229.7\ ft^2$$

The cost per vessel (C_v) was then calculated based on the following equation (Vatavuk et al., 1999):

$$C_v = 271 * S.A.^{0.778}$$

$$C_v = 271 * 229.7^{0.778}$$

$$C_v = \$18{,}620.66$$

Total Equipment Cost

The total equipment cost depends on the ratio (R_c) of the total adsorber equipment cost to the cost of the vessels and carbon, calculated below (Vatavuk et al., 1999).

$$R_c = 5.82 * Q^{-0.133}$$

$$R_c = 5.82 * 2559^{-0.133}$$

$$R_c = 2.050$$

The total equipment cost (C_a), including fans, pumps, condensers, piping, and other instrumentation can be approximated using the following equation (Vatavuk et al., 1999):

$$C_a = R_c \ * [C_c + C_v * (N_A + N_D)]$$

$$C_a = 2.050\ * [\$2580.50 + \$18{,}620.66 * (1+1)]$$

$$C_a = \$87{,}192.98$$

This calculated cost is based on 1999 currency value, and was converted to 2019 currency value using the cost indices below.

$$2019\,Cost = 1999\,Cost\ * \frac{2019\,Cost\,Index}{1999\,Cost\,Index}$$

$$2019\,Cost = \$81{,}760.23 * \frac{542}{391}$$

$$2019\,Cost = \$120{,}865.97$$

This cost estimation does not include the cost of installation or direct annual costs, such as cooling water, electricity, carbon replacement, or any other maintenance and operating costs.

Discussion

The vessel dimensions and amount of carbon required would increase if the cannabis cultivation facility had an attached or incorporated extraction facility. The addition of hydrocarbons such as butane or propane would increase the amount of VOC in the exhaust emissions. This would alter not only the total volumetric flow rate entering the filter, but the equilibrium mass loading and working capacity as well.

The cost associated with a filter for a 1,000 plant facility is upwards of $120,000. According to the EPA's *Top Down Best Available Control Technology: Guidance Document* (1990), the cost effectiveness of an air pollution control technology should be evaluated. The expectation is that a company can afford to spend about $15,000 per ton of VOC removed by the control technology. If a company were to spend more than $15,000 per ton of VOC, it is considered too expensive; less than $15,000 per ton of VOC is considered financially feasible (EPA, 1990). A 1,000 sq.ft facility that emits 0.063 ton per year (6.525 g hr^{-1}) would cost about $945 per year. Therefore, a $120,000 carbon adsorber is not financially feasible by this standard. Furthermore, agricultural activities are exempt from most air emissions regulations in many regions, so there is no pressure to install any kind of air pollution control technology.

Some best management practices encourage the installation of an activated carbon filter to reduce VOC and odor emissions (DDPH, 2018), but as the design calculations demonstrated, an effective carbon filter is too expensive for most facilities to install. Research needs to be conducted to determine a more cost-effective way to control emissions for both small and large facilities.

Future Air Pollution Control Research

Biofilters treat exhaust through both physical and biological means. When VOCs and other contaminants pass through the filter, they are adsorbed to the media and broken down by microorganisms. Biofilters are effective in treating odorous VOCs (i.e. ammonia and hydrogen sulfide) at wastewater treatment plants and livestock facilities (Liu, 2017; Iranpour et al., 2005).

Biofilters require media that provides enough nutrients for microbial growth to occur and maintains a high porosity for easy air flow. Typical biofilter media includes a mixture of materials to create the ideal environment. A mixture of wood chips and compost, in a ratio of 70 to 30 by weight, has been proven to be an effective biofilter media in agriculture (Liu, 2017). The compost contains sufficient nutrients and microorganisms and has a high moisture holding capacity, while the wood chips improve porosity. Other media materials may include peat, loam soil, and straw (Liu, 2017).

There is a potential opportunity to design a biofilter that uses cannabis plant waste as the media. One of the options for cannabis waste disposal allowed by some state regulations is composting. If the waste was composted onsite, a percentage of the compost could be mixed with wood chips or straw to create a biofilter media. Research would be required to determine the feasibility, cost, and effectiveness of this idea. If this idea was practicable, facilities could reduce their waste disposal costs, as well as their VOC and odor emissions.

Recommendations

Regulation Enforcement

Odor is a leading concern for communities surrounding cannabis cultivation and extraction facilities. Communities across the United States are demanding better odor regulations and enforcement. This leads to expensive lawsuits, blocked permits, and disgruntled communities. Many cities like Denver and Las Vegas are adopting more proactive policies in monitoring odor from facilities. The field olfactometer called “The Nasal Ranger” is used to monitor odor and to ensure regulations are being met, enforced, and documented (Bender, 2020). However, odor produced by cannabis production is difficult to control and requires significant planning.

Planning Ahead

According to experienced growers and industry experts, planning ahead is the best way to implement odor control (Hammon, 2018). Many odor control plans tend to be reactive; the problem is only addressed when a facility is out of compliance. Since odor control is an additional cost, without any direct revenue, cannabis cultivators do not take action until they have to (Sandy, 2019). Rather, cannabis cultivators should contact an odor mitigation company before they discover that there is an odor problem and be proactive when it comes to odor control (Sandy, 2019). Early in the facility planning process, cultivators should be aware of air pollution regulations. Many state and local regulations require that an odor control plan be established prior to issuing a permit (Sandy, 2019). Odor mitigation planning can be a stand-alone plan or coupled with HVAC preparation. Specialized engineering firms will consider environmental factors such as humidity, temperature, and biosecurity needs to mitigate odors. By planning ahead, odor mitigation can be incorporated into the same plan as the HVAC system, which can save time and costs (Hammon, 2018).

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Appendix A: Total Molar Flow Rate

Terpene	**Percent**	**Mass Flow Rate**	**Mass Flow Rate**	**Molar Mass**	**n**
	%	g C/hr	g C/hr	g/mol	mol/hr
Eucalyptol	0.32	6.525	2.088	154.25	0.0135
B-Myrcene	0.18	6.525	1.1745	136.23	0.0086
gamma-Terpinene	0.14	6.525	0.9135	136.23	0.0067
Sabinene	0.11	6.525	0.71775	136.23	0.0053
d-Limonene	0.04	6.525	0.261	136.23	0.0019
Terpinolene	0.04	6.525	0.261	136.23	0.0019
p-Cymene	0.04	6.525	0.261	134.22	0.0019
Thujene	0.03	6.525	0.19575	136.23	0.0014
alpha-Pinene	0.03	6.525	0.19575	136.23	0.0014
Caryophyllene	0.02	6.525	0.1305	204.36	0.0006
alpha-Terpinene	0.02	6.525	0.1305	136.23	0.0010
B-pinene	0.01	6.525	0.06525	136.23	0.0005
Totals			**6.3945**		**0.0449**

Appendix B: W_e Calculations

The carbon loading at equilibrium, G, is calculated from a regression equation in which all the terms are expressed in metric units. The equation for G is the Calogon fifth-order polynomial:

$$log_{10}(G) = A_0 + A_1\Upsilon + A_2\Upsilon^2 + A_3\Upsilon^3 + A_4\Upsilon^4 + A_5\Upsilon^5$$

Where the values for A_X are summarized in Table A.1 below and Y is calculated from several equations which follow.

Table A.1. Regression Equation Variables

Parameter	**Value**
A_0	1.71
A_1	-1.46×10^{-2}
A_2	-1.65×10^{-3}
A_3	-4.11×10^{-4}
A_4	3.14×10^{-5}
A_5	-6.75×10^{-7}

The first step in calculating Y is to calculate χ. The equation for χ is shown below:

$$\chi = (\frac{T}{V_m}) * log_{10}(\frac{P_s}{P_i})$$

where T is the absolute pressure (K), V_m is the liquid molar volume of terpenes (cm^3 g-$mole^{-1}$), P_s is the fraction-weighted vapor pressure of terpenes at temperature T (kPa), and P_i is the fraction-weighted partial pressure of terpenes (kPa).

The liquid molar volume of terpenes was calculated as shown below. The fraction-weighted V_m calculation is summarized in Table A.2.

$$V_m = \Sigma \frac{MW}{\rho}$$

$$V_m = 162.0 \frac{cm^3}{mole}$$

Table A.2. Fraction-weighted V_m

Terpene	Percent	Density	Molar Mass	Liquid Molar Volume
	%	g/cm^3	g/mol	cm^3/mol
Eucalyptol	0.32	0.9267	154.25	53.264
B-Myrcene	0.18	0.794	136.23	30.883
gamma-Terpinene	0.14	0.8458	136.23	22.549
Sabinene	0.11	0.844	136.23	17.755
d-Limonene	0.04	0.8383	136.23	6.500
Terpinolene	0.04	0.8632	136.23	6.313
p-Cymene	0.04	0.857	134.22	6.265
Thujene	0.03	0.935	136.23	4.371
alpha-Pinene	0.03	0.8544	136.23	4.783
Caryophyllene	0.02	0.9075	204.36	4.504
alpha-Terpinene	0.02	0.837	136.23	3.255
B-pinene	0.01	0.8673	136.23	1.571
Total				**162.014**

The partial pressure of terpenes was calculated as described. The volumetric flow rate of the terpene emissions and the volumetric flow rate of the facility were used to determine the fraction of terpenes in the exhaust emissions. The calculation is shown below:

$$Fraction\ Terpenes = \frac{Q_{terpenes}}{Q_{room}} = \frac{0.0011}{4247}$$

$$Fraction\ Terpenes = 2.58 \times 10^{-7}$$

The fraction of terpenes in the exhaust emission was used to calculate the partial pressure of the terpenes in the exhaust emissions. A standard pressure of 101.325 kPa (1 atm) was assumed. The calculation for the partial pressure is shown below:

$$P_{terpenes} = 101.325\ kPa * 2.58 \times 10^{-7}$$

$$P_{terpenes} = 2.62 \times 10^{-5}\ kPa$$

χ was calculated as shown below:

$$\chi = (\frac{298\ K}{162.0\frac{cm^3}{mole}}) * log_{10}(\frac{0.255\ kPa}{2.62 \times 10^{-5}\ kPa})$$

$$\chi = 7.336$$

The next step to calculate Y is to calculate the relative polarizability (Γ):

$$\Gamma = \frac{\theta_i}{\theta_o}$$

Where Θ_i is the polarizability component for the terpene flow per unit volume and Θ_o is the polarizability component for n-heptane per unit volume. To calculate the polarizability component for the terpene flow, the appropriate refractive index of the terpene flow was used. A fraction-weighted polarizability component for the terpene flow (Θ_i) and the polarizability component for n-heptane were calculated using the equation shown below, where n is the refractive index:

$$\theta = \frac{n^2-1}{n^2+1}$$

The calculations for the Θ_i are summarized in Table A.3 below. An example calculation for the polarizability component for n-heptane is given:

$$\theta_o = \frac{1.3855^2 - 1}{1.3855^2 + 1}$$

$$\theta_o = 0.235$$

Table A.3. Fraction-weighted Polarizability

Terpene	**Percent**	**n Refractive Index**	**Polarizability**
	%		i/unit volume
Eucalyptol	0.32	1.4586	0.273
B-Myrcene	0.18	1.4709	0.279
gamma-Terpinene	0.14	1.474	0.281
Sabinene	0.11	1.468	0.278
d-Limonene	0.04	1.473	0.281
Terpinolene	0.04	1.4883	0.288

p-Cymene	0.04	1.4909	0.290
Thujene	0.03	1.45	0.269
alpha-Pinene	0.03	1.4632	0.276
Caryophyllene	0.02	1.495	0.292
alpha-Terpinene	0.02	1.478	0.283
B-pinene	0.01	1.478	0.283
Total			**0.281**

The relative polarizability (Γ) of the terpene flow was calculated using Θ_i and Θ_o as shown below:

$$\Gamma = \frac{\Theta_i}{\Theta_o} = \frac{0.281}{0.235}$$

$$\Gamma = 1.198$$

Once χ and Γ were determined, the value of Y was calculated as shown below:

$$\Upsilon = \chi / \Gamma = \frac{7.336}{1.198}$$

$$\Upsilon = 6.125$$

The value of Y was substituted into the Calgon fifth-order polynomial for G. The value of G was calculated as 31.81 cm^3 per 100 g carbon.

