Quantification of the role of mineral fertilizer in the environmental performance of the Canadian cannabis (*Cannabis sativa*) industry and urban soil-less farms

Vincent Desaulniers Brousseau

Department of Bioresource Engineering
McGill University, Montreal, Qc, Canada
July 2024

A thesis submitted to McGill University
In partial fulfillment of the requirements of the degree of Doctor of Philosophy

Table of Content

List of Figures

List of Tables

List of Acronyms

Abiotic resource depletion potential (ADP)

Best management practices (BMP)

Cannabidiol (CBD)

Cannabidiolic acid (CBDa)

Cannabinoid production efficiency of nitrogen (CPE_N)

Cannabigerol (CBG)

Cannabigerolic acid (CBGa)

Carbon dioxide equivalent (CO_2-eq)

Controlled environment (CE)

Diode array detector (DAD)

Electrical conductivity (EC)

Emission factor (EF)

Fossil fuel depletion (FD)

Functional unit (FU)

Global warming potential (GWP)

Greenhouse (GH)

Greenhouse gas (GHG)

Heating, ventilating, and air conditioning (HVAC)

High-performance liquid chromatography (HPLC)

High pressure sodium (HPS)

Ion selective electrodes (ISE)

Life cycle assessment (LCA)

Light-emitting diode (LED)

Linear diode array detector (DAD)

Low-density polyethylene (LDPE)

Marine eutrophication potential (MU)

Metal resource depletion (MD)

Nitrogen use efficiency (NUE)

Nutrient film technique (NFT)

Organic liquid fertilizer (OLF)

Polyvinyl chloride (PVC)

Principal component analysis (PCA)

Relative humidity (RH)

Tetrahydrocannabinol (THC)

Tetrahydrocannabinolic acid (THCa)

Terrestrial acidification (TA)

Abstract

This thesis presents a comprehensive examination of the environmental impact and sustainability practices within the realms of cannabis (*Cannabis sativa*) production and hydroponic agriculture through three distinct experiments. The novelty of this research is represented by the fact that no previous research has quantified the global warming potential (GWP) of outdoor cannabis production. Despite having roughly 600 ha dedicated to outdoor cannabis production in Canada, no study has looked at the environmental footprint of this activity.

This thesis looks at fertilizer production and use in cannabis agriculture. In two experiments, it combines data generated in fertilizer-response trials with life-cycle assessments (LCA) methodology. This is a novel approach, as previous LCA studies on fertilizer production and use have only been based on modelization, where yield is assumed to be similar. However, no available studies combine both primary data from actual plant growth experiment for cannabis or basil (*Ocimum basilicum*), a model plant used in one experiment. Furthermore, it is the first report of the calculation of environmental impacts of cannabis production in a Canadian context.

The first experiment delves into the environmental impact assessment of outdoor photoperiod insensitive *Cannabis sativa* cultivation. Employing ISO recognized methodology, the study quantifies various parameters and unveils novel insights into sustainable cannabis production. Most notably, it shows how N-deficiency can be manipulated to enhance cannabinoid production efficiency. Key findings highlight the significant contribution of potting media to the GWP associated with cannabis cultivation, emphasizing the need for strategies to mitigate environmental impact associated with its use. It is shown that producers wanting to decrease their GWP can try to (1) refrain from using peat-based potting media and (2) explore N-deficiency as a mean to sustainably increase delta-9-tetrahydrocannabinol (also known as THC). Furthermore, the functional unit (FU) used in previous cannabis LCA, 1 kg of dried flower, is compared for the first time to a novel FU: 100 mg of THC. Although the difference is limited, it can be argued that it is a better FU for extract and edible producers.

Moving forward, the second experiment investigated the utilization of organic liquid fertilizer (OLF) in hydroponic, or soil-less, systems, utilizing a novel bioreactor and basil as a model plant. This study underscores the potential to achieve comparable plant growth while mitigating greenhouse gas (GHG) emissions. Notably, managing N loss

during the bioreaction process emerges as crucial for maximizing environmental benefits. However, growing concerns surrounding the need for greener means of production makes this a very attractive candidate, as it can enable nutrient cycling in cities. The decrease in demand for production and transport of conventional fertilizer products when using locally-sourced nutrient rich biomass usually discarded as waste could decrease GWP of urban food production 5-fold.

In the third experiment, cannabis production in Canada is analyzed, with models adapted and updated to reflect regional differences. Consideration of factors such as climate, energy sources and electrical grid carbon intensity reveals outdoor production as a more environmentally friendly option, able to decrease GWP up to 10-fold compared to indoor production.

Collectively, these experiments contribute significant advancements to our understanding of environmental impacts and sustainable practices in cannabis production and soil-less agriculture. By shedding light on the intricate relationship between cultivation methods, environmental impact, and sustainability, this research offers valuable insights for growers, policymakers, and environmental advocates alike. The findings presented herein serve as a cornerstone for informed decision-making towards the adoption of more sustainable agricultural practices. Furthermore, in an era marked by escalating concerns about climate change and resource depletion, the significance of this work extends beyond its immediate application, highlighting the imperative of sustainable practices in shaping the future of agriculture and environmental stewardship.

Résumé

Cette thèse présente un examen complet de l'impact environnemental et des pratiques de durabilité dans les domaines de la production de cannabis (*Cannabis sativa*) et de l'agriculture hydroponique à travers trois expériences distinctes. La nouveauté de cette recherche réside dans le fait qu'aucune recherche antérieure n'a quantifié le potentiel de réchauffement global (PRG) de la production de cannabis en extérieur. Bien que le Canada consacre environ 600 ha à la production de cannabis en extérieur et que les deux tiers de la production totale de cannabis aux États-Unis proviennent de serres ou de cultures en extérieur, aucune étude n'a examiné l'empreinte environnementale de cette activité. Cette thèse porte sur la production et l'utilisation d'engrais dans l'agriculture du cannabis. Dans deux expériences, elle combine les données générées dans les essais de réponse aux engrais avec la méthodologie des analyses du cycle de vie (ACV). Il s'agit d'une nouvelle approche, car les études ACV précédentes sur la production et l'utilisation d'engrais n'ont été basées que sur la modélisation, où le rendement est supposé être similaire. Cependant, aucune étude disponible ne combine à la fois des données primaires provenant d'expériences de croissance de plantes réelles pour le cannabis ou le basilic (*Ocimum basilicum*), une plante modèle utilisée dans une expérience. En outre, il s'agit du premier rapport sur le calcul des impacts environnementaux de la production de cannabis dans un contexte canadien.

La première expérience porte sur l'évaluation de l'impact environnemental de la culture en extérieur de Cannabis sativa, insensible à la photopériode. Utilisant une méthodologie reconnue par l'ISO, l'étude quantifie les différents impacts sur l'environnement de la culture de *Cannabis sativa.* Il montre notamment comment la carence en azote peut être manipulée pour améliorer l'efficacité de la production de cannabinoïdes. Les principaux résultats mettent en évidence la contribution significative des milieux de culture au PRP associé à la culture du cannabis, soulignant la nécessité de stratégies visant à atténuer l'impact sur l'environnement. Il est démontré que les producteurs souhaitant réduire leur PRP peuvent essayer (1) de s'abstenir d'utiliser des milieux de culture à base de tourbe et (2) d'explorer la carence en azote comme moyen d'augmenter durablement le delta-9-tétrahydrocannabinol (également connu sous le nom de THC). En outre, l'unité fonctionnelle (UF) utilisée dans les précédents ACV du cannabis, à savoir 1 kg de fleurs séchées, est comparée pour la première fois à une nouvelle UF : 100 mg de THC. Bien que la différence soit limitée,

on peut affirmer qu'il s'agit d'une meilleure UF pour les producteurs d'extraits et de produits comestibles.

La deuxième expérience porte sur l'utilisation d'engrais liquide organique (OLF) dans les systèmes hydroponiques, en utilisant un nouveau bioréacteur et le basilic comme plante modèle. Cette étude souligne la possibilité d'obtenir une croissance végétale comparable tout en réduisant les émissions de gaz à effet de serre (GES). Notamment, la gestion de la perte d'azote au cours du processus de bioréaction s'avère cruciale pour maximiser les avantages environnementaux. Les préoccupations croissantes concernant le besoin de moyens de production plus écologiques en font un candidat très attractif, car il peut permettre le cycle des nutriments dans les villes. La diminution de la demande de production et de transport de produits fertilisants conventionnels lors de l'utilisation de biomasse riche en nutriments d'origine locale, habituellement jetée comme déchet, pourrait diviser par cinq le PRP de la production alimentaire urbaine.

Dans la troisième expérience, la production de cannabis au Canada est analysée, avec des modèles adaptés et mis à jour pour refléter les différences régionales. La prise en compte de facteurs tels que le climat, les sources d'énergie et l'intensité en carbone du réseau électrique révèle que la production en extérieur est une option plus respectueuse de l'environnement, capable de diviser le PRP par 10 par rapport à la production en intérieur.

Collectivement, ces expériences contribuent à faire progresser de manière significative notre compréhension des impacts environnementaux et des pratiques durables dans la production de cannabis et l'agriculture hydroponique. En mettant en lumière la relation complexe entre les méthodes de culture, l'impact sur l'environnement et la durabilité, cette recherche offre des informations précieuses aux cultivateurs, aux décideurs politiques et aux défenseurs de l'environnement. Les résultats présentés ici constituent la pierre angulaire d'une prise de décision éclairée en vue de l'adoption de pratiques agricoles plus durables. En outre, à une époque marquée par des préoccupations croissantes concernant le changement climatique et l'épuisement des ressources, l'importance de ce travail va au-delà de son application immédiate, soulignant l'impératif de pratiques durables pour façonner l'avenir de l'agriculture et de la gestion de l'environnement.

Acknowledgements

I extend my heartfelt gratitude to my parents, whose unwavering dedication to hard work has been a guiding light throughout my life. Their love and support have been indispensable, without which I would not exist.

I am indebted to my brothers for their inspiring example, reminding me to stay true to myself amidst societal pressures. To my grandmother, uncles, and aunts, whose influence have enriched my journey, I offer my deepest appreciation.

I am incredibly thankful for my girlfriend, whose unwavering support and comforting presence have been a source of solace during times of overwhelming stress. Her ability to help me relax and find peace amidst chaos is truly invaluable.

I am immensely grateful to my supervisor, Dr. Mark Lefsrud, for his continuous support, patience, and encouragement throughout my Ph.D. journey. His guidance has been invaluable, motivating me to pursue my research with diligence and passion.

I also express my sincere thanks to Dr. Benjamin Goldstein and Dr. Sarah MacPherson for their invaluable guidance and insights during my graduate studies. Their mentorship and perspective have played a pivotal role in shaping my dissertation.

I am thankful for the opportunity provided by Circulus Ag Tech to lead a research project in their facilities. Additionally, I extend my gratitude to the entire teams at the Cannabis Lab of Health Canada and McGill Biomass Laboratory for their support, training, and funding, which have been instrumental in the success of my work.

There are too many to list individually, but I am immensely grateful to my coauthors and lab mates, who have not only been colleagues but have become dear friends.

I am also grateful for the privilege of being born into a society that values higher education and champions peaceful dialogue as a means for social advancement. I encourage those who may feel frustrated or disheartened by the current state of our society to engage with individuals from diverse backgrounds and consider how varying perspectives are essential for growth: *Je me souviens.*

Contribution to original knowledge

The following contribution to knowledge statement synthesizes findings from three experiments conducted in the domains of environmental impact assessment, sustainable agriculture, and carbon footprint analysis:

Experiment 1: Outdoor Cannabis Production Environmental Impact Assessment

1. Quantified the environmental impact of outdoor *Cannabis sativa* production using primary data and an LCA over three years, focusing on global warming, eutrophication, metal, and fossil resource potentials.
2. Introduced sustainable optimization insights for cannabinoid production, particularly through nitrogen deficiency response.
3. Highlighted the potential of low N and high K inputs to increase THC content.

Experiment 2: Utilization of Organic Liquid Fertilizer (OLF) in Soil-less Systems

1. Investigated the use of OLF derived from insect waste to enhance plant growth in soil-less systems.
2. Conducted comparative analysis with traditional inorganic fertilizers, evaluating plant yield and nutrient uptake.
3. Explored environmental implications through LCA, identifying OLF's potential to reduce GHG emissions.

Experiment 3: Carbon Footprint Analysis of Cannabis Production in Canada

1. Quantified the carbon footprint and environmental impacts of *Cannabis sativa* production in Canada using a model to reflect province-specific electrical grid emissions.
2. Identified heating in colder climates as the primary driver of carbon emissions in Canada.
3. Compared carbon emissions between outdoor and indoor production, showing outdoor cultivation as substantially less carbon-emitting, and provided insights for stakeholders to reduce environmental impact.

Contribution of Authors

Following the McGill Guidelines for a Manuscript-Based Thesis, the contributions made by the candidate and the co-authors to the completion of this work are described here.

Vincent Desaulniers Brousseau is the principal author of this work, supervised by Dr. Mark Lefsrud from the Department of Bioresource Engineering, McGill University, Sainte-Anne-de-Bellevue, Quebec, Canada.

Dr. Mark Lefsrud, the supervisor and director of the thesis, co-authored all manuscripts and provided scientific guidance in the planning and execution of the work, as well as co-editing and reviewing manuscripts.

Dr. Benjamin Goldstein co-supervised this thesis, co-authored all manuscript and made valuable comments to improve the manuscripts.

Dr. Sarah MacPherson reviewed and made valuable comments to improve Chapter 4. Circulus Ag Tech (David Leroux, Thomas Giguère) provided funding assistance for access to their facilities for the experiment made in Chapter 4. They co-authored Chapter 4.

Dr. Mathieu Lachapelle and M. Ilies Tazi co-authored and assisted in the methodology and data production used for Chapter 5.

Journal Papers

Chapter 3 : Desaulniers Brousseau, V., Goldstein, B. P. and Lefsrud, M. (2024). Environmental Impact of Outdoor Cannabis Production, in *ACS Agricultural and Science Technology*. https://doi.org/10.1021/acsagscitech.4c00054

Chapter 4: Desaulniers Brousseau, V., Goldstein, B. P., Leroux, D., Giguère, T., MacPherson, S., and Lefsrud, M. (2024) Inorganic nitrogen replacement in hydroponics: Global warming potential of animal waste-based organic liquid fertilizer for urban farms (under review in *Journal of Cleaner Production*)

Chapter 5 : Desaulniers Brousseau, V., Goldstein, B. P., Lachapelle, M., Tazi I. and Lefsrud, M. (2024). Greener Green: The Environmental Impacts of the Canadian Cannabis Industry, in *Resources, Convservation and Recycling*. https://doi.org/10.1016/j.resconrec.2024.107737

Organization of Thesis

Chapter 1 is the introduction of the thesis. The introduction explains the rationale behind the project. Chapter 2 encompasses the literature review and brief discussion of topics involved in this research. Chapter 3 to 6 describes the studies conducted to build an understanding of the effect of different postharvest handling/processing parameters. Between each Chapter, connecting texts provide the transition and rationale between each study. Chapter 7 discuss the limitations of the thesis and practical aspects of the findings. Chapter 8 provides a summary of each study, describing the significant contributions to knowledge and suggesting further studies on the research topic. References and appendix follow. International System of Units (SI) are used throughout.

Chapter 1：Introduction

1.1 *Cannabis sativa*

Cannabis sativa is an annual herbaceous flowering plant indigenous to Eastern Asia (Small & Cronquist, 1976). Its cultivation for fiber, food and oil started approximately 12,000 years ago (Ren et al., 2021) and archeological evidence dates the use of its psychoactive properties to 500 BC (Li, 1973; Ren et al., 2019). Cannabis is versatile partly because it is dioecious, meaning that only male or female flowers (colloquially "buds") are produced on a single plant (Sakamoto et al., 1995). For cannabis, the correct botanical term inflorescence is employed, as it refers to the cluster of individual flowers arranged on a stem (Spitzer-Rimon et al., 2019). This article will use the term flower for brevity sake.

When cultivated for its medicinal or psychoactive properties, growers cultivate female plants for their flowers (Coffman & Gentner, 1977). Indoor farming is common for cannabis flower production as it has been historically grown in hidden facilities because of its illicit nature (Vanhove et al., 2011). Indoor farming is still predominant in Canada, as licensed producers have the advantage of controlling photoperiod, which is necessary to induce flowering (Ahrens et al., 2023; Moher et al., 2021), as well as abide to strict security measure associated with the ownership of cultivation license (Government of Canada, 2018). In 2023, there was a reported 151 ha of indoor growing area in Canada versus 587 ha of outdoor growing area (Health Canada, 2023). Male plants are usually excluded from these environments because their flowers are less concentrated in bioactive compounds and pollen dispersal will cause generative fertilization of the female flowers (Ohlsson et al., 1971). Generatively fertilized female plants will develop seed biomass instead of flower and will be less concentrated in the desired cannabinoids compounds (Small & Naraine, 2016).

A total of 104 cannabinoids have been identified in the cannabis plant so far, with Δ9-tetrahydrocannabinol (THC) and cannabidiol (CBD) being the most studied for medical treatments (ElSohly & Gul, 2014). Other minor cannabinoids, such as cannabinol (CBN), cannabigerol (CBG), cannabichromene (CBC) and cannabicitran (CBT), have broad therapeutic potential (Appendino et al., 2011; Appendino & Taglialatela-Scafati, 2013). Recreational and medical cannabis growers are inclined to produce as much THC or CBD per area as possible to increase profit. Medical cannabis growers focus on the production of these compounds but must consider cannabinoid profile, a

necessary step to make cannabis-aided medicine through medical botanical extracts (Chandra et al., 2017).

1.2 Medical Botanical Extract

Cannabis-aided medicine relies on botanical extract from virgin female cannabis flower (Baron, 2018; Russo, 2011). Virgin female plants have a higher flower mass compared to a fertilized female or male flower (Raman et al., 2017). Furthermore, virgin female plants have a higher numbers of flower per plant, as well as higher average flower size and cannabinoid content (Small & Naraine, 2016).

Female flowers possess specific structures termed capitate stalked glandular trichomes, which are little hair that look like "frost" or "dew" when looking at a female flower that is ready for harvest (Punja et al., 2023), with bigger trichome heads correlating with potency (Small & Naraine, 2016). Capitate stalked glandular trichomes have excretory disc cells capable of producing cannabinoids, terpenes and other secondary metabolites that are stored in the trichome resinous heads (Kim & Mahlberg, 1997). Medical cannabis varieties have bigger trichome heads compared to fiber- or feed-type cannabis (Small & Naraine, 2016). Biomass with higher quantity of resin equals higher yield of cannabinoids (Livingston et al., 2020).

Cannabinoids are in part exploited for their therapeutic potential because their anti-inflammatory, antibiotic, cancericidal, sedative and neuroprotective properties (Amin & Ali, 2019; Page & Nagel, 2006). Terpenes, which were previously thought to only influence plant aroma (Zhou & Pichersky, 2020), have been investigated for their influence on the medical potency of the extract (Hanuš & Hod, 2020). This observed therapeutical synergy of terpenes and cannabinoids is called the "entourage effect" (Gaoni & Mechoulam, 1964; Russo, 2019). Anti-inflammatory and anti-nociceptive (pain) properties of purified CBD are lesser than whole plant extract in animal models studies, hinting that extracts with specific ratios of terpenes and cannabinoids could be more potent than cannabinoids alone (Gallily et al., 2015).

As these promises of next generation medicine are being investigated, very few studies looked at resource use and environment impact of large-scale cannabis production (Vujanovic et al., 2020). Methods to increase cannabis secondary metabolites concentration and profile, such as cannabinoid and terpene ratio, through environmentally performant horticultural practices are lacking.

1.3 Cannabis Cultivation and Environmental Performance

Researchers are actively studying the effect of cannabis secondary metabolites on cellular models: animals, and humans and studies on the ecological and agronomical aspects of cannabis cultivation are lacking (Hussain et al., 2021). To date, 50% of cannabis literature is related to the medical or food-related fields while cannabis agriculture accounts for less than 1% of published cannabis research (Vujanovic et al., 2020). Because research on cannabis cultivation, resource use, and emissions (e.g. nutrients in runoff) is lacking, the environmental impacts of this growing industry remain unclear (Butsic & Brenner, 2016; Wartenberg et al., 2021). For instance, growers could be over-fertilizing, which would contribute to resource exhaustion, global warming, and releases of active nitrogen to waterways (Butsic et al., 2018; Zheng et al., 2021), which are emerging issues of environmental concerns (UNEP, 2019).

The cannabis sector impact on land and water use, nutrient cycling and greenhouse gas emissions is slowly gaining attention (Wang et al., 2017). Studies looking at the carbon footprint of indoor cannabis production have shown that environmental conditioning (dehumidifying, ventilating and cooling) easily accounts for a third the GHG emissions for this industry (Mills, 2012; Summers et al., 2021). Furthermore, there is a concerning association of the expansion of the Californian legal markets with land fragmentation, deforestation, and wildlife habitat threat (Butsic et al., 2018; Butsic & Brenner, 2016; Wang et al., 2017). Scientifically informed guidelines are needed to prevent negative environmental externalities associated with the increase in cannabis cultivation.

Nutrient stewardship aimed at decreasing the negative environmental externalities of agricultural operation have been established for other crops (Johnston & Bruulsema, 2014). These practices can be adapted to the cannabis industry by using the same 4R principles (right time, right place, right source and right rate) to mitigate its environmental footprint (Tonitto et al., 2018). Sound mineral fertilization decreases environmental externalities while increasing profit for growers by potentially decreasing input cost (Menegat et al., 2022).

Previous studies on indoor cannabis production have shown the importance of the right time by using varying macronutrients concentrations during the vegetative versus flowering (Caplan et al., 2017; Morad & Bernstein, 2023; Saloner & Bernstein, 2020). The right rate and source were investigated for the flowering stage by varying macronutrients type and quantity of nitrogen (N) (Bevan et al., 2021; Saloner &

Bernstein, 2021, 2022), phosphorus (P) (Shiponi & Bernstein, 2021) and potassium (K) (Saloner & Bernstein, 2022). Future studies can still address the right source and place to help develop fertilizer best management practices (BMP) for this nascent industry.

New data could help enable fertilizer BMP to increase environmental performance, in part through nutrient use efficiency (Johnston & Bruulsema, 2014). In Canada, most greenhouse production do not re-use fertilizer solution, using a run-to-waste fertigation method (Mohammed, 2017). In these systems, waste nutrient solution is discharged into the environment. This inefficient nutrient cycling threatens water quality, through nutrient leaching, and can decrease profit for growers (Bugbee, 2004; Kumar & Cho, 2014). As in other crops, greenhouse gas generation inherent to fertilizer practices specific to the cannabis industry could be studied further (Snyder et al., 2009).

Always studying indoor cannabis production, a meta-analysis showed incorporated slow-release (right place) could increase yield compared to an industry-recommended soluble fertilizer regime (Backer et al., 2019). The possibility of increasing yield through this practice requires to be studied further.

Other concerning trends in the cannabis industry are related to fertilizer source. Most farmers in California use organic inputs (Wilson et al., 2019). Studies on the difference in environmental footprint of inorganic versus organic fertilizer and cannabis yield are needed. For example, in medical cannabis, organic fertilizer will require much more N in the vegetative phase versus inorganic fertilizer. It has been demonstrated that 389 ppm N is optimal for an organic fertilizer regime, versus 160 ppm for inorganic fertilizer regime (Caplan et al., 2017; Saloner & Bernstein, 2021). The discrepancy in optimal N content may be related to the fertilizer delivery method. For soil-grown plants, N recommendations typically do not differentiate between inorganic and organic N sources. However, with fertigation—where fertilizer is applied during each irrigation—there might not be enough time for the supplied N to be fully mineralized and absorbed by the plants before the next fertigation event. This could lead to increased N-leaching when using organic inputs in fertigation.

1.4 Mineral Fertilization for Optimal Yield

Mineral fertilization, or the addition of fertilizer to enhance mineral concentration in the root zone, plays a crucial role in optimizing plant production (Walworth & Sumner, 1987). There are 17 elements that are essential for plant growth. Elements are deemed essential when (1) A given plant cannot complete its life cycle without the mineral element. (2) The element's function cannot be replaced by another mineral element. (3)

The element must be directly involved in plant metabolism, or it must be required for a distinct metabolic step such as enzyme reaction. (Blake et al., 2008). Nutrient disorders have been characterized in *Cannabis sativa* and specie-specific symptoms are presented in other works (Cockson et al., 2019; Llewellyn et al., 2023).

Fourteen essential mineral nutrients may be obtained from soil: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl) and nickel (Ni). Carbon (C), hydrogen (H) and oxygen (O) are essential but are obtained from water and/or the air; they are deemed essential non-mineral nutrients (Taíz & Zeiger, 2010).

1.5 Primary Macronutrients

1.5.1 Nitrogen

N is the mineral element present in the highest concentration in plant tissue (Mengel & Kirkby, 2001). N is a constituent of multiple plant cell components, including nucleic acids, amino acids, phospholipids, and chlorophyll (Karthika et al., 2018). The application of commercial N is a key factor in estimating crop yield for winter wheat (*Triticum aestivum*) and rice (*Oryza sativa*), while accounting for 19% of the tripling of corn yield (*Zea mays*) from 1930 to 1980 (Cardwell, 1982; Lukina et al., 2001; Sui et al., 2013). N fertilization increases the concentration of soluble amino compounds in most plants in the form of free amino acids, amines, amides, while the concentration of protein increases to a limited extent (Mengel & Kirkby, 2001).

In cannabis, increasing the amount of N in fertilizer will produce bigger plants, but the cannabinoid content of the flower will decrease (Caplan et al., 2017; Saloner & Bernstein, 2020, 2021). This observed ‘dilution effect’ is caused in part by a metabolic shift towards production of low-N metabolites under N deficiency (Song et al., 2023). Sustainable production of cannabis could use this symptom of N-deficiency to decrease cost and environmental externalities of chemical N-fertilizer production and use (Menegat et al., 2022; Snyder et al., 2009). Studies have shown that cannabinoid yield per plant was equal whether the N content of the fertilizer is 160 or 240 mg N L^{-1} (Massuela et al., 2023). Fertilizer with sub-optimal N-content increases the quantity of stalked trichome on the plant, as highlighted in a study that showed a synergistic effect between N-deficiency and inoculation with plant-growth promoting rhizobacteria (PGPR) of the *Bacillus* type (Tanney et al., 2023).

To this date, values from the scientific literature recommends supplying 389 ppm N during the vegetative phase and 286 ppm N during the flowering phase to optimize flower yield when using an organic fertilizer in indoor production (Caplan et al., 2017). When using an inorganic fertilizer in indoor production, optimal N-content for flower yield is 160 ppm N in the flowering and vegetative stage (Saloner & Bernstein, 2020, 2021b). No recommended guidelines take PGPR biostimulant effect or N-deficiency induced cannabinoid production during the flowering phase into account.

1.5.2 Phosphorous

P is a structural component of DNA, RNA, and phospholipids. In membranes, it is added as phosphoryl groups. Two phosphoryl groups bind to Ca to stabilize membranes. P is required for the formation of ATP, in which it is linked by a high-energy pyrophosphate bond and acts as a storage mechanism for energy. P is crucial in other nucleotide triphosphate (GTP, UTP, CTP), which are essential for the synthesis of nucleic acid formation. It plays a vital role in optimal physiological processes such as photosynthesis, respiration, signal transduction and energy metabolism (Rebeille et al., 1983).

Adequate P nutrition can increase resistance to salinity, infection, and drought in plants, as well as increase water use efficiency (Karthika et al., 2018). P-deficient plants can have a lower shoot: root ratio because of impaired leaf formation (Jeschke et al., 1996). Several enzymes involved in the C and N metabolism see their activity decrease under P deficiency, which decreases the plant ability to react to drought stress (Burman et al., 2009).

In cannabis, the addition of the P mobilizing microbial consortium, available under the brand name “Mammoth P™”, could increase flower yield (Conant et al., 2017). In cannabis, P could be the nutrient with the most potential for on-site overfertilization. Recent guidelines do not consider the reduced need for soluble P in fertilizer solution when using a P mobilizing biostimulant (Baas et al., 2016). The demonstrated optimal concentration for cannabis was fixed at 30 mg P L^{-1} but it showed, again, a potent dilution effect where a higher concentration would produce bigger but less concentrated in cannabinoid plants (Shiponi & Bernstein, 2021). Furthermore, if producers follow a fertilizer strategy from the private industry, they could be putting 2 to 5 times more than necessary.

1.5.3 Potassium

K is considered by some experts as the second most important primary macronutrient after N for biomass yield increase (Usherwood, 2015). It is one of the most abundant elements in plant sap and helps in plant response and tolerance to abiotic stress (Hasanuzzaman et al., 2018). Sufficient K content in a plant enables optimal drought-stress response as it is a key regulator of water homeostasis by influencing stomatal conductance, water absorption and photosynthesis rate (Hasanuzzaman et al., 2018). Cannabis aerial biomass is affected by K fertilization (Saloner et al., 2019; Saloner & Bernstein, 2022). In the flowering phase, cannabis grown with varying K rate (15, 60, 100, 175 and 240 ppm) showed the highest above-ground biomass, chlorophyll, and carotenoid content with 175 ppm K for the genotype 'Desert Queen' and 240 ppm K for the genotype 'Royal Medic'.

Table 1.1: Average concentration of primary macronutrient (N, P and K) from private industry fertilizer recommendation and scientific literature. "Flo" and "Veg" refers to the flowering and vegetative phase respectively.

Source	Phase	mg N L^{-1}	mg P L^{-1}	mg K L^{-1}	Reference
Private industry	Veg	167	75	319	(Canna Canada, 2019; General Hydroponics, 2019d, 2019c, 2019a, 2019b)
	Flo	106	146	597	
Scientific literature	Veg	160	30	175	(Saloner et al., 2019; Saloner & Bernstein, 2020, 2021a, 2022a; Shiponi & Bernstein, 2021)
	Flo	160	30	175-240	

Both cannabis genotypes suffered from K deficiencies, as observed through suppression of stem expansion, slower transpiration range, and stomatal conductance at 15 ppm K. It needs to be mentioned that previous studies have shown the potential of timed and controlled stress on increasing cannabinoid production in cannabis. A controlled-drought stress during the flowering stage could increase total THC production by 50 % (Caplan et al., 2019). Knowing the importance of K in plant drought-stress response, further studies could be looking at optimal K content of fertilizer under different drought-stress scenarios.

1.6 Macronutrient Ratios and Interactions

Crops can have their yield, as biomass or total metabolite production, increased by fine-tuning nutrient ratios. For example, addition of Ca particles in the fertilizer solution of hydroponic lettuce (*Lactuca sativa*) can increase chlorophyl, flavonoids and polyphenols concentrations by a third (Jurić et al., 2020). Addition of 100 kg ha^{-1} of K in soil can double the number of specific terpenes in sage oil (β-Thujone, β-Caryophyllene, α-Humulene) (Piccaglia et al., 1989; Rioba et al., 2015). Fertilizer macronutrient ratio increasing yield, without mention on secondary metabolites, was also observed in other crops such as maize (*Zea mays*) and rice (*Oryza sativa*) (Abbasi et al., 2013; Biswas & Ma, 2016; Ding et al., 2018).

In cannabis, secondary metabolite concentrations can be increased by increasing N and/or K concentration from a baseline level in fertilizer solutions (Bernstein et al., 2019). Coffman and Gentner showed significant differences in above-ground biomass and total THC yield per plant in greenhouse grown cannabis under varying primary macronutrient (N-P-K) ratios (Coffman & Gentner, 1977). This experiment used pots with three different levels of NPK combinations incorporated at planting low (0 ppm), medium (25 ppm N, 50 ppm of P and K) and high (125 ppm for N, 150 ppm for P and K) concentration. Total yield of THC per plant found in combined leaf and flower tissue was highest in fertilizer treatment having either high N, high P and low K (125 ppm N, 150 ppm P, 0 ppm K, or 125-150-0) or low N, high P and moderate K (0-150-50) (Coffman & Gentner, 1977). These results indicate that the N or K content of the fertilizer regime can be modified simultaneously to optimize cannabis flower production. In this study, no treatment investigated high N, P and K simultaneously.

Moderate changes in NPK supplementation from a baseline level had a significant effect on secondary metabolite profiles in medical cannabis. An observed 71% increase of CBG levels in flowers was reported. Furthermore, greater uniformity in cannabinoid concentration between the bottom and top parts of the plant was further observed. Cannabis growers could aim at increased homogeneity of cannabinoid in the plant to increase total yield (Bernstein et al., 2019). The optimal NPK ratio for cannabis cultivation is (1) cultivar specific and (2) changes from the vegetative to flowering phase.

The lack of peer-reviewed knowledge about an adequate macronutrient ratio in fertilizer for medical cannabis means that some growers could be decreasing their yield by using

sub-optimized fertilizer rates or over fertilizing and increasing the risk of nutrient leaching, as was observed in other crops (Cerrato & Blackmer, 1990; Wilkins, 2008).

1.7 Sustainable Increase in Cannabinoid Production

Cannabinoid production can be increased sustainably by harnessing certain stress-response inherent to the plant. A biotic stressor that is well known in the industry is prolonged virginity. The exclusion of male plants from a female population will cause an absence of generative fertilization. This has been hypothesized to cause female cannabis plants to increase their resin secretion to increase pollen-catching potential (Small & Naraine, 2016).

Other than nutrient stresses, other abiotic stress in cannabis production can be used to decrease input need. Drought-stress can increase cannabinoid production (Caplan et al., 2019). This would be of utmost importance in low water availability locations.

Salt-stress could be a problem in certain regions, as it can reduce cannabinoid production. But this can be greatly reduced by exposing plants to a microbial consortium from an organic fertilizer made from fish culture (Yep et al., 2020). This waste to fertilizer input from a fish culture can be improved when supplemented with K and micronutrients (Yep & Zheng, 2021). Using other biostimulants, such as PGPR, can decrease mineral fertilizer need by increasing yield with the same input quantity (Lyu et al., 2022).

1.8 Sustainable Input Choice

Cannabis flowers can be produced outdoor or indoor. Indoor production requires more input (infrastructure and energy) than outdoor production (Summers et al., 2021). Outdoor producers can broadcast fertilizer in soil at a rate of 87-168 kg N ha^{-1} for optimal cannabinoid and biomass yield (Darby et al., 2021). Interestingly, recommended N-fertilizer values for outdoor cannabis production using broadcasted fertilizer translates to 20-40 g N per plant, whereas indoor production using fertigation will consume between 5-15 g N per plant (Caplan et al., 2017; Saloner & Bernstein, 2020, 2021). Fertigation should be able to decrease total N-input versus broadcast fertilizer application. One common input between both production systems, aside from fertilizer, is potting media.

Because cannabis is a heavy metal hyperaccumulator, meaning it can uptake and store large quantities of heavy metal, producers could use potting media in outdoor production to avoid heavy metal contamination (Citterio et al., 2003). This is attractive for phytoremediation strategies, where plants are used to remediate heavy metal

contaminated soils (Golia et al., 2023). However, the biomass resulting for this phytoremediation could be contaminated and unfit for human consumption under Schedule B of the Food and Drug Act of Canada which regulates maximum allowed concentration for cadmium (Ca), lead (Pb), mercury (Hg) and arsenic (As) (Government of Canada, 2018).

For producers wanting to circumvent potential heavy metal contamination, potting media is a viable solution. Potting media is a mixture of material that, similarly to soil, will enable plant anchor through root growth and can release nutrient for plant use (Sheng et al., 2005). For cannabis, peat-based media has attracted the most attention as it is still largely used in the horticultural industry in America, contrary to Europe where it is being phased out (Defra Press Office, 2023). Peat-based media will increase yield when comparing with media where peat is replaced with wood fibres or with coconut fibres (Burgel et al., 2020). Peat-based media with lower water-holding capacities has been reported to increase flower production in cannabis (Caplan et al., 2019). This might be caused by the tendency of cannabis to react positively to lower water availability. Replacing peat with coconut fiber or compost will reduce the carbon footprint of horticultural productions (Boldrin et al., 2010; Russo et al., 2011), and cannabis seems to have a genotype-specific reaction to different potting media composition (Burgel et al., 2020). Growers wanting to replace peat with other substrate should conduct trials on different genotypes before mass adoption. Reduction of the environmental impact of peat-based potting media can be made by on-site reuse via steam sterilization (Vandecasteele et al., 2020). Other inert media, like rockwool or perlite, are seen as less sustainable than organic-based potting media (Islam et al., 2002). These media are routinely used in cannabis production (Song et al., 2023). However, like peat, these materials can be much more environmentally performant by on-site reuse by removing organic material and thorough rinsing (Acuña et al., 2013).