Chapter 7: Energy

Introduction

The growth of the cannabis industry and its corresponding energy demands were unanticipated by utilities, public utility commissions, and government officials (Bezdek et al., 2017). The rapid legalization of the industry has resulted in a tendency to rush into the market, which has not been conducive to energy-efficient practices (Kolwey, 2017). In 2015, *Bloomberg* researchers estimated that cannabis cultivation facilities made up almost 50% of the new power demand in Colorado (Remillard & Collins, 2017). The industry is extremely energy-intensive, and is placing strains on local utilities and power grids (Bezdek et al., 2017).

This chapter focuses strictly on the energy requirements associated with indoor cultivation facilities. An indoor cultivation facility refers to buildings that do not supply natural light for growth (Small, 2018). The majority of commercial plants are grown outdoors since the production costs can be significantly less expensive than indoor cultivation. However, the demand for products outside of the outdoor growing season, as well as the other advantages associated with indoor cultivation, can make it economically feasible despite the high energy costs (Small, 2018).

Indoor cannabis cultivation uses significant energy primarily due to lighting, dehumidification, and HVAC (CCC, 2020). More specifically, indoor cultivation energy uses include high-intensity lighting, dehumidification to remove water vapor and avoid mold formation, space heating or cooling during non-illuminated periods and drying, pre-heating of irrigation water, and ventilation and air-conditioning to remove waste heat (Mills, 2012). Furthermore, significant energy inefficiencies occur in air cleaning, noise and odor control, and diesel generators (Mills, 2012).

Areas of Energy Use

A widely-cited study from 2012 estimated that national cannabis production requires approximately 20 TW per hour per year. This is 8-times as much energy per square foot as a typical U.S. commercial building, 4-times as much as a hospital, and 18-times that of an average U.S. home (Mills, 2012). The areas of energy use in cannabis cultivation can be broken down as shown in Figure 7.1.

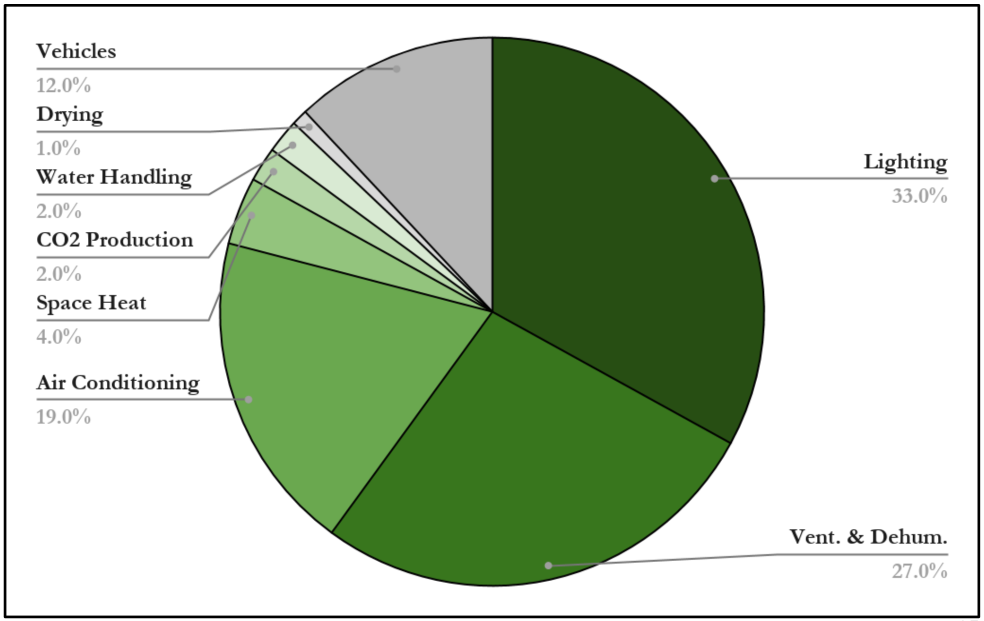

Figure 7.1. Carbon footprint of indoor Cannabis production (Mills, 2012).[25]

For the purposes of this research, vehicles will not be discussed, since it is associated with the transportation and distribution of small quantities of product (Mills, 2012). Such use of vehicles does not apply directly to indoor cultivation or processing of cannabis and is not a unique consideration for the industry. However, the energy use associated with vehicles would have to be considered for outdoor cultivation because the use of farming equipment is an integral component. This discussion will include the energy consumption of extractions, which is not included in Mills' analysis. Since extractions is the largest growing sector of the cannabis industry (New Frontier Data, 2019), it is a growing concern that must be addressed.

Dehumidification and Ventilation

Heating, ventilation, and air conditioning (HVAC) systems are the primary source of energy consumption in the cannabis industry. The main purpose of HVAC systems is to control the humidity and temperature of the facility. The growing environment is controlled through HVAC systems by cooling the air to remove water vapor and then reheating the air to desire room temperature (Remillard & Collins, 2017). The air needs to be cooled to offset the heat generated by the intense lighting (CCC, 2020) and proper ventilation is required to remove waste air, including excess heat (Mills, 2012) and plant emissions (i.e.terpenes, O_2). Dehumidification is necessary to remove water vapor from the air to prevent mold and mildew (CCC, 2020; Mills, 2012). Heating and cooling are also necessary during non-illuminated periods and drying (Mills, 2012).

The energy requirement for HVAC systems and dehumidifiers can vary depending on the facility. The type of HVAC system used for a particular facility depends on factors such as the local climate and building size. Proper maintenance and operation of the HVAC system, as well as building insulation, air changes per hour, and ventilation filters, can impact the efficiency of the system (Arnold, 2013). According to Mills (2012), HVAC and dehumidification account for 50%

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[25] Data can be found in Appendix A.

(2,288 kg) of the CO_2 emissions produced per kilogram of product. The energy intensity is equal to 3,436 kW per hour per kilogram of product (Mills, 2012).

A common industry practice is to choose the lowest-cost option for HVAC systems (Remillard & Collins, 2017). For cultivation facilities, HVAC systems are often retrofitted or not installed by licensed professionals (Arnold, 2013). For small or medium-sized facilities, the standard practice appears to be to install one or several rooftop HVAC units and portable dehumidifiers in the flower rooms. The rooftop HVAC units are designed and operated to minimize the use of outdoor air, in order to prevent contamination and maintain CO_2 levels (Kolwey, 2017). However, rooftop HVAC units are typically not designed to handle the significant cooling required to remove excess moisture from the plants' transpiration (Kolwey, 2017). When the HVAC systems are not designed for the unique conditions of a cannabis facility, it can be difficult to control the grow environment. This can lead to frustration with the installed system, which results in a "Band-Aid" fix where more and more standalone equipment is installed until the desired conditions are met, ultimately increasing the energy use (Remillard & Collins, 2017).

Lighting

Lighting is the second largest energy consumer in the cannabis industry. Indoor cultivation facilities require high-intensity lighting to achieve optimal plant growth and flower production (Kolwey, 2017). The lights used in cannabis production are very powerful and have significantly higher energy use and light intensity compared to typical screw-in light bulbs (CCC, 2020). The lighting levels of cultivation facilities are 500-times greater than the recommended lighting level for reading (Mills, 2020).

Energy estimates for lighting depend on the lighting schedule required for the various stages of plant growth. Therefore different amounts of electricity are used during the growing phase (Arnold, 2013). The lighting requirement for cannabis plants changes during the seedling/clone, vegetation, and flowering stages are summarized in Table 7.1. During the seedling/clone stage, low-intensity fluorescent lighting is preferred in order to reduce the chance of damaging the seedlings (Remillard & Collins, 2017). For vegetative growth, 600 W or 1,000 W metal halide (MH) high-intensity discharge (HID) fixtures or high-intensity T5 fluorescent lighting fixtures are used for each 4-ft by 4-ft area of plants. These lighting fixtures are preferred because plants thrive under red- and blue-spectra light in the vegetative stage (Remillard & Collins, 2017; Kolwey, 2017). During the flowering stage, 1,000 W high pressure sodium (HPS) fixtures are preferred for their concentration of yellow- and red-spectra light (Remillard & Collins, 2017; Kolwey, 2017). It should be noted that HPS fixtures can be used for all stages of the growing cycle (Remillard & Collins, 2017).

Table 7.1. Industry Standard Practices for Lighting[26]

Stage of Life	Type of Light	Hours per Day of Lighting
Seedling/Clone	T5HO Fluorescents	18-24
Vegetative	MH HID Fixtures	18-24
Flowering	HPS Fixtures	12

Cultivation facilities can contain 50,000 to 100,000 W of installed lighting power (Mills, 2012). According to Mills, lighting accounts for 33% (1,520 kg) of the CO_2 emissions produced per kilogram of product. The energy intensity is equal to 2,283 kW per hour per kilogram of product (Mills, 2012).

Carbon Dioxide Injection

In the cultivation stage of cannabis production, indoor carbon dioxide levels are raised to enhance plant growth (Bortek, 2017; Mills, 2012). Carbon dioxide levels are often increased to 800-1,000 ppm, or about 4-times the natural concentration, to increase yields by shortening the growth cycle (Bortek, 2017; Mills, 2012). Increasing the carbon dioxide to these levels can increase yields by 10-25% (Bortek, 2017). By decreasing the growth cycle, this practice could reduce final energy intensity (Mills, 2012). However, this practice adds heat to the grow room which may be utilized in the winter, but must be compensated for through air conditioning in the summer (Mills, 2012). It is common for cannabis facilities to obtain carbon dioxide through burning natural gases like propane or by purchasing it outright from a supplier (Bortek, 2017; Mills, 2012; Overcash et al., 2007). The Denver Cannabis Environmental Best Management Practices recommends that burning natural gases to obtain carbon dioxide should not be used due to the high levels of waste heat produced, as well as the potential to create dangerous indoor environments when improperly vented (DDPHE, 2018). Instead, they recommend that facilities should purchase bottled carbon dioxide from an outside manufacturer (DDPHE, 2018). It is estimated that carbon dioxide injection produces an energy intensity of 93 kW/h/kg yield and emissions of 82 kgCO_2 emissions/kg yield; accounting for 1-2% of a facility's carbon footprint (Mills, 2012).