1.9 Conclusion

Sustainable cannabis production has benefited from peer-reviewed studies on mineral fertilization, abiotic stress-response, biostimulant and potting media. Knowledge from these studies will greatly help prevent overfertilization and harness the natural pathways inherent to the plant to sustainably increase cannabinoid production efficiency. As in other crops, environmental externalities associated with fertilizer production and input choice, such as greenhouse gas emissions, eutrophication, and mineral resource depletion, will be reduced by adopting peer-reviewed guidelines. However, the

quantification of which strategies show the most potential in increasing overall environmental performance of the industry would require further analysis. As highlighted in previous studies, the scientific community would greatly benefit from large-scale surveys from the industry and life-cycle analysis (LCA) to address the knowledge gap necessary to quantify environmental externalities of the cannabis production (Wilson et al., 2019; Zheng et al., 2021). The overarching hypothesis is that adopting peer-reviewed guidelines on mineral fertilization in sustainable cannabis production will significantly reduce environmental externalities such as GHG emissions, eutrophication, and mineral resource depletion, while enhancing cannabinoid production efficiency. Quantitative analysis through large-scale industry surveys and LCA will identify the most effective strategies for improving the overall environmental performance of the cannabis industry.

1.10 References

Abbasi, M. K., Tahir, M. M., Rahim, N. (2013). Effect of N Fertilizer Source and Timing on Yield and N Use Efficiency of Rainfed Maize (*Zea mays* L.) in Kashmir-Pakistan. Geoderma, 195–196, 87–93. https://doi.org/10.1016/j.geoderma.2012.11.013.

Acuña, R. A., Bonachela, S., Magán, J. J., Marfà, O., Hernández, J. H., Cáceres, R. (2013). Reuse of Rockwool Slabs and Perlite Grow-Bags in a Low-Cost Greenhouse: Substrates' Physical Properties and Crop Production. Scientia Horticulturae, 160, 139–147. [https://doi.org/10.1016/j.scienta

Ahrens, A., Llewellyn, D., Zheng, Y. (2023). Is Twelve Hours Really the Optimum Photoperiod for Promoting Flowering in Indoor-Grown Cultivars of *Cannabis sativa*? Plants, 12(14). https://doi.org/10.3390/plants12142605.

Amin, M. R., Ali, D. W. (2019). Pharmacology of Medical Cannabis. In Advances in Experimental Medicine and Biology (Vol. 1162, pp. 151–165). Springer New York LLC. https://doi.org/10.1007/978-3-030-21737-2_8.

Appendino, G., Taglialatela-Scafati, O. (2013). Cannabinoids: Chemistry and Medicine. In Natural Products: Phytochemistry, Botany and Metabolism of Alkaloids, Phenolics and Terpenes (pp. 3415–3435). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-22144-6_147.

Appendino, G., Chianese, G., Taglialatela-Scafati, O. (2011). Cannabinoids: Occurrence and Medicinal Chemistry. Current Medicinal Chemistry, 18(7), 1085–1099. https://doi.org/10.2174/092986711794940888.

Baas, P., Bell, C., Mancini, L. M., Lee, M. N., Conant, R. T., Wallenstein, M. D. (2016). Phosphorus Mobilizing Consortium Mammoth PTM Enhances Plant Growth. PeerJ, (6), 1–16. https://doi.org/10.7717/peerj.2121.

Backer, R., Schwinghamer, T., Rosenbaum, P., McCarty, V., Eichhorn Bilodeau, S., Lyu, D., Ahmed, M. B., Robinson, G., Lefsrud, M., Wilkins, O., Smith, D. L. (2019). Closing the Yield Gap for Cannabis: A Meta-Analysis of Factors Determining Cannabis Yield. Frontiers in Plant Science, 10, 1–15. https://doi.org/10.3389/fpls.2019.00495.

Baron, E. P. (2018). Medicinal Properties of Cannabinoids, Terpenes, and Flavonoids in Cannabis, and Benefits in Migraine, Headache, and Pain: An Update on Current Evidence and Cannabis Science. Headache: The Journal of Head and Face Pain, 58(7), 1139–1186. https://doi.org/10.1111/head.13345.

Bernstein, N., Gorelick, J., Zerahia, R., Koch, S. (2019). Impact of N, P, K, and Humic Acid Supplementation on the Chemical Profile of Medical Cannabis. Frontiers in Plant Science, 10, 736. https://doi.org/10.3389/fpls.2019.00736.

Bevan, L., Jones, M., Zheng, Y. (2021). Optimization of Nitrogen, Phosphorus and Potassium for Soilless Production of Cannabis sativa in the Flowering Stage Using Response Surface Analysis. Frontiers in Plant Science, 12, https://doi.org/10.3389/fpls.2021.764103

Biswas, D. K., Ma, B. L. (2016). Effect of Nitrogen Rate and Fertilizer Nitrogen Source on Physiology, Yield, Grain Quality, and Nitrogen Use Efficiency in Corn. Canadian Journal of Plant Science, 96(3), 392–403. https://doi.org/10.1139/cjps-2015-0186.

Blake, G. R., Steinhardt, G. C., Pontevedra Pombal, X., Novoa Munoz, J. C., Martinez Cortizas, A., Arnold, R. W., Schaetzl, R. J., Parlange, J.-Y., Steenhuis, T. S., Chesworth, W., Mualem, Y., Morel-Seytoux, H. J., Spaargaren, O., & Oertli, J. J. (2016). Plant Nutrients. In Encyclopedia of Soil Science (pp. 560–571). Springer.

Boldrin, A., Hartling, K. R., Laugen, M., Christensen, T. H. (2010). Environmental Inventory Modelling of the Use of Compost and Peat in Growth Media Preparation. Resources, Conservation and Recycling, 54(12), 1250–1260. https://doi.org/10.1016/j.resconrec.2010.04.003.

Bugbee, B. (2004). Nutrient Management in Recirculating Hydroponic Culture. Acta Horticulturae, 648, 99–112. https://doi.org/10.17660/ActaHortic.2004.648.12.

Burgel, L., Hartung, J., Graeff-Hönninger, S. (2020). Impact of Different Growing Substrates on Growth, Yield and Cannabinoid Content of Two Cannabis sativa L. Genotypes in a Pot Culture. Horticulturae, 6(4), 1–14. https://doi.org/10.3390/horticulturae6040062.

Burman, U., Garg, B. K., Kathju, S. (2009). Effect of Phosphorus Application on Clusterbean under Different Intensities of Water Stress. Journal of Plant Nutrition, 32(4), 668–680. https://doi.org/10.1080/01904160802715620.

Butsic, V., Brenner, J. C. (2016). Cannabis (Cannabis sativa or C. indica) Agriculture and the Environment: A Systematic, Spatially-Explicit Survey and Potential Impacts. Environmental Research Letters, 11(4), 044023. https://doi.org/10.1088/1748-9326/11/4/044023.

Butsic, V., Carah, J. K., Baumann, M., Stephens, C., Brenner, J. C. (2018). The Emergence of Cannabis Agriculture Frontiers as Environmental Threats. Environmental Research Letters, 13(12), 124017. https://doi.org/10.1088/1748-9326/aaeade.

Canna Canada. (2019). Canna Aqua Feeding Chart. https://www.cannagardening.com/growguide.

Caplan, D., Dixon, M., Zheng, Y. (2017). Optimal Rate of Organic Fertilizer During the Flowering Stage for Cannabis Grown in Two Coir-Based Substrates. HortScience, 52(12), 1796–1803. https://doi.org/10.21273/HORTSCI12401-17.

Caplan, D., Dixon, M., Zheng, Y. (2019). Increasing Inflorescence Dry Weight and Cannabinoid Content in Medical Cannabis Using Controlled Drought Stress. HortScience, 54(5), 964–969. https://doi.org/10.21273/HORTSCI13510-18.

Cardwell, V. B. (1982). Fifty Years of Minnesota Corn Production: Sources of Yield Increase. Agronomy Journal, 74(6), 984–990. https://doi.org/10.2134/agronj1982.00021962007400060013x.

Cerrato, M. E., Blackmer, A. M. (1990). Comparison of Models for Describing; Corn Yield Response to Nitrogen Fertilizer. Agronomy Journal, 82(1), 138. https://doi.org/10.2134/agronj1990.00021962008200010030x.

Chandra, S., Lata, H., ElSohly, M. A., Walker, L. A., Potter, D. (2017). Cannabis Cultivation: Methodological Issues for Obtaining Medical-Grade Product. Epilepsy and Behavior, 70, 302–312. https://doi.org/10.1016/j.yebeh.2016.11.029.

Citterio, S., Santagostino, A., Fumagalli, P., Prato, N., Ranalli, P., Sgorbati, S. (2003). Heavy Metal Tolerance and Accumulation of Cd, Cr and Ni by *Cannabis sativa* L. Plant and Soil, 256, 243-252. https://doi.org/10.1023/A:1026113905129

Cockson, P., Landis, H., Smith, T., Hicks, K., Whipker, B. E. (2019). Characterization of Nutrient Disorders of *Cannabis sativa*. Applied Sciences, 9(20), 4432. https://doi.org/10.3390/app9204432

Coffman, C. B., Gentner, W. A. (1977). Responses of Greenhouse-grown *Cannabis sativa* L. to Nitrogen, Phosphorus, and Potassium. Agronomy Journal, 69(5), 832–836. https://doi.org/10.2134/agronj1977.00021962006900050026x

Conant, R. T., Walsh, R. P., Walsh, M., Bell, C. W., Wallenstein, M. D. (2017). Effects of a Microbial Biostimulant, Mammoth PTM, on Cannabis sativa Bud Yield. Journal of Horticulture, 04(01). https://doi.org/10.4172/2376-0354.1000191

Darby, H., Bruce, J., Lewins, S., Ziegler, S. (2021). Hemp Flower Nitrogen Fertility Trial. https://scholarworks.uvm.edu/nwcsp

Defra Press Office. (2023). Media Reporting on Peat-Ban for the Professional Horticulture Sector. https://deframedia.blog.gov.uk/2023/03/24/media-reporting-on-peat-ban-for-the-professional-horticulture-sector/

Ding, W., Xu, X., He, P., Ullah, S., Zhang, J., Cui, Z., Zhou, W. (2018). Improving Yield and Nitrogen Use Efficiency Through Alternative Fertilization Options for Rice in China: A Meta-Analysis. Field Crops Research, 227, 11–18. https://doi.org/10.1016/j.fcr.2018.08.001

ElSohly, M. A., & Gul, W. (2014). Constituents of Cannabis Sativa. In Handbook of Cannabis (1st ed., p. 20). Oxford University Press.

Gallily, R., Yekhtin, Z., Hanuš, L. O. (2015). Overcoming the bell-shaped dose-response of cannabidiol by using cannabis extract enriched in cannabidiol. Pharmacology & Pharmacy, 06(02), 75–85. https://doi.org/10.4236/pp.2015.62010

Gaoni, Y., Mechoulam, R. (1964). Isolation, Structure, and Partial Synthesis of an Active Constituent of Hashish. Journal of the American Chemical Society, 86(8), 1646–1647. https://doi.org/10.1021/ja01062a046

General Hydroponics. (2019). Flora Duo. General Hydroponics. https://generalhydroponics.com/category/documentation/feedcharts/

Golia, E. E., Bethanis, J., Ntinopoulos, N., Kaffe, G. G., Komnou, A. A., Vasilou, C. (2023). Investigating the Potential of Heavy Metal Accumulation from Hemp. The

Use of Industrial Hemp (*Cannabis sativa* L.) for Phytoremediation of Heavily and Moderated Polluted Soils. Sustainable Chemistry and Pharmacy, 31. https://doi.org/10.1016/j.scp.2022.100961

Government of Canada. (2018). Cannabis Regulations. Justice Laws Website. https://laws-lois.justice.gc.ca/PDF/SOR-2018-144.pdf

Hanuš, L. O., Hod, Y. (2020). Terpenes/Terpenoids in Cannabis: Are They Important? Medical Cannabis and Cannabinoids, 3(1), 25–60. https://doi.org/10.1159/000509733

Hasanuzzaman, M., Bhuyan, M. H. M. B., Nahar, K., Hossain, M. S., Al Mahmud, J., Hossen, M. S., Masud, A. A. C., Moumita, Fujita, M. (2018). Potassium: A Vital Regulator of Plant Responses and Tolerance to Abiotic Stresses. Agronomy, 8(3). https://doi.org/10.3390/agronomy8030031

Health Canada. (2023). Cannabis data overview: Inventory, Sales and Licensed Area. https://www.canada.ca/en/health-canada/services/drugs-medication/cannabis/research-data/market.html

Hussain, T., Jeena, G., Pitakbut, T., Vasilev, N., Kayser, O. (2021). Cannabis Sativa Research Trends, Challenges, and New-age Perspectives. IScience, 24, 103391. https://doi.org/10.1016/j.isci.

Islam, M. S., Khan, S., Ito, T., Maruo, T., Shinohara, Y. (2002). Characterization of the Physico-chemical Properties of Environmentally Friendly Organic Substrates in Relation to Rockwool. Journal of Horticultural Science and Biotechnology, 77(2), 143–148. https://doi.org/10.1080/14620316.2002.11511470.

Jeschke, W. D., Peuke, A., Kirkby, E. A., Pate, J. S., Hartung, W. (1996). Effects of P Deficiency on the Uptake, Flows and Utilization of C, N and H_2O Within Intact Plants of *Ricinus Communis* L. Journal of Experimental Botany, 47(11), 1737–1754. https://doi.org/10.1093/jxb/47.11.1737.

Johnston, A. M., Bruulsema, T. W. (2014). 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. Procedia Engineering, 83, 365–370. https://doi.org/10.1016/j.proeng.2014.09.029.

Jurić, S., Sopko Stracenski, K., Król-Kilińska, Ż., Žutić, I., Uher, S. F., Đermić, E., Topolovec-Pintarić, S., Vinceković, M. (2020). The Enhancement of Plant Secondary Metabolites Content in *Lactuca sativa* L. by Encapsulated Bioactive Agents. Scientific Reports, 10(1), 1–12. https://doi.org/10.1038/s41598-020-60690-3.

Karthika, K. S., Rashmi, I., Parvathi, M. S. (2018). Biological Functions, Uptake and Transport of Essential Nutrients in Relation to Plant Growth. In Plant Nutrients and Abiotic Stress Tolerance (pp. 1–49). Springer Singapore. https://doi.org/10.1007/978-981-10-9044-8_1.

Kim, E., Mahlberg, K. (1997). Plastid Development in Disc Cells of Glandular Trichomes of Cannabis (*Cannabaceae*). Molecular Cell, 7(3), 352–359.

Kumar, R. R., Cho, J. Y. (2014). Reuse of Hydroponic Waste Solution. Environmental Science and Pollution Research 21(16), 9569–9577. https://doi.org/10.1007/s11356-014-3024-3.

Li, H.-L. (1973). An Archaeological and Historical Account of Cannabis in China. Economic Botany, 28(4), 437–448. https://doi.org/10.1007/BF02862859.

Livingston, S. J., Quilichini, T. D., Booth, J. K., Wong, D. C. J., Rensing, K. H., Laflamme-Yonkman, J., Castellarin, S. D., Bohlmann, J., Page, J. E., Samuels, A. L. (2020). Cannabis glandular trichomes alter morphology and metabolite content during flower maturation. The Plant Journal, 101(1), 37–56. https://doi.org/10.1111/tpj.14516

Llewellyn, D., Golem, S., Jones, A. M. P., Zheng, Y. (2023). Foliar Symptomology, Nutrient Content, Yield, and Secondary Metabolite Variability of Cannabis Grown Hydroponically with Different Single-Element Nutrient Deficiencies. Plants, 12(3). https://doi.org/10.3390/plants12030422.

Lukina, E. V., Freeman, K. W., Wynn, K. J., Thomason, W. E., Mullen, R. W., Stone, M. L., Solie, J. B., Klatt, A. R., Johnson, G. V., Elliott, R. L., Raun, W. R. (2001). Nitrogen Fertilization Optimization Algorithm Based on in-season Estimates of Yield and Plant Nitrogen Uptake. Journal of Plant Nutrition, 24(6), 885–898. https://doi.org/10.1081/PLN-100103780.

Lyu, D., Backer, R., Smith, D. L. (2022). Three Plant Growth-promoting Rhizobacteria Alter Morphological Development, Physiology, and Flower Yield of *Cannabis sativa* L. Industrial Crops and Products, 178. https://doi.org/10.1016/j.indcrop.2022.114583.

Mariotti, B., Martini, S., Raddi, S., Tani, A., Jacobs, D. F., Oliet, J. A., Maltoni, A. (2020). Coconut Coir as a Sustainable Nursery Growing Media for Seedling Production of the Ecologically Diverse Quercus Species. Forests, 11(5). https://doi.org/10.3390/F11050522.

Massuela, D. C., Munz, S., Hartung, J., Nkebiwe, P. M., Graeff-Hönninger, S. (2023). Cannabis Hunger Games: Nutrient Stress Induction in Flowering Stage – Impact of Organic and Mineral Fertilizer Levels on Biomass, Cannabidiol (CBD) Yield and Nutrient Use Efficiency. Frontiers in Plant Science, 14. https://doi.org/10.3389/fpls.2023.1233232.

Menegat, S., Ledo, A., Tirado, R. (2022). Greenhouse Gas Emissions From Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture. Scientific Reports, 12(1), 1–13. https://doi.org/10.1038/s41598-022-18773-w.

Mengel, K., Kirkby, E. A. (2001). Principles of Plant Nutrition. 849. https://doi.org/10.1093/aob/mch063.

Mills, E. (2012). The Carbon Footprint of Indoor Cannabis Production. Energy Policy, 46, 58–67. https://doi.org/10.1016/j.enpol.2012.03.023.

Mohammed, N. (2017). The Advantages of a Closed Hydroponic System in Commercial Greenhouses. Greenhouse Research & Production Complex.

Moher, M., Jones, M., Zheng, Y. (2021). Photoperiodic Response of In Vitro *Cannabis sativa*. Plants. HortScience, 56(1), 108–113. https://doi.org/10.21273/HORTSCI15452-20.

Morad, D., Bernstein, N. (2023). Response of Medical Cannabis to Magnesium (Mg) Supply at the Vegetative Growth Phase. Plants, 12(14). https://doi.org/10.3390/plants12142676.

Ohlsson, A., Abou-Chaar, C. I., Agurell, S., Nilsson, I. M., Olofsson, K., Sandberg, F. (1971). Cannabinoid Constituents of Male and Female *Cannabis sativa*. United Nations Office on Drugs and Crime. https://www.unodc.org/unodc/en/data-and-analysis/bulletin/bulletin_1971-01-01_1_page006.html.

Page, J. E., Nagel, J. (2006). Biosynthesis of Terpenophenolic Metabolites in Hop and Cannabis. In Recent Advances in Phytochemistry 40, 179–210. https://doi.org/10.1016/S0079-9920(06)80042-0.

Piccaglia, R., Marotti, M., Galletti, G. C. (1989). Effect of Mineral Fertilizers on the Composition of Salvia officinalis Oil. Journal of Essential Oil Research, 1(2), 73–83. https://doi.org/10.1080/10412905.1989.9697754.

Punja, Z. K., Sutton, D. B., Kim, T. (2023). Glandular Trichome Development, Morphology, and Maturation Are Influenced by Plant Age and Genotype in High THC-Containing Cannabis (*Cannabis sativa* L.) Inflorescences. Journal of Cannabis Research, 5(1). https://doi.org/10.1186/s42238-023-00178-9.

Raman, V., Lata, H., Chandra, S., Khan, I. A., ElSohly, M. A. (2017). Morpho-Anatomy of Marijuana (*Cannabis sativa* L.). In Cannabis sativa L. - Botany and Biotechnology (pp. 123–136). Springer International Publishing. https://doi.org/10.1007/978-3-319-54564-6_5.

Rebeille, F., Bligny, R., Martin, J.-B., Douce, R. (1983). Relationship Between the Cytoplasm and the Vacuole Phosphate Pool in *Acer pseudoplatanus* Cells. In Archives of Biochemistry and Biophysics (Vol. 225, Issue 1).

Ren, G., Zhang, X., Li, Y., Ridout, K., Serrano-Serrano, M. L., Yang, Y., Liu, A., Ravikanth, G., Nawaz, M. A., Mumtaz, A. S., Salamin, N., Fumagalli, L. (2021). Large-Scale Whole-Genome Resequencing Unravels the Domestication History of *Cannabis sativa*. Science Advances, 7(29). https://doi.org/10.1126/sciadv.abg2286.

Ren, M., Tang, Z., Wu, X., Spengler, R., Jiang, H., Yang, Y., Boivin, N. (2019). The Origins of Cannabis Smoking: Chemical Residue Evidence from the First Millennium BCE in the Pamirs. Science Advances, 5(6). https://doi.org/10.1126/sciadv.aaw1391.

Rioba, N. B., Itulya, F. M., Saidi, M., Dudai, N., Bernstein, N. (2015). Effects of Nitrogen, Phosphorus and Irrigation Frequency on Essential Oil Content and Composition of Sage (*Salvia officinalis* L.). Journal of Applied Research on Medicinal and Aromatic Plants, 2(1), 21–29. https://doi.org/10.1016/j.jarmap.2015.01.003.

Russo, E. B. (2011). Taming THC: Potential Cannabis Synergy and Phytocannabinoid-Terpenoid Entourage Effects. British Journal of Pharmacology, 163(7), 1344–1364. https://doi.org/10.1111/j.1476-5381.2011.01238.x.

Russo, E. B. (2019). The Case for the Entourage Effect and Conventional Breeding of Clinical Cannabis: No “Strain,” No Gain. Frontiers in Plant Science, 9, 1969. https://doi.org/10.3389/fpls.2018.01969.

Russo, G., De Lucia, B., Vecchietti, L., Rea, E., Leone, A. (2011). Environmental and Agronomical Analysis of Different Compost-Based Peat-Free Substrates in Potted Rosemary. Acta Horticulturae, 891, 265–272. https://doi.org/10.17660/ActaHortic.2011.891.32.

Sakamoto, K., Shimomura, K., Komeda, Y., Kamada, H., Satoh, S. (1995). A Male-Associated DNA Sequence in a Dioecious Plant, *Cannabis Sativa* L. Plant and

Cell Physiology, 36(8), 1549–1554. https://doi.org/10.1093/oxfordjournals.pcp.a078920.

Saloner, A., Bernstein, N. (2020). Response of Medical Cannabis (*Cannabis Sativa* L.) to Nitrogen Supply Under Long Photoperiod. Frontiers in Plant Science, 11, 1517. https://doi.org/10.3389/fpls.2020.572293.

Saloner, A., & Bernstein, N. (2021). Nitrogen supply affects cannabinoid and terpenoid profile in medical cannabis (Cannabis sativa L.). Industrial Crops and Products, 167(December 2020), 113516. https://doi.org/10.1016/j.indcrop.2021.113516

Saloner, A., Bernstein, N. (2022a). Effect of Potassium (K) Supply on Cannabinoids, Terpenoids and Plant Function in Medical Cannabis. Agronomy, 12(5), 1242. https://doi.org/10.3390/AGRONOMY12051242.

Saloner, A., Bernstein, N. (2022b). Nitrogen Source Matters: High NH_4/NO_3 Ratio Reduces Cannabinoids, Terpenoids, and Yield in Medical Cannabis. Frontiers in Plant Science, 13(3), 1–17. https://doi.org/10.3389/fpls.2022.830224.

Saloner, A., Sacks, M. M., Bernstein, N. (2019). Response of Medical Cannabis (*Cannabis Sativa* L.) Genotypes to K Supply Under Long Photoperiod. Frontiers in Plant Science, 10. https://doi.org/10.3389/fpls.2019.01369.

Sheng, A.-Wu., He, Quan., Zhao, Y.-Fang., Zhang, W.-Feng. (2005). Effects of Substrate, Nutrient Solution and Chemical Agents on Growth and Flowering of *Anthurium Andraeanum*. Subtropical Plant Science. 34(3),34-36,33.

Shiponi, S., Bernstein, N. (2021). The Highs and Lows of P Supply in Medical Cannabis: Effects on Cannabinoids, the Ionome, and Morpho-Physiology. Frontiers in Plant Science, 12. https://doi.org/10.3389/fpls.2021.657323.

Small, E., Cronquist, A. (1976). A Practical and Natural Taxonomy for Cannabis. Taxon, 25(4), 405–435. https://doi.org/10.2307/1220524.

Small, E., Naraine, S. G. U. (2016). Expansion of Female Sex Organs in Response to Prolonged Virginity in *Cannabis sativa* (Marijuana). Genetic Resources and Crop Evolution, 63(2), 339–348. https://doi.org/10.1007/s10722-015-0253-3.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., & Fixen, P. E. (2009). Review of Greenhouse Gas Emissions from Crop Production Systems and Fertilizer Management Effects. In Agriculture, Ecosystems and Environment, 133(3), 247–266. https://doi.org/10.1016/j.agee.2009.04.021.

Song, C., Saloner, A., Fait, A., Bernstein, N. (2023). Nitrogen Deficiency Stimulates Cannabinoid Biosynthesis in Medical Cannabis Plants by Inducing a Metabolic

Shift Towards Production of Low-N Metabolites. Industrial Crops and Products, 202. https://doi.org/10.1016/j.indcrop.2023.116969.

Spitzer-Rimon, B., Duchin, S., Bernstein, N., Kamenetsky, R. (2019). Architecture and Florogenesis in Female Cannabis Sativa Plants. Frontiers in Plant Science, 10, 350. https://doi.org/10.3389/fpls.2019.00350.

Sui, B., Feng, X., Tian, G., Hu, X., Shen, Q., Guo, S. (2013). Optimizing Nitrogen Supply Increases Rice Yield and Nitrogen Use Efficiency by Regulating Yield Formation Factors. Field Crops Research, 150, 99–107. https://doi.org/10.1016/j.fcr.2013.06.012.

Summers, H. M., Sproul, E., & Quinn, J. C. (2021). The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States. Nature Sustainability, 4(7), 644–650. https://doi.org/10.1038/s41893-021-00691-w.

Taíz, E., & Zeiger, L. (2010). Plant Physiology 5th Ed. Sinauer Associates Inc., 782.

Tanney, C. A. S., Lyu, D., Schwinghamer, T., Geitmann, A., Ruan, E. D., Smith, D. L. (2023). Sub-Optimal Nutrient Regime Coupled with *Bacillus* and *Pseudomonas* Sp. Inoculation Influences Trichome Density and Cannabinoid Profiles in Drug-Type *Cannabis sativa*. Frontiers in Plant Science, 14, 1–10. https://doi.org/10.3389/fpls.2023.1131346.

Tonitto, C., Woodbury, P. B., McLellan, E. L. (2018). Defining a Best Practice Methodology for Modeling the Environmental Performance of Agriculture. In Environmental Science and Policy 87, 64–73. https://doi.org/10.1016/j.envsci.2018.04.009.

UNEP. (2019). Frontiers 2018/19 - Emerging Issues of Environmental Concern. http://www.un.org/Depts/Cartographic/english/htmain.htm.

Usherwood, N. R. (2015). The Role of Potassium in Crop Quality. In Potassium in Agriculture (pp. 489–513). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/1985.potassium.c21.

Vandecasteele, B., Blindeman, L., Amery, F., Pieters, C., Ommeslag, S., Van Loo, K., De Tender, C., Debode, J. (2020). Grow - Store - Steam - Re-peat: Reuse of Spent Growing Media for Circular Cultivation of Chrysanthemum. Journal of Cleaner Production, 276, 124128. https://doi.org/10.1016/j.jclepro.2020.124128.

Vanhove, W., Van Damme, P., Meert, N. (2011). Factors Determining Yield and Quality of Illicit Indoor Cannabis (*Cannabis* Spp.) Production. Forensic Science International, 212(1–3), 158–163. https://doi.org/10.1016/j.forsciint.2011.06.006.

Vujanovic, V., Korber, D. R., Vujanovic, S., Vujanovic, J., Jabaji, S. (2020). Scientific Prospects for Cannabis-Microbiome Research to Ensure Quality and Safety of Products. Microorganisms, 8(2), 290. https://doi.org/10.3390/microorganisms8020290.

Walworth, J. L., Sumner, M. (1987). The Diagnosis and Recommendation Integrated System (DRIS). Advances in Soil Science, 6, 149–188. https://doi.org/10.1007/978-1-4612-4682-4.

Wang, I. J., Brenner, J. C., Butsic, V. (2017). Cannabis, an Emerging Agricultural Crop, Leads to Deforestation and Fragmentation. Frontiers in Ecology and the Environment, 15(9), 495–501. https://doi.org/10.1002/fee.1634.

Wartenberg, A. C., Holden, P. A., Bodwitch, H., Parker-Shames, P., Novotny, T., Harmon, T. C., Hart, S. C., Beutel, M., Gilmore, M., Hoh, E., Butsic, V. (2021). Cannabis and the Environment: What Science Tells Us and What We Still Need to Know. Environmental Science and Technology Letters, 8(2), 98–107. https://doi.org/10.1021/acs.estlett.0c00844.

Wilkins, R. J. (2008). Eco-Efficient Approaches to Land Management: A Case for Increased Integration of Crop and Animal Production Systems. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363(1491), 517–525. https://doi.org/10.1098/rstb.2007.2167.

Wilson, H., Bodwitch, H., Carah, J., Daane, K., Getz, C., Grantham, T. E., Van Butsic. (2019). First Known Survey of Cannabis Production Practices in California. California Agriculture, 73(3), 119–127. https://doi.org/10.3733/ca.2019a0015.

Yep, B., Zheng, Y. (2021). Potassium and Micronutrient Fertilizer Addition in a Mock Aquaponic System for Drug-Type *Cannabis sativa* L. Cultivation . Canadian Journal of Plant Science, 101(3), 341–352. https://doi.org/10.1139/cjps-2020-0107.

Yep, B., Gale, N. V., Zheng, Y. (2020). Aquaponic and Hydroponic Solutions Modulate NaCl-Induced Stress in Drug-Type *Cannabis Sativa* L. Frontiers in Plant Science, 11, 1–14. https://doi.org/10.3389/fpls.2020.01169.

Zheng, Z., Fiddes, K., Yang, L. (2021). A Narrative Review on Environmental Impacts of Cannabis Cultivation. Journal of Cannabis Research, 3(1). https://doi.org/10.1186/s42238-021-00090-0.

Zhou, F., Pichersky, E. (2020). More Is Better: The Diversity of Terpene Metabolism in Plants. In Current Opinion in Plant Biology, 55, 1–10.. https://doi.org/10.1016/j.pbi.2020.01.005

Connecting text

The preceding Chapter underscored the existing knowledge regarding mineral fertilization in cannabis cultivation and identified a gap in understanding the environmental implications of using these fertilizers. It emphasized the necessity of employing rigorous methodologies like LCA to quantify these environmental externalities accurately. The subsequent Chapter will elucidate the process and rationale behind utilizing LCA in agriculture, shedding light on its significance in evaluating environmental impacts comprehensively.

Chapter 2 : Overview of life-cycle assessments

2.1 Life-cycle Assessment

LCA estimates the inputs, outputs and potential environmental impacts associated with a product's life-cycle. The "life-cycle" encompasses the different stages of the value chain – resource extraction, material production, fabrication and assembly, use, and disposal – as well as distribution between these stages. The aim is to quantify the environmental dimension of sustainability. Direct applications of LCA include public policy making, marketing, strategic planning, and product development/improvement. LCA involves four steps: definition of goals and objectives, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation of results. Stages and framework of an LCA is shown in Figure 2.1.

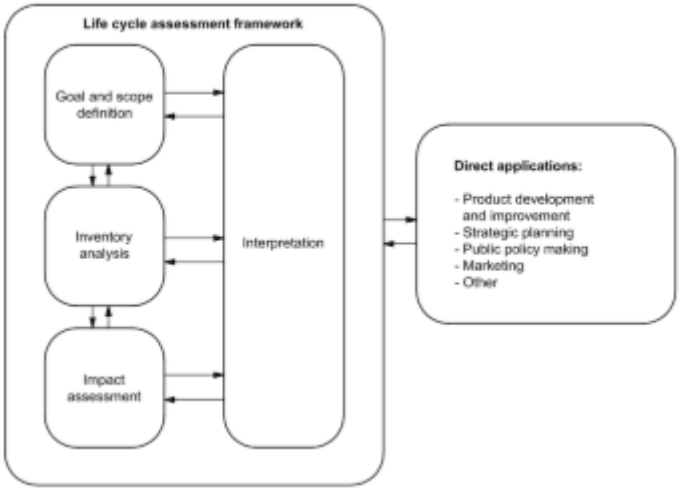


Figure 2.1: Stages and framework of a LCA. Taken from ISO:14044

2.2 Goal and Scope Definition

The aim of any LCA study is to compare the environmental impact resulting of a product, from its fabrication to the end of its life. Identifying parameters that have the largest environmental impact, or "hot-spots", can help in proposing improved production practices. For a LCA to be able to compare between two fabrication practices, a functional unit (FU) must be chosen. In the case of fertilizer practices, yield of biomass in kg is routinely used (De Backer et al., 2009; Girgenti et al., 2014). However, in the case of cannabis, where cannabinoid yield is the metric of interest, cannabinoid concentration of the biomass must be considered.

FU is necessary to compare between varying production practices, as it normalizes environmental externalities for a standard unit of production. If one treatment produces

more biomass per area but is associated with a substantial increase in greenhouse gas (GHG) emission, it will be addressed in the interpretation phase. GHG emission kg^{-1} biomass is a metric that is relevant for policymaking and aimed at increasing the environmental performance of a given production. System boundaries reflect the boundary between the natural and technical system under study (Girgenti et al., 2014). When studying agricultural system, the "cradle-to-grave" approach is preferred where it encompasses all necessary inputs from production (soil preparation, seed acquiring etc.) to how it is discarded after use (landfills, composting or recycling center). These studies require an immense amount of work, where data is gathered from all parts of the supply-chain, either by direct measurement, models or surveys being filled out by actors of the industry (De Backer et al., 2009). Plant nutrition studies would provide crucial data for LCA, as it would be associated with an in-depth analysis of inventory.

2.3 Impact Assessment

The life cycle inventory (LCI) compiles and quantifies all relevant inputs and outputs associated with the production. This comprises of background systems, which is obtained from the literature, and foreground systems which is obtained from on-site measurements (Tabatabaie & Murthy, 2016). This data is used to assess the environmental impact of varying fabrication practices. Examples of foreground processes for which primary data will be collected are total fertilizer input, total water input, total electricity used. Examples of processes in the background system include production of input (extraction of peat, mineral, fixation of N through the Haber-Bosch process). Data for the background system will be collected from previous LCAs, grey literature, and commercial databases (e.g. EcoInvent 3).

2.4 Inventory Analysis

The life-cycle impact assessment (LCIA) phase converts the LCI into estimated environmental impacts using impact factors that account for the environmental burdens of consumed resources (e.g. oil to exhaustion of non-renewables) or chemical emissions (e.g. kg of methane to global warming) (Guinée et al., 2006). Impact categories routinely used in agricultural studies are climate change, particulate matter production, acidification, eutrophication, toxicity, land use and resource depletion (water, fossil and renewables) (European Commission, 2011). There are a few existing methods to estimate these impacts from LCI data, each one based on different assumptions and fate and impact models. This project utilized the latest iteration of the ReCiPe LCIA method which is widely used in industry and academia.