Drying Process

The drying stage in the cultivation process requires proper ventilation, humidity, and temperature control. Temperatures in the drying room range from 65-75°F to preserve the terpenes in the plants and a relative humidity of approximately 50% to prevent mold from forming (Mills, 2012; Morrow, 2020). The drying room uses both a humidifier and a dehumidifier, as well as oscillating fans to closely monitor the conditions of the room. It is estimated that this stage of the production process produces an energy intensity of 90 kW/h/kg yield and emissions of 60 kgCO_2 emissions/kg yield; accounting for 1% of a facility's carbon footprint (Mills, 2012).

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[26] Arnold, 2013; Remillard & Collins, 2017; Kolwey, 2017

Water Handling

Water handling refers to the way water is stored and drawn. Water must be handled in a safe manner in order to prevent contamination (van Wijk & Christoffers, 2005). In the cannabis industry, cultivators rely on large storage tanks to hold water for multiple days' worth of normal operation. To ensure water quality, the tanks are disinfected on a regular basis and the water is delivered through clean, water delivery systems (Badertscher & Badertscher, 2018).

The energy requirements of water handling include the application and heating of irrigation water (Mills, 2012). Cannabis water-systems, described in Chapter 3, deliver a consistent rate of water to the plants. The energy required to run the water-system depends on the quantity of water that must be delivered at any given time, how long the system must run, and what type of system is used. For example, a system that delivers water to one grow room at a time requires less pump capacity, and therefore less energy, than a system that delivers water to multiple grow rooms at once (Badertscher & Badertscher, 2018). In addition to delivery, the water is often heated to enhance nutrient solubility and the oxygen content of the water. If dry fertilizers are used, nutrient mixing can be improved by using warm water. The warm temperature of the water will help the fertilizer dissolve (Badertscher & Badertscher, 2018). During delivery, water temperatures are kept between 72°F and 75°F. At 72°F, water retains more oxygen, which can aid in plant growth (Badertscher & Badertscher, 2018).

According to Mills, water handling accounts for 2% (115 kg) of the CO_2 emissions produced per kilogram of product. The energy intensity is equal to 117 kW per hour per kilogram of product (Mills, 2012).

Natural Gas Generators

Other contributors to a facility's energy consumption are generators that rely on the combustion of natural gas. While common in illegal grow facilities to avoid suspicion from energy companies, legal facilities may wish to use them in addition to obtaining power from the grid. Complete off-grid production increases the estimated 4,600 kg of carbon dioxide emissions by 50% to 6,600 kg (Mills, 2012).

Extractions

The energy consumption of the extraction process is dependent on the extraction method used as well as the specific model of machinery used. Extraction techniques vary in energy consumption, with some techniques requiring much more energy, such as supercritical CO_2, than others. Since there is no formal method to estimate the energy consumption of the extraction process, an estimation of the energy requirements based on the phase changes in each process was calculated in Chapter 5. The results are summarized below in Table 7.2.

Table 7.2. Total Energy & Equivalent CO_2 Emissions of Extraction Methods

Extraction Method	Total Energy Required $(\frac{kWh}{lb\ extract})$	Equivalent CO_2 Emissions $(\frac{lb\ CO_2}{lb\ extract})$
Pure Butane	4.34	6.77
Cooled Ethanol	0.53	0.83
Supercritical CO_2	14.91	23.24
Cold Water	0.57	0.89
Food-based*	0.49	0.77

*This extraction method was evaluated using vegetable and olive oil.

Industry Analysis

Projection of Carbon Dioxide Emissions

To estimate the carbon dioxide emissions as the industry grows, projected industry sales were obtained from the U.S. Cannabis Report: 2019 Industry Outlook (New Frontier Data, 2019). The data used for the analysis included estimated adult-use only sales and full legal sales, which included medical sales, for the years 2017 to 2025. According to the report, the U.S. legal cannabis industry is expected to grow to $29.7 billion by 2025. The market projections are based solely on the state markets that have passed medical and adult-use legalization initiatives as of July 2019, and do not include assumptions for any additional states that may pass legalization measures before 2025 (NFC, 2019).

As the industry continues to grow, so will the amount of CO_2 emissions released. The future CO_2 emissions of the cannabis industry were estimated from the projected sales growth, the average cost of cannabis products, and the amount of CO_2 released per kg of product. The average cost per kg of final product was calculated based on a report that surveyed 13 U.S. cities for the average price of cannabis in each city (ABCD Agency, 2018). These values were averaged to obtain a value of $10,313.08 per kg of cannabis (Appendix B). The estimated kg of product sold per year was calculated from the projected sales growth and the average cost of cannabis products (Appendix C). An example calculation for the kg of product for adult-use only sales in 2025 is shown below:

$$kg\ of\ Product = \frac{Estimated\ Sales}{Average\ Cost}$$

$$kg\ of\ Product = \frac{\$16{,}600{,}000{,}000}{\$10{,}313.08\ per\ kg}$$

$$kg\ of\ Product = 1{,}609{,}607\ kg$$

The equivalent CO_2 emissions for the quantity of cannabis sold each year was determined using the value of 4,600 kg of CO_2 per kg of final product (Mills, 2012). The estimated amount of

CO_2 emissions per year was calculated from the kg of product sold per year and the emissions per kg of product (Appendix C). An example calculation for the CO_2 emissions for adult-use only sales in 2025 is shown below:

$$kg\ of\ CO_2 = kg\ of\ Product * 4600\,\frac{kg\ CO_2}{kg\ product}$$

$$kg\ of\ CO_2 = 1{,}609{,}607\ kg * 4600\,\frac{kg\ CO_2}{kg\ product}$$

$$kg\ of\ CO_2 = 7{,}404{,}191{,}840\ kg$$

The projected CO_2 emissions for adult-use only and all legal cannabis are shown below in Figure 7.2.

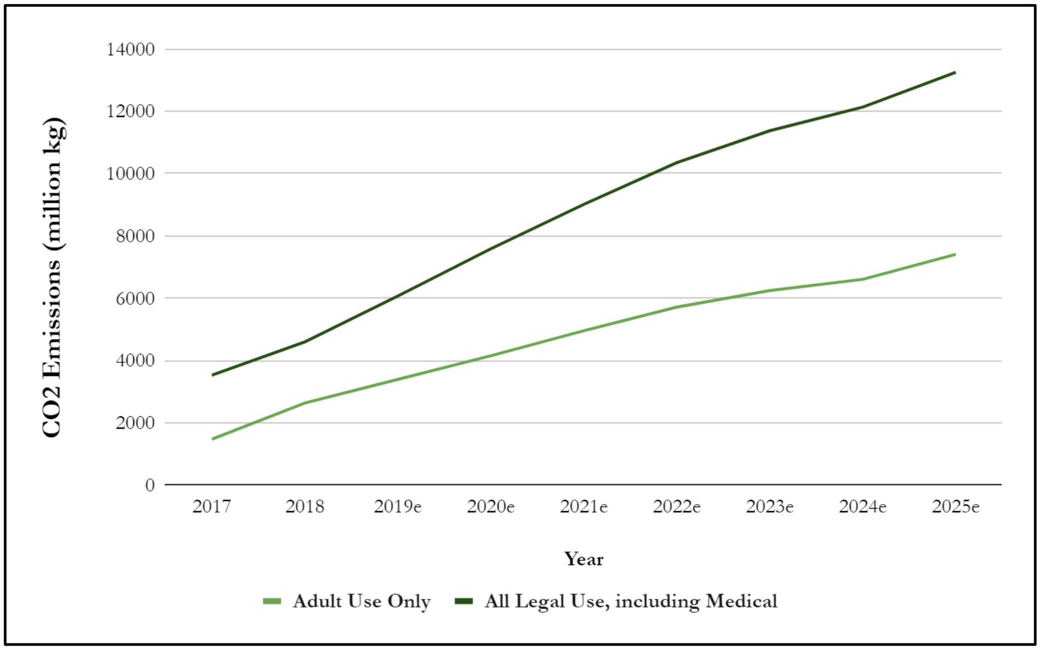

Figure 7.2. Projected CO_2 Emissions

Projection of Energy Costs

It is estimated that the total energy costs for indoor cannabis facilities varies between 20-50% of total operating costs (Remillard & Collins, 2017). Energy also accounts for nearly 50% of the wholesale price of cannabis, depending on the grower, strain, state, and operating costs. As competition increases, the price of cannabis will fall and margins will decrease, resulting in an increase in the share of energy in total production costs (Bezdek et al., 2017). As the price of cannabis decreases the need for lower operational costs will increase, which can be predominantly achieved through energy efficiency (Remillard & Collins, 2017).

Mills (2012) estimated that the national-average energy costs to produce one kg of final product was $2,500 per kg. The future energy costs per year was estimated from the kg of product sold per year and the national-average energy costs (Appendix D). An example calculation for the energy costs for adult-use only sales in 2025 is shown below:

$$Energy\ Cost = kg\ of\ Product * \$2500\frac{USD}{kg\ product}$$

$$Energy\ Cost = 1{,}609{,}607\ kg * \$2500\frac{USD}{kg\ product}$$

$$Energy\ Cost = \$4.02\ Billion$$

The projected energy costs for adult-use only and all legal cannabis are shown below in Figure 7.3.

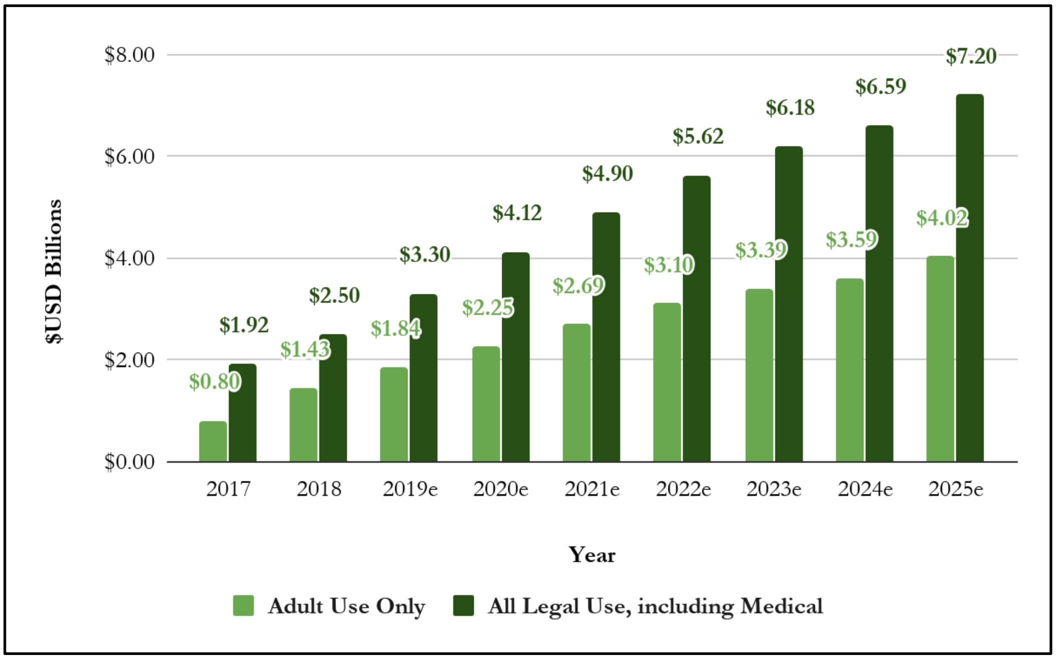

Figure 7.3. Projected Energy Costs

Discussion

These calculations were based on a number of assumptions; the first was that the average price of cannabis would remain at $10,313.08 per kg. The price of cannabis has varied over the years, with most states experiencing a decline in the price due to the issuing of more licenses and an increase in supply. When Colorado first legalized recreational cannabis in 2014, the prices peaked 6 months after legalization and has continued to decrease since then. Washington and Oregon experienced similar trends; the prices in both states continue to fall (New Frontier Data, 2019; Willis 2018). Prices for cannabis may continue to fall as more states legalize the product and compete with the illicit market (New Frontier Data, 2019).

The second assumption is that the cost of energy has remained the same since 2012. The national-average energy costs to produce one kg of final product was estimated to be $2,500 per kg by Mills. This value is based on the cost of energy in 2012. The May 2012 energy cost for the industrial sector was approximately 6.6 cents/kwh and the cost in January 2020 was approximately 6.3 cents/kwh (United States Energy Information Administration, 2020). While the cost of energy does vary, it was decided that this was not a significant enough difference to recalculate Mills' value.

The other assumptions used in the calculations are in regard to the values presented by Mills. The model utilized by Mills calculated the total energy consumption per production module, which is defined as a 4 x 4 x 8ft. Based on the model, each production module produces 0.5 kg of product, per production cycle. The energy cost for one module is approximately $5500 or $2500 per kg of final product (Mills, 2012). Using this model, Mills also calculated a value of 4600 kg CO_2 per kg of final product. These values do not include the energy inputs required for the soil, fertilizer, building materials, refinement, or retailing (Mills, 2012). Furthermore, the values presented in the study are based on the common practices of the cannabis industry of 2012, which do not include common techniques used today. These practices include "energy-intensive" practices such as hydroponics, large-scale water purification, and air, noise and odor control (Mills, 2012). Additionally, Mills does not include the energy usage of extractions, which is the largest growing sector of the cannabis industry (New Frontier Data, 2019).

Despite the missing energy parameters, the energy cost of $2500 per kg of final product and the carbon emissions of 4600 kg CO_2 per kg of final product were not adjusted for ease of analysis. As Mills (2012) mentions, processes exist that will use less or more energy per-unit-yield and strategies for lowering energy inputs may result in lower yields, which would not necessarily reduce the energy cost and carbon emissions per unit weight. It was assumed that the practices would be variable enough for Mills' value to still be a valid approximation.

In Mills' (2012) evaluation, transportation accounts for 546 kg (12%) of the CO_2 emissions produced per kilogram of product. The transportation portion accounts for vehicle use associated with production and distribution. According to Mills (2012), this accounts "both for workers and for large numbers of small-quantities transported and then redistributed over long distances before final sale." Mills (2012) states that the "assumptions about vehicle energy use are likely conservative, given the longer-range transportation associated with interstate distribution." While the long-term transportation is important to consider, Mills' transportation assumptions may be misguided. As of 2020, interstate distribution of cannabis products is restricted by federal law and there is no national market (New Frontier Data, 2019).

To understand the full environmental impacts of cannabis production as the industry grows, the effects of the national market would have to be considered. A national market could lead to reduced competition, which may or may not encourage more sustainable practices, as a larger company with higher profit margins could afford to invest in energy efficient technology and other sustainable practices. However, a national market would mean that interstate distribution would occur, which may significantly increase the CO_2 emissions.

Despite the fact that the Mills study is from 2012, the values are still widely referenced by best management practices and other researchers. As more cannabis companies are established, more data will be available. A current, comprehensive evaluation of the cannabis could be performed to update Mills' 2012 evaluation. A comprehensive evaluation would have to include the "energy-intensive" practices that Mills chose to omit, as well as the increased energy demand of investing in more sustainable practices.

Recommendations

Planning Ahead

Overall, the nature of the cannabis market has not been conducive to energy-efficient practices (Kolwey, 2017). When recreational cannabis is legalized in a new state, eager entrepreneurs tend to rush into the market. Most new operations, particularly small- and medium-sized growers, start their businesses by leasing an empty warehouse and set up simple, low-cost equipment. When new entrepreneurs hastily enter the industry, they miss the opportunity to carefully plan an energy efficient operation (Kolwey, 2017).

By implementing lighting and HVAC best practices, a medium-size or larger indoor grow operation can achieve up to 30-35% energy savings compared to a standard indoor cultivation facility (Kolwey, 2017). However, energy-efficiency does not always result in sufficient energy use reductions. A 90,000 sq.ft indoor warehouse facility installed a $2,000,000 rooftop solar array, LED lights, and the most efficient HVAC and insulation products, but still pays over $1,000,000 per month for the electric bill (Bezdek et al., 2017). This discrepancy may be attributed to the energy-intensive practices that are standard across most cultivation facilities. Cannabis facilities need to find a way to balance energy-intensive practices with less-intensive methods, as well as the use of energy-efficient technology through proper planning in order to reduce their footprint.

Alternative Lighting

Light-Emitting Diode (LED) lamps are an energy efficient lighting alternative for indoor cultivation facilities. One case study, referenced by the Denver Cannabis Environmental Best Management Practices Guide (2018), replaced 72 1,000 W single-ended HPS lights with a mix of 6 bar and 10 bar BML LED lights in a vegetative grow room. By replacing the HPS lights with LEDs, there was an immediate energy savings of 36,360 W, which equated to $1,400 in electric cost savings. The study found that using LEDs decrease the vegetative growing period by 1-2 weeks. The study also reported a decreased demand on the HVAC equipment, due to a lower heat load (DDPHE, 2018). According to Kolwey (2017), LED lighting has been successfully installed in vegetative and flowering rooms. LED fixtures have saved up to 50% of the lighting energy in vegetative rooms and double-ended HPS lights have saved 20-25% of the lighting energy compared to the standard practice. Facilities have also successfully implemented LED and LED/HPS hybrid fixtures in flower rooms for up to 30-40% energy savings (Kolwey, 2017).

However, the industry has been slow to adopt LED lighting due to the initial costs of installing LEDs and concerns about their effectiveness in terms of product yield and quality. LED grow lighting is still developing, and research regarding the effectiveness of LEDs compared to HID lighting are not are not widely available (Remillard & Collins, 2017). Furthermore, direct comparisons between HID, HPS, and LED lighting are challenging to establish. Even under the exact same growing conditions and plant genetics, a 10-20% difference in yield can be expected (Caulkins et al., 2013). Therefore, meaningful comparisons when assessing the difference in lighting techniques are difficult to establish. It is difficult to determine if the differences in yield are due to the lighting or are inherent to the growth of the plant (Remillard & Collins, 2017).

Ventilation and Dehumidification Alternatives

The Denver Cannabis Environmental Best Management Practices Guide (2018) details alternative ventilation and dehumidification systems that may be more energy efficient than traditional systems. Alternative cooling methodologies to standard HVAC systems include evaporative cooling, mini splits, variable refrigerant flow, chilled water systems, and water-cooled condensers with cooling towers and geothermal systems. Alternative dehumidification methodologies in standalone dehumidifiers, reheat systems, desiccant dehumidifiers, and economizers (DDPHE, 2018).

Smaller indoor cultivation facilities have installed split ductless air conditioning units in place of standard rooftop units to save energy on cooling and split ductless air conditioning units in place of standard rooftop units. Medium- and large-sized facilities have saved up to 40% of energy costs compared to standard practices by implementing chilled water systems for both cooling and dehumidification (Kolwey, 2017).

Combined Heat and Power Systems

For facilities that generate power on-site, Combined Heat & Power (CHP) systems may be economically, environmentally and operationally advantageous. CHP systems, also known as cogeneration systems, use a natural gas generator to produce electricity. When installed and run properly, CHP systems can reduce a facility's CO_2 emissions by 25-45% (DDPHE, 2018). In the cannabis industry, CHP systems are being used to generate electricity to operate the grow lights (Kuack, n.d.).

CHP systems repurpose waste products to offset a facility's HVAC and CO_2 needs (DDPHE, 2018). The system purifies the exhaust gases from the burning of natural gas or biogas and produces CO_2. The CO_2 can then be used to supplement the atmospheric CO_2 injections in the cultivation facility. The waste heat generated by the CHP system can be used to produce chilled water or air to cool the facility (DDPHE, 2018; Kuack, n.d.).

While CHP systems are an attractive alternative for on-site energy production, they are complex install and run. Significant technical expertise is required for the design, build, and maintenance of these systems. Facilities interested in CHP systems should consult qualified personnel to ensure a successful system (DDPHE, 2018).

Greenhouses

Greenhouse grow operations can save 60-75% of the energy needed per pound of flower compared to indoor grow facilities (Kolwey, 2017). The most efficient greenhouses required less energy than indoor cultivation facilities due to the use of natural sunlight instead of artificial lights (Small, 2018). As discussed previously, plants require 18-24 hours of light per day during the vegetative stage and 12 hours of light per day during the flowering stage when grown inside. Greenhouses can provide a majority of the light during the day; only up to six hours of supplemental artificial lighting is needed per day for the vegetative stage and the flowering stage may not need any supplemental lighting (Kolwey, 2017). In addition, greenhouses can be designed to increase air circulation, saving up to 75% of the energy needed for typical HVAC and dehumidification systems (Kolwey, 2017).

The simplest form of greenhouses are temporary, tent-like structures referred to as "tunnels." Low tunnels are 1.2 m high, semi-circular covers that must be moved to access the plant. High tunnels, also known as hoop houses, are high enough to allow a person to walk inside. Larger, simple greenhouses are often by covering a frame with plastic. These "low-tech" greenhouses are cheap to build and operate, but are temporary and serve mainly to extend the growing season in early spring and/or late fall by providing warmth (Small, 2018). Advanced greenhouses that allow for environmental controls, such as temperature, humidity, air movement, and light intensity and duration, are often built in cool and cold climates. Hybrid greenhouses are buildings with solid side walls and a translucent ceiling that can provide natural sunlight while also protecting the plants from public view (Small, 2018).