2.4.1 Eutrophication

Eutrophication from agricultural run-off causes the excessive plant growth that results from nutrient enrichment by human activity. This leads to an increase in biomass of algae and, ultimately, deprives the water body of oxygen. Some of the consequences of this implies a decrease in the aesthetic value and the harvestable fish and shellfish biomass of water bodies. It can increase cost of water treatment, as well as risk of harmful algae blooms (Smith & Schindler, 2009). In terrestrial ecosystems, an increase in soil nitrate can be detrimental to some plants (ie. trees) but beneficial to other species like tall grasses. This can change native plant and animal communities, impact timber production and fire regimes, to name a few (Clark et al., 2017). Freshwater eutrophication potential (FEP) is accounted for in LCA by calculating P present in agricultural soil and imported for fertilization. It is assumed that 10 percent of all P from agricultural soil will be transported to surface water. FEP is expressed in kg P to freshwater-equivalents (Huijbregts et al., 2017). Terrestrial eutrophication potential is expressed as the sum of equivalent NO_x and NH_3 deposited ha^{-1} yr^{-1} (Sepp et al., 2006). No studies have looked at accumulated exceedance or N deposition caused by cannabis fertilization. Following private industry fertilizer recommendation could cause over-fertilization. Knowing that only around 30 percent of greenhouse producers in Canada reuse their fertilizer solution, investigation of eutrophication potential of the cannabis industry has to be investigated (Nicola et al., 2020)

2.4.2 Abiotic Resource Depletion Potential

Abiotic resource depletion potential (ADP) is defined as the ratio of annual production and the square of the ultimate reserve of the crustal content (content of the earth's crust) divided by the same ratio for a reference resource, chosen as antimony (Sb). The choice of reference element is unimportant, as it will not affect the relative scores in a comparative analysis. LCA uses two subcategories of ADP, one for fossil fuels and another for elements, and their units are in kg (van Oers et al., 2020). No studies have looked at the ADP of the cannabis industry.

2.4.3 Global Warming Potential

Global warming potential (GWP) is a reference measure permitting comparison processes that emit different gases into a commonly shared unit: "CO_2 equivalence effect". Its unit is in CO_2 equivalent kg. For processes that emit GHG other than CO_2, for example methane, it is multiplied by 28. Nitrous oxide (N_2O) is multiplied by 265.

The amount of CO_2 equivalency is normalized on a 100-year duration. Global warming potential of cannabis agriculture has been studied from small-scale illicit production setup (Mills, 2012) as well as from licensed producer in the US (Summers et al., 2021). Given the dependence of these findings on the fuel mix of the electrical grid, these findings do not apply to other large cannabis producing countries such as Canada, The Netherlands, or elsewhere. Data used by these studies come from the US where the electrical grid is not powered by hydroelectricity. These studies showed that most of the carbon footprint is caused by energy-intensive climate control apparatus (dehumidifying, ventilation, and air conditioning) and high-intensity lamps. These studies are not proper LCA, as carbon footprint is only one indicator. Not only are these conclusions hard to translate to Quebec or other parts of Canada, even less so if outdoor production is used. This would greatly decrease GHG emissions related to direct energy use. For reference, it has been measured at 2500-5000 kg CO_2-eq per kg of dried flower. These studies found that curtailing GHG emission from grow lights, cooling, heating and humidity management, these values could be significantly reduced. No studies have looked at the effect of different fertilizer practices on carbon footprint in cannabis production. Indeed, previous studies assume the same fertilizer practice recommended by the industry. LCA studies looking at fertilizer regimen potential for eutrophication, global warming, fossil fuel and resource depletion are present for other crops (Hasler et al., 2015; Hanserud et al., 2018; Antón et al., 2010; Skowroñska & Filipek, 2014). For example, the choice of fertilizer product type of inorganic fertilizer can decrease life-cycle GHGs by up to 20 percent in soil agriculture (Hasler et al., 2015). Studying fertilizer product type through LCA could help in setting realistic goals for the future of the cannabis industry.

2.5 Interpretation

The interpretation phase is when findings from the previous steps are combined. This step should include identification of significant issues based on results of the impact assessments. An evaluation of the study, assessing its completeness and consistency should be done. Recommendations aimed at growers and, ultimately, policymakers, should be clearly made available. LCA of different fertilizer regimen in the cannabis industry should give growers the tools necessary for a reduced environmental impact, while providing necessary information for optimal mineral fertilization.

2.6 References

Antón, A., Torrellas, M., Montero, J. I., Ruijs, M., Vermeulen, P., Stanghellini, C. (2010). Environmental Impact Assessment of Dutch Tomato Crop Production in a Venlo Glasshouse. International Symposium on Greenhouse and Soilless Cultivation (p. 781–791). Acta Horticulturae. https://doi.org/10.17660/ActaHortic.2012.927.97

Clark, C. M., Bell, M. D., Boyd, J. W., Compton, J. E., Davidson, E. A., Davis, C., Blett, T. F. (2017). Nitrogen-Induced Terrestrial Eutrophication: Cascading Effects and Impacts on Ecosystem Services. Ecosphere, 8(7), 1877. https://doi.org/10.1002/ecs2.1877.

De Backer, E., Aertsens, J., Vergucht, S., Steurbaut, W. (2009). Assessing the Ecological Soundness of Organic and Conventional Agriculture by Means of Life Cycle Assessment (LCA): A Case Study of Leek Production. British Food Journal, 111(10), 1028–1061. https://doi.org/10.1108/00070700910992916.

European Commission - Joint Research Centre - Institute for Environment and Sustainability: (2010) International Reference Life Cycle Data System (ILCD) Handbook - Review schemes for Life Cycle Assessment. First edition March 2010. EUR 24710 EN. Luxembourg. Publications Office of the European Union

Girgenti, V., Peano, C., Baudino, C., Tecco, N. (2014). From "Farm to Fork" Strawberry System: Current Realities and Potential Innovative Scenarios from Life Cycle Assessment of Non-Renewable Energy Use and Greenhouse Gas Emissions. Science of the Total Environment, 473, 48–53. http://dx.doi.org/10.1016/j.scitotenv.2013.11.133.

Guinée, J., van Oers, L., de Koning, A., Tamis, W. (2006). Life Cycle Approaches for Conservation Agriculture. CML Report, 171, 708–711. https://api.semanticscholar.org/CorpusID:131347254.

Hanserud, O. S., Cherubini, F., Øgaard, A. F., Müller, D. B., Brattebø, H. (2018). Choice of Mineral Fertilizer Substitution Principle Strongly Influences LCA Environmental Benefits of Nutrient Cycling in the Agri-Food System. Science of The Total Environment, 615, 219–227. https://doi.org/10.1016/j.scitotenv.2017.09.215.

Hasler, K., Bröring, S., Omta, S., Olfs, H. W. (2015). Life Cycle Assessment (LCA) of Different Fertilizer Product Types. European Journal of Agronomy, 69, 41–51. https://doi.org/10.1016/j.eja.2015.06.001.

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Van Zelm, R. (2017). Recipe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and 5 Endpoint Level. The International Journal of Life Cycle Assessment, 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Mills, E. (2012). The Carbon Footprint of Indoor Cannabis Production. Energy Policy, 46, 58–67. https://doi.org/10.1016/j.enpol.2012.03.023.

Nicola, S., Pignata, G., Ferrante, A., Bulgari, R., Cocetta, G., Ertani, A. (2020). Water Use Efficiency in Greenhouse Systems and Its Application in Horticulture. AgroLife Scientific Journal, 9(1). https://agrolifejournal.usamv.ro/index.php/agrolife/article/view/587.

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.-P. (2006). Country-Dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. The International Journal of Life Cycle Assessment, 11, 403–416. http://dx.doi.org/10.1065/lca2005.06.215.

Skowrońska, M., Filipek, T. (2014). Life Cycle Assessment of Fertilizers: A Review. International Agrophysics, 28(1). https://doi.org/10.2478/intag-2013-0032.

Smith, V. H., Schindler, D. W. (2009). Eutrophication Science: Where Do We Go from Here? Trends in Ecology & Evolution, 24(4), 201–207. https://doi.org/10.1016/j.tree.2008.11.009.

Summers, H. M., Sproul, E., Quinn, J. C. (2021). The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States. Nature Sustainability, 4(7), 644–650. https://doi.org/10.1038/s41893-021-00691-w.

Tabatabaie, S. M. H., Murthy, G. S. (2016). Cradle to Farm Gate Life Cycle Assessment of Strawberry Production in the United States. Journal of Cleaner Production, 127, 548–554. https://doi.org/10.1016/j.jclepro.2016.03.175.

van Oers, L., Guinee, J. B., & Heijungs, R. (2020). Abiotic Resource Depletion Potentials (ADPs) for Elements Revisited—Updating Ultimate Reserve Estimates and Introducing Time Series for Production Data. The International Journal of Life Cycle Assessment, 25, 294–308. https://link.springer.com/article/10.1007/s11367-019-01683-x.

Connecting text

The previous chapter provided an overview of the current understanding of mineral fertilization in cannabis cultivation and the methodology of LCA. Drawing from the previous application of these concepts in other crops to calculate GWP, the subsequent chapter integrates both notions to assess, for the first time, the environmental impact of outdoor cannabis production.

Chapter 3 : The Environmental Impact of Outdoor Cannabis Production

Abstract

Environmental impacts of cannabis production are of increasing concern because it is a newly legal and growing industry. Although a handful of studies have quantified the impacts of indoor production, very little is known about the impacts of outdoor cannabis agriculture. Outdoor production typically uses little direct energy but can require significant fertilizer and other inputs due to dissipative losses via runoff and mineralization. Conversely, fertilizer high in nitrogen can be counterproductive as it produces flowers with decreased cannabinoid content. This study has two aims: (1) To identify reduced-fertilizer regimes that provide optimal cannabis flower yields with reduced inputs and (2) To quantify how this shifts greenhouse gas emissions, resource depletion (fossil and metal), terrestrial acidification, and eutrophication potential of outdoor cannabis production. Primary data from a fertilizer response trial was incorporated in a life-cycle assessment model. Results showed outdoor cannabis agriculture could be 50 times less carbon emitting than indoor production. Dissemination of this knowledge is of utmost importance for producers, consumers and government officials in nations that have either legalized or will legalize cannabis production.

3.1 Introduction

The rapid expansion of legal *Cannabis sativa* (cannabis) production raises questions regarding its resource use and environmental impacts (Wartenberg et al., 2021). These impacts are critically understudied, as research to date has prioritized the medicinal aspects of cannabis (Vujanovic et al., 2020). Limited data is available for cannabis cultivation, as 50% of the research on cannabis relates to the medical or food-related fields, while cannabis cultivation accounts for less than 1% of studies (Vujanovic et al., 2020; Hussain et al., 2021).

To date, only two studies have investigated the carbon footprint of indoor cannabis production (Mills, 2012; Summers et al., 2021). Results showed that the production of 1 kg of dried flower could produce between 2500 and 5000 kg CO_2-equivalent (CO_2-eq), a measure of global warming potential (GWP) emission. Of this, the vast majority of GHG emissions comes from the energy needed for grow room climate control via heating, ventilating and air conditioning (HVAC) systems, supplemental lighting, and CO_2. These emissions sources can be avoided by growing cannabis outdoors, where

such energy-demanding technologies are not used (Wilson et al., 2019), but there is a lack of empirical demonstrating this.

Outdoor cannabis production should emit much less CO_2-eq compared to indoor cannabis production, but could come at the expense of forests, wildlife habitats and water quality, as observed with the Californian expansion of cannabis production (Butsic et al., 2018). As in other agricultural crops grown outdoors, the most efficient way to reduce environmental externalities is by optimizing N-fertilizer use (Xu et al., 2012; X. Chen et al., 2021; Gao & Cabrera Serrenho, 2023; Snyder et al., 2009; Chen et al., 2013). Synthetic N-fertilizer use is associated with GHG emission during its production and use phase (IPNI, 2011). When N-fertilizer is applied in the field, nitrous oxide (N_2O) will be emitted depending on soil parameters such as temperature and moisture (Chen et al., 2013). N_2O is one of the most potent greenhouse gas, with a GWP 298 times the one of CO_2 at equivalent amount. N-fertilizer is a major driver of GWP in most crop production and can be responsible for up to 90% of the total carbon footprint (Snyder et al., 2009; Flugge et al., 2017).

Furthermore, waste nutrient solution is routinely discharged into the environment despite being loaded with fertilizer (Mohammed, 2017). This inefficient nutrient cycling threatens water quality, through nutrient leaching and subsequent eutrophication, as well as decreases profit for growers (Kumar & Cho, 2014; Huang et al, 2017). Scientifically informed guidelines are essential to prevent fertilizer-associated negative environmental externalities while increasing profit for farmers (Menegat et al, 2022).

Previous studies have shown that enhancing the N content in cannabis fertilizer results in larger plants, but the cannabinoid levels in both the flowers and leaves decreased (Bocsa et al, 1997; Saloner & Bernstein, 2020). This reduction, known as the “dilution effect”, is partly attributed to a metabolic shift favoring the production of low-N metabolites under N deficiency, such as cannabinoids (Bernstein et al, 2023). Leveraging this symptom of N deficiency could offer a sustainable approach to cannabis production, potentially reducing costs and environmental impacts associated with chemical N fertilizer production and utilization while simultaneously boosting yields (Snyder et al., 2009; Menegat et al., 2022). Suboptimal N content in the fertilizer promotes the growth of stalked trichomes on the plant, plant structures responsible for the synthesis of 9-tetrahydrocannabinol (THC), typically the most valuable active chemical in cannabis (Tanney et al., 2023; Tanney et al., 2021). Outdoor-grown

cannabis plants have less oxidized and degraded cannabinoids than their indoorgrown counterpart, possibly caused by an increase in the antioxidant capacity of outdoor-grown plants (Zandkarimi et al., 2023). New data on increasing N-fertilizer efficiency could help optimize fertilizer use in outdoor cannabis production. Replacing some N-fertilizer input with K-fertilizer input is beneficial in other flower crops (Heidemann & Barbosa, 2017; Barbosa et al, 2000; Barbosa et al., 2012).

We assess potential tradeoffs between yield, THC, and environmental impacts through field-trials of outdoor cannabis production combined with life cycle assessment (LCA). LCA is a commonly used decision support tool in agriculture (Antón et al., 2010; Maham et al., 2020; Tabatabaie & Murthy, 2016) that can be used to guide farming practices and policies (ISO, 2006a, 2006b).

The effects of different fertilizer recipes (varying N and K ratios) were tested on the outputs of outdoor cannabis grown in Quebec, Canada over three growing seasons and tracked inputs of equipment and supplies at the farm. LCA was then used to quantify environmental impacts for five indicators: GWP, marine eutrophication potential (MU), terrestrial acidification (TA), fossil fuel depletion (FD), and metal resource depletion (MD). In addition to providing the first full LCA of outdoor cannabis production, our study brings novelty by quantifying impacts using both on a yield basis and on a THC basis. Previous studies have only focused on impacts per kg dried flower (Mills, 2012; Summers et al., 2021). This ignores the potential impacts of production practices on concentration of cannabinoids in the dried flower, thereby undermining the functional equivalence of the systems being compared, as it is ultimately these chemicals, and not the dried flower, that are of value to both medicinal and recreational growers.

3.2 Methods

This study combined fertilizer trials of open-field cannabis production with a detailed LCA. Below we outline the details of the field trials and statistical analysis used to analyze the effects of fertilizer regimes on yield and THC, and then describe the LCA model.

3.2.1 Experimental Site

The study was conducted from 2020-2022 in an experimental farm near Thetford Mines, QC, Canada (46° 10’ 52.824’’ N; 71° 18’ 58.068’’ W), during the months of May-September. All three seasons were typical, averaging 290 mm precipitation and

13.5 °C. For details see Supplementary Table S3.1 (Appendix A). Plants were grown in pots located outdoor.

3.2.2 Plant Culture and Field Conditions

To decrease the risk of frost-associated crop failure, a photoperiod insensitive cannabis plant was chosen. This study used feminized auto-flowering seeds of 'Candy Cane'. Seeds were germinated then put in 12 L black pots filled with peat-based potting mix (ProMix HP, Premier Tech, Rivière-du-Loup, QC, Canada) with muriate of potash (KCl) and incorporated controlled-release fertilizers (Osmocote classic 14-14-14, 3-4 months; ICL Fertilizer, Dublin, OH, US) composed of 5.8 % nitrate N and 8.2 % ammoniacal N. Irrigation was supplied via sprinkler every 2-3 days, and plants were randomly spaced at a density of 5.6 plants m^2.

3.2.3 Fertilizer Treatment

Seedlings were randomly divided into six treatments. Three treatments used manufacturer recommended N-levels of 3.2, 7.7 and 11.8 g N per pot. These treatments had a fertilizer K:N ratio of 1. Three treatments used the same N levels but at a K:N ratio of 2:1 (3.2, 7.7 and 11.8 g K_2O equivalent per pot).

3.2.4 Harvest, Drying, Growth and Yield Measurements

Plants were harvested after 10 weeks, and measured for individual plant height, stem diameter, total fresh mass, fresh flower mass, fresh stem mass, and leaf fresh mass. Flower from the same treatment were pooled and air dried in a dark room for a week, leaves were pooled per treatment before drying. From these treatment-pooled flowers and leaves, randomly selected samples were sent for analysis. N use efficiency (NUE) calculations followed Saloner and Bernstein (2020, 2021), with slight modification. Dry flower over the cumulative N-input from the whole grow cycle was used. N-input accounts for the fertilizer and potting media. We calculated the cannabinoid production efficiency of N (CPE_N) as total N-input over total THC yield.

3.2.5 Elemental and Cannabinoid Analysis

Our samples of leaves and potting media were sent to a third-party lab (A&L Laboratory, London, ON, Canada) for elemental analysis. Metals were analyzed by acid digestion (ICP-OES Ref. EPA3050B/EPA6010B). Nitrate was measured by colorimetric dosage (Standard Methods 4500-NO3-F automated cadmium reduction method), total N by combustion/thermal conductivity (Dumas method), and chloride by K_2SO_4 extraction with the standard method 4500-Cl-G mercuric thiocyanate flow

injection analysis. For cannabinoids, treatment-pooled flowers were sent to a third-party lab (Phytochemia, Chicoutimi, QC, Canada). Cannabinoids were analyzed using standard methods (Lazzerini et al., 2016). For details see Supplementary Methods S3 (Appendix A). Pour-through analysis of leachate was done according to Wright (1986). THC content is on an anhydrous basis and total THC is the sum of neutral and acid forms. Samples were collected from 2020 to 2022.

3.2.6 Statistical Analyses

The experiment was designed using a complete randomized block design with six treatments, and each plant represented a single-year replicate. Collected data were analyzed using two-way ANOVA with fertilizer treatment and harvest year as the two categorical variables to determine statistical significance of treatment, sampling year and their interactive effects on whole plant mass, flower mass, stem mass, plant height, stem diameter, plant THC content and yield, N content, CPE_N and NUE. Tukey-Kramer Honestly Significant Difference (HSD) test was performed to compare means for all pairs. The relationship between leaf N content and flower total THC content used a linear regression model.

3.2.7 Life-Cycle Assessment

The LCA consists of four stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

3.2.7.1 Life-Cycle Assessment Goal and Scope

The goal and scope of the study were to measure six environmental performance indicators associated with fertilizer use in outdoor cannabis agricultural: GWP, marine eutrophication potential, freshwater eutrophication potential, terrestrial acidification, fossil fuel depletion, and metal resource depletion. These indicators were chosen because of their direct links to synthetic fertilizer production and application (Hasler et al., 2015). For details see Supplementary Table S3.2 (Appendix A). All environmental impacts were normalized to a FU consisting of 1kg of dried cannabis flower, as in other works (Mills, 2012; Summers et al., 2021), and 100 grams of THC.

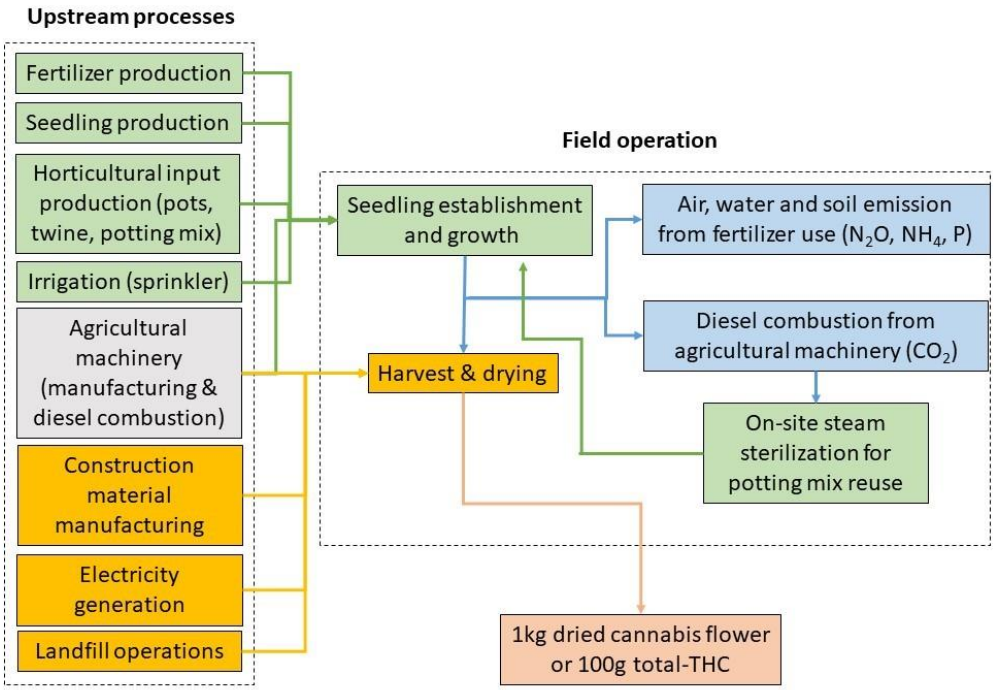


Figure 3.1: System boundaries in our LCA of outdoor cannabis. Upstream processes include material inputs for building construction, fertilizer production and other chemicals, electricity, and production of machinery. Field operation includes plant growth.

3.2.7.2 Life-Cycle Inventory

LCI was compiled, detailing all relevant inputs and outputs of each production stage which can be summed and converted to potential environmental impacts across the product's life-cycle. Primary data collected during the field experiment were used as the foreground system. Measured inputs and outputs were fertilizer, potting mix, plastic, nylon trellis, dried flower yield and total cannabinoid yield from the fertilizer-trial. Background data on material extraction and production processes were taken from scientific literature, agricultural extension services, official industry communications, technical sheets, and the EcoInvent v3.8 database. For data sources, assumptions and modeling details see Supplementary Table S3.2 (Appendix A) and in the Supplementary Methods (Appendix A).

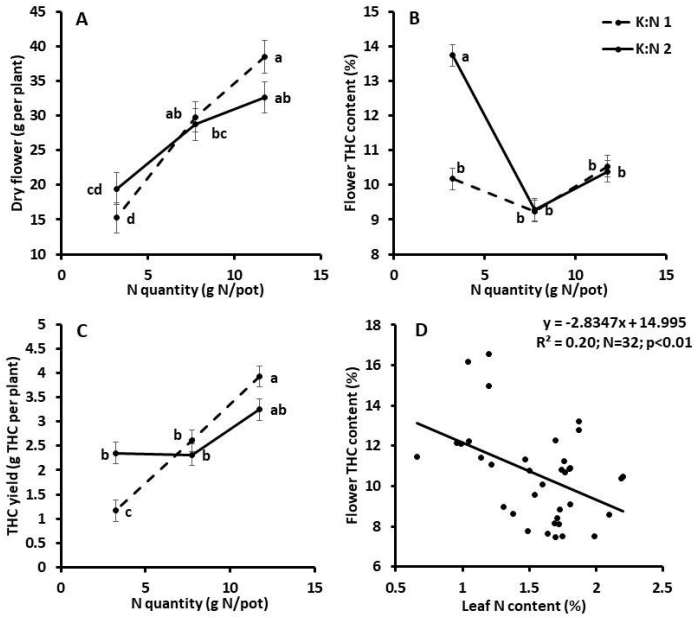
3.2.7.3 Scenarios and Impact Assessments

Scenario used primary data from two fertilizer treatments, one from the high N-input with a K:N of 1 and one from the low N-input with a K:N of 2, renamed H- and L+ respectively for brevity. These two treatments showed the most difference in flower yield and THC content. Both fertilizer treatments output was used to calculate the impact of functional unit (FU) choice (100g of THC or 1 kg dried flower). After the first modelization, another scenario modeled on-site steam sterilization of potting soil to see if it would decrease the environmental impact of new potting media acquisition every year. The system was modeled in OpenLCA software v2.0 (www.openlca.org) using the ReCiPe midpoint (hierarchist v.1.13) impact assessment method.

3.3 Results And Discussion

3.3.1 Effect of Treatment and Planting Year on Plant Growth, Flower and Cannabinoid Yield.

Across sampling years, higher levels of N-input were associated with an increase in flower yield (Figure 3.2 A). Flower THC content and whole plant THC yield did not follow the same trend (Figure 3.2 B-C). Most plant characteristics were significantly impacted by the interaction between treatment and sampling year except flower yield and NUE. See Supplementary Table S3.3 (Appendix A).



Code	Fertilizer treatment	
	g N/pot	g K/pot
L-	3.2	3.2
M-	7.7	7.7
H-	11.7	11.7
L+	3.2	6.4
M+	7.7	15.3
H+	11.7	23.5

Figure 3.2: Effect of fertilizer N-level and K:N ratio on cannabis plants. Cannabis dry flower yield (g per plant) (A), flower THC content (%) (B), THC yield (g THC per plant) (C) and linear regression between inflorescence THC content and leaf N content. Fertilizer treatment alphanumeric code is shown on the right with corresponding fertilizer mass; where L, M and H stands for low, medium and high N, while – stands for a K:N of 1 and + a K:N of 2. Different letters mean significant differences at $p<0.05$, by Tukey HSD test. For (A), each treatment had n=6 for gathered on 3 different years. For (B-D), each treatment had n=3 from collected on 2 different growing years

Flower THC content did not change significantly between treatments except for the treatment L+ (Figure 3.2 B). This treatment had a substantial 28% increase in total THC content when comparing to the average of the other treatments: 13.7% total THC (L+) versus 9.9 % total THC for the average of other treatments. The significant increase in total THC content for this treatment did not translate to a substantial increase in total THC yield, as the treatment with a high N and a K:N of 1 (H-) had the highest total THC yield of 3.9 g THC per plant (Figure 3.2 C). There was a statistically significant negative correlation between foliar N content and flower total THC content ($p<0.01$) (Figure 3.2 D).

3.3.2 Beyond Standard NUE

Previous studies on cannabis fertilizer response have focused on NUE (dry flower yield/total N input). In accordance with literature, it was observed that higher N input fertilizer treatment seems to decrease NUE. While this captures how efficiently the

plant transforms N-fertilizer into biomass, it overlooks the effects on the production of THC.

The ‘dilution effect’ shows how total THC concentration decreases as N-input increases. However, only one treatment (low N high K) significantly impacted total THC content in this study. This could be the first report of a fertilizer treatment impacting cannabinoid content at this magnitude (~30% increase). The current NUE index for cannabis does not consider cannabinoid yield, which is why a new metric was used.

The cannabinoid production efficiency of N (CPE_N) was measured by dividing total THC yield over N-input. This is akin to other studies that have looked at lighting energy relative to THC output (Morello et al., 2022; Rodriguez-Morrison et al., 2021). We found CPE_N was very high for the low N high K treatment with a value of 0.7 versus 0.35 for other treatments, see supplementary Figure S3.1 (Appendix A). Normalizing the fertilizer input to cannabinoid output could help growers decrease environmental impacts and costs.

An explanation for the improved NUE and CPE_N with less N is N-deficiency. This happens when leaf N content is between 1.5-2.5% as opposed to 2.2 and 4.3% in plants with sufficient N. (Rodriguez-Morrison et al, 2021; Llewellyn et al., 2023). Leaf N value in this study were in the range of 1-2 %. Even when plants were grown under a high N-input fertilizer treatments, the elemental analysis of the leaves at the end of the growing season diagnosed them as N-deficient plants. When using slow-release or controlled-released fertilizer, most of the nutrient will be released in the beginning of the growing season (Javazmi et al., 2021). High N treatment allowed plants to grow larger early in the season compared to low N treatment. However, by the end of the season, minimal N was available for the plants in all treatment, as indicated by the poor-through analysis (Table S3.4). In our study, the THC content in flowers could have been lower if the leaf N content and N input were higher, as N-deficiency appears to be correlated with higher cannabinoid content (Song et al., 2023). Interestingly, fertilizing to prevent N deficiency in cannabis, which is said to be when leaf N content is lower than 2.2%, could be counter-productive if high cannabinoid content in flower is the goal. N-deficiency could be exploited to sustainably increase cannabinoid production, as has been done with tobacco plants (*Nicotiana tabacum*) and hops (*Humulus lupulus*), where phenolic and alkaloid secondary metabolites content increase under N-

deficiency (Fritz et al., 2006). This LCA explored the potential benefits of this for cannabis.

3.3.3 Global Warming Potential of Outdoor Cannabis

We found that THC content increased with N deficiency, but total dried flower decreased. Results from the L+ and the H- treatments were used as primary data for the LCA model to understand whether this reduced the environmental impacts of cannabis production relative to higher N application rates.

The average GWP for cannabis was 86.3 kg CO_2-eq per kg of flower. This is at least 25 times less than indoor production, which ranges from 2283 to 5164 kg CO_2-eq per kg of flower (Mills, 2012; Summers et al., 2021). Outdoor production averaged 76.2 kg CO_2-eq per 100 g of THC. But there were large variations between fertilizer treatments. GHG emission when using 1 kg of dried flower were 61.8 kg CO_2-eq per FU for H- versus 110.7 kg CO_2-eq per FU for L+ (Figure 3.3). When using 100 g THC as FU, GWP value for treatment H- was calculated to be 60.7 kg CO_2-eq. Change in FU caused a 2 % decrease in GWP values for treatment H+. For treatment L+, using 100 g THC as a FU caused a GWP value of 91.7 kg CO_2-eq, a decrease of 17% in GWP when comparing with the original FU.

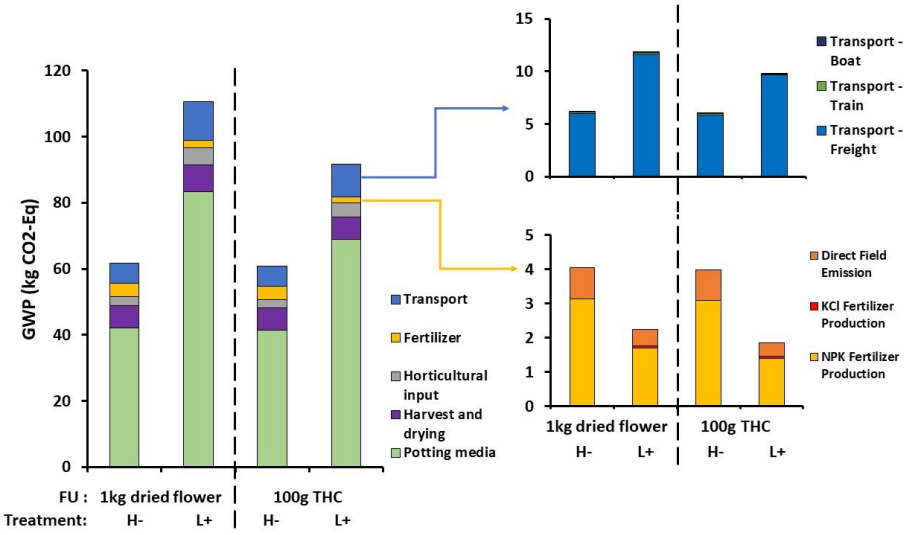


Figure 3.3: Drivers of GWP in outdoor cannabis production. GWP for FUs of 1 kg dried flower and 100 g THC, are shown for the high fertilizer-input treatment (H-) and low fertilizer-input treatment (L+) respectively (See figure 3.2). Total process GHG emission is shown.

Potting media contributed between 65 and 75 % of GWP impacts, predominantly because of peat moss production. Because L+ requires roughly 50 plants per FU

compared to 25 for H-, this doubles the volume of potting media needed for L+ making it more GWP intensive than H-. It should be noted that we used potting media to control soil nutrient content during the fertilizer response trial. Cannabis producers with appropriate machinery for soil work may not need potting media for outdoor production. This would undoubtedly greatly decrease the carbon footprint of the L+ treatment, where potting media drives most of its impact. Future studies could focus on estimating yield differences in potting media versus soil.

One limitation of LCA study is translating findings to the real-world industry. Hypothetically, if L+ treatment did have the same efficiency in soil agriculture, there would still be no incentive for growers to use this treatment, as it would achieve lower total yield per area at similar planting density which could have implications for land use. Future studies could investigate the difference in total area yield of high planting density of smaller, more concentrated cannabis plants versus bigger and less concentrated plants.

Further analysis of the transport process shows how freight vehicles had the most impact in CO_2 footprint, or around 97% of total transport related GHG emission which is largely caused by the fact that the location of the study is very remote from nearby towns and inputs were modeled to be transported in an inefficient freight truck.

3.3.4 High Environmental Impact of Potting Media

This study aligns with others showing how the environmental burden of outdoor production in pots or raised beds is driven by potting media (Lazzerini et al., 2016; Russo et al., 2009). Enabling on-site potting media reuse instead of acquiring fresh potting media every grow cycle can reduce these impacts (Vandecasteele et al., 2022, 2020).

To assess the environmental performance of reusing potting media, a scenario was run for on-site steam sterilization of media. This model assumed a decrease in necessary potting media and associated transport, but an increase in agricultural machinery and diesel consumption. We incorporated on-site agricultural steamer using 26 L of diesel per m^3 of used potting mix into the LCA model. Use of the treatment H- with the 100 g FU was used as it was the least GHG emitting of all treatment per FU combinations. Total GHG emission of 100 g of THC under the H- treatment using on-site potting media reuse via steaming decreased GWP 52.7 kg CO_2-eq per FU versus 60.7 kg CO_2-eq per FU when using fresh potting mix every year. This small shift suggests that

relative GWP performance of H- and L+ would be unchanged if both systems employed soil reuse.

The most GHG emitting processes when reusing potting media was steam sterilization via diesel combustion in agricultural machinery. Transport associated GWP decreased 85% when using on-site reuse of potting media because of the absence annual potting media delivery. For details see Supplementary Table S3.5 (Appendix A). Transport had a GWP of 6 kg CO_2-eq per FU when using fresh potting mix every year versus 0.8 kg CO_2-eq per FU when reusing it. Using new potting media has a GHG emission of 41.5 kg CO_2-eq per FU, ten-fold the value of 4.2 kg CO_2-eq per FU when reusing it on site. The main process to decrease when using fresh potting media every year was 'tractor and steamer operation', specifically diesel consumption. When reusing potting media via steam sterilization, tractor operation was estimated to generate 36 kg CO_2-eq per FU. When using fresh potting media, GWP value of the tractor process is <0.1 kg CO_2-eq per FU.

3.3.5 Impacts of Outdoor Cannabis in Other Dimensions

Further analysis only used 100g THC as FU. Comparing GWP, fossil depletion, terrestrial acidification, eutrophication (freshwater and marine) and metal depletion potential showed how treatment H- without potting media reuse seems to have overall better environmental performances than L+ or H- with potting media reuse (Figure 3.4). H- and L+ without potting media reuse seem to have the lowest marine eutrophication potential and metal depletion potential. L+ had the highest GWP. H- with potting media reuse has the highest GWP.