Since greenhouses require much less energy than indoor cultivation facilities, they could be a viable alternative to combat high energy costs. However, the decision to establish a greenhouse versus an indoor cultivation facility involves many factors. The energy needs of a greenhouse depend largely on the climate in which they are located. They are effective in mild climates, such as Colorado, but can be challenging to operate in hot climates such as Arizona or southern Nevada (Kolwey, 2017). Many indoor cultivation facilities are established in old warehouses or industrial spaces. Therefore, cities already have the infrastructure required to support indoor cultivation facilities, whereas there may not be enough space for greenhouses (Kolwey, 2017). Warehouses are also more versatile spaces that can be used for another business if the cannabis business fails. Investors may be hesitant to fund greenhouse grows because they cannot be repurposed as easily as warehouses (Kolwey, 2017). Furthermore, obtaining a permit for a cannabis greenhouse can be challenging compared to obtaining a permit for an indoor facility. The permitting and inspection process for greenhouses tends to be less established than the processes for warehouse spaces. Therefore, city officials and regulators are not as knowledgeable or comfortable with greenhouse grows. In some states, permits are not available for greenhouse grows at all (Kolwey, 2017).

Regulatory Controls

To compensate for the intensive energy requirements of the industry, many states are using regulations to pressure the industry to adopt more energy-efficient practices. States like Massachusetts and Illinois are requiring cannabis establishments (i.e. cultivators, processors, dispensaries) to adopt specific energy-saving measures as part of the application process. In Massachusetts, in order to obtain a license, potential energy reduction opportunities and a plan for implementation must be outlined (935 CMR 500.000). The plan must include strategies to reduce the facility's energy demand such as, lighting schedules, active load management, energy storage, and renewable energy generation. If renewable energy generation is not feasible, the state requires an explanation as to why. In addition to the plan, Massachusetts provides incentives to using renewable energy sources through certifications. The facility owner may obtain an "Energy and Environmental Leader" certification if they have met or exceeded energy and environmental impact goals, complied with best management practices, and offset 100% of their energy consumption with renewable energy credits. By having this certification, their products may be labelled "made with 100% renewable energy."

Illinois has adopted similar regulations for facilities. In order to produce cannabis in Illinois, facilities must not use lighting that exceeds 36 watts per square foot of canopy, with a photosynthetic photon efficacy (ppe) of no less than 2.2 micromoles per joule. Additionally, the lighting must be certified by DesignLights Consortium on their Horticultural Specification Qualified Products List, to ensure energy efficiency. In regard to HVAC systems, for facilities with less than 6,000 sq.ft of canopy space, HVAC systems must be high efficiency ductless, split HVAC units. For canopies greater than 6,000 sq.ft all HVAC must be variable refrigerant flow HVAC units or better (Ill. Admin. Code tit. 101-0027 (2019)).

Other states are requiring cannabis facilities to purchase renewable energy certificates. Renewable energy certificates (RECs) represent one megawatt hour of energy generated from a renewable source, such as wind, solar, hydro, or certain types of renewable biomass (The International REC Standard, n.d.). Essentially, when facilities purchase certificates, they pay a renewable energy generator to produce energy from a renewable source to offset the amount of energy the facility consumed from a non-renewable source. For example, in California, regulations require facilities to purchase RECs from the American Carbon Registry, Climate Action Reserve, or Verified Carbon Standard if their "greenhouse gas emissions intensity is greater than the local utility provider's greenhouse gas emission intensity" (Cal. Code Regs. tit. 16, § 8307, 2018). Another example of this can be seen in the regulations for Boulder, CO, where 100% of a cannabis cultivation facility's energy use must be offset with RECs (Boulder, CO Municipal Code § 6.16.8).

While there is still insufficient economic pressure for facilities to adopt more energy-efficient technology and renewable energy sources, regulations can be used in tandem with proper planning to reduce the impacts of the industry as a whole.

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Appendix A: Carbon footprint of indoor Cannabis production, by end use

Data obtained from Mills, 2012

Category	**Emissions Factor** $(\frac{kg\ CO_2\ emissions}{kg\ yield})$
Lighting	1520
Ventilation & Dehumidification	1231
Air Conditioning	855
Space Heating	202
CO_2 Injection	82
Water Handling	115
Drying	60
Vehicles	546
Total	4611

Note: The calculations are based on U.S.-average carbon burdens of 0.666 kg/kW/h. “CO_2 injected to increase foliage” represents combustion fuel to make on-site CO_2. Assumes 15% of electricity is produced in off-grid generators (Mills, 2012).

Appendix B: Price of Cannabis

Data obtained from ABCD Agency, 2018

Cost of 1 kg of Cannabis	**Cost**	**Cost**
City	$/gram	$/kg
Washington D.C.	$18.08	$18,080.00
Chicago	$11.46	$11,460.00
Philadelphia	$11.30	$11,300.00
Boston	$11.01	$11,010.00
New York	$10.76	$10,760.00
Dallas	$10.03	$10,030.00
Houston	$10.03	$10,030.00
Phoenix	$9.35	$9,350.00
Miami	$9.27	$9,270.00
San Francisco	$9.27	$9,270.00
Los Angeles	$8.14	$8,140.00
Denver	$7.79	$7,790.00
Seattle	$7.58	$7,580.00
Avg ($/ kg of final product)		**$10,313.08**

Appendix C: Projected CO_2 Emissions

Year	**Adult Use Only**			**Legal Use, including Medical**		
	Estimated Sales[1]	**Estimated Amount of Product[2]**	**CO_2 Emissions[3]**	**Estimated Sales[1]**	**Estimated Amount of Product[2]**	**CO_2 Emissions[3]**
	$USD Billion	kg cannabis	kg CO_2	$USD Billion	kg cannabis	kg CO_2
2017	3.3	319982.10	1471917655	7.9	766017.75	3523681659
2018	5.9	572089.21	2631610353	10.3	998732.01	4594167226
2019e	7.6	736928.47	3389870963	13.6	1318714.10	6066084881
2020e	9.3	901767.73	4148131573	17	1648392.63	7582606101
2021e	11.1	1076303.42	4950995748	20.2	1958678.30	9009920191
2022e	12.8	1241142.69	5709256359	23.2	2249571.12	10348027150
2023e	14	1357499.81	6244499142	25.5	2472588.95	11373909152
2024e	14.8	1435071.23	6601327665	27.2	2637428.21	12132169762
2025e	16.6	1609606.92	7404191840	29.7	2879838.89	13247258895

[1] Estimated sales from New Frontier Data, 2019

[2] Estimated amount of product calculated based on average cost of cannabis from ABCD Agency, 2018. See Appendix B for average cost calculations.

[3] Based 4600 kg CO_2 emissions per kg of final product from Mills, 2012

Appendix D: Projected Energy Costs

Year	**Adult Use Only**			**Legal Use, including Medical**		
	Estimated Sales[1]	**Estimated Amount of Product[2]**	**Energy Cost[3]**	**Estimated Sales[1]**	**Estimated Amount of Product[2]**	**Energy Cost[3]**
	$USD Billion	kg cannabis	$USD Billion	$USD Billion	kg cannabis	$USD Billion
2017	3.3	319982.10	0.80	7.9	766017.75	1.92
2018	5.9	572089.21	1.43	10.3	998732.01	2.50
2019e	7.6	736928.47	1.84	13.6	1318714.10	3.30
2020e	9.3	901767.73	2.25	17	1648392.63	4.12
2021e	11.1	1076303.42	2.69	20.2	1958678.30	4.90
2022e	12.8	1241142.69	3.10	23.2	2249571.12	5.62
2023e	14	1357499.81	3.39	25.5	2472588.95	6.18
2024e	14.8	1435071.23	3.59	27.2	2637428.21	6.59
2025e	16.6	1609606.92	4.02	29.7	2879838.89	7.20

[1] Estimated sales from New Frontier Data, 2019
[2] Estimated amount of product calculated based on average cost of cannabis from ABCD Agency, 2018. See Appendix B for average cost calculations.
[3] Based $2500 USD per kg of final product from Mills, 2012

Chapter 8: Solid and Hazardous Waste

Introduction

As the sale of cannabis products continues to grow, so does the production of cannabis waste. The two main waste streams from cannabis are the plant material and the packaging waste. Some estimates place the amount of cannabis (and hemp) waste at about 1 million tons in North America in 2019 (Peterson, 2019).

Multiple wastes are produced by cannabis facilities, as shown in Figure 8.1. These are highly regulated, either under state cannabis regulations or as hazardous wastes under the EPA. For most wastes produced by the cannabis industry, their fate is in landfills (Thompson, 2019).

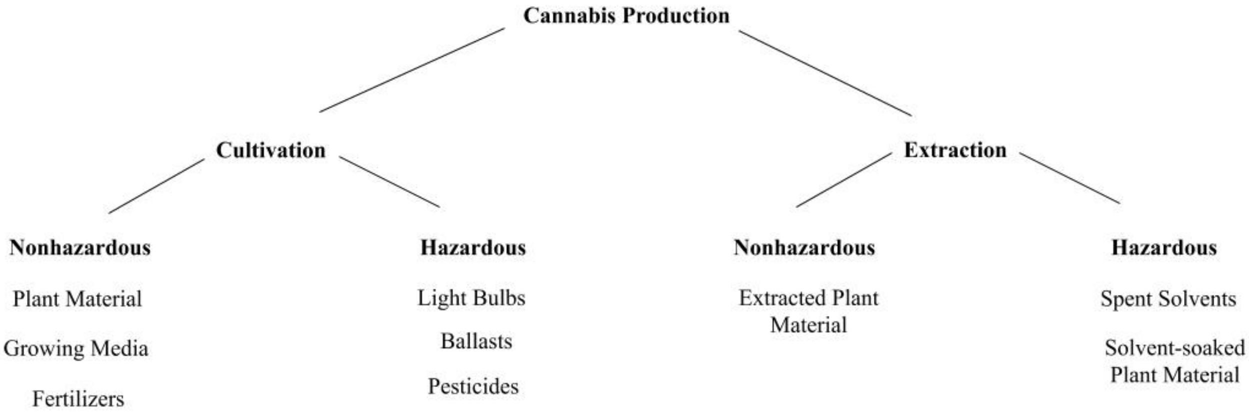

Figure 8.1. Types of Waste.

Types of Waste

Plant Material

Cannabis biomass waste, which includes leaves, flowers, and stems, is a regulated material. Cannabis biomass is heavily regulated in order to prevent it from being diverted outside of the operation (Badertscher & Badertscher, 2018). A common requirement in legal states is a form of biomass tracking system under which cultivators are required to keep an audit trail of all of the cannabis biomass. The biomass is tracked from the moment it is removed from the flower room until it is disposed of (Badertscher & Badertscher, 2018).