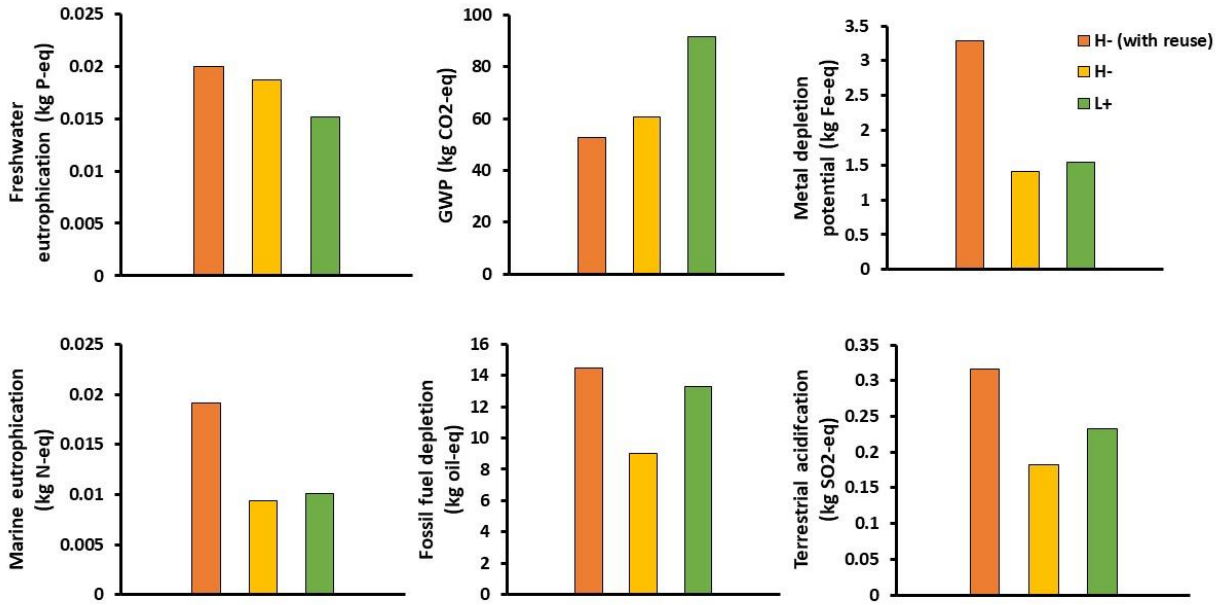


Figure 3.4: Impact category results for the different fertilizer treatment H- or L+ for all life cycle stages to produce 100g of THC. Results from modelling of the H- fertilizer treatment with on-site potting media reuse via steam sterilization are shown.

3.3.6 Fossil Fuel Depletion

When using fresh potting media every year, the processes with the most impact was potting media production, especially perlite production with 40-45% of contribution in treatment H- and L+. The need to transport potting media will drive transport-associated externalities, contributing to around 25% of this indicator. See supplementary Table S3.6 (Appendix A).

In the on-site reuse of potting media scenario, most of this indicator impact is driven by diesel combustion (78%) and the second contributing process are horticultural input (LDPE plastic, nylon, reused potting media) accounting for 7%.

3.3.7 Terrestrial Acidification

Roughly 50-60% of it is caused by potting media production. The second most contributing process for the H- treatment is fertilizer production, accounting for 24% of the impact. The contribution of fertilizer in the L+ treatment decreased to 9%. Like fossil fuel depletion, diesel combustion is what drives most (74%) of this indicator when on-site reuse of potting media is done. See Supplementary Table S3.7 (Appendix A).

3.3.8 Eutrophication

Fertilizer accounts for 66-67% of the impact in freshwater environment in treatment H- regardless of potting media reuse. This decreases to 38% in treatment L+. Again, the increase in necessary potting media and associated transport drives the rest of the impact, with a higher impact in L+ treatment as it requires more of these processes. Marine eutrophication potential is driven by diesel combustion, responsible for 70% of the impact when reusing potting media. See Supplementary Table S3.8 (Appendix A).

3.3.9 Metal Depletion

As in other impact categories, the potting reuse scenario, tractor and steamer use was the most contributing process (69%). When fresh potting media is used, potting media production becomes the most contributing processes, with 25% and 38% of the total impact in treatment H- and L+. H- treatments has a lower impact as it requires less potting media. Interestingly, the drying process (shed and electricity) is responsible for 50% of the impact in the H- treatment and 38% in the L+ treatment. In the potting media reuse scenario, this is closer to 22%. See Supplementary Table S3.9 (Appendix A).

3.3.10 Life-cycle Assessment Interpretation

This is the first study looking at other environmental externalities than GWP. Carbon footprint studies for cannabis have historically used 1 kg of dried flower as their FU. However, when using primary data from two fertilizer treatments studied here, L+ and H-, it was shown how FU choice would slightly affect LCA conclusions. Choice of FU greatly environmental impact when looking at the impacts of 1 kg of dried flower versus 100 g of THC in L+ treatment but did not have a significant impact in the H- treatment. This is important as growers usually produce with a finished product in mind.

For a producer focused on doing extraction, where doses are calculated as mg of THC according to Canadian law (Jack, 2022), this has important implication for product eco-labeling or carbon tax credit. Furthermore, as total THC yield will dictate how many units can be sold, product environmental impact and final profit. For reference, cannabis extracts (e.g., oils) represents roughly 30 % of sales in Canada. For a grower aiming for dried flower as a final product, 1 kg of dried flower might still be more relevant to use.

The issue with using low-fertilizer input is that it decreases yield. Agronomical index like NUE and CPE_N seem to show low-input is more sustainable, but when

considering the increase need for other inputs, specifically potting media, this does not seem to be true. Growers using potted media but wanting to increase their environmental performance would be advised to look for substituting potting media with locally-source material instead of on-site steaming. Bioresources, such as treated agricultural waste seem to be a sustainable alternative (Gruda, 2019). The conclusion on the use of on-site potting media reuse seemed to show that, even if it slightly decreases GWP, all other indicators were increased by it.

For future studies, looking at the industry total GWP by considering the entire Canadian volume of production would help in sizing the environmental burden of the industry. If this turned out to be a very large number, then the industry might look at outdoor growing to mitigate GHG emission. It is important to point out that the GWP of outdoor cannabis could be 20 to 50 times lower than the indoor grown cannabis (Mills, 2012; Summers et al., 2021).

3.4 References

Antón, A., Torrellas, M., Montero, J. I., Ruijs, M., Vermeulen, P., Stanghellini, C. (2010). Environmental Impact Assessment of Dutch Tomato Crop Production in a Venlo Glasshouse. International Symposium on Greenhouse and Soilless Cultivation (p. 781–791). Acta Horticulturae. https://doi.org/10.17660/ActaHortic.2012.927.97

Barbosa, J. G., Kampf, A. N., Martinez, H. E., Koller, O. C., & Bohnen, H. (2000). Chrysanthemum Cultivation in Expanded Clay. I. Effect of the Nitrogen-Phosphorus-Potassium Ratio in the Nutrient Solution. Journal of Plant Nutrition, 23(9), 1327–1336. https://doi.org/10.1080/01904160009382103

Barbosa, J., Barbosa, M., Almeida, D., Sa, P., Finger, F., Martinez, H., Grossi, J. (2012). Production and Postharvest Quality of Chrysanthemum Flowers Grown in Hydroponic System Under Different N: K Ratios. In X International Symposium on Postharvest Quality of Ornamental Plants 1060 (pp. 281–287). Acta Horticulturae. https://doi.org/10.17660/ActaHortic.2015.1060.42

Bocsa, I., Mathé, P., Hangyel, L. (1997). Effect of Nitrogen on Tetrahydrocannabinol (THC) Content in Hemp (*Cannabis sativa* L.) Leaves at Different Positions. Journal of the International Hemp Association, 4(2), 78–79. http://www.internationalhempassociation.org/jiha/jiha4207.html

Butsic, V., Carah, J. K., Baumann, M., Stephens, C., & Brenner, J. C. (2018). The Emergence of Cannabis Agriculture Frontiers as Environmental Threats. Environmental Research Letters, 13(12), 124017. https://doi.org/10.1088/1748-9326/aaeade

Chen, H., Li, X., Hu, F., Shi, W. (2013). Soil Nitrous Oxide Emissions Following Crop Residue Addition: A Meta-Analysis. Global Change Biology, 19(10), 2956–2964. https://doi.org/10.1111/gcb.12274

Chen, X., Ma, C., Zhou, H., Liu, Y., Huang, X., Wang, M., Cai, Y., Su, D., Muneer, M. A., Guo, M., Chen, X., Zhou, Y., Hou, Y., Cong, W., Guo, J., Ma, W., Zhang, W., Cui, Z., Wu, L., Zhou, S., Zhang, F. (2021). Identifying the Main Crops and Key Factors Determining the Carbon Footprint of Crop Production in China, 2001–2018. Resources, Conservation and Recycling, 172, 105661. https://doi.org/10.1016/j.resconrec.2021.105661

J. Rosenfeld, J. Lewandrowski, T. Hendrickson, K. Jaglo, K. Moffroid, D. Pape, (2018). A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol. Report prepared by ICF under USDA Contract No. AG-3142-D-17-0161.

Fritz, C., Palacios-Rojas, N., Feil, R., Stitt, M. (2006). Regulation of Secondary Metabolism by the Carbon–Nitrogen Status in Tobacco: Nitrate Inhibits Large Sectors of Phenylpropanoid Metabolism. The Plant Journal, 46(4), 533–548. https://doi.org/10.1111/j.1365-313X.2006.02715.x

Gao, Y., Cabrera Serrenho, A. (2023). Greenhouse Gas Emissions from Nitrogen Fertilizers Could Be Reduced by Up to One-Fifth of Current Levels by 2050 with Combined Interventions. Nature Food, 4(2), 170–178. https://doi.org/10.1038/s43016-023-00698-w

Gruda, N. S. (2019). Increasing Sustainability of Growing Media Constituents and Stand-Alone Substrates in Soilless Culture Systems. Agronomy, 9(6), 298. https://doi.org/10.3390/agronomy9060298

Heidemann, J. C., Barbosa, J. G. (2017). Producao e Qualidade de Tres Variedades de Crisantemo em Vaso Sob Diferentes Doses de NPK. Ornamental Horticulture, 23(4), 426–431. https://doi.org/10.14295/aohl.v21i2.809

Huang, J., Xu, C.-C., Ridoutt, B. G., Wang, X.-c., Ren, P.-A. (2017). Nitrogen and Phosphorus Losses and Eutrophication Potential Associated with Fertilizer Application to Cropland in China. Journal of Cleaner Production, 159, 171–179. https://doi.org/10.1016/j.jclepro.2017.05.008

Hussain, T., Jeena, G., Pitakbut, T., Vasilev, N., Kayser, O. (2021). *Cannabis sativa* Research Trends, Challenges, and New-Age Perspectives. iScience, 24(12). https://doi.org/10.1016/j.isci.2021.103391

International Organization for Standardization. (2006a). ISO 14040:2006 Environmental management–life cycle assessment—Principles and framework. https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. https://www.iso.org/standard/38498.html

IPNI. (2011). Nitrogen Fertilizer Production and Technology. Retrieved 15 Sep from http://nitrogen.ipni.net/article/NNN-5037.

Jack, S. (2022). Pharmacovigilance of Cannabis Products for Medical and Non-Medical Purposes. Pharmacovigilance for Herbal and Traditional Medicines: Advances,

Challenges and International Perspectives (pp. 317–333). Springer. http://dx.doi.org/10.1007/978-3-031-07275-8_20

Javazmi, L., Young, A., Ash, G. J., Low, T. (2021). Kinetics of Slow Release of Nitrogen Fertiliser from Multi-Layered Nanofibrous Structures. Scientific Reports, 11(1), 4871. https://doi.org/10.1038/s41598-021-84460-x.

Kumar, R. R., Cho, J. Y. (2014). Reuse of Hydroponic Waste Solution. Environmental Science and Pollution Research, 21, 9569–9577. https://doi.org/10.1007/s11356-014-3024-3

Lazzerini, G., Lucchetti, S., Nicese, F. P. (2016). Green House Gases (GHG) Emissions from the Ornamental Plant Nursery Industry: A Life Cycle Assessment (LCA) Approach in a Nursery District in Central Italy. Journal of Cleaner Production, 112, 4022–4030. https://doi.org/10.1016/j.jclepro.2015.08.065

Llewellyn, D., Golem, S., Jones, A. M. P., Zheng, Y. (2023). Foliar Symptomology, Nutrient Content, Yield, and Secondary Metabolite Variability of Cannabis Grown Hydroponically with Different Single-Element Nutrient Deficiencies. Plants, 12(3), 422. https://doi.org/10.3390/plants12030422

Maham, S. G., Rahimi, A., Subramanian, S., Smith, D. L. (2020). The Environmental Impacts of Organic Greenhouse Tomato Production Based on the Nitrogen-Fixing Plant (*Azolla*). Journal of Cleaner Production, 245, 118679. https://doi.org/10.1016/j.jclepro.2019.118679

Menegat, S., Ledo, A., Tirado, R. (2022). Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture. Scientific Reports, 12(1), 1–13. https://doi.org/10.1038/s41598-022-18773-w

Mohammed, N. (2017). The Advantages of a Closed Hydroponic System in Commercial Greenhouses. Greenhouse Research & Production Complex.

Mills, E. (2012). The Carbon Footprint of Indoor Cannabis Production. Energy Policy, 46, 58–67. https://doi.org/10.1016/j.enpol.2012.03.023

Morello, V., Brousseau, V. D., Wu, N., Wu, B.-S., MacPherson, S., Lefsrud, M. (2022). Light Quality Impacts Vertical Growth Rate, Phytochemical Yield and Cannabinoid Production Efficiency in Cannabis sativa. Plants, 11(21), 2982. https://doi.org/10.3390/plants11212982

Neto, B., Dias, A. C., Machado, M. (2013). Life Cycle Assessment of the Supply Chain of a Portuguese Wine: From Viticulture to Distribution. The International Journal

of Life Cycle Assessment, 18, 590–602. http://dx.doi.org/10.1007/s11367-012-0518-4

Rodriguez-Morrison, V., Llewellyn, D., Zheng, Y. (2021). Cannabis Yield, Potency, and Leaf Photosynthesis Respond Differently to Increasing Light Levels in an Indoor Environment. Frontiers in Plant Science, 12, 646020. https://doi.org/10.3389/fpls.2021.646020

Russo, G., De Lucia, B., Vecchietti, L., Rea, E., Leone, A. (2009). Environmental and Agronomical Analysis of Different Compost-Based Peat-Free Substrates in Potted Rosemary. In International Symposium on Growing Media and Composting 891 (pp. 265–272).

Saloner, A., Bernstein, N. (2020). Response of Medical Cannabis (*Cannabis sativa* L.) to Nitrogen Supply Under Long Photoperiod. Frontiers in Plant Science, 11, 572293. https://doi.org/10.3389/fpls.2020.572293

Saloner, A., Bernstein, N. (2021). Nitrogen Supply Affects Cannabinoid and Terpenoid Profile in Medical Cannabis (*Cannabis sativa* L.). Industrial Crops and Products, 167, 113516. https://doi.org/10.1016/j.indcrop.2021.113516.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., Fixen, P. E. (2009). Review of Greenhouse Gas Emissions from Crop Production Systems and Fertilizer Management Effects. Agriculture, Ecosystems & Environment, 133(3-4), 247–266. https://doi.org/10.1016/j.agee.2009.04.021

Song, C., Saloner, A., Fait, A., Bernstein, N. (2023). Nitrogen Deficiency Stimulates Cannabinoid Biosynthesis in Medical Cannabis Plants by Inducing a Metabolic Shift Towards Production of Low-N Metabolites. Industrial Crops and Products, 202, 116969. https://doi.org/10.1016/j.indcrop.2023.116969

Summers, H. M., Sproul, E., Quinn, J. C. (2021). The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States. Nature Sustainability, 4(7), 644–650. https://doi.org/10.1038/s41893-021-00691

Tabatabaie, S. M. H., Murthy, G. S. (2016). Cradle to Farm Gate Life Cycle Assessment of Strawberry Production in the United States. Journal of Cleaner Production, 127, 548–554. https://doi.org/10.1016/j.jclepro.2016.03.175

Vandecasteele, B., Blindeman, L., Amery, F., Pieters, C., Ommeslag, S., Van Loo, K., De Tender, C., Debode, J. (2020). Grow-Store-Steam-Re-Peat: Reuse of Spent Growing Media for Circular Cultivation of Chrysanthemum. Journal of Cleaner Production, 276, 124128. https://doi.org/10.1016/j.jclepro.2020.124128

Vandecasteele, B., Similon, L., Moelants, J. Hofkens, M., Visser, R., Melis, P. (2023) End-of-Life Stage of Renewable Growing Media with Biochar Versus Spent Peat or Mineral Wool. Nutrient Cycling Agroecosystem (2023). https://doi.org/10.1007/s10705-023-10315-8

Vujanovic, V., Korber, D. R., Vujanovic, S., Vujanovic, J., Jabaji, S. (2020). Scientific Prospects for Cannabis-Microbiome Research to Ensure Quality and Safety of Products. Microorganisms, 8(2), 290. https://doi.org/10.3390%2Fmicroorganisms8020290

Wartenberg, A. C., Holden, P. A., Bodwitch, H., Parker-Shames, P., Novotny, T., Harmon, T. C. (2021). Cannabis and the Environment: What Science Tells Us and What We Still Need to Know. Environmental Science & Technology Letters, 8(2), 98–107. http://dx.doi.org/10.1021/acs.estlett.0c00844

Wilson, H., Bodwitch, H., Carah, J., Daane, K. M., Getz, C. M., Grantham, T. E., Butsic, V. (2019). First Known Survey of Cannabis Production Practices in California. California Agriculture, 73(3). http://dx.doi.org/10.3733/ca.2019a0015

Wright, R. D. (1986). The Pour-Through Nutrient Extraction Procedure. American Society for Horticultural Science, 21(2), 227–229.

Xu, G., Fan, X., Miller, A. J. (2012). Plant Nitrogen Assimilation and Use Efficiency. Annual Review of Plant Biology, 63, 153–182. https://doi.org/10.1146/annurev-arplant-042811-105532

Zandkarimi, F., Decatur, J., Casali, J., Gordon, T., Skibola, C., Nuckolls, C. (2023). Comparison of the Cannabinoid and Terpene Profiles in Commercial Cannabis from Natural and Artificial Cultivation. Molecules, 28(2), 833. https://doi.org/10.3390/molecules28020833

Connecting Text

Chapter 3 delved into sustainable strategies for enhancing cannabinoid production efficiency in an outdoor cropping system. The utilization of potting media was found to be driving most of the GWP. However, when looking at fertilizer-associated GHG emission, it seems that a high N, low K fertilizer regimen could be a sustainable strategy to produce cannabinoid. The fertilizer treatment relied on incorporated controlled-release granular fertilizer.

However, when looking at indoor production of plants, this type of fertilizer is not one that is routinely used. Indoor production of cannabis and other plants will usually be limited by space. This will force growers to use soluble fertilizer and soil-less production systems.

With around 140 ha of indoor and 580 of outdoor cannabis production in Canada (Health Canada, 2023), it was deemed necessary to assess fertilizer use in indoor cannabis production. Without proper license, it is impossible to conduct research on cannabis in Canada. With the absence of opportunity for primary data acquisition for an LCA of indoor cannabis production, it was decided to use a model plan. Basil (*Ocimum basilicum*) was chosen as a plant surrogate model. The reason to use basil were:

- It is a high-value crop routinely grown in soil-less system (Walter et al., 2020).
- Mineral nutrient demand and disorders are known and characterized, making it easier to assess the potential of experimental fertilizer recipes (Owen et al., 2018).
- It secretes its essential oil via glandular trichomes, like cannabis (Mofikoya et al., 2019).
- No need to obtain the necessary license as it is not a controlled-substance like cannabis.

This choice proved especially relevant amidst the COVID crisis, where disrupted supply chains and bureaucratic delays highlighted the importance of adaptable research methods. Furthermore, it facilitated a meaningful collaboration between a private startup and the Biomass production laboratory. Circulus Ag Tech's mission of advancing circular economy principles and valorizing waste was highly interesting for a research project wanting to decrease environmental externalities. Exploring avenues such as recycling urban farm food byproducts, like mealworms frass, could also be beneficial for other indoor plant production systems.

Hence, Chapter 4 shifted focus to examine the environmental ramifications of inorganic N fertilizer production and utilization in soil-less production. Leveraging Circulus Ag Tech's pioneering bioreactor technology for organic liquid fertilizer (OLF) production offered an innovative alternative to traditional methods. The OLF, boasting high K and lower N than conventional inorganic fertilizer recipe, emerged as a promising solution for sustainable agriculture.

Because direct experimentation on cannabis was logistically unfeasible due to regulatory constraints, basil served as a proxy. Drawing insights from basil cultivation, the chapter laid the groundwork for implementing sustainable practices in cannabis production, signaling a potential transformative shift towards environmentally conscious cultivation techniques. Moreover, it underscored the importance of indoor farming, circular economy principles, and envisioning a future where recycling urban protein byproducts could extend to initiatives such as filtering greywater, all relying on soil-less plant production to harness vertical space and enhance sustainability.

References

Health Canada. (2023). Cannabis data overview: Inventory, sales and licensed area. Govement of Canada. https://www.canada.ca/en/health-canada/services/drugs-medication/cannabis/research-data/market.html

Mofikoya, A. O., Bui, T. N. T., Kivimäenpää, M., Holopainen, J. K., Himanen, S. J., Blande, J. D. (2019). Foliar behaviour of biogenic semi-volatiles: potential applications in sustainable pest management. In Arthropod-Plant Interactions (Vol. 13, Issue 2, pp. 193–212). Springer Netherlands. https://doi.org/10.1007/s11829-019-09676-1

Owen, W. G., Cockson, P., Henry, J., Whipker, B. E., Currey, C. J. (2018). Nutritional Monitoring Series Basil (Ocimum basilicum). E-GRO (Electronic Grower Resources Online) Nutritional Monitoring, 1(14), 1–6. www.fertdirtandsquirt.com

Walters, K. J., Currey, C. J. (2018). Effects of nutrient solution concentration and daily light integral on growth and nutrient concentration of several basil species in hydroponic production. HortScience, 53(9), 1319–1325. https://doi.org/10.21273/HORTSCI13126-18

Chapter 4 : Inorganic nitrogen replacement in soil-less agricultures: Environmental impact of animal waste-based organic liquid fertilizer for urban farms

Abstract

Urban farms, particularly those utilizing vertical space and soil-less production systems, have the potential to address many challenges of the existing food system. The use of organic inputs in soil-less systems can conserve dwindling non-renewable resources and mitigate greenhouse gas (GHG) emissions associated with inorganic nitrogen (N) fertilizer production and use. The study aims to compare plant growth using organic liquid fertilizer (OLF) using insect and chicken waste from a two-step aerobic bioreactor. Basil plants were grown with an inorganic fertilizer control and a novel OLF at two separate locations. Plant yield, nutrient uptake and tissue elemental composition were used to validate functional equivalence of OLF versus the inorganic control. From these results, a life-cycle assessment (LCA) was used to quantify GHG mitigation potential of the novel OLF. N-mass balance showed the bioreaction converted approximately 40% of total N-input into nitrate in liquid form. Solid output from the bioreaction contained approximately 35% of the initial N. N-gaseous loss was estimated to be 25% of total N-input. Because the nature of gaseous N-loss was unknown, LCA modeled different scenarios varying the percent of gaseous N-loss as N_2O, as it is the only gaseous N with appreciable global warming potential. It was concluded that OLF would be able to mitigate GHG emissions from soil-less production only if the percent of gaseous N-loss as N_2O during bioreaction was below 15%. Further studies should focus on direct quantification and characterization of gaseous N-loss during this type of bioreaction.

4.1 Introduction

Urban farms can play an important part in ensuring year-round access to locally produced vegetables while decreasing agri-food system greenhouse gas (GHG) emission (Dorr et al., 2021; Hawes et al., 2024; Kulak et al., 2013). One method for growing climate-friendly food in cities is by using vertical space and low-carbon energy sources (Goldstein et al., 2016). The verticality of urban farms is achieved by combining the design of buildings and farms in high-rise structures (Kalantari et al., 2017). The use of vertical space, also known as vertical farming, was made possible by combining highly efficient technologies that, together, creates agricultural systems with

increased water, fertilizer, and land use efficiency (Benke & Tomkins, 2017; Ivus et al., 2021). Accordingly, the promises of fresh produce year-round, reduced GHG emission, increased efficiency and profitability have attracted many companies willing to invest in this burgeoning technology (Butturini & Marcelis, 2019).

Soil-less growing systems that permit plant growth without the use of soil are central to vertical farming (Raviv et al., 2019). This is particularly useful for urban farms, as projects are often constrained by space, building load carrying capacities, or by costs of structural reinforcements (Specht et al., 2014).

Other advantages of soil-less systems are the ability to grow high-value plants such as tomatoes (*Solanum lycopersicum*), peppers (*Capsicum annuum*), and lettuces (*Lactuca sativa*) (AAFC, 2018). Soil-less operations have recently started to diversify, producing other fragrant herbs like basil (*Ocimum basilicum)* (Walter et al., 2020).

However, there are existing drawbacks of the current soil-less production systems. They are heavily reliant on inorganic mineral fertilizers. Soil-less producers hold the view that inorganic inputs offer superior plant nutrient availability compared to organic alternatives. This perception is thought to be a factor hindering the widespread acceptance of organic fertilizers in soil-less production (Bergstrand, 2022).

Adoption of organic input in soil-less and urban farms could mitigate the GHG production associated with inorganic fertilizer food production. Production and use of inorganic N-fertilizer is accountable for 10% of agricultural GHG emissions (Menegat et al., 2022). Adoption of organic input in soil-less and urban farms could mitigate the GHG production associated with inorganic fertilizer food production. Production and use of inorganic N-fertilizer is accountable for 10% of agricultural GHG emissions (Capdevila-Cortada, 2019). Production and use of inorganic N-fertilizer accounts for an estimated 5% of world GHG (Gao & Cabrera Serrenho, 2023).

The potential GHG emission can be decreased by switching to organic input but further work needs to quantify this reduction. Case-by case studies need to be used, with particular attention given to uncertainties in emissions factors (Walling & Vaneeckhaute, 2020). Emission factors, or how much of CO_2-equivalent (CO_2-eq) is released in the atmosphere during a particular industrial activity, relies on previous studies that calculated the emissions of a given activity (Kang et al., 2022). When these values are lacking, emission factors from published guidelines can be used but can lack accuracy (IPCC, 2014a). In the case of substituting inorganic N-fertilizer with organic inputs, parameters such as plant yield and total fertilizer input are crucial for providing

information to stakeholders that are actively trying to increase the environmental and economic performance of urban farms production.

To confidently recommend substitution of inorganic-N with organic input in urban farms, two main concerns need to be addressed: (1) the ability for organic inputs to provide similar yield compared to inorganic fertilizer and (2) the potential decrease in GHG emissions and associated global warming potential (GWP) compared to the inorganic fertilizer use.

Previous research has shown the potential of using organic liquid fertilizer (OLF) to provide all necessary nutrients to the plants for optimal growth. OLF derived from animal manure could provide adequate yield in kale (*Brassica napus*) and lettuce versus an inorganic control. A substantial amount of N and P could be made available for plants, but concerns regarding K and Fe availability have been raised (Tikasz et al., 2019).

Other studies have shown an overall reduced yield under organic fertilization in soil-less lettuce (Williams and Nelson, 2016) and tomatoes (*Solanum lycopersicum*) (Zhai et al., 2009). These studies reported that closer attention to input choice and growing solution parameters (electrical conductivity (EC), pH, unrestricted bacterial growth, and nutrient composition) were the main reason for reduced plant growth. Conversely, studies that did not report problems with growing solution parameters have demonstrated higher or similar yield for tomatoes and lettuce when compared to an inorganic control (Kechasov et al., 2021; Martínez-Alcántara et al., 2016; Phibunwatthanawong & Riddech, 2019). The working hypothesis is that organic input in soil-less systems could increase the presence of beneficial microbe, which can boost yield by increasing bioavailability of N and P (Conant et al., 2017; Saijai et al., 2016; Taghinasab & Jabaji, 2020).

It needs to be noted that reliance on inorganic fertilizers to guarantee crop productivity is said to reduce the overall resilience and sustainability of food systems (Ibn-Mohammed et al., 2021; Rowan & Galanakis, 2020). This makes growers reliant on an input prone to market volatility because of its dependency on fossil fuels (specifically natural gas), which has been increasing to record high prices since September 2021 (Stiewe et al., 2022).

Insect excreta, known as frass, is a nutrient-rich biomass often overlooked as waste. Insect production, for feed and food, is argued to be more sustainable than conventional

sources (Alfiko et al., 2022; Tanga et al., 2021). Frass output from insects can exceed animal biomass by up to 40 times in insect farms (Poveda, 2021). Despite its potential as a fertilizer, the accumulation of frass poses challenges for urban insect production sustainability. Dealing with voluminous by-products increases municipal solid waste production and associated GHG emissions (Gautam & Agrawal, 2020), while reducing space efficiency, crucial for sustainable urban farm design (Li et al., 2020).

This study aimed to (1) compare plant growth using a novel uric-acid rich waste-based organic liquid fertilizer (OLF) with conventional inorganic fertilizer, and (2) assess the environmental impact of on-site waste-to-fertilizer production in urban soil-less systems. Collaboration with two soil-less producers enabled access to uric-acid rich biomass from insects (*Tenebrio molinor*) and chickens (*Gallus gallus domesticus*). Like insects, birds excrete nitrogen waste in the form of uric acid, which can be processed into OLF using a proprietary bioreactor.

4.2 Materials and Methods

This study used plant growth and nutrient solution data from two different experiments. One experiment was done at an urban farm where plants were grown for one month in a controlled environment (CE) using vertical farming infrastructure with nutrients supplied by a closed loop recirculating ebb-and-flow system. This location was chosen because of the proximity of mealworm producers who were looking for an innovative way to valorize insect frass.

The second experiment was done in a greenhouse (GH) in a peri-urban setting. Plants were grown for two months in a semi-closed loop recirculating nutrient film technique (NFT) system. This location was chosen because the farm had a plant-producing greenhouse and chicken barn. Like the insect producer, the chicken producer wanted its unused manure to be valorized by using it in its NFT system. Experimental parameters are summarized in Table 4.1. Additional information on each parameter is presented in the following sections.

4.2.1 Growing Systems and Locations

4.2.1.1 Controlled Environment Experiment

The bench-scale growing location was an indoor CE room located in a 5-story building in Montreal, QC, Canada. The CE location used the existing building with a functional heating, ventilation, and air conditioning (HVAC) system. Plants grown in CE benefit from optimal climatic conditions with very little variation in atmospheric parameters

over time compared to a GH. Temperature and humidity were maintained between 22-23°C and 53-60% respectively. Photoperiod was set to 12:12 with 640 W wide-spectrum white LEDs with supplemental red and blue wavelengths (EG-MC640, Elite Grow Supply Industry, Shenzhen, China). Average photosynthetic photon flux density (PPFD) was ~240 μmol m^{-2} s^{-1}, measured with a spherical underwater quantum sensor (LI-193, LI-COR, Lincoln, USA).

Table 4.1: Summary of parameters of the controlled-environment and greenhouse experiment.

	CE	GH
Location	Montreal	Greater Montreal
Plants grown	Basil	Basil
Animal waste from	Mealworm	Chicken
Growing structures	Controlled environment room	Greenhouse
Water source	Municipal water	Well water
Soil-less system	Ebb-and-flow, solutions recirculated for a month	Nutrient-Film Technique, solutions changed every week
Lighting	640W wide-spectrum LED; PPFD ~240 μmol m^{-2} s^{-1}	Sun, with supplemental T-5 fluorescent lightbulbs PPFD varied with time
Harvest type	Total: each plant was grown for 1 month before total harvest	Successive: Each plant was grown for two months, with a partial harvest conducted after the first month. During this initial harvest, all aerial biomass above the first internode was collected. The plants were then allowed one month to regrow from the first node. At the end of the second month, a final harvest was performed, collecting all the aerial biomass.
Statistical model	Two-way ANOVA	Repeated-Measure Linear Mixed Effect

4.2.1.2 Greenhouse Experiment:

The pilot-scale growing location was in a 70 m^2 metal framed polyethylene sheet covered GH located in the greater Montreal area (Île-Bizard, QC, Canada). The temperature was semi-controlled with shade cloth and fans during the warmer season. Colder seasons had heating supplied by a central wood-burning oven and fans. Temperature fluctuated between the three time-separated blocks, with an average temperature of 21.3 ± 5.1 °C, 18.9 ± 3.2 °C and 15.9 ± 4.6 °C respectively for the three harvests. See supplementary methods (Appendix B).

4.2.2 Plants

Basil plants were chosen as they are fast growing, were already grown by producers on site and are a representative plant grown in soil-less production (Walter et al., 2020). Basil plants have had their mineral disorder (deficit or excess) characterized previously and make an excellent model for soil-less production (Owen et al., 2018; Walters & Currey, 2018). Basil seeds of the 'Genovese gigante' variety were germinated in seedling trays for a period of two weeks then introduced in the soil-less systems once the first true leaves were formed. More information on the germination step is provided supplementary methods (Appendix B). No plants had flowers at harvest.

4.2.2.1 Controlled Environment Harvest

The CE experiment had three time-separated blocks from September 2021 to December 2022. Each treatment had 15 basil plants per treatment, spaced 1 foot apart. Plants were grown in 1m x 1.3 m ebb-and-flow Tables. Plants were grown for 1 month before harvest. Harvest was done once where the entirety of aerial biomass was collected. Plant height, root mass and root height were measured.

4.2.2.2 Greenhouse Harvest

The GH experiment had 3 time-separated blocks spanning from October 2020 to September 2021. Each treatment had seven basil plants per block, spaced 1 foot apart in a polyvinyl chloride (PVC) pipes NFT system. Plants were grown for a total of 2 months, with two successive harvest every 30 days, like other previous experiments (Ciriello et al., 2021; Corrado et al., 2020). Only aerial biomass was weighted for each harvest.

4.2.3 Nutrient Solutions

Three fertilizer solutions were used at each location: OLF, Inorganic and a 50:50 mix of both deemed OLF+. Plants were fertilized with nutrient solutions defining each

treatment group. All treatments have the same micronutrient content addition by using a solution having 2.86 mg L^{-1} H_3BO_3, 1.81 mg L^{-1} $MnCl_2$, 0.22 mg L^{-1} $ZnSO_4$, 0.08 mg L^{-1} $CuSO_4$, 0.12 mg L^{-1} Na_2MoO_4, 5.57 mg L^{-1} $FeSO_4$ and 7.45 mg L^{-1} of NaEDTA at a rate of 0.75mL L^{-1} of nutrient solution final volume.

4.2.3.1 Inorganic Fertilizer Solution Primary Input:

Both experiments used an inorganic fertilizer solution as a control. This solution was made up of a modified Hoagland's solution (Hoagland & Arnon, 1938). This is a standard inorganic control used in previous research (Cockson et al., 2019; Tikasz et al., 2019; Yang et al., 2018). Fertilizer salts were used to provide macro- and micronutrients. Macronutrients were added using salts of $CaNO_3$, KNO_3, $MgSO_4$ and K_2PO_4 (Sigma Aldrich, Oakville, ON, Canada). The supplementary methods (Appendix B) detail quantity and instructions for fertilizer solution for each location.

4.2.3.2 Organic Liquid Fertilizer Primary Input

The primary input for OLF in the GH experiment was chicken manure. Manure was harvested from chicken fed a conventional feed diet supplemented with municipal food scraps. Insect frass was used as the primary input for the CE experiment. Frass used in this experiment was harvested from mealworms fed with municipal food scraps. Organic matter from both experiments was harvested with manual tools (shovel and sieves) and came from animals raised on the same geographical location where the soil-less systems were situated. No motorized transport was needed for the transport of manure or frass to the bioreactor.

4.2.3.3 Organic Liquid Fertilizer Bioreaction

OLF was made using a two-step proprietary bioreactor, developed by Circulus Agtech. The first step is a two-day extraction method sometimes referred to as a "tea-method" in the literature (Szekely & Jijakli, 2022). During this step, 4kg of animal manure was put in a porous bag and then suspended in 200L of aerated water. Aeration was supplied with an air pump running non-stop for 48h. This first step results in an NH_4^+/NH_3-rich liquid and porous bag filled with wet nutrient-depleted manure. Before injection in the soil-less system, NH_4^+/NH_3 was converted to NO_3^- to prevent N-toxicity and maximize yield (Hoque et al., 2008).

The second step in OLF production is an aerobic digestion in a proprietary bioreactor. This bioreaction inspired by the one described in Tikasz et al., (2019). The bioreaction was monitored by ion-selective electrode (ISE). See supplementary methods (Appendix

B) for details on ISE monitoring. OLF was deemed ready when N-pool was comprised of mostly NO_3^- and NH_4^+ was present in minimal amount (<15 mg NH_4^+ L^{-1}). Before injection in the soil-less system, OLF was diluted to the desired EC and supplemented with a micronutrient solution like the one used in the inorganic solution preparation (Section 2.3.1). The only difference was the absence of NaEDTA. Na was not added in the micronutrient solution for OLF treatments as it was present in primary input: chicken manure or insect frass.