Prior to disposal, many waste regulations require that the biomass be rendered unrecognizable and unusable. Often, this involves grinding the biomass and mixing it with other materials, such as growing media, soil, mulch, or food waste (Badertscher & Badertscher, 2018; CCC, 2020). When the biomass is mixed with other materials, it becomes a commercial trash rather than a regulated waste and can be sent to a landfill. If the biomass is not immediately disposed of, it must be securely stored (Badertscher & Badertscher, 2018).

Disposing of cannabis biomass is not always as simple as sending it to a landfill. For example, under the waste ban regulations in Massachusetts, the biomass "is banned from disposal in the trash if a business generates one ton or more per week for disposal" (CCC, 2020). If a facility produces more than one ton of "commercial organic matter" per week for disposal, the must be disposed of by other methods. Other disposal methods for biomass include composting or anaerobic digestion (CCC, 2020). In Massachusetts, the biomass needs to be stored in a secure and locked container and location prior to collection. The regulations require that "at least two Marijuana Establishment agents must witness and document how the marijuana waste is handled" (CCC, 2020). The facility must also develop and maintain a record of the biomass for at least three years (CCC, 2020).

Growing Media

More media waste is usually produced than biomass waste. Growing media is often used once and disposed of (Badertscher & Badertscher, 2018). Depending on the material, the media can be reused, composted, or must be disposed of. Growing media can be made of organic materials, such as peat or coco, and inorganic materials, such as foam (Badertscher & Badertscher, 2018).

Organic materials have more potential for reuse than inorganic materials. Media reuse requires root material removal, grading, blending, amending, sanitizing and recharging. After processing organic media, including peat, coco, and other organic nutrient soil mixtures can be reused daily as long as it delivers a consistent performance level (Badertscher & Badertscher, 2018). Composting could be used to reduce the amount of media waste, but some organic materials do not break down readily. If the media does not compost readily, and there is not enough cannabis biomass to media ratio, supplemental biomass may need to be acquired (Badertscher & Badertscher, 2018).

Inorganic media typically produce less waste than organic media. Block media, which include rockwool and foam blocks are popular inorganic media. Block growing is similar to container growing, but removes the need for containers. Overall, the volume of waste is lower when using block media due to the lack of containers. However, block media can be difficult to reuse due to the root structures grown into the blocks. Block media cannot be incorporated into compost or field soil because it does not break down (Badertscher & Badertscher, 2018). Other types of inorganic media include fired clay balls, perlite, gravel, crushed lava rock and similar materials. These loose, inorganic media are typically used in ebb-and-flow systems. Roots can easily be removed from the media and the media can be treated with heat or chemicals to kill pathogens. The reuse potential of these loose, inorganic media is indefinite, meaning media waste could be eliminated entirely (Badertscher & Badertscher, 2018). Another option to eliminate media waste is to grow medialess. Media-less growing is an advanced technique, discussed in Chapter 3.

Fertilizers

Depending on the growing technique, cannabis cultivators may use fertilizer solutions to support plant growth. The solutions are often recycled, but eventually must be replaced and disposed of. To dispose of fertilizer solutions, concentration or dilution may be used. Concentration involves evaporating the excess liquid off to produce a low volume of solid residual salts. Dilution, as the name implies, involved diluting the fertilizer solution with another liquid, typically water (Badertscher & Badertscher, 2018).

Fertilizers are regulated on a state and local level. Local regulations may or may not allow for fertilizer solutions to be dumped into a municipal sewer. Local regulations may also allow sufficiently diluted fertilizer solutions to be released back into watersheds (Badertscher & Badertscher, 2018). Due to the variety of fertilizer disposal methods in each state and locality, it is important to verify local laws to ensure proper disposal.

Hazardous Waste

Cannabis facilities, particularly extraction facilities, generate hazardous wastes. The hazardous wastes include: mercury-containing lighting and ballasts, pesticides, solvents, used oil, other chemicals used in facility operation and maintenance, cannabis soaked in a flammable solvent for purposes of producing concentrates, electronics (e-waste) and batteries (CCC, 2020; DDPHE, 2018). Most of the hazardous wastes generated by cannabis facilities are considered universal wastes (DDPHE, 2018), and are regulated by the EPA under the Resource Conservation and Recovery Act (RCRA). RCRA is the public law that creates the framework for the proper management of hazardous and non-hazardous solid waste (EPA, 2020). Federal, as well as state regulations, include provisions for governing how much hazardous material is stored and for how long, labeling, manifest, transportation, management, and disposal. If a cannabis facility generates hazardous waste, they must obtain an EPA ID. A facility's status as a hazardous waste generator determines how much waste they may accumulate onsite at one time and how frequently they must remove the waste to be recycled or disposed of (CCC, 2020).

A particular challenge with hazardous waste is how to manage spent solvent contaminated with cannabis residue. Under federal law, spent solvents that are contaminated with cannabis residue cannot cross state lines. This can be problematic if a state does not have a local disposal site (Thompson et al., 2019). Another concern with hazardous waste is for environmental health officials who need to identify which wastes are hazardous and which are not when a cannabis facility shuts down. When a cannabis facility goes out of business or gets shut down due to regulatory violations, unidentified wastes may be left behind. Until the waste is properly identified, it must be considered hazardous waste (Keenan & Duazo, n.d.). This can make the cleanup process more timely and expensive.

Methods of Disposal

There are several options for the disposal of cannabis waste including, landfilling, composting, in-vessel digestion, and incineration. The two most common methods are landfilling and composting (Thompson, 2019).

Compost

Cannabis waste may be composted after it is ground up and mixed with other organic material. This organic material includes, "paper waste, cardboard waste, food waste, grease or other compostable oil waste, bokashi or other compost activators and soil" (DPHE, n.d.). Many states across the country are looking to reduce the amount of organic material entering landfills and are requiring cannabis waste to be composted, such as Massachusetts and California (Thompson, 2019). Composting is more sustainable than the other common alternative, landfilling, because the waste is reused in another form. There are several challenges in composting cannabis biomass, including space requirements, cannabis waste regulations, and obtaining other organic material. Composting requires a certain amount of land area to set up an appropriately-sized compost pile, which may be problematic for indoor facilities. There is the option to send the organic waste to a composting facility; however, to avoid concerns about the legal status of cannabis, many composting facilities do not accept cannabis waste (Thompson, 2019). If a facility does not have ample space on their property to compost onsite, this leaves them with limited options. Facilities need to dispose of the waste as quickly as possible, so they are forced to combine the organics with other facility trash and landfill the mixture, even though it is not the most cost-effective or sustainable option (Thompson, 2019). Obtaining proper organic material may also be an issue for indoor facilities that use hydroponics or other soilless media (Thompson et al., 2019). These facilities then have to purchase materials specifically for the purpose of composting.

Landfills

Despite the fact that most of the waste produced by the industry (biomass and growing media) can be composted, many facilities opt for landfilling. Using landfills is one of the most inefficient forms of waste disposal for cannabis since it produces more waste than was originally generated. Cannabis must be, at maximum, 50% of the waste when it is disposed of, so when biomass waste is mixed with other materials (cat litter, sawdust, shredded paper), double the amount of organic material is ending up in a landfill. The quantities of this material may be on the order of several tons per week per facility. When in a landfill, organic matter undergoes anaerobic decomposition and produces the powerful greenhouse gas, methane. To address this issue, some states, like Massachusetts, do not allow more than one ton of commercial organic waste per week to be disposed of in municipal landfills. This quantity includes both cannabis plant material and the mixing material, so only a half-ton of cannabis biomass could be landfilled per week (CCC, 2020).

Additionally, many states do not have exact guidelines for what is considered “unusable and unrecognizable,” with definitions for proper mixing materials as vague as “garbage” (OLCC, n.d.). This leaves the decision on what is appropriate to the generator. Generators have used bleach, ammonia, paint, smashed vape pens, and other chemicals to render biomass waste unusable (Thompson et al., 2019). This type of waste cannot be composted or put in a digester, so it must be disposed of in a landfill. An example of this can be seen in Figure 8.2.

Figure 8.2. Properly disposed cannabis waste (Peterson, 2019), improperly disposed (Thompson et al., 2019).

In-vessel Digestion

Anaerobic and aerobic digesters are a promising waste disposal technology for the cannabis industry. Anaerobic digestion occurs when microorganisms break down organic matter in the absence of oxygen to produce methane, carbon dioxide, and digestate, a wet mixture that is rich in nutrients (EPA, 2019). Digestate can then be used as a fertilizer for plants and the gases can be captured and used for another purpose. Technology that utilizes aerobic decomposition looks to reduce the production of methane. Aerobic decomposition takes place in the presence of oxygen to produce carbon dioxide and digestate. Aerobic decomposition has a higher energy demand than anaerobic decomposition and also produces more solids (Eklund, 2009). New technology has been developed by Micron Technology that takes advantage of aerobic decomposition while generating potable water. Micron Technology developed The Cannavore™ specifically to address the growing problem of excessive amounts of organic waste generated by the cannabis industry. The bioprocess utilized in the digester does not generate methane and reduces greenhouse gases overall, by eliminating those generated by hauling the material and landfilling (Micron Technology, n.d.). The use of anaerobic or aerobic digesters are associated with large up-front costs which may not be practical for a company that does not produce a large amount of waste.

Incineration

The incineration of biomass waste produces ash, heat, and flue gas. This flue gas can include carbon dioxide, nitrogen oxides, particulate matter, volatile organic compounds, and any other byproducts of the combustion of biomass material (Chen et al., 2017). Waste incinerators may be installed onsite at cannabis cultivation facilities (OLCC, n.d). The ashes produced may be used as a source of additional nutrients for plants, like composting, it is an opportunity to recover essential plant nutrients (source). Research has shown that the application of incinerator ash to plants increases soil available phosphorus (P) as well as improve P uptake in plants, which can increase crop yields (Zhang et al., 2001). Air pollution control technology would have to be implemented if an incinerator is used to mitigate the pollutants that may be present in the flue gas. These pollutants are highly dependent on the content of the waste, depending on the pesticides and other chemicals used on the plants. The production of toxic byproducts (ex. dioxin at low temperatures and high chlorine concentration) during incineration can be mitigated through proper incineration temperatures (850–950°C) and air emissions control (Zhang et al., 2001). In addition to onsite incineration, waste may be shipped offsite to be incinerated as municipal trash.

Recommendations

Regulations

The regulations surrounding the management of waste generated by the cannabis industry can be ambiguous. As stated previously, states like Oregon allow cannabis biomass waste to be rendered unusable by mixing with “soil, sand, other garbage” (OLCC, n.d.). These disposal guidelines are not specific enough and have the potential to create significant health, safety, and contamination issues for haulers, generators, and processors (Commendatore, 2019).