4.2.4 Controlled Environment Experiment Nutrient Solutions:

The CE experiment had each flood Table connected to an independent reservoir that was filled with 120 L OLF, Hoagland or OLF+ nutrient solution at the start of the growing cycle. The solution was recirculated for the entire 1-month plant growth cycle.

4.2.4.1 Nutrient Uptake

Samples of freshly made solutions as well as spent solution were analyzed to calculate fresh solution nutrient content as well as nutrient uptake over the duration of plant growth. Freshly made and spent nutrient solutions were sent to a third-party lab (A&L Laboratory, London, ON, Canada). See supplementary methods (Appendix B) for analytical methods details. Nutrient uptake kinetics units (mg L^{-1} d^{-1}) were calculated for 120 L reservoirs using Formula 1. Where m_1 is initial total nutrient content (mg), m_2 final total nutrient content and n experiment duration (days).

$$Nutrient\ uptake = \frac{m_1 - m_2}{120L} \times \frac{1}{n} \quad (1).$$

4.2.5 Greenhouse Experiment Nutrient Solutions

Each NFT system was connected to an independent reservoir that was filled with 120 L OLF, Hoagland or OLF+ nutrient. Contrary to the CE experiment, where nutrient solution was recirculated for an entire month, the nutrient solution was changed every week. All solutions had a pH between 5.5-6.5, controlled weekly by addition of phosphoric acid (17 % H_3PO_4). Nutrient solution volume was maintained by adding well water. Only fresh solution was analyzed for elemental composition with the same method as described in See supplementary methods (Appendix B).

4.2.6 Statistical Model

Both CE and GH experiments followed a randomized complete block design with three time-separated blocks. Treatments had 15 plants in the CE experiment and 5-7 plants in the GH experiment for every block. See the Appendix for more details.

4.2.6.1 Elemental Composition Analyses

Fresh nutrient solutions from both experiments, nutrient uptake kinetics from the CE experiment and plant tissue analysis from the GH experiment were subjected to a one-way ANOVA (at $\alpha = 0.05$) to assess significant differences in elemental content between treatment.

4.2.6.2 Controlled Environment Harvest Statistical Analyses

The CE experiment had its data analyzed using two-way ANOVA with nutrient solution as a fixed-effect and block number as a random-effect to determine statistical significance of treatment on plant harvested mass, height, root mass and root length.

4.2.6.3 Greenhouse Harvest Statistical Analyses

GH experiment yield data was analyzed using a repeated measure linear mixed effect model. Repeated measure was used because individual plants had two time-separated harvests: cutting 1 and cutting 2, as it was routine practice in the already operating greenhouse.

4.2.7 Global Warming Potential Calculations

To calculate the GWP of the inorganic fertilizer and the OLF, a cradle-to-gate life cycle assessment (LCA) methodology was used, in accordance with the ISO 14040 and 14044 standards (ISO 2006a, 2006b).

Because the quality of fresh basil was inferior in the GH experiment (nutrient deficiency symptoms), this dataset could not be used. GHG emissions from all stages of the product life cycle, including raw material extraction, manufacturing, transportation, use, and disposal were accounted for.

4.2.7.1 Life-cycle Inventory and Data Collection for Global Warming Potential Calculations

Two scenarios were modeled to assess their GWP: inorganic and OLF. Both models were calculated with a functional unit (FU) of 1 kg of fresh basil production. Only fertilizer-associated processes were considered, as all other processes (use, disposal, transport etc.) were assumed to have no difference because both treatments have the same infrastructure, environmental control and horticultural practices needs.

4.2.7.2 Raw Material Extraction and Manufacturing

For the inorganic input, the amount of material used was collected during the life-cycle inventory (LCI) phase. For the inorganic treatment, fertilizer salt quantity used during fertilizer solution mixing was compiled. See Supplementary Table S4.1.1 and S4.1.2

(Appendix B). Energy used in the extraction and manufacturing processes were calculated using the EcoInvent 3.8 database. Modeled solid, liquid and gaseous N-losses were based on averaged measured N-values from the GH and CE bioreactor. Initial manure input, final manure output, intermediary tea solution and final OLF N-content were measured by a third-party lab as described in the supplementary methods (Appendix B). Based off these, modeled N-losses in solid and gasses were assumed to be 25% and 35% respectively. Because the identity of N-forms in gaseous emissions is unknown, multiple scenarios based on % of gaseous N-losses as N_2O were used to calculate GWP of the bioreactor (Table S4.1.1 and S4.1.2). Gaseous N-losses can take the form of NH_3, NO_x, N_2 or N_2O. From these forms, N_2O has 298 times more GWP than CO_2, (Huijbregts et al., 2017) while the other forms do not have a GHG effect (Mosier, 2008). Because of this, the only gaseous N-loss form of interest in the study was N_2O, as other forms are irrelevant when using GWP as the only impact. Information on modeled transport can be found in the supplementary methods (Appendix B).

4.2.7.3 Use

Fertilizer use and plant yield were based off primary data from the fertilizer response trial. Emission factor for modeling N_2O emissions from the soil-less system were set as 0.31% N_2O of total N input, as observed in other soil-less systems (Karlowsky et al., 2021), as well as the 1% value, recommended by the International Panel on Climate Change for agricultural systems (IPCC, 2014b)

4.2.7.4 Disposal

Apart from the difference in insect frass needed to be sent to the composting facility, other disposal processes (spent nutrient solution, harvest residue) were assumed to be identical in both systems.

4.3 Results

This study used a proprietary bioreactor to enable on-site use of uric-acid rich biomass usually discarded as waste into an organic input for soil-less production. Basil plants grown in an experimental OLF were compared with ones grown in an inorganic control. Yield, nutrient uptake and elemental tissue composition were used to assess functional equivalency of the OLF. Values from the plant experiment were incorporated in a LCA model to quantify GHG emission from both fertilizer solution.

4.3.1 Organic Liquid Fertilizer Nutrient Content Differs from Inorganic Control for Most Nutrients

N is the most important mineral element for plant growth, extra precaution was taken to supply similar N quantities to plant during their growth cycle. Independent lab analysis of fertilizer solutions showed no significant difference in NO_3 content for all solutions at the CE and GH experiments (Figure 4.1 A). Significant differences were observed for all other primary and secondary macronutrients (P, K, Ca, Mg and S) (Figure 4.1 A-B). P was significantly increased in OLF and OLF+ solutions at the CE experiment. Overall P concentrations were lower in the GH experiment, with OLF+ having the highest P content. OLF and OLF+ solutions were significantly lower in Ca, Mg and S in both experiments. Conversely, OLF and OLF+ solutions were significantly higher in Na content. Cl content had no significant difference observed across all solutions and experiments. There was no observed significant difference in NH_3/NH_4 content across all solutions with an average concentration of 5.7 mg $N\text{-}NH_4$ L^{-1}. See Supplementary Table S4.3.1 to S4.3.2 (Appendix B).

Significant differences were observed for B, Cu and Fe content depending on experiments. In the CE experiment, the inorganic control solution had significantly lower levels of B, Cu and Fe when compared with OLF and OLF+ solution from the same experiment. In the GH experiment, OLF had the highest measured Fe and Cu, while the inorganic control had the highest B content. Inorganic solution had undetectable levels of Cu and Fe. OLF+ had more B and Cu than the inorganic control but undetectable levels of Fe. See Supplementary Table S4.3.1 to S4.3.2 (Appendix B).

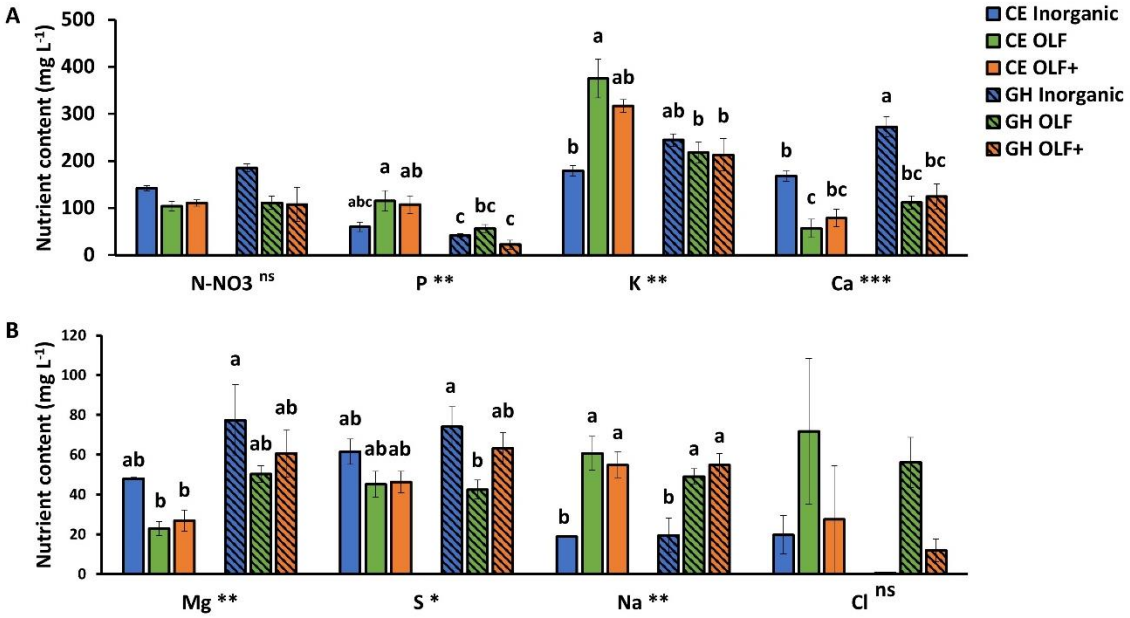


Figure 4.1: Average measured concentration of primary and secondary macronutrients of all fresh solutions used in the controlled environment and in the greenhouse experiment. Solution content of nitrogen in nitrate form ($N\text{-}NO_3$), phosphorus (P), potassium (K), calcium (Ca) (A) magnesium (Mg), sulfur (S), sodium (Na) and chlorine (Cl) (B). CE and GH stand for controlled environment and greenhouse respectively, identifying the experiment where solution was used. Data are means ± SEM with n=3 except for GH organic liquid fertilizer (OLF) with n=9. Inorganic stands for inorganic control solution and OLF+ refers to a solution comprised of a 50:50 mixture of both inorganic and OLF (v:v). Different small letters above means represent significant differences between treatments determined by Tukey HSD test at $\alpha = 0.05$. F-tests results of one-way ANOVA indicated as 'ns' for not significant, * for $p<0.05$, ** for $p<0.005$ and *** for $p<0.0001$. Micronutrients content is presented in Supplementary Table S4.2 (Appendix B).

4.3.2 Plant Response to Organic Liquid Fertilizer

During both experiments, nutrient solution did not have a significant effect on yield. A two-way mixed ANOVA analysis revealed that nutrient solution had no significant impact on plants grown in the CE. Fresh mass ($p=0.5876$), plant height ($p=0.7871$), root length ($p=0.1134$) and root mass ($p=0.2023$) were not affected by treatment. Average values are presented in Table 4.2.

Table 4.2: Average values of plant grown in the controlled environment experiment fertilized with three different solutions.

	Inorganic (n=45)	OLF (n=43)	OLF+ (n=44)
Fresh mass (g per plant)	84.7±6.1	85.5±4.9	92±5.0
Plant height (cm)	58.5±1.3	59.4±1.1	59.1±0.8
Root length (cm)	17.1±1.8	17.2±1.2	13.6±1.2
Root fresh mass (g per plant)	84.2±3.7	91.1±4.6	94.5±4.6

Data from the GH experiment was fitted to a linear mixed model using REML for covariance estimates to predict yield based on nutrient solution, harvest month and cutting number. The model included individual plant as random effect. Average values (LSmeans±SEM) for fresh mass harvest every cut was 29.4±1.8 g per plant in the inorganic treatment, 29.8±1.8 g in the OLF treatment and 34.7±1.8 g in the OLF+ treatment. Nutritional deficiency was observed in the GH experiment. See Supplementary Results (Appendix B). There was no noticeable difference in quality (ie.: smell or taste) unless in the OLF treatment in the CE experiment where deficiency or toxicity was observed, and plants were less fragrant.

4.3.2.1 Fertilizer Solution Does Not Significantly Alter Nutrient Uptake Kinetics for Most Elements but Ca.

Analysis of nutrient uptake in the CE experiment showed no significant impact for all nutrient except for Ca ($p<0.05$) (Figure 4.1 A-C). A trend for higher Na uptake was observed but was not significant ($p=0.0852$). Inorganic solution had undetectable amounts of Fe after 1 month of recirculation on three separate occasions. Cu was undetectable in the spent inorganic nutrient solution on one occasion. See Supplementary Table S4.4 (Appendix B).

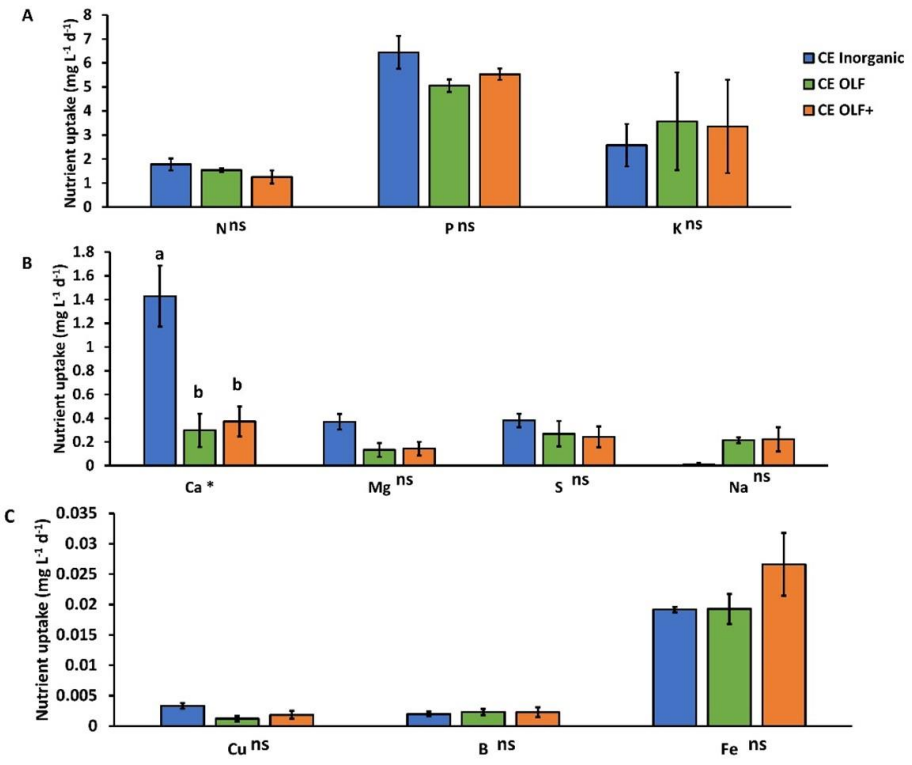


Figure 4.2: Nutrient uptake of basil plants under different fertilizer nutrient solutions in the controlled environment experiment. Uptake is calculated as the difference between fresh solution nutrient content and the nutrient content of the same solution after 1 month of recirculation. Uptake rate for N, P, K (A), Ca, Mg, S, Na (B), Cu, B and Fe (C) is represented as averages ± se (n=3). Inorganic stands for inorganic control solution and OLF+ refers to a solution comprised of a 50:50 mixture of both inorganic and OLF. Results of the one-way ANOVA are indicated as * $p<0.05$ and ns for nonsignificant. Different small letters above means represent significant differences between treatments determined by Tukey HSD test at $\alpha = 0.05$.

4.3.3 N-conversion Efficiency of the Bioreactors

Quantifying the efficiency of N conversion to NO_3 of the bioreactors was done using results from the elemental analysis of fresh animal excreta and OLF from both experiments. Combining data collected from both sites enabled the modeling of realistic emission factors. Specifically, out of the initial N-input, 25% was projected to accumulate in solid waste, 40% in OLF, and 35% in a gaseous form with unknown composition. These assumptions were used when calculating input for the LCA modeling. Values from elemental analysis and associated calculations are presented in Supplementary Table S4.4 (Appendix B).

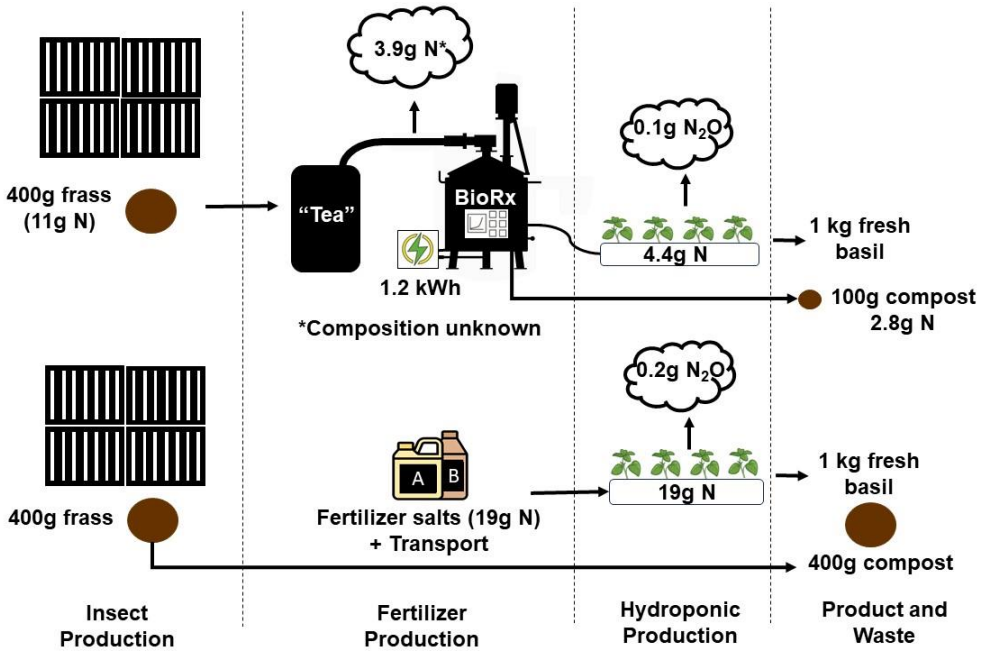


Figure 4.3: Schematic representation of nitrogen conversion during the two-step bioreaction. Total N-input and N-output in solid form were calculated with elemental analysis of animal excreta, "tea" extraction process and liquid fertilizer. N content in liquids was calculated using elemental analysis of undiluted liquids. Gaseous emissions from the bioreaction are estimated based on unaccounted N mass in solid and liquid form outputs. BioRx stand for bioreaction. Production of microelement is not shown.

4.3.4 Global Warming Potential of Fertilizer-associated Processes

Using LCA methodology, the GWP of fertilizer-associated processes were calculated for the inorganic and OLF treatments. The GWP value for inorganic treatment ranged from 0.727 to 0.788 kg CO_2-eq per FU, depending on the emission factor used: 0.31 % or 1 % of total N input as N_2O. The process with the highest contribution (46-49 % contribution) was transport, with 0.362 kg CO_2-eq per FU, followed by $CaNO_3$ (30 % contribution) with 0.229 kg CO_2 per FU. Depending on the EF chosen, KNO_3 production and N_2O emission from the soil-less plant production were third and fourth contributors with 0.074 kg CO_2 per FU for KNO_3 production (9.4-10.2 % contribution) and 0.088-0.027 kg CO_2-eq per FU for N_2O emission (11.2-3.8 % contribution). See Supplementary Table S4.5.1 and S4.5.2 (Appendix B).

In the OLF treatment, modeling gaseous N-loss as 100 % N_2O dramatically increased the GWP of the product, driving up to 4.71 kg CO_2-eq per FU. In this scenario, gaseous emission from the bioreactor comprised almost the entirety of the GWP with 98.5%

contribution. When gaseous N-loss was modeled as 0 % N_2O, the GWP of the FU is only 0.110 up kg CO_2-eq. In the scenario where no N2O emission comes out of the bioreaction, the GWP of the FU is of only 0.104 kg CO_2-eq and transport is the most contributing process (36%) with 0.038 kg CO_2-eq. See Supplementary Table S4.5.3 and S4.5.4 (Appendix B).

When examining the GWP of the OLF treatment in relation to the percentage of gaseous N-loss as N_2O, it was found that for the OLF treatment to achieve an equivalent GWP to the inorganic treatment, the percentage of nitrogen losses as N_2O from the bioreaction should fall within the range of 14.7 to 16.0 % (Figure 4.3).

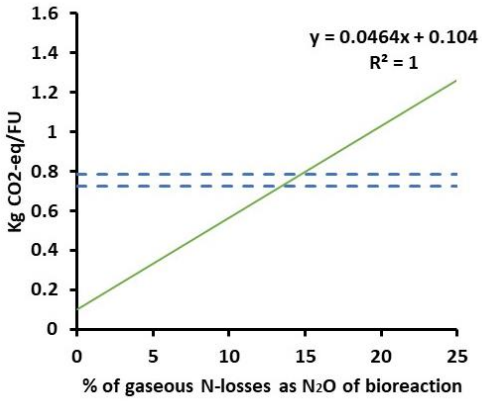


Figure 4.4: Modelled CO_2 emissions from fertilizer-associated processes for the inorganic and OLF treatments depending on percent composition of N_2O of calculated gaseous N-losses of the bioreaction. FU stands for functional unit (1kg fresh basil), OLF stands for organic liquid fertilizer (OLF). Inorganic stands for inorganic control solution. Two scenarios were used to calculate the GWP of the inorganic treatment (blue dashed lines), one with a modelled 0.31 % and another with 1% total N-input as N_2O emission. Multiple scenarios were used to calculate the GWP of the OLF bioreaction by varying the % of measured gaseous N-losses as N_2O (green line). Values of GWP of OLF above 15% of bioreaction gaseous N-losses as N_2O are not shown for Figure clarity.

4.4 Discussion

4.4.1 Organic Liquid Fertilizer Can Deliver All Necessary Nutrients for Basil Plant Growth.

In this study, uric acid rich biomass from chicken and insects was used to produce organic liquid fertilizer (OLF) sourced from urban and peri-urban farms. Nutrient solutions were compared with an inorganic control at two locations. Fertilizers had

slight macro- and micronutrient variations across locations but similar nitrogen content. Yield did not significantly differ between treatments at both locations.

In the controlled environment (CE) experiment, no nutrient deficiencies occurred during growth. However, in the greenhouse (GH) study, despite weekly nutrient solution changes, plants displayed deficiency symptoms likely due to salt buildup from high well water salt concentration. The observed deficiencies in OLF and OLF+ treatments in GH were unlikely due to phosphorus deficiency, as phosphorus levels were within the reported sufficiency range for basil (Owen et al., 2018).

All treatments had potassium levels exceeding reported sufficiency ranges. Ca and Fe levels were higher than reported sufficiency ranges for all treatments. Interveinal chlorosis may have been caused by increased sodium content in leaves. Although OLF solutions from both locations had similar sodium levels, only GH location plants showed deficiency symptoms. Possible causes include the microbial community mixed with higher phosphorus and potassium content in CE, aiding plant resistance to sodium stress. Alternatively, the longer growing cycle and repeated exposure to freshly made solution in GH allowed sodium buildup in plant tissue.

Variation in Hoagland solution EC across locations is not a study limitation, as previous research indicates EC does not affect basil growth (Walters & Currey, 2018). Optimal EC for basil growth is around 1.4 mS cm^{-1} (Hosseini et al., 2021). Yield differences between locations may be attributed to environmental factors such as light intensity and temperature, lower in GH.

Significant differences in calcium uptake occurred between solutions, though this did not increase yield significantly. Higher calcium content in the fresh inorganic solution may explain the apparent increase in uptake (Wada, 2018). Undetectable iron and copper in the inorganic treatment may limit nutrient uptake characterization. Supplementing the inorganic solution with more iron and copper could improve micronutrient uptake calculation.

4.4.2 Organic Liquid Fertilizer Can Compete With Inorganic Solution for Yield

The OLF used in this study yielded comparable results to the inorganic treatment. No significant differences were observed in plant growth parameters (yield, height, mass, root length) among the three nutrient solutions, indicating OLF's compatibility with plant growth compared to Hoagland solution. These findings suggest OLF's potential as a replacement for inorganic fertilizers in soil-less systems. Replacing half of the

inorganic fertilizer with OLF showed a non-significant positive impact on yield, hinting at a potential synergy between OLF's microbial community and inorganic fertilizer. Transitioning from conventional fertilization to OLF should maintain similar yields, contrary to studies using other organic waste-based fertilizers in indoor lettuce production, which showed reduced yields (da Silva Cuba Carvalho et al., 2018; Yang et al., 2018). Discrepancies may stem from variations in nutrient content and uptake dynamics among different organic wastes. Wongkiew et al., (2021) demonstrated distinct nitrogen generation patterns in different waste types, affecting nutrient uptake and plant development. These factors should be considered when formulating new OLF recipes.

4.4.3 Global Warming Potential

Previous studies on conversion of solid waste to OLF have overlooked the potential GHG production of this process (Xie et al., 2022). This study aimed to address concerns regarding GHG emissions in soil-less fertilizer-associated processes by exploring a new technology. The CO_2 GWP of inorganic and OLF treatments was compared using data from the CE experiment. Due to a lack of data on gaseous N-losses during the bioreaction, the GWP of the OLF treatment could only be estimated. The calculated gaseous N-loss from the bioreactor ranged around 35% of total N-inputs from animal waste, which, coupled with the fact that 1 kg of N_2O is equivalent to 298 kg of CO_2, suggests that the GWP of the OLF treatment could be up to 6 times greater than that of the inorganic treatment.

The GH experiment data revealed no significant N-losses during the tea extraction process, as all N-inputs were accounted for in the solid and liquid outputs. Most organic N-compounds underwent ammonification in the liquid phase or were found as NH_3/NH_4 or organic N. The subsequent nitrification step in the bioreactor, conducted in an aerobic environment, is suspected to be where gaseous losses occur. N_2O production occurs during various steps of the nitrification process, especially when ammonia transforms to nitrate (Ma et al., 2019), or during denitrification when NO_3 and NO_2- concentrations are high (Hidalgo-García et al., 2019; Stein, 2011). These conditions are likely in the bioreaction, aiming to increase NH_4 and NO_3 concentrations, substrates for N_2O-producing enzymatic reactions.

Environmental parameters like transient oxygen exposure, temperature, and pH significantly influence N_2O emissions in bioreactors. pH control between 5.5 and 6.5,

adjusting oxygen levels, and implementing a cooling system could mitigate potential nitrification (Lu and Chandran, 2010). Additionally, future research should investigate enzyme kinetics during the bioreaction and characterize gaseous N types (NH_4, N_2O or NO_x) to understand immobilization-mineralization dynamics. Notably, the study omitted potential N-incorporation in the microbial community, which could be explored in subsequent studies examining temperature, pH, and oxygenation rate effects on mitigating N_2O emissions in bioreactors, which are known parameters of high importance in soil and aquaculture nitrification (Khiari et al., 2019; Paudel, 2020; Wang et al., 2012).

4.5 Conclusion

Before widespread implementation of the system, there is a need to thoroughly investigate ways to decrease potential N_2O emission during the force nitrification bioreaction. Exploring the implementation of biological air purifier known to decrease N_2O could also be a way to achieve this (Yewale et al., 2022).

Of note, OLF are versatile, meaning they can be developed from other differently sourced N-rich biomass usually discarded as waste, and can provide plants with necessary nutrient for growth. Future research should focus on characterizing N-losses in the bioreaction and investigating potential ways to mitigate GWP of the bioreactor.

4.6 References

AAFC. (2018). Statistical Overview of the Canadian Vegetable Industry. Government of Canada. https://agriculture.canada.ca/en/sector/horticulture/reports/statistical-overview-canadian-field-vegetable-industry-2022.

Alfiko, Y., Xie, D., Astuti, R.T., Wong, J., Wang, L. (2022). Insects as a Feed Ingredient for Fish Culture: Status and Trends. Aquaculture Fish, 7, 166–178. https://doi.org/10.1016/j.aaf.2021.10.004.

Benke, K., Tomkins, B. (2017). Future Food-Production Systems: Vertical Farming and Controlled-Environment Agriculture. Sustainability: Science, Practice, and Policy, 13, 13–26. https://doi.org/10.1080/15487733.2017.1394054.

Bergstrand, K.J. (2022). Organic Fertilizers in Greenhouse Production Systems – A Review. Sci Hortic, 295, 110855. https://doi.org/10.1016/j.scienta.2021.110855.

Butturini, M., Marcelis, L.F.M. (2019). Vertical Farming in Europe: Present Status and Outlook, in: Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production: Second Edition. Elsevier Inc., pp. 77–91. https://doi.org/10.1016/B978-0-12-816691-8.00004-2.

Capdevila-Cortada, M. (2019). Electrifying the Haber–Bosch. Nature Catalogue, 2, 1055. https://doi.org/10.1038/s41929-019-0414-4.

Ciriello, M., Formisano, L., El-Nakhel, C., Kyriacou, M.C., Soteriou, G.A., Pizzolongo, F., Romano, R., De Pascale, S., Rouphael, Y. (2021). Genotype and Successive Harvests Interaction Affects Phenolic Acids and Aroma Profile of Genovese Basil for Pesto Sauce Production. Foods, 10. https://doi.org/10.3390/foods10020278.

Cockson, P., Landis, H., Smith, T., Hicks, K., Whipker, B.E. (2019). Characterization of Nutrient Disorders of *Cannabis sativa*. Applied Sciences (Switzerland), 9. https://doi.org/10.3390/app9204432.

Conant, R.T., Walsh, R.P., Walsh, M., Bell, C.W., Wallenstein, M.D. (2017). Effects of a Microbial Biostimulant, Mammoth PTM, on *Cannabis sativa* Bud Yield. Journal of Horticulture, 04. https://doi.org/10.4172/2376-0354.1000191.

Corrado, G., Chiaiese, P., Lucini, L., Miras-Moreno, B., Colla, G., Rouphael, Y. (2020). Successive Harvests Affect Yield, Quality and Metabolic Profile of Sweet Basil (*Ocimum basilicum* L.). Agronomy, 10, 1–13. https://doi.org/10.3390/agronomy10060830.

da Silva C.C., R., Bastos, R.G., Souza, C.F. (2018). Influence of the Use of Wastewater on Nutrient Absorption and Production of Lettuce Grown in a Hydroponic System. Agriculture and Water Management, 203, 311–321. https://doi.org/10.1016/j.agwat.2018.03.028.

Dorr, E., Goldstein, B., Horvath, A., Aubry, C., Gabrielle, B. (2021). Environmental Impacts and Resource Use of Urban Agriculture: A Systematic Review and Meta-Analysis. Environmental Research Letters. https://doi.org/10.1088/1748-9326/ac1a39.

Gao, Y., Cabrera Serrenho, A. (2023). Greenhouse Gas Emissions from Nitrogen Fertilizers Could Be Reduced by up to One-Fifth of Current Levels by 2050 with Combined Interventions. Nature Food, 4. https://doi.org/10.1038/s43016-023-00698-w.

Gautam, M., Agrawal, M. (2020). Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario, Environmental Footprints and Eco-Design of Products and Processes. https://doi.org/10.1007/978-981-15-9577-6_2.

Goldstein, B., Hauschild, M., Fernández, J., Birkved, M. (2016). Testing the Environmental Performance of Urban Agriculture as a Food Supply in Northern Climates. Journal of Cleaner Production, 135, 984–994. https://doi.org/10.1016/j.jclepro.2016.07.004.

Hawes, J.K., Goldstein, B.P., Newell, J.P., Dorr, E., Caputo, S., Fox-Kämper, R., Grard, B., Ilieva, R.T., Fargue-Lelièvre, A., Poniży, L., Schoen, V., Specht, K., Cohen, N. (2024). Comparing the Carbon Footprints of Urban and Conventional Agriculture. Nature Cities, 1, 164–173. https://doi.org/10.1038/s44284-023-00023-3.

Hidalgo-García, A., Torres, M.J., Salas, A., Bedmar, E.J., Girard, L., Delgado, M.J. (2019). Rhizobium etli Produces Nitrous Oxide by Coupling the Assimilatory and Denitrification Pathways. Frontiers in Microbiology, 10, 1–11. https://doi.org/10.3389/fmicb.2019.00980.

Hoagland, D.R., Arnon, D.I. (1938). Growing Plants Without Soil by the Water-Culture Method. Circular California Agricultural Experimental Station.

Hoque, M.M., Ajwa, H.A., Smith, R. (2008). Nitrite and Ammonium Toxicity on Lettuce Grown Under Hydroponics. Communication in Soil Science and Plant Analysis, 39, 207–216. https://doi.org/10.1080/00103620701759194.

Hosseini, H., Mozafari, V., Roosta, H.R., Shirani, H., van de Vlasakker, P.C.H., Farhangi, M. (2021). Nutrient Use in Vertical Farming: Optimal Electrical Conductivity of Nutrient Solution for Growth of Lettuce and Basil in Hydroponic Cultivation. Horticulturae, 7. https://doi.org/10.3390/horticulturae7090283.

Ibn-Mohammed, T., Mustapha, K.B., Godsell, J., Adamu, Z., Babatunde, K.A., Akintade, D.D., Acquaye, A., Fujii, H., Ndiaye, M.M., Yamoah, F.A., Koh, S.C.L. (2021). A Critical Review of the Impacts of COVID-19 on the Global Economy and Ecosystems and Opportunities for Circular Economy Strategies. Resource, Conservation and Recycling, 164, 105169. https://doi.org/10.1016/j.resconrec.2020.105169.

International Organization for Standardization. (2006a). ISO 14040:2006 Environmental management–life cycle assessment—Principles and framework. https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. https://www.iso.org/standard/38498.html

IPCC (2014a). Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland. https://doi.org/10.1016/S0022-0248(00)00575-3.

IPCC (2014b). Climate Change 2014 Synthesis Report - Summary Chapter for Policymakers. 31. https://doi.org/10.1017/CBO9781107415324.

Ivus, M., Matthews, M., Snider, N., Taillon, P., Watson, M. (2021). Canadian Agri-food Technology: Sowing the Seeds for Tomorrow. Information and Communications Technology Council (ICTC). https://ictc-ctic.ca/reports/canadian-agrifood-technology

Kalantari, F., Mohd Tahir, O., Mahmoudi Lahijani, A., Kalantari, S. (2017). A Review of Vertical Farming Technology: A Guide for Implementation of Building Integrated Agriculture in Cities. Advanced Engineering Forum, 24, 76–91. https://doi.org/10.4028/www.scientific.net/aef.24.76.

Kang, S., Kim, G., Roh, J., Jeon, E.C. (2022). Ammonia Emissions from NPK Fertilizer Production Plants: Emission Characteristics and Emission Factor Estimation. Int Journal of Environmental Research and Public Health, 19. https://doi.org/10.3390/ijerph19116703.

Karlowsky, S., Gläser, M., Henschel, K., Schwarz, D. (2021). Seasonal Nitrous Oxide Emissions From Hydroponic Tomato and Cucumber Cultivation in a Commercial Greenhouse Company. Frontier in Sustainable Food Systems, 5, 1–13. https://doi.org/10.3389/fsufs.2021.626053.

Kechasov, D., Verheul, M.J., Paponov, M., Panosyan, A., Paponov, I.A. (2021). Organic Waste-Based Fertilizer in Hydroponics Increases Tomato Fruit Size but Reduces Fruit Quality. Frontier in Plant Science, 12, 1–20. https://doi.org/10.3389/fpls.2021.680030.

Khiari, Z., Kaluthota, S., Savidov, N. (2019). Aerobic Bioconversion of Aquaculture Solid Waste into Liquid Fertilizer: Effects of Bioprocess Parameters on Kinetics of Nitrogen Mineralization. Aquaculture, 500, 492–499. https://doi.org/10.1016/j.aquaculture.2018.10.059.

Kulak, M., Graves, A., Chatterton, J. (2013). Reducing Greenhouse Gas Emissions with Urban Agriculture: A Life Cycle Assessment Perspective. Landscape Urban Plan, 111, 68–78. https://doi.org/10.1016/j.landurbplan.2012.11.007.

Li, L., Li, X., Chong, C., Wang, C.H., Wang, X. (2020). A Decision Support Framework for the Design and Operation of Sustainable Urban Farming Systems. Journal of Cleaner Production, 268, 121928. https://doi.org/10.1016/j.jclepro.2020.121928

Lu, H., Chandran, K. (2010). Factors Promoting Emissions of Nitrous Oxide and Nitric Oxide from Denitrifying Sequencing Batch Reactors Operated with Methanol and Ethanol as Electron Donors. Biotechnology and Bioengineering, 106, 390–398. https://doi.org/10.1002/bit.22704

Ma, L., Lin, H., Xie, X., Dai, M., Zhang, Y. (2019). Major Role of Ammonia-Oxidizing Bacteria in N2O Production in the Pearl River Estuary. Biogeosciences 16, 4765–4781. https://doi.org/10.5194/bg-16-4765-2019

Martínez-Alcántara, B., Martínez-Cuenca, M.R., Bermejo, A., Legaz, F., Quiñones, A. (2016). Liquid Organic Fertilizers for Sustainable Agriculture: Nutrient Uptake of Organic Versus Mineral Fertilizers in Citrus Trees. PLoS One 11, 1–20. https://doi.org/10.1371/journal.pone.0161619

Menegat, S., Ledo, A., Tirado, R. (2022). Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture. Science Reports 12, 1–13. https://doi.org/10.1038/s41598-022-18773-w

Mosier, A.R. (2008). Exchange of Gaseous Nitrogen Compounds Between Terrestrial Systems and the Atmosphere. Nitrogen in the Environment 443–462. https://doi.org/10.1016/B978-0-12-374347-3.00013-5

Owen, W.G., Cockson, P., Henry, J., Whipker, B.E., Currey, C.J. (2018). Nutritional Monitoring Series Basil (*Ocimum basilicum*). e-GRO (Electronic Grower Resources Online) Nutritional Monitoring 1, 1–6. https://urbanagnews.com/wp-content/uploads/2018/05/Nutritional-Factsheet_Basil.pdf

Paudel, S.R. (2020). Nitrogen Transformation in Engineered Aquaponics with Water Celery (*Oenanthe javanica*) and Koi Carp (*Cyprinus carpio*): Effects of Plant to Fish Biomass Ratio. Aquaculture 520, 734971. https://doi.org/10.1016/j.aquaculture.2020.734971

Phibunwatthanawong, T., Riddech, N. (2019). Liquid Organic Fertilizer Production for Growing Vegetables Under Hydroponic Condition. International Journal of Recycling of Organic Waste in Agriculture 8, 369–380. https://doi.org/10.1007/s40093-019-0257-7

Poveda, J. (2021). Insect Frass in the Development of Sustainable Agriculture. A Review. Agronomy and Sustainable Development, 41. https://doi.org/10.1007/s13593-020-00656-x

Raviv, M., Lieth, J.H., Bar-Tal, A. (2019). Soilless Culture : Theory and Practice. 2nd Edition, Elsevier. https://www.sciencedirect.com/book/9780444636966/soilless-culture

Rowan, N.J., Galanakis, C.M. (2020). Unlocking Challenges and Opportunities Presented by COVID-19 Pandemic for Cross-Cutting Disruption in Agri-Food and Green Deal Innovations: Quo Vadis? Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2020.141362

Saijai, S., Ando, A., Inukai, R., Shinohara, M., Ogawa, J. (2016). Analysis of Microbial Community and Nitrogen Transition with Enriched Nitrifying Soil Microbes for Organic Hydroponics. Bioscience Biotechnology Biochemistry, 80, 2247–2254. https://doi.org/10.1080/09168451.2016.1200459

Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A. (2014). Urban Agriculture of the Future: An Overview of Sustainability Aspects of Food Production in and on Buildings. Agriculture Human Values 31, 33–51. https://doi.org/10.1007/s10460-013-9448-4

Stein, L.Y. (2011). Surveying N2O-Producing Pathways in Bacteria. Methods in Enzymology 486, 131–152. https://doi.org/10.1016/B978-0-12-381294-0.00006-7

Stiewe, C., Ruhnau, O., Lion, H. (2022). European Industry Responds to High Energy Prices: The Case of German Ammonia Production. Econstor. https://www.econstor.eu/handle/10419/253251

Szekely, I., Jijakli, M.H. (2022). Bioponics as a Promising Approach to Sustainable Agriculture: A Review of the Main Methods for Producing Organic Nutrient Solution for Hydroponics. Water (Switzerland) 14. https://doi.org/10.3390/w14233975

Taghinasab, M., Jabaji, S. (2020). Cannabis Microbiome and the Role of Endophytes in Modulating the Production of Secondary Metabolites: An Overview. Microorganisms. https://doi.org/10.3390/microorganisms8030355

Tanga, C.M., Egonyu, J.P., Beesigamukama, D., Niassy, S., Emily, K., Magara, H.J., Omuse, E.R., Subramanian, S., Ekesi, S. (2021). Edible Insect Farming as an Emerging and Profitable Enterprise in East Africa. Current Opinion in Insect Science 48, 64–71. https://doi.org/10.1016/j.cois.2021.09.007

Tikasz, P., MacPherson, S., Adamchuk, V., Lefsrud, M. (2019). Aerated Chicken, Cow, and Turkey Manure Extracts Differentially Affect Lettuce and Kale Yield in Hydroponics. International Journal of Recycling of Organic Waste in Agriculture 8, 241–252. https://doi.org/10.1007/s40093-019-0261-y

Wada, T. (2018). Theory and Technology to Control the Nutrient Solution of Hydroponics, Plant Factory Using Artificial Light: Adapting to Environmental Disruption and Clues to Agricultural Innovation. Elsevier. https://doi.org/10.1016/B978-0-12-813973-8.00001-4

Walling, E., Vaneeckhaute, C. (2020). Greenhouse Gas Emissions from Inorganic and Organic Fertilizer Production and Use: A Review of Emission Factors and Their Variability. Journal of Environmental Management, 276, 111211. https://doi.org/10.1016/J.JENVMAN.2020.111211

Walter, P., Wilson, R., Saavedra, S. (2020). Controlled Environment Agriculture: A Futuristic Fix for the Food System | L.E.K. Consulting. L.E.K. Insights XXII. https://www.lek.com/insights/ei/controlled-environment-agriculture-futuristic-fix-food-system

Walters, K.J., Currey, C.J. (2018). Effects of Nutrient Solution Concentration and Daily Light Integral on Growth and Nutrient Concentration of Several Basil Species in Hydroponic Production. HortScience 53, 1319–1325. https://doi.org/10.21273/HORTSCI13126-18

Wang, H., Zhang, S.S., Yang, L.Y., Chen, Q.L., Yang, B.S. (2012). Effects of Environmental Factors on the Soil Nitrogen Transformation in Terrestrial Ecosystems. Proceedings - 2012 International Conference on Biomedical Engineering and Biotechnology, iCBEB 2012 1404–1407. https://doi.org/10.1109/iCBEB.2012.178

Williams, K.A., Nelson, J.S. (2016). Challenges of Using Organic Fertilizers in Hydroponic Production Systems. Acta Horticulturae 1112, 365–370. https://doi.org/10.17660/ActaHortic.2016.1112.49

Wongkiew, S., Hu, Z., Lee, J.W., Chandran, K., Nhan, H.T., Marcelino, K.R., Khanal, S.K. (2021). Nitrogen Recovery via Aquaponics–Bioponics: Engineering Considerations and Perspectives. ACS ES&T Engineering 1, 326–339. https://doi.org/10.1021/acsestengg.0c00196

Xie, Y., Spiller, M., Vlaeminck, S.E. (2022). A Bioreactor and Nutrient Balancing Approach for the Conversion of Solid Organic Fertilizers to Liquid Nitrate-Rich Fertilizers: Mineralization and Nitrification Performance Complemented with Economic Aspects. Science of the Total Environment 806. https://doi.org/10.1016/j.scitotenv.2021.150415

Yang, P., Guo, Y. zhi, Qiu, L. (2018). Effects of Ozone-Treated Domestic Sludge on Hydroponic Lettuce Growth and Nutrition. Journal of Integrative Agriculture 17, 593–602. https://doi.org/10.1016/S2095-3119(17)61868-9

Yewale, P., Wagle, N., Lenka, S., Bannigol, P., Junnarkar, M., Prakash, D., Mandal, A., Stigh, C., Sahasrabudhe, T., Vannalwar, T., Thakare, P., Nikam, D., Pawar, S., Nawani, N. (2022). Studies on Biosmotrap: A Multipurpose Biological Air Purifier to Minimize Indoor and Outdoor Air Pollution. Journal of Cleaner Production 357, 132001. https://doi.org/10.1016/J.JCLEPRO.2022.132001

Zhai, Z., Ehret, D.L., Forge, T., Helmer, T., Lin, W., Gv, C. (2009). Organic Fertilizers for Greenhouse Tomatoes : Productivity and Substrate Microbiology. Methods 44, 800–809. https://doi.org/10.21273/HORTSCI.44.3.800

Connecting Text

Chapter 4 shed light on the potential of utilizing biomass, typically discarded as waste, to offset the global warming potential (GWP) of soil-less plant production. However, the GWP contribution of fertilizer in cannabis production, particularly when utilizing potting media, is relatively low, as demonstrated in Chapter 3.

The forthcoming Chapter aims to provide context by examining the impact of fertilizer production and use within the Canadian cannabis landscape. Recognizing that the HVAC (heating, ventilating, and air conditioning) energy demand in Canada may be significantly higher compared to the United States due to lower temperatures, the Chapter seeks to investigate the GWP of the Canadian cannabis industry, both indoor and outdoor cultivation methods included.

This analysis will facilitate a realistic assessment of the environmental footprint of the Canadian cannabis sector, guiding stakeholders in identifying and implementing strategies to make the industry more sustainable. By understanding the specific challenges and opportunities within the Canadian context, stakeholders can chart a course toward greener practices, ensuring the long-term viability and environmental responsibility of the cannabis industry in Canada.

Chapter 5 : Greener green: The environmental impacts of the Canadian cannabis industry

Abstract

The burgeoning global cannabis industry, particularly in legal recreational and medical markets, raises environmental concerns. This study integrates Canada's cannabis industry data, employing a life cycle assessment with primary HVAC energy modeling. Six key environmental dimensions—carbon footprint, fossil fuel scarcity, metal depletion potential, terrestrial acidification, and marine and freshwater eutrophication—are examined. Indoor cultivation, though high yielding, relies heavily on energy-intensive HVAC systems. Regional factors like electrical grid efficiency and climate influence indoor production's carbon footprint, with colder regions exhibiting higher footprints from natural gas heating. Conversely, warmer climates rely more on electricity for cooling. Outdoor cultivation significantly reduces carbon footprint due to lower HVAC use but raises pest control concerns. Urgent comprehensive research on cannabis cultivation's environmental impacts is underscored, advocating for standardized carbon footprint calculations, eco-labeling, and consumer awareness. Industrial symbiosis, co-locating cannabis producers with CO_2 emitters, could mitigate environmental externalities from indoor cultivation's supplemental CO_2 use.

5.1 Introduction

Cannabis cultivation for legal markets, recreational and medical, is a lucrative industry globally. In Canada, over 700 hectares were dedicated to the production of legal cannabis in 2023 (Health Canada, 2023a). Other nations, like Germany and Thailand, are also legalizing non-medical uses, suggesting that cannabis production worldwide will most likely increase in the coming years (Fischer & Hall, 2022).

Concerns arise regarding the environmental impacts of this expansion. Cannabis cultivation processes emit substantial greenhouse gas (GHG) emissions and degrade landscapes and water resources (Mills, 2012; Summers et al., 2021; Butsic et al., 2018; Butsic and Brenner, 2016; Wang et al., 2017; Wartenberg et al., 2021). The impact's size and scale depend on cultivation methods and locations.

Indoor production via controlled environment agriculture (CEA) yields high outputs (~18,500 kg dry flower ha^{-1} per year) but comes with energy-intensive heating, ventilating, and air conditioning (HVAC) systems (Summers et la., 2021; Mills, 2012).

The carbon footprint of indoor cannabis production is impacted by regional factors like electrical grid efficiency, measured in kg of CO_2-equivalents (kg CO_2-eq) produced per kWh delivered, and outdoor temperature and humidity (Summers et al., 2021). For example indoor growing operations located in higher altitudes will require more heating energy to maintain indoor temperature at a desired setpoint (Summers et al., 2021). In the United States (US), producing one kg of dried cannabis flower can emit 2,000 to 5,000 kg CO_2-eq (Summers et la., 2021; Mills, 2012). Summers et al. (2021), showed that the electricity accounted for an average of 30 % of the carbon footprint of cannabis across the US, but this ranged from 20% to 60%, depending on the energy grid and climate.

No data has been reported for outdoor production energy use and yield estimates from the literature suggests ~4000 kg dry flower ha^{-1} per year, less than a quarter of indoor production yield (Benke & Tomkins, 2017; Darby et al., 2021a, 2021b; Summers et al., 2021; Wilson et al., 2019). Energy use in outdoor production could be comparatively lower, as the energy needed to power CEA technology (HVAC systems and horticultural lighting operation) is still needed but to a much smaller extent. The time when such systems are needed is smaller, usually confined to the propagation/seedling production and the drying/curing steps. These spaces occupy roughly 12% of an indoor cannabis production site (Summers et al., 2021).

However, to accurately assess the sustainability of outdoor cannabis production, like any other outdoor plant production, fertilizer use must be considered. Nitrogen fertilizers (N-fertilizers) enhance plant productivity but also emit greenhouse gases through natural gas (NG) combustion during ammonia synthesis (Gao & Carbera Serrenho, 2023; Eickemeier et al., 2019; UNEP, 2019). Fertilizer usage is linked to dinitrogen monoxide (N_2O) emission to the air (Deng et al., 2015). N-fertilizers use can cause nutrient runoff, leading to contamination of air, water, and soil (Chandini et al., 2019). The direct emission of N_2O following fertilizer application in outdoor cannabis cultivation need to be evaluated, given its global warming potential 300 times higher than carbon dioxide (Robertson & Vitousek, 2009). For reference, N-fertilizer use in outdoor agriculture can account for up to 90% of a crop's carbon footprint: 40% from synthesis and 50% from application-related N_2O (Rosenfield et al., 2018).

Due to the growing market and unknown environmental intensity of cannabis, there's an urgent need for comprehensive studies on its environmental impacts. Existing studies, mostly limited to the US, focused on global warming potential (GWP), calculated on a kg CO_2-eq per kg of dried cannabis flower basis, of indoor cultivation only (Summers et al., 2021; Mills, 2012). This research addresses these unknown, presenting an environmental assessment of Canada's cannabis industry, combining primary data with an HVAC energy model for a comprehensive life cycle assessment (LCA). Six environmental dimensions were analyzed, providing insights for sustainable decision-making, and supporting efforts to standardize cannabis carbon footprint calculations and develop eco-labels, promoting environmentally conscious choices among cannabis consumers (ISO 2006a, b).

5.2 Methods

The goal of this study was to compare the environmental impacts of cannabis cultivation in Canada using LCA. LCA is a widely used method to estimate the potential environmental impacts of a product or service across its entire value chain. Here, we used an attributional LCA modeling approach, which is ideal for product-systems that are not expected to largely influence background systems (e.g. energy grid mixes, etc.). The study scope, the data inputs, and the environmental metrics used in this model are explained further below.

5.2.1 Description Product System

Cannabis production encompasses four steps: cloning, seedling, flowering, and curing. Cloning is done by keeping mother plants in a vegetative state by providing an 18 h per day photoperiod. Seedlings are propagated by cuttings of the mother plants. Flowering requires a 12 h per day photoperiod, which requires a separate larger room. Drying and curing of harvested flower is usually done in a separate room with lower light intensities (Figure 5.1).

Note absence of HVAC and lighting energy for outside flowering plants. Horticultural input involves potting media, pest control and fertilizer.

For the model, indoor and outdoor facilities had a fixed plant density and yield parameters, determined from literature and industry communications. Indoor systems had 2.7 plants m^{-2} with and an average yield of 163 g of dry flower per plant. Outdoor had a modeled planting density of 1.9 plants m^{-2} with an average yield of 532 g dry flower per plant (Danziger and Bernstein, 2022; Mills, 2012; Summers et al., 2021).

For the outdoor production, it was assumed that all area reserved to flowering was outside, hence the energy needed for this phase was excluded.

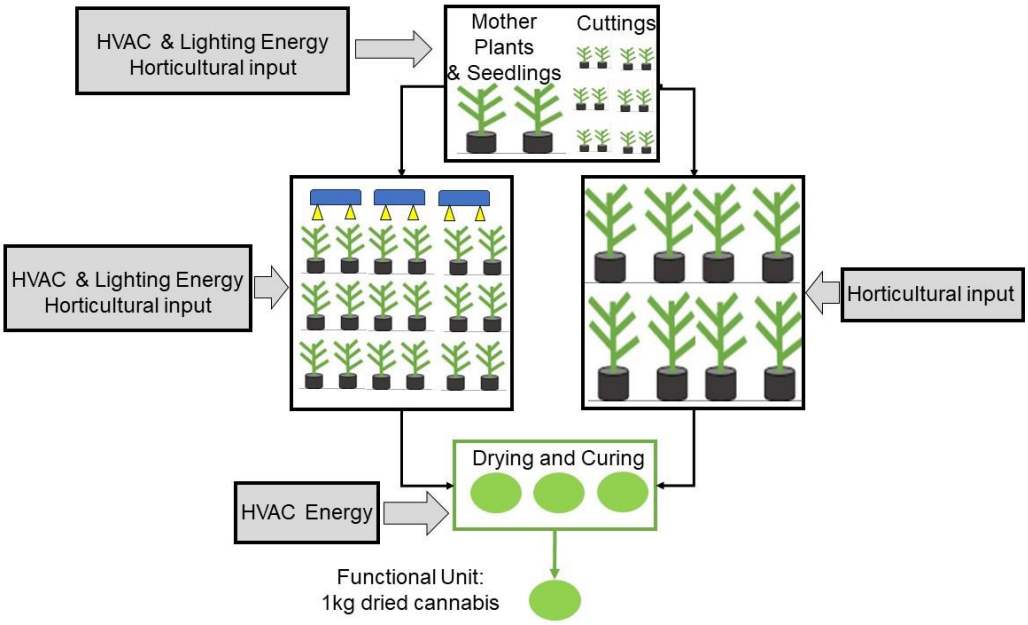


Figure 5.1: Schematic representation of needed input and space needed per growing stage to produce 1 kg of dried flower.

5.2.2 Scope and Functional Unit

This study uses a cradle-to-gate approach, encompassing energy, soil amendments, nutrients, and irrigation from seedling to cured final product. Packaging was not considered, assuming comparability across systems, and life-cycle stages such as use and end-of-life were excluded, assuming uniformity. Differences in waste production between systems were acknowledged. Transportation of inputs and organic waste adhered to Canadian Cannabis Regulations (Government of Canada, 2018).

Infrastructure-related impacts were omitted, aligning with agricultural LCAs. Studies on controlled environment agriculture (CEA) infrastructure, such as vertical farming, indicated minimal embodied impacts, particularly in energy-intensive indoor cannabis production, as observed in studies on warehouse-style buildings (Parkes et al., 2023, 2022; Guggemos & Horvath, 2005). The functional unit for comparison was set as one kilogram of dried cannabis flower at the farm gate, facilitating alignment with prior studies.

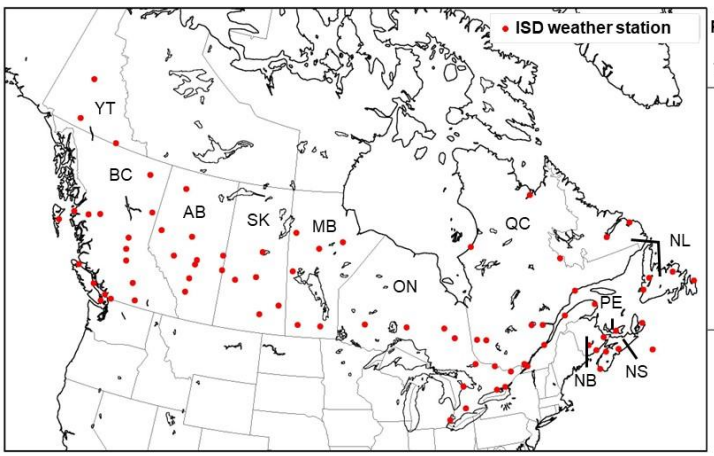
5.2.3 Life-Cycle Inventories

Different background data were used to build life cycle inventories (LCI) for indoor and outdoor cannabis cultivation. For indoor and outdoor cultivation, we combined outputs from an existing model of energy use in indoor cannabis production (Summers et al, 2021) with industry data and literature values. Inventories for background data (e.g. energy grids, landfill operations, etc.) came from Ecoinvent v3.8 (www.ecoinvent.org) in OpenLCA software v 2.0.1 (www.openlca.org). Details on the LCIs for each cultivation method is described below. For complete LCI, quantity per kg of dry bud and reference for each. See Supplementary Table S5.1.1 and Table S5.1.2 (Appendix C).

5.2.3.1 Indoor Cultivation

The energy consumption model, based on facility specifications from a prior study (Summers et al., 2021), estimates HVAC demand for maintaining temperature and humidity setpoints (See Supplementary Table S5.2 (Appendix C) in a warehouse-like cannabis plant factory exposed to varying external temperature and humidity conditions. Simulating humidity from plant evapotranspiration and heat from high-intensity lights, the model covers all stages of cannabis cultivation. A yearly harvest frequency of 6.2 was used like prior studies (Summers et al., 2021).

To assess energy consumption's regional impact on Canadian cannabis production, 80 weather stations across 10 provinces and one territory were utilized (Figure 5.2). Meteorological data, including hourly outdoor temperatures, humidity, and ambient pressure, were obtained from the Integrated Surface Database (ISD) for each location (Smith et al., 2011).



Province or territory	Cultivation licenses (count)	ISD weather station (count)		Avg annual temp. (°C)	Avg annual RH (%)
AB	92	10		2.7	68.5
BC	164	16		7.3	73.4
MB	16	6		0.3	70.8
NB	23	3		6.3	74.5
NL	6	7		2.9	76.4
NS	33	5		7.8	79.6
ON	199	12		5.6	71.4
PE	4	1		6.6	76.8
QC	158	12		3.1	72.1
SK	30	5		2.2	71.0
YU	1	3		-0.6	68.7
Sum	726	80	**Avg**	4.0	73.0

Figure 5.2: Location of Integrated Surface Database (ISD) weather stations used for meteorological data acquisition. Number of cultivation licenses was acquired from Health Canada, (2023b)

In the model, cooling and dehumidification equipment used electricity while heating, humidification and tap water heater systems used NG. Additional model parameters and are presented in supplementary methods (Appendix C). Total energy demand to maintain indoor temperature and humidity was summed and averaged for the duration every calendar year for the 80 locations.

To convert electricity to GHGs, EcoInvent v3.8 GHG intensity factors were used for each provincial grid-mix for the year 2019 including line losses. For NG, an average value from EcoInvent was applied across all locations (4.01 kg CO_2-eq kg^{-1} of NG). This value includes manufacturing, pressurization, distribution, and losses (i.e., flaring, venting, and fugitive emissions) up to the point of purchase, followed by combustion in a central heater with boiler condensing modulating <100 kW.

5.2.3.2 Horticultural Inputs

Horticultural inputs, including fertilizer, potting media, pesticides, supplemental CO_2, and HPS lighting maintenance, were incorporated into an OpenLCA model based on literature values (Health Canada, 2021; Incrocci, 2007; Maxim et al., 2014; Summers et al., 2021; Zhang et al., 2017). Adjustments for HPS lighting maintenance and perlite density were made using data from previous models (Zhang et al., 2017; Maxim et al., 2014). Detailed modeling of horticultural inputs for plant protection and potting mix was performed on a per-plant basis, with additional information available in supplementary methods (Appendix C). Fertilizer input was considered to leave the system proportionally to its mass following emission factor guidelines. Air emissions were modeled, with 1% of total nitrogen (N) represented as N_2O, following IPCC guidelines (2014). NO_x and NH_4 emissions were estimated at 21% and 4% of N_2O emissions, respectively, in accordance with earlier research recommendations (Nemecek & Kägi, 2007). For fertigation water, modeling included 12% of total phosphorus (P) as PO_4 (Liu et al., 2018) and 1% of total N as NO_3 (Hasler et al., 2015). The model assumed no recirculation of the fertilizer solution in both indoor and outdoor production, mirroring practices in small-scale soil-less facilities to prevent salt buildup. Appendix A contains details on modeled distances. To comply with Canadian regulations, all waste, including spent soil and harvest by-products, was directed to

landfills, with associated lorry transport (40 km) and landfill equipment operation included in the model. Transport distances were assumed as follows: 805 km from manufacturing to distribution centers by train, 80 km from distribution centers to small retail locations by lorry, and 15 km in a passenger car for employee travel to the grow facility. These distances align with those used in a prior study (Summers et al., 2021). Additionally, energy usage for water delivery to the cultivation facility was included in the model.

5.2.4 Estimating Carbon Sequestration

Estimated landfill emissions from waste decomposition were based on the inventory in Summers et al. (2021). Briefly, the model assumes that landfilling operation will both sequester carbon in harvest byproducts (potting media, stem, leaves etc.) as well as release certain quantities of methane (CH_4) and CO_2. Based off previous studies, emission factors were set at 7.3 % of landfill mass would be released as CH_4, 6.9 % as CO_2 and 51.4 % would be sequestered. Readers are suggested to read Lee et al. (2017) for more information.

5.2.5 Outdoor Cultivation

For outdoor cannabis, vegetative and flowering phases happen outdoors while seedling production and curing occur indoors. Only one harvest per year was modeled for this system. Cloning and curing stages were modeled as identical to the indoor system: 22 and 14 days, respectively. The growing duration for the vegetative and flower stage was set at 6 months (May to October).

Outdoor cannabis requires electricity and NG for lighting and HVAC during the cloning and drying/curing stages. We assumed energy requirements for these processes to be 12 % of the indoor HVAC model, as this was the proportion of floor space dedicated to mother plants, clones, and curing (Summers et al., 2021). No supplemental CO_2 is assumed to be used in indoor production in all phases.

For horticultural inputs, it was assumed that each plant would receive the same quantity of input (potting mix and bio-pesticide) as in the indoor setting. The assumption is that plants grown outdoors will grow for a longer period and produce more dry flower per plant than indoors. The assumption is that 6.1 indoor-grown plants are needed to produce 1 kg of dry flower whereas 1.9 outdoor-grown plants are needed to produce 1 kg of dry flower. In other words, 1 kg of outdoor dry flower requires about 3 times less

of these inputs. For fertilizer, the same fertilizer solution was used (500 mL d^{-1} per plant of a 1.8 mS cm^{-1}) but for the total duration of the grow cycle (6 months).

5.2.6 Environmental Indicators

This study included five LCA impact categories relevant to cannabis production: climate change, marine eutrophication, freshwater eutrophication, fossil fuel depletion, and mineral resource depletion. Although relevant when studying agricultural production at resource frontiers, we excluded agriculture and natural land transformation since cannabis cultivation in Canada occurs on pre-existing farms. ReCiPe midpoint (H)V1.13 impact assessment method was used (Huijbregts et al., 2017) with all conversion of the LCI to impact potentials done using OpenLCA V.2.0.1.

5.2.7 Statistical Analysis

Principal component analysis (PCA) with JMP version 17.0.0 software was used to determine the effect average annual temperature and relative humidity (RH), electrical consumption, NG consumption, altitude, and grid efficiency on carbon footprint.

5.3 Results

In line with other studies, the bulk of environmental impacts in cannabis production, including the carbon footprint, were driven by natural-gas consumption during heating for indoor and outdoor production. Of note is the relatively minor contribution of electricity to these impacts. This points to the need for continued application of energy-sparing strategies in cannabis production and to the challenges of decarbonizing this crop, given the continued reliance of facilities on fossil-fuels for heating. As energy use is the largest driver of impacts in our study, we start with results for energy consumption and then move into environmental indicators.

5.3.1 Trends in Energy Use for Indoor Cultivation

NG consumption was highest in the coldest regions MB, YT with values of approximately 45,000 MJ kg^{-1} (Figure 5.3 A). These colder regions had average annual temperature <1 ºC (Figure 5.2). NG consumption levels were closer to 40,000 MJ kg^{-1} in AB, SK, QC and NL. These regions had average annual temperatures between 2-3 ºC. Values between 30,000 and 36,000 MJ kg^{-1} were reported for hotter regions of ON, NB, PE, BC and NS. These values are, again, directly related to the average annual temperature observed in these locations, which are above 5ºC.

The indoor cannabis cultivation model shows that electrical energy consumption was highest in warmer provinces like ON, NB, NS and PE, with values ranging from 2,000

to 2,100 kWh kg^{-1} (Figure 5.3 B). Colder provinces (AB, SK, MB, NL: <3ºC) had lower electrical energy consumption (~1,900 kWh kg^{-1}) with BC and YT having the lowest values of ~1,850 kWh kg^{-1}.

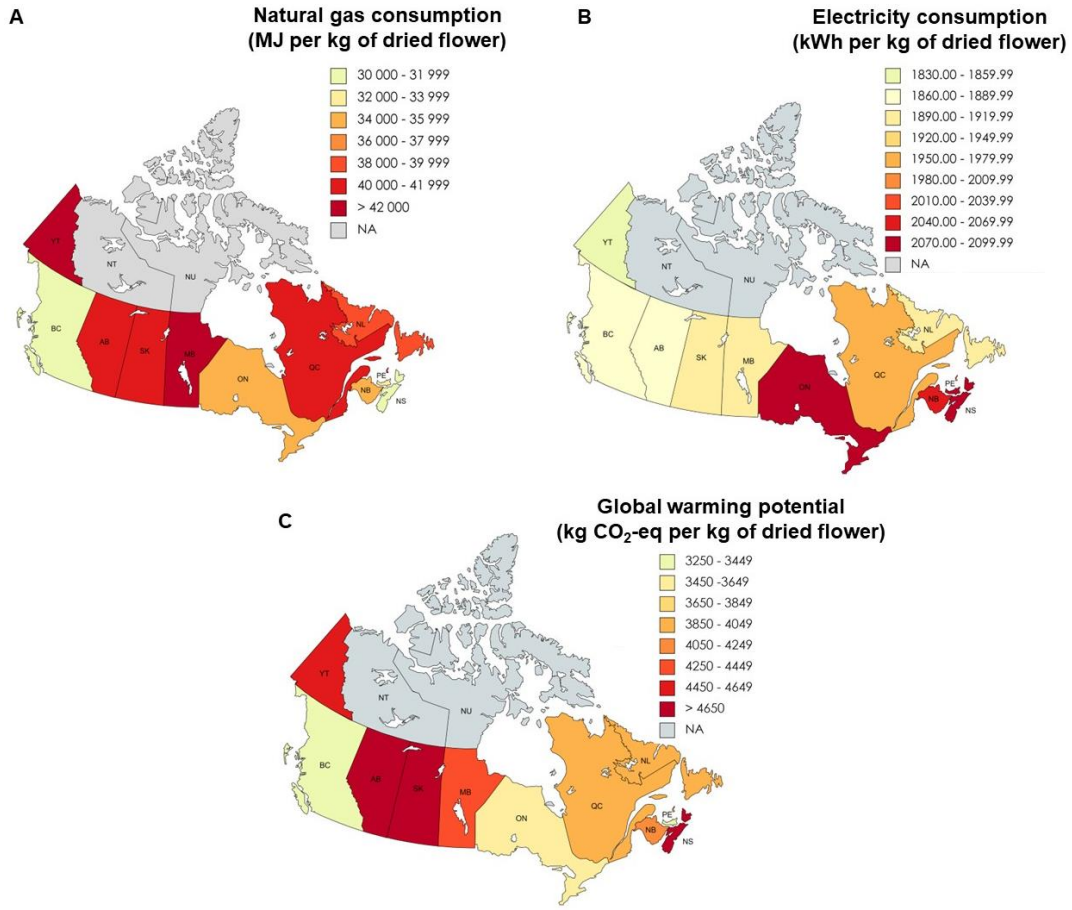


Figure 5.3: Average provincial values for (A) electrical energy and (B) natural gas consumption and (C) greenhouse gas emissions for the indoor production of 1 kg of dried cannabis in Canada. Province and territory abbreviations and names: BC = British Columbia, PE = Prince Edward Island, ON = Ontario, QC = Québec, NL = Newfoundland & Labrador, NB = New Brunswick, NS = Nova Scotia, MB = Manitoba, YT = Yukon Territory, SK = Saskatchewan, AB = Alberta.

Given that lighting and cooling are the main drivers of electricity usage, despite the consistent baseline energy consumption for lighting at 1,350 kWh kg^{-1} across all sites, the additional electrical consumption will primarily stem from cooling demand. Thus, HVAC (air cooling and air circulation) accounts for the remainder of energy use, ranging from 500 to 850 kWh kg^{-1} across all regions studied. Higher demand for electrical energy comes from warmer average outdoor temperatures, where demand for

air cooling is needed to maintain grow rooms at set temperatures. Output for each individual location are presented in Additional Table S5.3 (Appendix C).

The average GWP of indoor cannabis in Canada was 3,800 ± 750 kg CO_2-e kg^{-1}, ranging from 3,200 to 5,400 when looking at individual provincial values (Figure 5.3 C). This is comparable to the estimated US average of 4600 kg CO_2-e per kg of dried flower (Mills, 2012) However, US regional analysis gave a range of value from 2,500 to 5,000 kg CO_2-e per kg of dried flower (Summers et al., 2021). Overall, higher values were observed in Canadian values calculated as part of this study.

The province with the highest indoor cannabis production GWP was Alberta at 5,370 kg CO_2-eq kg^{-1}. Emissions are largely driven by colder temperatures and the carbon intensity of the province's electrical grid (0.798 kg CO_2-eq kWh^{-1}), which is highly dependent on fossil fuels (Figure 5.4 A). However, grid efficiency does not explain everything. For example, Quebec, which has the least carbon intensive grid in Canada at 0.015 kg CO_2-eq kWh^{-1} has a relatively high GWP of 3,860 kg CO_2-eq kg^{-1}, relative to provinces with more carbon intensive grids like BC, PE and ON. Hence, one primary driver of GWP is the need for heating in a colder climate. Because this model assumed 100% NG heating, NG contributes between 40 and 50 % of the GWP of all indoor production models. Even for outdoor production, the need for heating via NG consumption accounts for roughly 30 % of the net GHG emission (Figure 5.4 B).

The lowest GWP for indoor cannabis production was 3,260 kg CO_2-eq kg^{-1} in British Columbia (BC), where the climate is relatively mild. These results suggest that BC is the current benchmark for carbon-friendly cannabis production in Canada. As such, we use this province for comparisons to outdoor cannabis production.

GWP for outdoor production in BC was estimated to be ~10 % of total indoor production in the same province. Because HVAC energy demand was the most important category, the same trend could be observed in other provinces and territory. Evaluating the emissions from outdoor production and comparing these to the "other" emissions category for indoor production shows the disparity between indoor and outdoor cannabis production in Canada. For instance, total emissions from outdoor production were like the GWP from water heating and pumping, fans for air circulation, and horticultural inputs alone in NS, SK and AB (Figure 5.4 B).

Drivers of GWP were confirmed using PCA using environmental parameters, energy consumption and resulting GWP resulting in a model. Resulting PCA explained 70.3

% of variance (PC1 47.6 % and PC2 22.7 %) (Figure 5.5). A clear inverse relationship between NG consumption and average temperature was shown.