In addition to vague wording, regulations can be a hurdle to sustainable practices in the industry. The rule in most states that requires the 50/50 mix of cannabis waste with non-cannabis waste can more than double the amount of waste ending up in a landfill (Peterson, 2019). While there are valid reasons for adopting this type of regulation, it further increases the industry’s footprint. Regulations have since been altered in Colorado to allow cannabis waste to be mixed with other compostable waste in the hauling vehicle to mitigate this issue (Peterson, 2019). Additionally, prior to the passing of Senate Bill 18-187 in 2019, a third party could not pick up unadulterated cannabis waste in Colorado (Peterson, 2019). This severely limited the options for reuse in other industries as well as composting offsite, since cannabis has to be unadulterated in order to compost or further process it.

New technologies for cannabis waste disposal have also required changes to regulations (i.e. Kind ReDesigned Bokashi fermentation waste disposal, Alpine Waste and Recycling’s compactor, and Sesh Technologies Manufacturing rosin press) (McGregor, 2017). However, getting regulations passed that support more sustainable practices is not a straightforward process and can be challenging engaging with a non-scientific audience (McGregor, 2017).

Reducing, Reusing, and Recycling

The standard approach to a product life cycle is often referred to as cradle-to-grave, with resources flowing in one end and waste flowing out the other, from production to disposal. Most industries are a collection of linear flows described as “take-make-waste” (Robertson, 2017). Like most industries, the cannabis industry follows the cradle-to grave concept, with most waste ending up in landfills (Thompson, 2019).

Industrial ecology studies materials and energy flows through an industrial system, shifting them from a linear model to a closed-loop model (Robertson, 2017). A different approach to the cradle-to-grave concept is a cradle-to-cradle system. Cradle-to-cradle systems are a circular-economy concept that is modeled on nature. The idea is to use the waste from one process as materials for another industrial process, where output from one industry is input for another and materials are reused (Robertson, 2017). This idea can be applied to the cannabis industry in several facets of the process including: solvents, packaging, and biomass waste.

Solvents

Even with the use of closed-loop extraction systems, discussed in Chapter 4, solvents still need to be disposed of. After multiple runs with the same batch of solvent, the solvent must be replaced with new solvent. Ignitable and other hazardous solvents, such as butane, are hazardous and must be handled carefully according to regulations. Organic solvents, such as ethanol, have the potential to be repurposed.

The two main ways alternatives to land disposal for organic liquid wastes are reuse, including use as a fuel substitute, and incineration (Blaney, 1986). Prior to reuse or incineration, the waste must undergo some form of pretreatment. Major solid components need to be removed, then the organics need to be separated from the waste (Blaney, 1986). In this case, any waxes, chlorophyll, or other plant compounds would need to be removed. It is emphasized that reuse solvents should not contain solid material, organics, or other reaction products that may affect the reuse purpose (König, 2018).

Incineration is simply to destroy the waste and dispose of it as ash (Blaney, 1986). Instead of incineration, organic solvents can easily be reused for their original purpose or energy recovery. The solvent can be collected and recycled by distillation. Numerous solvents that are used regularly at high volumes, such as ethanol, can be recycled by distillation. The solvent can be purified via column distillation and reused by the facility (König, 2018). However, the purified solvent will still need to meet quality requirements established by the regulations. The other approach for solvent reuse is thermal treatment and energy recovery. Thermal reutilization allows spent solvents to be used as cost-effective input materials for energy production (König, 2018). The reuse product should contain minimal amounts of water and should only consist of hydrocarbons and oxygen containing solvents. They should not contain compounds with halogen, sulfur, and nitrogen molecules (König, 2018).

The potential reuse of solvents from the cannabis industry is a large grey area. Research needs to be conducted to determine if spent solvents can be purified to the necessary requirements for extraction or energy recovery. It is also unclear from the current regulations if this would be possible.

Packaging

Packaging cannabis products for sale to consumers represents a significant downstream waste source. Cannabis products are sold in a variety of different packaging. Common types of packaging include: vials, mylar bags, concentrate containers, pre-roll tubes, and exit bags (DDPHE, 2018). While packaging is not an avoidable waste, there are ways to reduce the impact of packaging on the industry's sustainability efforts. Packaging that is lightweight requires less fuel to ship, reducing the associated emissions. Packaging can be made from recycled content and is recyclable and/or compostable, such as recycled PET plastics, recycled high-density polyethylene (HDPE) or cardboard. Child-resistant packaging can be used to eliminate the need for an additional exit package. If exit packaging is necessary, a reusable exit bag can be used and facilities can encourage customers to return them to the store (DDPHE, 2018).

A closed-loop system for product packaging can be established by investing in a packaging return program at the point of sale. This would allow customers who do not have access to recycling services to recycle their packages. It also prevents small plastic containers and pieces from ending up in a landfill if they are not properly sorted during the recycling process. There is also potential to establish a takeback program with the packaging supplier or manufacturers that may be able to reuse the packaging or reform it into new packaging (DDPHE, 2018).

In order to manage the packaging waste from cannabis sales, the companies TerraCycle and Tweed launched a cannabis packing recycling program throughout Canada (Commendatore, 2019). The Tweed x TerraCycle Cannabis Packaging Recycling Program collects all cannabis containers from all licensed producers including tins, plastic bags, tubes and bottles with child-proof caps. All of the packaging products collected by this joint venture are typically difficult to recycle. Since its debut, the program has collected over 165,000 containers, which would otherwise would have ended up in landfills. The program is free to join and is active in more than 106 legal cannabis retail locations across Canada. To make the recycle program accessible to as many consumers as possible, participants can use drop-off points located at participating retail stores or register online for free pickup and recycling of discarded containers (Waste360 Staff, 2019).

Repurposing Plant Waste

Bioremediation

There is already significant research on how to repurpose waste hemp fibers. One study by Vukčević et al. (2015) investigated the production of activated carbon sorbents from waste hemp fibers for pesticide removal. The study found that activated hemp fibers could successfully be used as a sorbent in water purification. The activated hemp fibers were highly efficient in removing pesticides, and mimicked the adsorption capacities of other activated carbon materials (Vukčević et al., 2015). Another study by Pejic et al. (2009) investigated the use of waste hemp fibers as raw materials for producing biosorbents and biocarbon sorbents for heavy metal ion removal from wastewater. The study found that hemp fibers were able to sorb lead, cadmium, and zinc ions from different ion solutions. During one trial, the hemp fibers sorbed approximately more than 80% of the metal ions within 5 minutes (Pejic et al., 2009). Hemp fibers have also been used to extract nickel from sewage sludge and selenium from soil (Leonard, 2018).

According to the current body of research, industrial hemp plants and waste hemp fibers have potential to be applied in various forms of bioremediation due to its ability to remove a multitude of toxic substances from soils and water. However, a similar body of literature does not exist for all forms of cannabis waste. If cannabis waste from recreational cannabis facilities has similar properties to waste hemp fibers, it may be capable of removing toxic metals from soils and waters as well.

Energy Production

Cannabis biomass and extracted plant material wastes could potentially be used for energy production. The use of hemp to produce biofuel is currently being explored. One study by Prade et al. (2011) found that hemp is a suitable energy crop in the cold climate regions of Northern Europe. The study concluded that hemp has a high energy yield for both solid fuel and biogas production. The results show that hemp has a similar or superior energy yield compared to other common energy crops grown in Northern Europe (Prade et al., 2011). Another study by Kreuger (2012) investigated the energy efficiencies and economic performance of methane and ethanol production from hemp. The study concluded that despite high energy efficiencies, no biogas production process is currently not economically viable. For the co-production of biogas, heat, and power from hemp to be economically viable, the total cost would have to be reduced by one third (Kreuger, 2011). As noted in the study, the cost of the feedstock accounted for more than half of the total process cost (Kreuger, 2011). If waste cannabis biomass can produce similar biogas yields as hemp, it could be a low-cost feedstock source. The extraction plant material waste could provide another source for biogas production. In the beer industry, brewery mash, a by-product of beer brewing, is commonly processed to produce biogas (Konrád et al., 2014). Extraction plant material that is soaked in nonhazardous solvents may have the required properties to process it like beer mash. In theory, a mixture of biomass and extracted plant material waste could be used in a similar manner to beer mash to produce a clean fuel source.

Another option for energy production from cannabis waste is to create fuel pellets. The pelletization process includes milling, drying, and mechanically densifying the biomass to enhance its heating value and burning characteristics (Pirragalia et al., 2013). For pellets to be an effective fuel source, the biomass must have low moisture content, low ash and particulate emissions content, as well as ease of transportation and storage (Pirragalia et al., 2010). A low moisture content (MC) is needed for solid fuel sources in order to decrease microbial degradation during storage (30%) and “achieve sufficient cohesion of e.g. pellets after compression of biomass (10% < MC < 20%)” (Prade et al., 2011). Studies have been conducted to determine the feasibility of using hemp pellets as an energy source and have promising results (Han et al., 2009; Prade et al., 2011).

The study by Prade et al. (2011) explored the moisture content (MC) and energy yield of hemp in Northern Europe. Prade et al. determined that the MC of hemp decreased from an original value of 81% to 29% during harvesting periods. They determined the MC decreases with later harvesting dates, which increases the energy yield. However, the research also showed that biomass is lost at later harvesting periods, which counteracted the energy yield gained from decreased MC (Prade et al., 2011). Prade et al. concluded that hemp has a high energy yield for both solid fuel that is comparable to other energy crops in Northern Europe (Prade et al., 2011).

A study conducted by Han et al. (2009) explored the potential of creating hemp pellets for energy production. They found that the woody core of the hemp plant had a similar lignin content of 19.4% to that of hardwood (20-25%). Additionally, Han et al. determined the core had low ash content of 0.5%, which resulted in low ash formation during pellet burning. Han et al. also measured a heating value of 18.4 MJ/kg for hemp pellets, which is comparable to that of hardwood pellets. This research suggests that hemp may be suitable for pelletization and as an energy source, which warrants research into the feasibility of using cannabis waste as a pellet energy source.

Future Research

It is unclear why cannabis waste reuse potential has not been researched in depth. It may be due to the tight regulations regarding cannabis waste disposal. As the industry continues to grow, more cannabis waste will be produced. It is important to look for opportunities to reuse this waste and prevent it from entering landfills. Future research could be conducted to investigate the use of cannabis waste to produce energy, to create compostable packaging, or other sustainable uses.

Outside of academic research, cannabis waste is a potentially marketable commodity. There are opportunities to find new end uses for cannabis waste, such as animal bedding or particle boards (Peterson, 2019). There is an opportunity for entrepreneurs and investors to invent and discover new back-end products that can be made from cannabis waste.