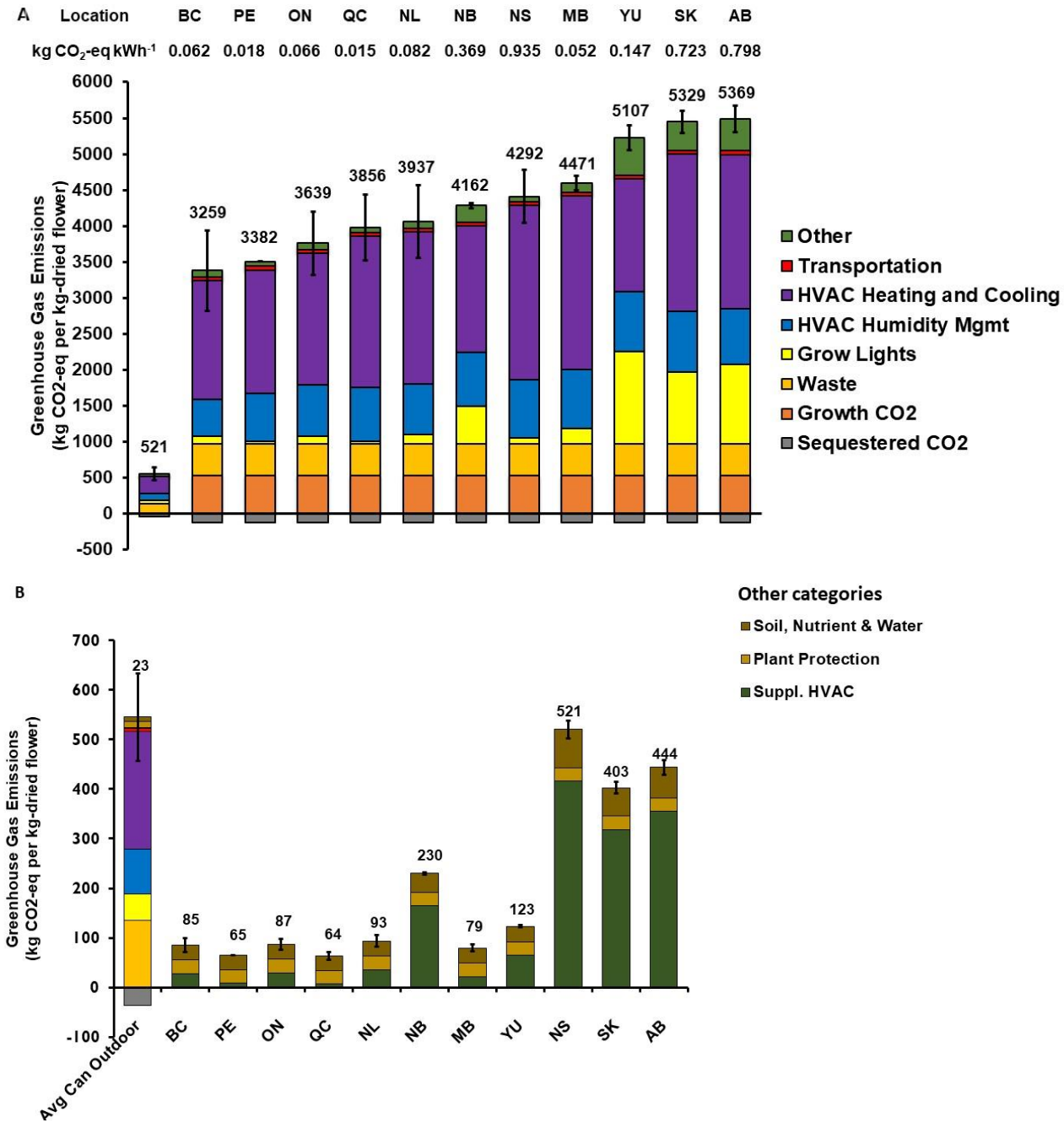


Figure 5.4: Average values for GHG emission of indoor and outdoor cannabis production, separated by processes.

GHG emissions averages across are given as provincial averages for indoor and Canadian average for outdoor. Major contributing processes for indoor culture are shown (A) and minor contributing processes (other) (B). Bars are averages Numbers above the bar is the net carbon footprint calculated with the sum of negative processes (sequestered carbon) and positive processes.

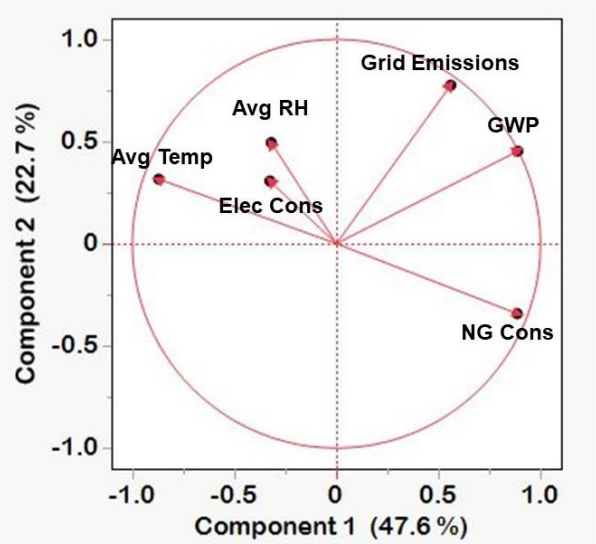


Figure 5.5: Principal component analysis from the 80 modelled Canadian locations. The highest explained variance for measuring GWP per location was obtained by using 2 geographical parameters (average relative humidity [Avg RH] and average temperature [Avg Temp]) and 3 energy parameters (grid efficiency [Grid Eff], electrical consumption [Elec Cons] and NG consumption [NG Cons]).

Two clusters were identified. The first one shows how average RH, average temperature and electrical consumption are positively correlated, highlighting the modeled electrical consumption for dehumidification and cooling. The second cluster shows how grid emissions is correlated with GWP.

5.3.2 Other Impact Categories

Table 5.1 shows estimated impacts for indoor and outdoor production in BC across five LCA indicators. Overall, most impact categories decreased 5 to 10-fold for outdoor cannabis production. Heating via NG combustion and pressurized liquid CO_2 for carbon enrichment in the growing area were the most contributing process for the five studied impact categories for indoor production.

For outdoor production, it was observed that heating via NG was still the most important driver of GWP, fossil fuel scarcity, metal depletion potential and terrestrial acidification. This process was assumed to be 12 % of the total energy required in the indoor production to model the portion of that energy allocated for the seedling production and drying/curing phases of outdoor cannabis production.

Interestingly, horticultural inputs for pest management were the main drivers for marine eutrophication and freshwater acidification. These findings suggests that it would be the second priority for environmental harm reduction in outdoor production.

Because heating via NG combustion was the hotspot across most indicators in indoor and outdoor production, reducing the modest impacts of outdoor cannabis production necessitates a broader strategy to use energy and horticultural inputs more efficiently.

Table 5.1: Environmental impacts of outdoor and indoor dry cannabis flower production in British Columbia

.	Indoor				Outdoor			
	Sum of processes (units)	**Hotspot**	**Percent contribution (%)**	**Activity**	**Sum of processes (units)**	**Hotspot**	**Percent contribution (%)**	**Activity**
Fossil Fuel Scarcity (kg oil-Eq)	1284.5	Heat production via NG	83.7	Indoor environnemental control	140.5	Heat production via NG	91.9	Indoor environmental control
Metal Depletion Potential (kg Fe-Eq)	53.7	Carbon dioxide production	53.3	Indoor environmental control	3.4	Heat production via NG	58.5	Indoor environmental control
Terrestrial Acidification (kg SO_2-eq)	4.3	Heat production via NG	45.3	Indoor environmental control	0.4	Heat production via NG	66.1	Indoor environmental control
Marine Eutrophication (kg N-Eq)	0.29	Carbon dioxide production	49.4	Indoor environmental control	0.03	Bio-pesticide production	64.9	Horticultural practices
Freshwater Eutrophication (kg P-Eq)	0.26	Carbon dioxide production	54.4	Indoor environmental control	0.02	Bio-pesticide production	45.1	Horticultural practices

5.4 Discussion

Cannabis production and consumption is growing. Results presented here show that the GWP per kilogram of indoor-grown cannabis flower can be extremely high. Studies show that the occasional cannabis user in Canada that smokes dried flower consumes nearly a gram daily on average (Hammond et al., 2022). Using national averages for indoor production, this amounts to 4.25 kg CO_2-eq day^{-1} or 1.5 tons CO_2-eq $year^{-1}$. A heavy smoker consuming indoor-grown cannabis from Alberta, where cannabis production is most carbon intensive, who consumes 1.6 grams day^{-1} would have impacts of 8.6 kg CO_2-eq day^{-1} or 3.1 tons CO_2-eq $year^{-1}$, nearly equivalent to per-capita emissions from housing or transport in Canada (Akenji et al., 2021). Given the immense scale of these impacts, there is a critical need to chart a path towards cannabis production with low environmental intensity. Below we discuss practical steps for stakeholders and a future research agenda to make this happen.

5.4.1 Addressing Heating Use in Canadian Cannabis Production

The initial hypothesis that electrical grid efficiency would be a strong determinant of the GWP of cannabis production was proven wrong. This was one of the conclusions from previous LCA studies in the US, where indoor cannabis grown in Hawaii was very carbon intensive (5,000 kg CO_2-eq kg^{-1}) because of continued electrical grid-reliance on fossil-fuels (Summers et al., 2021a).

However, one important environmental parameter of Hawaiian facilities is their need to manage high levels of atmospheric humidity, which was also observed in our study in NS. In both models, dehumidification is done via electrical process. Average kWh kg^{-1} of dried cannabis was between 1,800-2,100 here, versus 1,700-5,300 in the United States, with maximum values in southern states like Texas and Florida. High electrical consumption is associated with the need for dehumidification and cooling.

Provincial and territorial electrical grid carbon emission correlated positively with GWP of cannabis. When comparing provinces with similar average temperatures - PE, BC and NS - grid intensity made BC and PE stand out. The small difference between PE and BC could be accounted to the extra RH present in PE.

It is important to note that the Open LCA model used here did have different values than the previous study considering carbon emission of NG. In Summers et al. (2021) a factor

of 3.06 kg CO_2-eq kg^{-1} of NG combustion was used for NG carbon footprint. However, a small-scale natural gas boiler unit of <100 kW process was modeled here, which had a kg CO_2-eq kg^{-1} of NG combustion of 4.1. This could explain in part how colder locations in previous studies, like Alaska, did have lower GWP than MB, YT, NS, SK or AB. Future studies could fine-tune the NG model by accounting for transport between NG production and use, where major NG producing provinces, like AB, might see a decrease in the GWP calculated.

The need for heating will need to be addressed by stakeholders. At the time of writing this manuscript, no census on heating system in commercial plant production facilities in Canada is available. Assuming most producers will have a NG-powered seemed sensible, as it was the same assumption used in a previous study (Summers et al., 2021).

Colder locations have higher GWP because of the increased need for NG-powered heating processes. Heating via NG combustion easily account for 50% of the GWP. It could be said that production of cannabis grown in QC and AB could be having a disproportionate effect on the carbon footprint of the industry versus cannabis grown in ON and BC. There is a need to question whether incentives for QC and AB producers to adopt carbon-reducing strategy is needed.

Switching to electrical heating systems would undoubtedly reduce carbon footprint in regions with a low carbon emitting grid. For example, generating 40,000 MJ (11,111 kWh, assuming 3.6 MJ kWh^{-1}) of heating via a 100% efficient electrical heating system would generate ~160 kg CO_2-eq in QC versus ~8,800 kg CO_2-eq in AB. Producer wanting to switch heating system should go through a rigorous decision-making process considering energy cost, system efficiency and carbon emission (Hansen, 2019).

5.4.2 Improving LCIs of Cannabis Production

The main objective of this LCA was to assess the environmental impact of the Canadian cannabis industry. We followed recommendations from earlier LCA of cannabis by including additional horticultural inputs such as potting media, fertilizer, pesticides, and maintenance of lighting (Zhang et al., 2017). We included improved data on these inputs and moved away from generic industry data. For instance, we used optimized fertilizer regimes as determined through field trials (Saloner and Bernstein, 2022a, 2021). A previous cannabis LCA assumption that was revised was perlite density. Previously set at

1,100 kg m^{-3}, a literature review showed it was closer to 50 kg m^{-3} (Maxim et al., 2014). Even if packed perlite density is higher during transport, the packed perlite would be loosened before incorporation in a potting mix. Because the input is calculated on a per plant basis, using the lower density value seemed appropriate.

Our model did not factor in the impact of pesticide use. Pest control in the US model was an unspecified synthetic pesticide. However, in Canada, synthetic pesticides are not allowed in cannabis production (Health Canada, 2021). In Canada, there are limited sprays or organisms that can be employed. These products usually are alkaline solutions (e.g., KOH) to contain fungal contamination or vegetable oil to suffocate insects. The process of vegetable oil and one synthetic pesticide were added to this model. Vegetable oil is permitted for use as a pest control product in cannabis (Health Canada, 2021), but not Folpet, a fungicide that was incorporated into the LCA model from a previous US study (Summers et at, 2021).

Literature review and industry communications show that, in accordance with Canadian law, very few synthetic plant protection products are used in the Canadian cannabis market. Most producers we contacted during this study used biological agents, such as beneficial microbes or predatory mites, as well as cultural methods, such as defoliating and increasing air flow (Punja et al., 2019). The process of spraying synthetic pesticide and its associated environmental impact were not included. It was assumed that using pest control products like in the Canadian cannabis market would have a lower environmental impact than the synthetic ones used in the United States.

However, plant protection input production were shown to be the most contributing processes for marine eutrophication and terrestrial acidification in the outdoor culture model, pointing to the need for research in decreasing the impact of these practices. Consideration for horticulture input lead to some adjustment to the fertilizer input parameter. Adjusting fertilizer quantities with peer-review literature greatly decreased the total N input. The previous indoor cannabis model used a value of 10 g N per plant, whereas the model used here used 7 g N per plant as recommended by the scientific literature (Saloner and Bernstein, 2022a, 2022b, 2021). By following optimal fertilizer regimen, the carbon footprint of fertilizer was decreased five-fold: 3.3 kg CO_2-eq kg^{-1} versus 0.7 kg CO_2-eq kg^{-1}. However, fertilizer only played a minor role in the GWP and other

environmental impact of indoor or outdoor cannabis culture. This points to the uniqueness of cannabis compared to other crops and the need for better LCI data. For example, 90 % of the GWP of corn comes from fertilizer production and use (Rosenfield et al., 2018). Even if the fertilizer mainly comes from non-renewable resources, the main driver of GWP and most environmental impact in outdoor production where NG combustion for heating rooms for seedling production and drying/curing.

5.4.3 Limitations, Future Work and Framework for Future Research in Other Countries

Limited data led to simplifications, particularly in geographic considerations and outdoor model parameters and energy input. Furthermore, transportation impacts were greatly reduced by replacing most of the transport from the original model. The transport processes using light commercial vehicle were replaced by large trucks in this study, and train transport was added. Future studies should increase resolution of transport processes, like natural gas transport. Improved modeling resolution would likely greatly modulate region-specific values.

International cooperation in cannabis industry environmental impact assessment will contribute to better understanding of the environmental impacts of cannabis production worldwide, ultimately facilitating mitigation. Collaborative efforts among countries that have legalized, decriminalized, or are considering legalization can facilitate knowledge exchange, data sharing, and the development of standardized methodologies. This can lead to more informed decision-making and the adoption of sustainable practices across the industry.

One conclusion from this study is the challenge of reducing heating using NG in a colder climate. Until now, growers have been preoccupied with more energy efficient lighting. In Canada, replacing HPS lamp with LEDs could have conflicting results if the goal is to reduce economical cost and environmental externalities. Indeed, “lost” energy in HPS is heat. As the need for heating drives most of the environmental and economic costs, growers should think carefully before replacing lighting systems. In this study, HPS lighting, even with added processes for maintenance (i.e., bulbs every 2 years and metal fixtures every 15), had a small influence on environmental impact.

The easiest way to have a profound impact on this industry would be to use technologies capable of using CO_2 from on-site combustion (Ghiat et al., 2021). On site CO_2 generation in northern greenhouse could replace the need for supplemental CO_2 (Roy et al., 2014). Supplemental CO_2 production and wastes are two processes that had large GWP, mineral resource scarcity potential and eutrophication potential. Technology linking on-site CO_2 production, waste processing and heating would increase environmental performance of the industry. This problem could be addressed by adopting policies for promotion of industrial symbiosis (Chertow, 2007). Indeed, the concept of financial incentives for indoor cannabis production facilities to be paired with local carbon emitting industries would turn this problem in a solution. In Canada, indoor cannabis production is routinely found in industrial parks. These are perfect locations for carbon emission from one industry to be used as an input in cannabis production. This would result in reducing the need for liquid carbon dioxide production, an important driver of environmental externalities, as well as reduce carbon emission in the atmosphere by the carbon emitting partner industry (Lawal et al., 2021).

5.5 Conclusions

The Canadian cannabis industry surpasses its US counterpart in greenhouse gas emissions, attributed to colder climates which necessitate heating. Currently, no data on adoption rate or usage proportion of heating technology by type (ie: electrical, natural gas, geothermal etc.) in controlled environment agriculture (CEA) industry in Canada exists. Transitioning to low-carbon heating technologies could benefit from governmental financial incentives. Outdoor cannabis production proves 6 to 10 times less carbon-intensive, reducing environmental impacts by 90 %. Eco-labeling could mitigate industry carbon footprints, enhancing consumer awareness. Widespread dissemination of this information and implementing eco-labeling for outdoor cannabis can empower consumers to make environmentally conscious choices.

5.6 References

Benke, K., Tomkins, B. (2017). Future Food-Production Systems: Vertical Farming and Controlled-Environment Agriculture. Sustainability: Science, Practice, and Policy, 13, 13–26. https://doi.org/10.1080/15487733.2017.1394054

Bevan, L., Jones, M., Zheng, Y. (2021). Optimization of Nitrogen, Phosphorus and Potassium for Soilless Production of Cannabis Sativa in the Flowering Stage Using Response Surface Analysis. Frontiers in Plant Science, 12. https://doi.org/10.3389/fpls.2021.764103

Butsic, V., Brenner, J.C. (2016). Cannabis (*Cannabis sativa* or *C. indica*) Agriculture and the Environment: A Systematic, Spatially-Explicit Survey and Potential Impacts. Environmental Research Letters, 11, 044023. https://doi.org/10.1088/1748-9326/11/4/044023

Butsic, V., Carah, J.K., Baumann, M., Stephens, C., Brenner, J.C. (2018). The Emergence of Cannabis Agriculture Frontiers as Environmental Threats. Environmental Research Letters, 13, 124017. https://doi.org/10.1088/1748-9326/aaeade

Chandini, Kumar, Randeep, Kumar, Ravendra, Prakash, O. (2019). The Impact of Chemical Fertilizers on Our Environment and Ecosystem. Research Trends in Environmental Sciences, 69–86. https://www.researchgate.net/publication/331132826

Chertow, M.R. (2007). "Uncovering" Industrial Symbiosis. Journal of Industrial Ecology. https://doi.org/10.1162/jiec.2007.1110

Danziger, N., Bernstein, N. (2022). Too Dense or Not Too Dense: Higher Planting Density Reduces Cannabinoid Uniformity but Increases Yield/Area in Drug-Type Medical Cannabis. Frontiers in Plant Science, 13, 1–18. https://doi.org/10.3389/fpls.2022.713481

Darby, H., Bruce, J., Krezinski, I., & Ruhl, L. (2021). Hemp Flower Variety Trial. https://scholarworks.uvm.edu/nwcsp/416/

Darby, H., Bruce, J., Lewins, S., & Ziegler, S. (2021b). 2021 Hemp Flower Nitrogen Fertility Trial (Issue April). https://scholarworks.uvm.edu/nwcsp/417/

de Chalendar, J.A., Taggart, J., Benson, S.M. (2019). Tracking Emissions in the US Electricity System. Proceedings of the National Academy of Sciences U.S.A., 116, 25497–25502. https://doi.org/10.1073/pnas.1912950116

Deng, Q., Hui, D., Wang, J., Iwuozo, S., Yu, C.L., Jima, T., Smart, D., Reddy, C., Dennis, S. (2015). Corn Yield and Soil Nitrous Oxide Emission under Different Fertilizer and Soil Management: A Three-Year Field Experiment in Middle Tennessee. PLoS One, 10, 1–14. https://doi.org/10.1371/journal.pone.0125406

Eickemeier, P., Schlömer, S., Farahani, E., Kadner, S., Brunner, S., Baum, I., Kriemann, B. (2019). IPCC, 2012: Summary for Policymakers, Planning for Climate Change. https://doi.org/10.4324/9781351201117-15

Fischer, B., Hall, W. (2022). Germany's Evolving Framework for Cannabis Legalization and Regulation: Select Comments Based on Science and Policy Experiences for Public Health. The Lancet Regional Health - Europe, 23, 100546. https://doi.org/10.1016/j.lanepe.2022.100546

Gao, Y., Cabrera Serrenho, A. (2023). Greenhouse Gas Emissions from Nitrogen Fertilizers Could Be Reduced by Up to One-Fifth of Current Levels by 2050 with Combined Interventions. Nature Food, 4. https://doi.org/https://doi.org/10.1038/s43016-023-00698-w

Ghiat, I., Mahmood, F., Govindan, R., Al-Ansari, T. (2021). CO2 Utilisation in Agricultural Greenhouses: A Novel 'Plant to Plant' Approach Driven by Bioenergy with Carbon Capture Systems within the Energy, Water and Food Nexus. Energy Conversion Management, 228, 113668. https://doi.org/10.1016/j.enconman.2020.113668

Government of Canada. (2018). Cannabis Regulations. Justice Laws Website. https://laws-lois.justice.gc.ca/eng/regulations/SOR-2018-144/

Government of Canada. (2023a). Cannabis Market Data. Government of Canada. https://www.canada.ca/en/health-canada/services/drugs-medication/cannabis/research-data/market.html

Government of Canada. (2023b). Licensed Cultivators, Processors and Sellers of Cannabis under the Cannabis Act. Producing and Selling Cannabis. https://www.canada.ca/en/health-canada/services/drugs-

medication/cannabis/industry-licensees-applicants/licensed-cultivators-processors-sellers.html?may-19-2023#wb-auto-6

Hansen, K. (2019). Decision-Making Based on Energy Costs: Comparing Levelized Cost of Energy and Energy System Costs. Energy Strategy Reviews, 24, 68–82. https://doi.org/10.1016/j.esr.2019.02.003

Hasler, K., Bröring, S., Omta, S.W.F., Olfs, H.W. (2015). Life Cycle Assessment (LCA) of Different Fertilizer Product Types. European Journal of Agronomy, 69, 41–51. https://doi.org/10.1016/j.eja.2015.06.001

Health Canada. (2021). Pesticide Label Search. https://pr-rp.hc-sc.gc.ca/

Health Canada. (2023a). Cannabis Market Data. Government of Canada. https://www.canada.ca/en/health-canada/services/drugs-medication/cannabis/research-data/market.html

Health Canada. (2023b). Licensed Cultivators, Processors and Sellers of Cannabis under the Cannabis Act. Producing and Selling Cannabis. https://www.canada.ca/en/health-canada/services/drugs-medication/cannabis/industry-licensees-applicants/licensed-cultivators-processors-sellers.html?may-19-2023#wb-auto-6

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G. (2016). ReCiPe 2016 v1.1-A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level: Report I, National Institute for Public Health and the Environment. Rijksinstituut voor Volksgezondheid en Milieu RIVM.

Incrocci, L. (2007). Nutrient Solution Calculator. https://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros/Calculation-tools/Nutrient-Solution-Calculator.htm

International Organization for Standardization. (2006a). ISO 14040:2006 Environmental Management–Life Cycle Assessment—Principles and Framework. https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines. https://www.iso.org/standard/38498.html

IPCC. (2014). Climate Change 2014 Synthesis Report - Summary Chapter for Policymakers. IPCC, 31. https://doi.org/10.1017/CBO9781107415324

Lawal, M., Wan Alwi, S.R., Manan, Z.A., Ho, W.S. (2021). Industrial Symbiosis Tools—A Review. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.124327

Lee, U., Han, J., Wang, M. (2017). Evaluation of Landfill Gas Emissions from Municipal Solid Waste Landfills for the Life-Cycle Analysis of Waste-to-Energy Pathways. Journal of Cleaner Production, 166, 335–342. https://doi.org/10.1016/j.jclepro.2017.08.016

Li, L., Li, X., Chong, C., Wang, C.H., Wang, X. (2020). A Decision Support Framework for the Design and Operation of Sustainable Urban Farming Systems. Journal of Cleaner Production, 268, 121928. https://doi.org/10.1016/j.jclepro.2020.121928

Liu, W., Yang, H., Ciais, P., Stamm, C., Zhao, X., Williams, J.R., Abbaspour, K.C., Schulin, R. (2018). Integrative Crop-Soil-Management Modeling to Assess Global Phosphorus Losses from Major Crop Cultivations. Global Biogeochemical Cycles, 32, 1074–1086. https://doi.org/10.1029/2017GB005849

Maxim, L.D., Niebo, R., Mcconnell, E.E. (2014). Perlite Toxicology and Epidemiology - A Review. Inhalation Toxicology, 26, 259–270. https://doi.org/10.3109/08958378.2014.881940

Mills, E. (2012). The Carbon Footprint of Indoor Cannabis Production. Energy Policy, 46, 58–67. https://doi.org/10.1016/j.enpol.2012.03.023

Nemecek, T., Kägi, T. (2007). Life Cycle Inventories of Agricultural Production Systems, Ecoinvent Report No. 15. Zurich and Dübendorf. https://db.ecoinvent.org/reports/15_Agriculture.pdf

Parkes, M.G., Azevedo, D.L., Cavallo, A.C., Domingos, T., Teixeira, R.F.M. (2023). Life Cycle Assessment of Microgreen Production: Effects of Indoor Vertical Farm Management on Yield and Environmental Performance. Science Reports, 13, 11324. https://doi.org/10.1038/s41598-023-38325-0

Parkes, M.G., Cubillos Tovar, J.P., Dourado, F., Domingos, T., Teixeira, R.F.M. (2022). Life Cycle Assessment of a Prospective Technology for Building-Integrated Production of Broccoli Microgreens. Atmosphere (Basel), 13. https://doi.org/10.3390/atmos13081317

Punja, Z.K., Collyer, D., Scott, C., Lung, S., Holmes, J., Sutton, D. (2019). Pathogens and Molds Affecting Production and Quality of Cannabis Sativa L. Frontiers in Plant Science, 10, 1–23. https://doi.org/10.3389/fpls.2019.01120

Robertson, G.P., Vitousek, P.M. (2009). Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. Annual Review of Environmental Resources, 34, 97–125. https://doi.org/10.1146/annurev.environ.032108.105046

Rosenfield, J., Lewandrowsky, J., Hendrickson, T., Jaglo, K., Moffroid, K., Pape, D. (2018). A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol.https://www.usda.gov/sites/default/files/documents/LCA_of_Corn_Ethanol_2018_Report.pdf

Roy, Y., Lefsrud, M., Orsat, V., Filion, F., Bouchard, J., Nguyen, Q., Dion, L.M., Glover, A., Madadian, E., Lee, C.P. (2014). Biomass Combustion for Greenhouse Carbon Dioxide Enrichment. Biomass and Bioenergy, 66, 186–196. https://doi.org/10.1016/j.biombioe.2014.03.001

Saloner, A., Bernstein, N. (2020). Response of Medical Cannabis (*Cannabis sativa* L.) to Nitrogen Supply under Long Photoperiod. Frontiers in Plant Science, 11, 1517. https://doi.org/10.3389/fpls.2020.572293

Saloner, A., Bernstein, N. (2021). Nitrogen Supply Affects Cannabinoid and Terpenoid Profile in Medical Cannabis (*Cannabis sativa* L.). Industral Crops and Products, 167, 113516. https://doi.org/10.1016/j.indcrop.2021.113516

Saloner, A., Bernstein, N. (2022). Effect of Potassium (K) Supply on Cannabinoids, Terpenoids and Plant Function in Medical Cannabis. Agronomy, 12, 1242. https://doi.org/10.3390/AGRONOMY12051242

Smith, A., Lott, N., Vose, R. (2011). The Integrated Surface Database: Recent Developments and Partnerships. Bulletin American Meteorology Society, 92, 704–708. https://doi.org/10.1175/2011BAMS3015.1

Summers, H.M., Sproul, E., Quinn, J.C. (2021). The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States. Nature Sustainability, 4, 644–650. https://doi.org/10.1038/s41893-021-00691-w

UNEP. (2019). Frontiers 2018/19 - Emerging Issues of Environmental Concern, UN Environment. https://www.unep.org/resources/frontiers-201819-emerging-issues-environmental-concern

Walter, P., Wilson, R., Saavedra, S. (2020). Controlled Environment Agriculture: A Futuristic Fix for the Food System | L.E.K. Consulting. L.E.K. Insights XXII. https://www.lek.com/insights/ei/controlled-environment-agriculture-futuristic-fix-food-system

Wang, I.J., Brenner, J.C., Butsic, V. (2017). Cannabis, an Emerging Agricultural Crop, Leads to Deforestation and Fragmentation. Frontiers in Ecology and Environment, 15, 495–501. https://doi.org/10.1002/fee.1634

Wartenberg, A.C., Holden, P.A., Bodwitch, H., Parker-Shames, P., Novotny, T., Harmon, T.C., Hart, S.C., Beutel, M., Gilmore, M., Hoh, E., Butsic, V. (2021). Cannabis and the Environment: What Science Tells Us and What We Still Need to Know. Environmental Science and Technology Letters, 8, 98–107. https://doi.org/10.1021/acs.estlett.0c00844

Wilson, H., Bodwitch, H., Carah, J., Daane, K., Getz, C., Grantham, T.E., Van Butsic. (2019). First Known Survey of Cannabis Production Practices in California. (Berkeley), 73, 119–127. https://doi.org/10.3733/ca.2019a0015

Zandkarimi, F., Decatur, J., Casali, J., Gordon, T., Skibola, C., Nuckolls, C. (2023). Comparison of the Cannabinoid and Terpene Profiles in Commercial Cannabis from Natural and Artificial Cultivation. Molecules, 28, 1–15. https://doi.org/10.3390/molecules28020833

Zhang, H., Burr, J., Zhao, F. (2017). A Comparative Life Cycle Assessment (LCA) of Lighting Technologies for Greenhouse Crop Production. Journal of Cleaner Production, 140, 705–713. https://doi.org/10.1016/j.jclepro.2016.01.014

Chapter 6 : Comprehensive Scholarly Discussion

The global cannabis industry has experienced unprecedented growth in recent years, driven primarily by the legalization of recreational and medicinal cannabis in various regions. However, this expansion has brought to the forefront significant environmental concerns surrounding the cultivation and production processes of cannabis. As this industry continues to evolve, there is a critical need for comprehensive research and analysis to understand and mitigate its environmental impacts.

In this thesis, the multifaceted environmental dimensions of cannabis cultivation and production, with a particular attention to fertilizer practices, was investigated. Three distinct experiments helped draw insights for orienting the future of a sustainable cannabis industry. Each experiment offered a unique perspective and contributed to understanding of the environmental implications of different cultivation methods and inputs. Through rigorous examination and synthesis of these experiments, the overarching hypotheses of the thesis, that adapted fertilizer practices can decrease cannabis production environmental impact, is discussed below.

In experiment 1, a fertilizer-response trial on outdoor-grown cannabis plants was combined with LCA. This experiment highlighted the significant disparity in global warming potential (GWP) between two fertilizer regimens, one being a low-N/high K:N ratio (L+) and the other a high-N/low K:N ratio (H-). The findings underscore the potential of increasing cannabinoid content of floral biomass to substantially reduce carbon intensity. However, the increase in demand for horticultural input, especially potting media, was brought up as a weak point in this low-fertilizer input scenario.

In experiment 2, the focus shifted towards innovative approaches to nutrient production in soil-less systems. By evaluating the efficacy of organic liquid fertilizer (OLF) derived from insect and chicken waste, this experiment explored the potential of organic inputs to mitigate GHG associated with conventional inorganic fertilizers production and use. Through a combination of plant growth studies and LCA, the experiment provided insights into the feasibility and challenges of integrating organic inputs into soil-less cultivation systems. The findings emphasized the importance of optimizing nutrient management strategies to minimize environmental impacts while maximizing productivity. The use of OLF in cannabis production would warrant its own study and should:

- use of municipal water source as to decrease the potential of Na toxicity.
- Assess the potential of the microbial consortium present in OLF in inducing a synergistic action with N deficiency on cannabinoid production.
- Investigate the detrimental effect of Na concentration.

Regardless of the plant chosen (cannabis or basil), the large uncertainty in potential GWP of the bioreactor, especially when it comes to gaseous N-losses, warrants caution when trying to use this technology to decrease GWP of soil-less production.

Experiment 3 expanded the scope of previous studies with a comprehensive assessment of Canada's cannabis industry, integrating data from HVAC energy modeling and LCA. By examining key environmental dimensions such as GWP, fossil fuel scarcity, and terrestrial acidification, this experiment offered a holistic understanding of the environmental impacts of indoor cannabis cultivation. Furthermore, it underscores the potential benefits of transitioning to low-carbon heating technologies and implementing industrial symbiosis to mitigate environmental externalities. Through detailed analysis and policy recommendations, this experiment contributes to shaping sustainable pathways for the cannabis industry in Canada and beyond.

Collectively, these experiments offer valuable insights into the environmental challenges and opportunities associated with cannabis cultivation and production. By synthesizing these findings, informing policymakers, industry stakeholders, and consumers about the critical importance of adopting sustainable practices in this burgeoning industry can be done. Notable differences in results and assumptions between experiments could hinder experiment accuracy. Highlighted below are model parameters and measures that have noticeable difference in terms of plant type, plant yield, planting densities, drying processes and GWP (Table 6.1).

Table 6.1 Summary of discrepancies regarding cropping system assumptions, parameters, and subsequent global warming potential measurement between Chapters. Usable growing area refers to the spaces specifically designated for plant cultivation. Unusable areas are those essential for the overall operation of the farm or factory, such as storage rooms, hallways, employee break rooms, etc.

	Plant type	Planting density (plants m^{-2})	Plant yield (g per plant)	Harvest per year	Usable growing area (%)	Field yield (kg ha^{-1})	GWP (CO_2-eq kg^{-1})
Chapter 3 (outdoor)	Auto-flowering	5.2	20-40	1-2	0.68	707-2829	60-110
Chapter 5 (indoor)	Photoperiod sensitive	2.7	163	6.2	0.68	18555	3200-5200
Chapter 5 (outdoor)	Photoperiod sensitive	0.2	532	1	0.68	849	450-630

6.1 Planting Density

Plant density is a parameter that did not receive much attention in any of the previous studies. The LCA in Chapter 3 assumed a 1 ha field with the same planting density used in the fertilizer trial (5.6 plants m^{-2}) for both fertilizer recipes. The planting density used in this experiment was chosen to prevent inter-individual competition for lighting, but a thorough evaluation on inter-plant and row spacing could be of great use to increase yield. Even if no data was collected on plant size, the general appearance of the plants can help us assess the effect of planting density on field yield (Figure S6.1). Using values from this experiment, a simple model to evaluate the influence of planting density on total field production was devised (Figure 6.1).

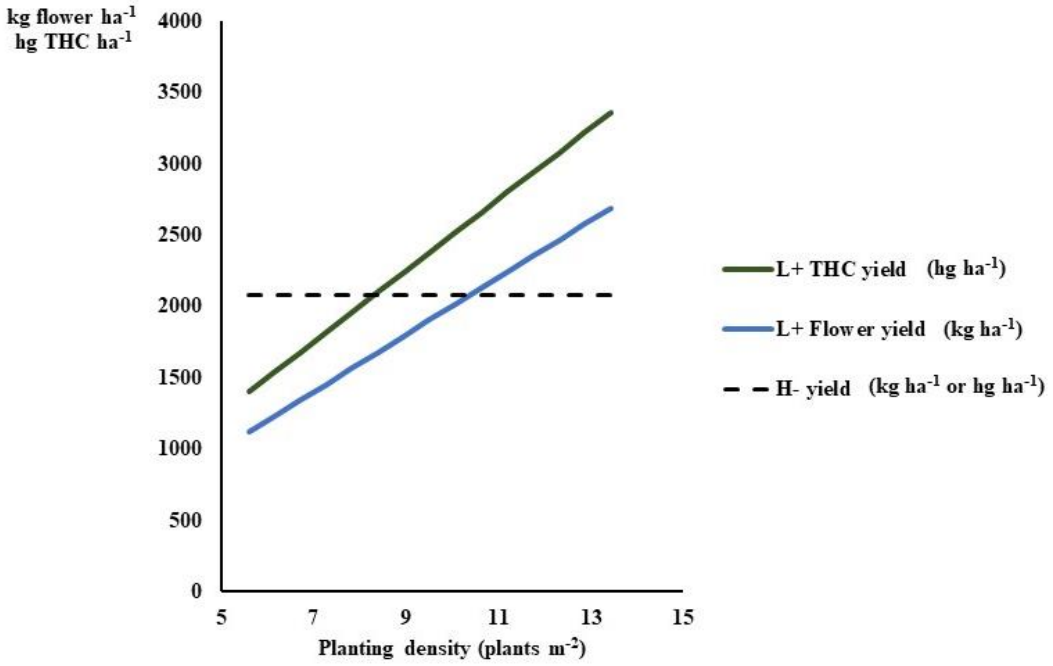


Figure 6.1: Planting density effect on area yield of flower and THC for a low N-fertilizer input compared to a high N-fertilizer input with fixed planting density. Modeling of a 1 ha field at varying planting density of cannabis plants under a L+ fertilizer regimen (low N and K:N ratio of 2) was made using values from experiment of Chapter 3. Planting density for H- (plants grown using a high N and a K:N ratio of 1) was fixed in the model.