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Chapter 9: Future Research

Ecosystem Degradation

In California, the largest producer of cannabis in the United States, cannabis cultivation is mainly concentrated in remote forested watersheds, on private, public, and Native American tribal lands, and is largely grown outdoors (Carah et al., 2015). Cannabis cultivation practices do not follow the same practices as other forms of agriculture. More established agriculture on the north coast of California relies on captured and stored water from heavy winter stream flows for later summer use. On the contrary, cannabis cultivators typically irrigate their summer and fall crops with surface water diversions directly from streams and springs. These diversions are localized in smaller, more sensitive watersheds, which are often biodiversity hotspots. (Carah et al., 2015). Surface water diversions for cannabis cultivation can significantly reduce or eliminate low stream flows during California's dry summer season, especially during drought years. High volumes of surface water diversions can threaten the survival of the rare and endangered salmonids, amphibians, and other animals located in these watersheds (Carah et al., 2015). Furthermore, these watersheds can be polluted by pesticides, fertilizers, and petroleum fuels used by cannabis cultivators (Carah et al., 2015).

Outdoor and greenhouse cannabis cultivation are often located in remote watersheds with high conservation value and biodiversity in California. Rare and endangered species such as coho salmon (*Oncorhynchus kisutch*), steelhead trout (*Oncorhynchus mykiss*), northern spotted owl (*Strix occidentalis caurina*), and Pacific fisher (*Pekania pennanti*) can be negatively impacted by cannabis cultivation (Butsic et al., 2018). Land terracing, road construction, and deforestation remove native vegetation and increase erosion. Erosion increases fine-sediment deposits into streams, which can damage spawning and rearing habitat for fish. Furthermore, the heavy use of pesticides and fertilizers can poison ecosystems and make their way into terrestrial food chains, posing significant risks to mammalian and avian predators (Carah et al., 2015). Wildlife poisoning occurs through direct poisoning or bioaccumulation in the food chain if cultivators use harmful pesticides, such as rodenticides (Butsic et al., 2018).

Land Use

Humboldt, Trinity, and Mendocino Counties, located in Northern California, are known as the "Emerald Triangle." The Emerald Triangle is arguably the birthplace of modern cannabis production in the United States, and Humboldt County may be the top cannabis-producing region in the world (Bustic & Brenner, 2016). The Emerald Triangle and Humboldt County are often the center of studies on the environmental impacts of the cannabis industry, specifically in regard to land use and degradation. In a study by Bustic & Brenner (2016), 4428 grow sites in 60 watersheds located in Humboldt County were digitized to assess the environmental impact. Bustic & Brenner (2016) found that grows were clustered, suggesting disproportionate impacts in ecologically important locales. Over 68% of grows were located more than 500 meters from a developed road, highlighting the risk of landscape fragmentation. Twenty-three percent of grows were located on greater than 30% slopes, indicating a potential for erosion, sedimentation, and landslides. The study concluded that abundant grow sites clustered in steep locations far from developed roads, potential for significant water consumption, and close proximity to habitat for threatened species, all point toward high risk of negative ecological consequences (Bustic & Brenner, 2016).

The current footprint of outdoor cannabis farms has relatively minor landscape impacts (Wang et al., 2017). It is not the amount of land or water resources consumed by the cannabis industry that is of concern. Rather, it is the spatial distribution of cannabis cultivation facilities that determines that scale of environmental harm (Bustic & Brenner, 2016). The per-unit-area impacts could cause extensive habitat modification when scaled up to meet increasing demand (Wang et al., 2017). The overall size of most outdoor cannabis farms is small (less than 0.5 ha), but a large number of grows concentrated in one area can have a large impact on forest habitat. Outdoor cannabis farms are typically isolated in forest interiors, placed away from roads. This results in losses of core forest area and greater increases in forest edge and shape complexity. Outdoor cultivation tends to cause perforation of forest patches, which reduces the forest core area by creating "holes" in the forest. More edge area generated, which leads to irregularity in patch shape (Wang et al., 2017).

In California, outdoor cannabis farms are limited to 1 acre (0.4 ha) per parcel. The size restriction is intended to prohibit industrial-scale outdoor farms from developing. While there are good intentions behind the regulation, it is encouraging the continued spread of small farms. The more small farms that are established, the more the landscape will be fragmented (Wang et al., 2017). More research on land-use in the cannabis industry should be conducted, especially in regions outside of the Emerald Triangle, to help predict future cannabis expansion and moderate its impacts (Bustic & Brenner, 2016). More research will provide invaluable information for planners when handling difficult land use questions regarding allowable locations, buffering from sensitive uses, and distribution of facilities (Németh & Ross, 2014).

While most of the focus for land use degradation is focused on outdoor cannabis farms, it should be noted that many greenhouses are surrounded by large forest clearings created during construction with exposed soils subject to erosion (Bustic & Brenner, 2016).

Life Cycle Assessment

Life cycle assessment (LCA) is a method for measuring a product's impact on the environment throughout its entire life cycle, from cradle to grave (Robertson, 2017). Specifically, LCA is a holistic view of environmental interactions that covers a range of activities, from the extraction of raw materials and the production of the final product to delivery, use, and final disposal or recycling the product (Curran, 2008; Robertson, 2017). LCA quantifies energy flows, material flows, and environmental impacts of the entire lift of a product, and typically involves an ever-expanding scope. LCA is intended for comparison and is not an absolute evaluation. It is intended to help decision makers compare the major environmental impacts of their alternative choices (Robertson, 2017).

Performing a full LCA can be complex, challenging, and time-consuming (Robertson, 2017), but could provide invaluable information about the environmental impacts of the cannabis industry. An abbreviated LCA, while not comprehensive, could also provide a deeper understanding of the relative impacts of the industry. LCA performed by an expert could provide an improved basis for making informed decisions on how to regulate and mitigate the environmental impacts of the cannabis industry.

Industry Practices

There is currently no comprehensive documentation of common industry practices. Best management practices (BMPs) are provided by regulatory bodies and shared among industry professionals. However, BMPs do not encompass every industry practice. While conducting this study, some industry practices were only revealed by word of mouth; no formal reporting or documentation existed on these practices. For example, when speaking with consultant engineers, it was discovered that some facilities sanitized their washrooms with caustic chemicals. This practice may cause spikes in pH in the facility's wastewater. This practice is not documented in any best management practices or regulations that were found. It can be assumed that there are a multitude of industry practices that were missed in this research. Without conversations with industry professionals, it is difficult to identify every aspect of the industry. In order to fully assess and understand the environmental impacts of the industry, every part of the process must be known. Additionally, field based measurements of water use, chemical use, cropping systems, yields, and other direct measurements are all needed to inform effective environmental analyses and regulations (Bustic & Brenner, 2016).

Influence of Illegal Grows

Even with the legalization of recreational cannabis, the illicit cannabis market will likely remain intact. For example, illicit cannabis cultivation still exists in Colorado and California, despite the legalization of recreational use (Carah et al., 2015). The impact of illicit grows on the environment is often more detrimental, since they do not adhere to any regulations. These environmental impacts include, "loss and fragmentation of sensitive habitats via illegal land clearing and logging; grading and burying of streams; delivery of sediment, nutrients, petroleum products, and pesticides into streams; toxic pesticide use; surface water diversions for irrigation resulting in reduced flows and completely dewatered streams" (Bauer et al., 2015).

In 2011 the U.S. Forest Service reported illicit grow sites in 67 national forests in 20 states (Thompson et al., 2017). In 2018, an estimated 14,000 illicit grow sites on public and private lands were located in Humboldt County, California (Helmer, 2019). There have been several studies documenting the effects of illicit grow sites in California (Helmer, 2019). Many of these studies have focused on toxic pesticide use at illegal grow sites, which can make their way up food chains, killing mammalian and avian species. For example, a study conducted in 2012 found that 80% of deceased Pacific fishers recovered in northern California and the southern Sierra Nevada were exposed to anticoagulant rodenticides from illicit grow sites (Carah et al., 2015). The use of carbofuran, a federally banned pesticide, has also been documented at illicit grow sites. Prior to 2014, the presence of carbofuran at illegal grow sites in California was sporadically discovered. However a 34% increase of carbofuran at 32 cannabis cultivation sites was documented in 2015 (Thompson et al., 2017).

The use of toxic pesticides also poses a risk to recreational users of public lands. Illicit grow sites often leave pesticides, like carbofuran, in soda and Gatorade bottles. Contact with a single drop has the capacity to kill an adult human. These bottles may remain on the ground for years at unremediated grow sites and be punctured by animals or humans long after the site has been abandoned (Thompson et al., 2017). The heavy use of pesticides, as well as fertilizers and petroleum fuels, at illicit grow sites can also contaminate watersheds (Carah et al., 2015).

Illicit cannabis cultivation and its associated environmental impacts are not expected to decrease as more states legalize recreational cannabis. As seen in Colorado, the illicit market is still a problem, despite the legalization of recreational cannabis in 2014 (Carah et al., 2015). Legalization most likely will lead to an increased consumption of cannabis, which will increase the demand for the product. Depending on the regulations of the market and level of enforcements, the black market may continue to fill a portion of the demand. Until cannabis is federally legal, shipping the product across state lines will remain illegal, which will keep the black market relevant. Addressing illegal production of cannabis will require specifically addressing and remediating its impacts (Carah et al., 2015).

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Chapter 10: Conclusions

The current body of research on recreational cannabis is limited to a handful of peer-reviewed studies, blog posts, and independent researchers publishing articles online. These peer-reviewed studies are quickly becoming outdated since the industry is evolving at a rapid pace. The research undertaken with this project has resulted in an in-depth, comprehensive document on the environmental impacts of cannabis cultivation and processing.

Many of the current studies include impacts from illegal cannabis cultivation, which is a separate issue in itself. Many studies are also a combination analysis of medical and recreational cannabis regulations and processing. Medical and recreational cannabis do not fall under the same regulations. The regulations for medical cannabis are often much stricter than the regulations for recreational cannabis, affording medical consumers better protections than nonmedical consumers. Regardless, neither set of regulations address the full scope of environmental impacts.

As we have demonstrated throughout this document, there are opportunities to implement more sustainable practices throughout various aspects of cannabis production. However, the tradeoffs between adopting sustainable practices versus increased energy consumption and cost must be evaluated. Incentives as well as regulatory and enforcement efforts can be established to mitigate this tradeoff. Incentive programs, such as certification and ecolabeling, have been widely used to help reduce the environmental impacts of other agricultural crops and could play a similar role in the cannabis industry (Carah et al., 2015). Improved regulatory and enforcement efforts will help cultivators and producers comply with environmental laws and protect environmental resources. Additionally, technical assistance and outreach programs could help encourage the adoption of best management practices and voluntary compliance (Carah et al., 2015).

As the legal cannabis industry continues to grow, so will the environmental issues that are associated with it. More fundamental and applied research to identify these issues before the industry scales and the environmental damage become too widespread to mitigate. The environmental degradation caused by the cannabis industry requires a direct policy response. The current regulatory framework is inadequate to afford any real environmental protections. The opportunity to reduce, regulate, and mitigate environmental degradation will be missed if policymakers continue to ignore the environmental impacts of the industry.

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