The planting density required for the total field yield of L+ plants to equal the total field yield of a H- plants is 8.4 plants m^{-2} for THC and 10.6 plants m^{-2} for flower yield. In a field where no potting media is used, using a 10.6 plants m^{-2} would not increase the fertilizer demand for the field. Assuming no other horticultural input, it could be possible to have equal field yield and decrease GWP. Experiment 1 was able to show how using low-N fertilizer can sustainably increase flower and THC yield. Further investigation of the effect of planting density shows how this would not necessarily decrease total field yield. With these results, the next experiment tried to elucidate how low N, high K:N ratio fertilizer production could decrease environmental externalities in soil-less production.

6.2 Plant and Field Yield.

In addition to planting density, plant yield (g per plant) and subsequent field yield (kg ha^{-1}) used in the LCA from Chapter 5 were fixed at the start of the experiment based on relevant literature and industry communication. For the indoor production model, the plant density and yield were the same as previous literature using the same energy model. However, for the outdoor yield, a great range of values can be found in the literature. When comparing field yield values from outdoor production of cannabis from available scientific literature, Chapter 3 and 5, there is no clear consensus (Table 6.2).

Table 6.2: Summary of parameters with high potential for yield increase in outdoor cannabis production

Source of variation	plant density range (plant m^{-2})	Field yield range (kg ha^{-1})	Plant yield range (g per plant)	Ref
Fertilizer	5.2	707-2828	13.6-54.4	Chapter 3
Fertilizer	0.4	2941-3194	683-742	Darby et al. (2021a)
Fertilizer	0.4	2675-3230	621-750	Darby et al. (2021b)
Fertilizer	0.4	921-4151	263-1186	Bruce et al. (2022)
genotype	0.4	564-4796	131-1113	Darby et al. (2021)
genotype/ fertilizer	0.4-0.9	1254-6489	330-721	Farnisa et al. (2023)
Planting density	1.0-2.0	2215-2920	146-222	Danziger & Bernstein (2022)
Planting density	0.4-10.8	2129-24649	206-229	Darby et al. (2022)

Values seem to show that planting density and genotype could increase yield 10-fold, while fertilizer can only account for a 5-fold increase in outdoor production. Future studies addressing how use of a low N, high K:N ratio fertilizer recipe could be beneficial for increasing yield using an outdoor production with photoperiod sensitive phentoypes. There is also much potential for selection a genotype that would be productive, climate-hardy for northern latitudes found in Canada and responds positively to N-deficiency.

6.3 Energy Demand and Global Warming Potential Discrepancy

During the experiments of Chapter 3, drying was done by forced air using a 35-watt mechanical fan in an unheated shed. The scale of the harvest permitted this, and the moisture content of the biomass was efficiently brought down to the acceptable 12-15% moisture content before being sealed. This was possible because the outdoor temperature and humidity at harvest were adequate. However, in the event where the climatic parameters would not permit this, additional energy input would have been needed to efficiently dry the biomass.

The semi-passive technique used in the experiment, an unheated shed and with forced air drying using electrical fans, is unlikely to be doable at an industrial setting and scale. This is why the modeled drying parameter in Chapter 3 was based on the average kWh m^{-2} found in the literature for cannabis production. Hence, under these assumptions, drying of 1 kg of cannabis in Chapter 3 only necessitated around 120 kWh per kg of dried cannabis. It was also assumed that cannabis seedling production required similar energy and material than tomato seedling production.

However, in Chapter 5, the energy and material needed for drying and seedling production in the outdoor cannabis model used different assumptions. The drying and seedling production processes were approximated using a fraction (12%) of the total energy needed to produce 1kg of dried cannabis in the indoor plant-factory year long. This modeled furnishing an outdoor producer with material and energy for (1) cannabis seedlings to start the crop and (2) the drying process to cure the harvest. Based on available literature, it was assumed that, on average, 12% of the total floor area of indoor production is needed for seedling production and drying. Under these assumptions, 61 kWh of electrical energy and 3.7 GJ of natural gas energy was deemed necessary for the outdoor process.

The demand for natural gas alone, modeled in Chapter 5, adds around 275 kg CO_2-eq per kg of dried cannabis. Depending on provinces, the carbon footprint of electrical demand for the drying process would be between 1 and 100 kg CO_2-eq per kg.

The GWP of cannabis production could be reduced by:

- -Careful selection of drying infrastructure; where semi passive or electrical systems should be preferred, as it accounts for up to half of the GWP

- -Use of climate-hardy and high-yielding cultivar, would proportionally decrease GWP of all processes excluding the drying one.
- -Using locally sourced organic fertilizer, like the OLF in Chapter 4, where, if N_2O emissions are limited below 15% total gaseous N losses, could decrease up to 5% of the total GWP. This GWP reduction could be even high if using a cultivar that greatly increases cannabinoid production under N-deficiency

6.4 Limits of the Studies and Future Work

This case study being limited in time and resources, some decisions were made to simplify the modelization process and palliate the lack of data collection. Land use change was deemed outside of the scope of our study, as most production facilities visited during the research were using either abandoned warehouses retrofitted into controlled environment or unused agricultural land. However, for a project that would involve deforestation or changing the crop produced on an existing agricultural land, there would need to consider the destruction and rehabilitation of the land. In this case, outdoors production could potentially have greater impacts on ecosystem quality and human health and not necessarily be the clear winner of this comparison.

To assess whether these life cycle analyses are reliable, and representative of the goal and scope described earlier, a data quality assessment was conducted. (Table 6.3)

Table 6.3: Results of data quality assessment

Process	Reliability	Represent-ativeness	GWP Contribution	Comment
Potting media	4	2	1-75%	High priority for outdoor production. Needs to reassess if the assumption that potting media is needed in outdoor production.
HVAC system	3	3	10-50%	High priority - HVAC energy can highly vary between regions. The assumptions used here use a recent, peer-reviewed model.

Process	Reliability	Represent-ativeness	GWP Contribution	Comment
Electricity	4	4	10-25%	Intermediate priority - Eco Invent process is up to date, could be updated but trends would be similar.
Seedling	4	3	1-10%	Intermediate priority - Difference between tomato seedling and cannabis seedling could be very different depending on natural-gas use
Horticultural lighting	4	3	5-10%	High priority - Potential for LED to decrease the electrical demand, however, could offset the generated heat from HPS lamps.
Growth CO_2	3	4	5-10%	Intermediate priority – has sizeable consequence, could be eliminated via industrial symbiosis
Fertilizer	3	3	1-5%	Data from most recent agronomical studies were used. The assumption of 100% inorganic source could be revised but is still a very low contributor to total GWP of indoor.
Infrastructure	4	2	1-2%	Not included in any LCA, it was assumed to be

Process	Reliability	Represent-ativeness	GWP Contribution	Comment
				negligeable but could be reassessed.
Irrigation	3	3	<1%	Water use in the cannabis sector could be a problem in drier regions (Morrocco) or where water resources are limited (California), but was not assessed here.
Pesticide	4	2	<1%	Pesticide use in cannabis production in Canada is highly regulated and data from the US is not viable. Products used in Canada (canola oil and beneficial organism) probably have lower impacts than available Eco Invent process
Transport	3	3	<1%	Fuel consumption could be revised, but still a minor process compared to HVAC energy demand.

In addition to careful selection for cannabis genotype, future studies should target energy demanded by HVAC and lighting systems as well as supplemental CO_2 use for indoor production, as these are the three most contributing processes to GWP and other environmental externalities.

As previously mentioned, industrial symbiosis could be a very powerful strategy to mitigate the environmental externalities of indoor cannabis production while decrease the carbon footprint of other industries. Previous studies have looked at the impact of air change rate, which seems like an important parameter in reducing total energy demand

(Summers et al., 2021). Although reducing air change rate could have important implications in total humidity and disease incidence, especially fungal (Punja et al., 2019). Future studies could look at what is the minimum air change rate possible without increase disease incidence.

For outdoor production, environmental hotspots would be (1) potting media use, (2) energy demand for seedling production/curing and, to a lesser extent, (3) fertilizer production and use. Future studies should look at production efficiency of cannabis in soil agriculture to circumvent the need for potting media. There is still a lot of improvement possible when comparing with other agricultural crops.

The GWP of Canadian cannabis flowers varies widely, ranging from 60 to 5500 kg CO_2-eq per kg of flower. The emissions from outdoor-grown cannabis exceed those of outdoor-grown tomatoes by a staggering factor of 1200 (0.05 kg CO2-eq per kg of tomatoes) (Muñoz et al., 2008).

Direct comparisons with food are challenging since a kilogram of cannabis flower is not measured in terms of caloric value. However, direct comparison between a food product and a recreational product violates the functional reality of each. Comparing recreational cannabis with a food with recreational potential product like alcohol is more appropriate. For example, a 0.75 L unit of wine has a GWP of 2 kg CO_2-eq (Neto et al., 2013), which is significantly higher than one 0.5g joint of outdoor cannabis (0.03 kg CO2-eq) but comparable to one 0.5 g joint of indoor cannabis (0.75-1.5 kg CO_2-eq).

When looking at smokable herb product, such as tobacco, it is possible to set realistic goal for the cannabis industry. The emissions from outdoor cannabis surpass those of field-grown tobacco by at least 95 times (0.64 kg CO2-eq per kg of green tobacco) (Zafeiridou et al., 2018). Meaning that increase in productivity via fertilizer treatments, genetics, cropping practices and HVAC efficiency could realistically bring the GWP of outdoor cannabis down significantly.

However, normalizing by another FU, such as hours of altered consciousness for the recreational aspect, reveals that 1 unit of alcohol results in higher CO2-eq emissions (2 kg CO_2-eq) than 1 joint of outdoor cannabis (0.03 kg CO_2-eq) but is almost equivalent to 1 joint of indoor cannabis (0.75-1.5 kg CO_2-eq).

6.5 References

Bruce, D., Connelly, G., & Ellison, S. (2022). Different Fertility Approaches in Organic Hemp (*Cannabis sativa* L.) Production Alter Floral Biomass Yield but Not CBD:THC Ratio. Sustainability (Switzerland), 14(10). https://doi.org/10.3390/su14106222

Danziger, N., & Bernstein, N. (2022). Too Dense or Not Too Dense: Higher Planting Density Reduces Cannabinoid Uniformity but Increases Yield/Area in Drug-Type Medical Cannabis. Frontiers in Plant Science, 13. https://doi.org/10.3389/fpls.2022.713481

Darby, H., Bruce, J., Krezinski, I., Malone, R., & Ziegler, S. (2022). 2020 Hemp Flower Plant Spacing x Planting Date Trial. https://scholarworks.uvm.edu/nwcsp

Darby, H., Bruce, J., Krezinski, I., & Ruhl, L. (2021). Hemp Flower Variety Trial. https://scholarworks.uvm.edu/nwcsp/416/

Darby, H., Bruce, J., Lewins, S., & Ziegler, S. (2021a). Hemp Flower Combined Phosphorus-Potassium Fertility Trial. https://scholarworks.uvm.edu/nwcsp/419/

Darby, H., Bruce, J., Lewins, S., & Ziegler, S. (2021b). 2021 Hemp Flower Nitrogen Fertility Trial (Issue April). https://scholarworks.uvm.edu/nwcsp/417/

Farnisa, M. M., Miller, G. C., Solomon, J. K. Q., & Barrios-Masias, F. H. (2023). Floral Hemp (*Cannabis sativa* L.) Responses to Nitrogen Fertilization Under Field Conditions in the High Desert. PLoS ONE, 18(5 May). https://doi.org/10.1371/journal.pone.0284537

Muñoz, P.; Antón, A.; Nuñez, M.; Paranjpe, A.; Ariño, J.; Castells, X.; Montero, J. I.; Rieradevall, J. Comparing the Environmental Impacts of Greenhouse Versus Open-field Tomato Production in the Mediterranean Region. Acta Horticulturae. 2008, 801, 1591– 1596. https://doi.org/17660/ActaHortic.2008.801.197

Neto, B., Dias, A. C., Machado, M. (2013). Life Cycle Assessment of the Supply Chain of a Portuguese Wine: From Viticulture to Distribution. The International Journal of Life Cycle Assessment, 18, 590–602. http://dx.doi.org/10.1007/s11367-012-0518-4

Punja, Z. K., Collyer, D., Scott, C., Lung, S., Holmes, J., & Sutton, D. (2019). Pathogens and Molds Affecting Production and Quality of *Cannabis sativa* L. Frontiers in Plant Science, 10(1120), 1–23. https://doi.org/10.3389/fpls.2019.01120

Summers, H. M., Sproul, E., & Quinn, J. C. (2021). The Greenhouse Gas Emissions of Indoor Cannabis Production in the United States. Nature Sustainability, 4(7), 644–650. https://doi.org/10.1038/s41893-021-00691-w

Zafeiridou, M.; Hopkinson, N. S.; Voulvoulis, N. Cigarette Smoking: An Assessment of Tobacco's Global Environmental Footprint Across Its Entire Supply Chain. Environ. Sci. Technol. 2018, 52 (15), 8087– 8094. https://doi.org/10.1021/acs.est.8b01533

Chapter 7 : Conclusion and Summary

In conclusion, this thesis has aimed to evaluate the environmental implications of producing 1kg of cannabis flower in Canada. The findings indicate that indoor cultivation, which accounts for approximately half of the Canadian cannabis production, generates between 3000-5500 kg CO_2-eq, with HVAC energy consumption emerging as the primary contributor. Conversely, outdoor cultivation registers a significantly lower impact, at around 500 kg CO_2-eq on average.

These results surpass the findings of previous studies conducted in other regions, notably in the United States. The primary areas for potential enhancement lie in optimizing energy consumption and the efficiency of lighting and HVAC systems in indoor cultivation. It is imperative for governmental bodies to advocate for and incentivize reductions in these areas moving forward.

Furthermore, the adoption of a new Functional Unit (gram of THC) proves advantageous as the market landscape shifts, with edible products comprising nearly 50% of consumption in Canada. This shift highlights the importance of adapting assessment methodologies to reflect evolving consumer trends accurately.

In summary, this research underscores the urgent need for sustainable practices in cannabis cultivation, particularly within the indoor sector. By prioritizing energy efficiency improvements and embracing evolving market dynamics, stakeholders can mitigate the environmental footprint associated with cannabis production in Canada.

Appendix-A : Supplementary Material Chapter - 3

Supplementary Methods

Plant experiment: Photoperiod-sensitive cannabis can have a variable maturation period, and limited knowledge of an appropriate genotype for the study location was available at the time. Seeds were soaked for 16 h in tap water (0.3 EC, pH 7.2) then placed in a moist paper towel on a thermostat heating mat (Vivosun, Ontario, CA, US) set at 30 ℃. The paper towel was kept moist until the seeds had a 1 cm radicle. Pots were randomly rearranged after 1 month of growing, when soft mesh nylon trellis was put up to prevent branches from dropping to the ground and pots from toppling over during high wind event.

Cannabinoid analysis: Briefly, sample is ground and 1g is mixed with extraction solvent (methanol:Dichloromethane, 9:1). The sample was filtrated before injection in a high-performance liquid chromatography (HPLC). The column used is Kinetex 2.5 µM C18, 150 x 4.6 mm. The detector was a diode-array (DAD). Primary mobile phase is formic acid (0.1%) and secondary mobile phase is methanol:acetonitrile (75:25), 0.1 % formic acid. THCa, CBDa, CBGa, THC, CBD and CBG CAS numbers are 23987-85-0; 1244-58-2; 25555-57-1;1972-08-3; 13956-29-1; 25654-31-3 respectively.

LCA indicator choice rationale: Goal and scope: Climate change was chosen for N fertilizer's contribution to N_2O emissions, a gas with 298 times greater global warming potential than CO_2. Terrestrial acidification assessed the impact of NH_3, SO_2, and NO_x emissions. Eutrophication assessed the impact of post-application nitrate and phosphorus leaching as well as surface runoff. Fossil fuel depletion assessed the high energy-intensive production of N-containing fertilizers. Metal resource depletion is representative of K-fertilizer production.

LCA system boundary: This included the mining of raw materials, nutrient extraction, transportation of raw materials and pre-products, manufacturing of fertilizer products, transportation processes of final fertilizers to marketplaces, application of fertilizer, field operations, emissions immediately after fertilizer application in the field and drying of fresh biomass. Post-farm-gate impacts were not included in the study.

LCA data sources, assumptions and modeling details: To accurately model reusability of certain inputs (plastic pots and/or potting mix), it was assumed that the needed material to produce 1 FU was used for all the lifetime of the farm, modeled at 20 years. Plastics for pots and potting mix wrap were assumed to be low-density polypropylene (LDPE) pellets from China but molded in Montréal after being shipped by boat. Nylon twine was assumed to be produced in Europe, shipped to Montréal also by boat. Potting mix, consisting of peat, limestone, and perlite, was assumed to be produced in Trois-Rivières, Québec. To quantify the effect of on-site potting mix reuse, the use of an agricultural steamer and its associated diesel consumption were modeled 45–48. A 5 % yearly "top off" was added to model material wear and need for new input acquisition for potting mix and total stock renewal every 20 years.

NPK and KCl fertilizers were modeled to be shipped by train to Montréal from the US and Saskatchewan, respectively. All inputs were modeled to brought to the production site near Thetford Mines, Québec by light commercial vehicle. Both NPK and KCl fertilizer were assumed to be consumed completely on-site every year. Production of seedling was modeled as a tomato seedling in unheated greenhouse. Production was assumed to be made on 1 ha of land, with tractor used to deliver inputs to the field and transport harvested biomass to a drying shed. Average parameters for fuel use were used for the tractor 49.

Emission factors following fertilizer application was modeled as 1 % of total N for N_2O emission to air (IPCC, 2014), 21% of N_2O emission for NOx emission to air (Nemecek and Kägi, 2007), 4 % of total N for NH_4 emission to air (Nemecek and Kägi, 2007), 12% of total P for PO4 to water 50, 1 % of total N for NO_3 emission to water (Hasler et al., 2015) and CO_2 capture by plant growth was fixed as 50% of dried biomass. Drying was modeled after previous LCA studies on cannabis (Summers et al., 2021). All data sources are presented in Supplementary Table S3.1 (Appendix 2)

Availability of code, data and material Link to electronic supplementary material
https://github.com/VinceDebile/EnvImpactOutCanna

Supplementary Tables

Table S3.1: Summary of temperature, growing degree days (GDD), natural precipitation, average plant mass at harvest, planting and harvest date. Different letters in the same column indicate statistical significance ($p<0.05$)

Planting year	T_{max}	T_{min}	T_{avg}	GDD	Natural precipitation (mm)	Average plant mass	Planting date	Harvest date
2020	34	5	14.6	1018.9	275.1	201.6[b]	July 1st	Sep 8th
2021	30.2	-1.1	13.1	931.5	255.8	390.9[a]	May 18th	July 28th
2022	30.5	2	13	935.2	340.8	244.3[b]	May 20th	July 30th

Table S3.2: LCI and data source for model with and without on-site potting media reuse via steaming (1/4)

No on-site reuse of potting media

Functional Unit (FU)	kg flower		100g THC		EcoInvent Process
Trématent	H-	L+	H-	L+	
Water use (L/FU)	3.77E+03	7.46E+03	3.71E+03	6.17E+03	Irrigation, sprinkler | irrigation | Cutoff, U - CA-QC
Land use (m^2/FU)	1.46E+02	2.88E+02	1.43E+02	2.38E+02	NA
Peat (cm^3/FU)	2.18E+05	4.32E+05	2.15E+05	3.57E+05	Peat moss production, horticultural use | peat moss | Cutoff, U - CA-QC
Limestone (g/FU)	1.30E+03	2.57E+03	1.28E+03	2.13E+03	Limestone production, crushed, washed | limestone, crushed, washed | Cutoff, U - CA-QC
Perlite (g/FU)	1.23E+04	2.43E+04	1.21E+04	2.01E+04	Market for expanded perlite | expanded perlite | Cutoff, U - GLO
Plastic pots (g/FU)	2.73E+02	5.40E+02	2.68E+02	4.47E+02	Market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO
Plastic wrap (g/FU)	1.73E+02	3.43E+02	1.71E+02	2.84E+02	Market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO
Nylon (g/FU)	2.40E+01	4.74E+01	2.36E+01	3.93E+01	Nylon 6 production | nylon 6 | Cutoff, U
NPK fert (g /FU)	2.34E+03	1.27E+03	2.30E+03	1.05E+03	Market for NPK (15-15-15) fertiliser | NPK (15-15-15) fertiliser | Cutoff, U - RNA
KCl fert (g /FU)	0.00E+00	2.97E+02	0.00E+00	2.46E+02	Potassium mining and beneficiation | potassium chloride | Cutoff, U - CA-SK
Waste (g/FU)	2.39E+05	4.64E+05	2.35E+05	3.84E+05	Market for process-specific burdens, sanitary landfill | process-specific burdens, sanitary landfill | Cutoff, U - RoW
Seedlings (#/FU)	2.60E+01	5.14E+01	2.56E+01	4.26E+01	Tomato seedling production, in unheated greenhouse, for planting | tomato seedling, for planting | Cutoff, U - RoW
Srying kWh/FU	1.18E+02	1.18E+02	1.16E+02	9.78E+01	Electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - CA-QC
50 year life shed (m^2*a/FU)	1.00E-02	1.00E-02	1.00E-02	1.00E-02	Market for shed | shed | Cutoff, U - GLO
g N_2O to air (1% total N)	3.06E+00	1.65E+00	3.01E+00	1.37E+00	ID = 20185046-64bb-4c09-a8e7-e8a9e144ca98

Table S3.2: LCI and data source for model with and without on-site potting media reuse via steaming (2/4)

No on-site reuse of potting media

Functional Unit (FU)	kg flower		100g THC		EcoInvent Process
Treatment	H-	L+	H-	L+	
g NOx to air (21% of N_2O)	6.40E-01	3.50E-01	6.30E-01	2.90E-01	ID = c1b91234-6f24-417b-8309-46111d09c457
carbon fixation (50% of dry mass)	1.12E+03	9.16E+02	1.10E+03	7.58E+02	ID 7ae371aa-8532-11e0-9d78-0800200c9a66
g NH4 to air (0.2% total N)	1.22E+01	6.62E+00	1.20E+01	5.48E+00	ID = 87883a4e-1e3e-4c9d-90c0-f1bea36f8014
Phosphate to water (12% total P)	3.67E+01	1.99E+01	3.61E+01	1.64E+01	ID = c8791f3c-3c4a-4278-91c0-483797d14da2
g N-Nitrate to water (1% total N)	3.06E+00	1.65E+00	3.01E+00	1.37E+00	ID = 5189de76-6bbb-44ba-8c42-5714f1b4371f
Tractor (kg/FU)	9.00E-05	1.80E-04	9.00E-05	1.50E-04	Market for tractor, 4-wheel, agricultural | tractor, 4-wheel, agricultural | Cutoff, U - GLO
Diesel (MJ/FU)	1.60E-01	3.20E-01	1.60E-01	2.60E-01	diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO
Steamer (kg/FU)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Market for agricultural machinery, unspecified | agricultural machinery, unspecified | Cutoff, U - GLO
Total t*km (light vehicule)	3.54E+01	6.93E+01	3.48E+01	5.74E+01	Transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | Cutoff, U
Total t*km (train)	2.57E+00	2.26E+00	2.53E+00	1.87E+00	Market for transport, freight train | transport, freight train | Cutoff, U
Total t*km (boat)	5.52E+00	1.09E+01	5.43E+00	9.04E+00	Transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U
Molding (g/FU)	2.75E+02	5.43E+02	2.70E+02	4.49E+02	Injection moulding | injection moulding | Cutoff, U

Table S3.2: LCI and data source for model with and without on-site potting media reuse via steaming (3/4)

With on-site reuse of potting media

Functional Unit (FU)	kg flower		100g THC		EcoInvent Process
Treatment	H-	L+	H-	L+	
Water use (L/FU)	3.77E+03	7.46E+03	3.71E+03	6.17E+03	Irrigation, sprinkler | irrigation | Cutoff, U - CA-QC
Land use (m^2/FU)	1.46E+02	2.88E+02	1.43E+02	2.38E+02	
Peat (cm^3/FU)	2.18E+04	4.32E+04	2.15E+04	3.57E+04	Peat moss production, horticultural use | peat moss | Cutoff, U - CA-QC
Limestone (g/FU)	1.30E+02	2.57E+02	1.28E+02	2.13E+02	Limestone production, crushed, washed | limestone, crushed, washed | Cutoff, U - CA-QC
Perlite (g/FU)	1.23E+03	2.43E+03	1.21E+03	2.01E+03	Market for expanded perlite | expanded perlite | Cutoff, U - GLO
Plastic pots (g/FU)	2.73E+02	5.40E+02	2.68E+02	4.47E+02	Market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO
Plastic wrap (g/FU)	1.73E+01	3.43E+01	1.71E+01	2.84E+01	Market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO
Nylon (g/FU)	2.40E+01	4.74E+01	2.36E+01	3.93E+01	Nylon 6 production | nylon 6 | Cutoff, U
NPK fert (g /FU)	2.34E+03	1.27E+03	2.30E+03	1.05E+03	Market for NPK (15-15-15) fertiliser | NPK (15-15-15) fertiliser | Cutoff, U - RNA
KCl fert (g /FU)	0.00E+00	2.97E+02	0.00E+00	2.46E+02	Potassium mining and benefication | potassium chloride | Cutoff, U - CA-SK
Waste (g/FU)	2.99E+04	5.06E+04	2.94E+04	4.19E+04	Market for process-specific burdens, sanitary landfill | process-specific burdens, sanitary landfill | Cutoff, U - RoW
Seedlings (#/FU)	2.60E+01	5.14E+01	2.56E+01	4.26E+01	Tomato seedling production, in unheated greenhouse, for planting | tomato seedling, for planting | Cutoff, U - RoW
Drying kWh/FU	1.18E+02	1.18E+02	1.16E+02	9.78E+01	Electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - CA-QC

Table S3.2: LCI and data source for model with and without on-site potting media reuse via steaming (4/4)

With on-site reuse of potting media

Functional Unit (FU)	kg flower		100g THC		EcoInvent Process
Treatment	H-	L+	H-	L+	
50 year life shed (m2*a/FU)	1.00E-02	1.00E-02	1.00E-02	1.00E-02	Market for shed | shed | Cutoff, U - GLO
g N_2O to air (1% total N)	3.06E+00	1.65E+00	3.01E+00	1.37E+00	ID = 20185046-64bb-4c09-a8e7-e8a9e144ca98
Carbon fixation (50% of dry mass)	1.12E+03	9.16E+02	1.10E+03	7.58E+02	ID 7ae371aa-8532-11e0-9d78-0800200c9a66
g Nox to air (21% of N_2O)	6.40E-01	3.50E-01	6.30E-01	2.90E-01	ID = c1b91234-6f24-417b-8309-46111d09c457
g NH_4 to air (0.2% total N)	1.22E+01	6.62E+00	1.20E+01	5.48E+00	ID = 87883a4e-1e3e-4c9d-90c0-f1bea36f8014
phosphate to water	3.67E+01	1.99E+01	3.61E+01	1.64E+01	ID = c8791f3c-3c4a-4278-91c0-483797d14da2
g N-Nitrate to	3.06E+00	1.65E+00	3.01E+00	1.37E+00	ID = 5189de76-6bbb-44ba-8c42-5714f1b4371f
Tractor (kg/FU)	9.00E-05	1.80E-04	9.00E-05	1.50E-04	Market for tractor, 4-wheel, agricultural | tractor, 4-wheel, agricultural | Cutoff, U - GLO
Diesel (MJ/FU)	2.93E+02	5.80E+02	2.88E+02	4.80E+02	Diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO
Steamer (kg/FU)	8.00E-02	1.60E-01	8.00E-02	1.30E-01	Market for agricultural machinery, unspecified | agricultural machinery, unspecified | Cutoff, U - GLO
Total t*km (light vehicule)	4.11E+00	7.37E+00	4.05E+00	6.10E+00	Transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | Cutoff, U
Total t*km (train)	2.57E+00	2.26E+00	2.53E+00	1.87E+00	Market for transport, freight train | transport, freight train | Cutoff, U
Total t*km (boat)	5.52E+00	1.09E+01	5.43E+00	9.04E+00	Transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U
Molding (g/FU)	2.75E+02	5.43E+02	2.70E+02	4.49E+02	Injection moulding | injection moulding | Cutoff, U

Table S3.3: Significance of the effects of treatment, sampling year and their interactions on cannabis flower cannabinoid content and leaf N content based on ANOVAs.

Source	Fresh mass total	Flower Yield	Plant height	Flower Total THC content (%)	g THC per plant	Leaf N content	NUE	CPE_N
Year	24.2048***	11.0179***	24.6923***	2.0554	16.9272**	38.37**	20.1805***	25.4826***
Treatment	14.1475***	14.2166***	7.7473***	27.2445**	18.0866**	87.227**	4.9073**	20.0611***
Year*Treatment	2.6822*	1.4779	2.3221*	30.827**	5.5449*	8.613**	2.0552	12.548***

Total THC is the sum of neutral and acid forms. NUE stands for *N* use efficiency and CPE_N stands for cannabinoid production efficiency of *N*. Numbers are F-values. Asterisks indicate the level of significance (*p<0.05, **p<0.001, ***p<0.0001).

Table S3.4: Nutrient content measured in pour-through analysis for the year 2021. See Wright (1986) for details on the procedure. N.D. stands for non-detectable.

Treatment	June		July	
	Ammonia (NH_3/NH_4-N mg L^{-1})	Nitrate-N (mg L^{-1})	Ammonia (NH_3/NH_4-N mg L^{-1})	Nitrate-N (mg L^{-1})
H-	484.04	213.7	N.D.	60.2
H+	429.63	238.7	N.D.	54.4
M-	364.06	72.0	N.D.	4.3
M+	368.37	72.7	N.D.	5.0
L-	59.36	58.3	N.D.	16.2
L+	57.07	53.0	N.D.	13.6

Table S3.5: Main processes contribution to global warming potential of outdoor cannabis plant with or without on-site potting media reuse at varying fertilizer treatment. (1/2)

GWP FU: 100g THC, on-site reuse of potting media	H-		GWP, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg CO_2-Eq]	Process	Contribution [%]	Total result [kg CO_2-Eq]	Contribution [%]	Total result [kg CO_2-Eq]
Full outdoor production	100.0	52.65	Full outdoor production	100.0	60.75	100.00	91.68
Outdoor drying of fresh cannabis flower	100.0	52.65	Outdoor drying of fresh cannabis flower	100.0	60.75	100.00	91.68
Outdoor growing of fresh cannabis flower	89.7	47.23	Outdoor growing of fresh cannabis flower	91.1	55.33	95.00	87.11
Outdoor tractor and steamer production and use	68.2	35.93	Outdoor Horticultural practice	70.6	42.92	77.90	71.43
Diesel, burned in agricultural machinery	67.5	35.53	Peat moss production, horticultural use	45.0	27.32	49.60	45.47
market for agricultural machinery, unspecified	0.8	0.40	Expanded perlite production	23.3	14.13	25.70	23.52
Market for tractor, 4-wheel, agricultural	0.0	0.00	Polyethylene production, low density, granulate	1.8	1.07	1.93	1.77
Outdoor Horticultural practice	9.9	5.24	Market for nylon 6 | nylon 6 | Cutoff, U - RER	0.4	0.22	0.40	0.37
Peat moss production, horticultural use	5.2	2.73	Irrigation, sprinkler | irrigation | Cutoff, U - CA-QC	0.3	0.18	0.32	0.29
Expanded perlite production	2.7	1.41	Limestone production, crushed, washed	0.0	0.00	0.01	0.01
polyethylene production, low density, granulate	1.3	0.69	Transport and molding	10.2	6.18	11.00	10.06
Market for nylon 6 | nylon 6 | Cutoff, U - RER	0.4	0.22	market for transport, freight, lorry 16-32 metric ton	9.6	5.85	10.50	9.65
Irrigation, sprinkler | irrigation | Cutoff, U - CA-QC	0.3	0.18	Transport, freight train, diesel	0.2	0.14	0.12	0.11
Limestone production, crushed, washed	0.0	0.00	Injection moulding | injection moulding	0.2	0.14	0.25	0.23

Table S3.5: Main processes contribution to global warming potential of outdoor cannabis plant with or without on-site potting media reuse at varying fertilizer treatment. (2/2)

GWP FU: 100g THC, on-site reuse of potting media	H-		GWP, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg CO_2-Eq]	Process	Contribution [%]	Total result [kg CO_2-Eq]	Contribution [%]	Total result [kg CO_2-Eq]
Outdoor fertilizing	7.5	3.93	Transport, freight, sea, container ship	0.1	0.05	0.09	0.08
NPK (15-15-15) fertiliser production	5.8	3.04	Outdoor fertilizing	6.5	3.93	2.01	1.84
tomato seedling production, in unheated greenhouse,	1.9	1.01	NPK (15-15-15) fertiliser production	5.0	3.04	1.51	1.38
Transport and molding	1.8	0.96	Potassium mining and benefication | potassium chloride	NA	NA	0.05	0.05
market for process-specific burdens, sanitary landfill	0.3	0.16	Market for process-specific burdens, sanitary landfill	2.1	1.26	2.25	2.06
Market for electricity, low voltage	5.7	3.00	Tomato seedling production, in unheated greenhouse,	1.7	1.01	1.84	1.68
Market for shed | shed |	4.6	2.43	Outdoor tractor and steamer production and use	0.0	0.02	0.04	0.03
			Market for electricity, low voltage | electricity, low voltage	4.9	3.00	2.75	2.52
			Market for shed | shed | Cutoff, U - GLO	4.0	2.43	2.23	2.04

Table S3.6: Main processes contribution to fossil fuel depletion of outdoor cannabis plant with or without on-site potting media reuse at varying fertilizer treatment.

Fossil fuel depletion, FU: 100g THC, on-site reuse of potting media	H-		Fossil fuel depletion, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg oil-Eq]	Process	Contribution [%]	Total result [kg oil-Eq]	Contribution [%]	Total result [kg oil-Eq]
Full outdoor production	1.00E+02	1.45E+01	Full outdoor production	1.00E+02	9.04E+00	1.00E+02	1.33E+01
Outdoor drying of fresh cannabis flower	1.00E+02	1.45E+01	Outdoor drying of fresh cannabis flower	1.00E+02	9.04E+00	1.00E+02	1.33E+01
Outdoor growing of fresh cannabis flower	9.43E+01	1.36E+01	Outdoor growing of fresh cannabis flower	9.08E+01	8.21E+00	9.47E+01	1.26E+01
Outdoor tractor and steamer production and use	7.83E+01	1.13E+01	Outdoor Horticultural practice	5.18E+01	4.68E+00	5.87E+01	7.78E+00
Diesel, burned in agricultural machinery |	7.75E+01	1.12E+01	Expanded perlite production	3.95E+01	3.57E+00	4.47E+01	5.94E+00
Market for agricultural machinery, unspecified |	7.50E-01	1.08E-01	Polyethylene production, low density, granulate	9.39E+00	8.48E-01	1.06E+01	1.41E+00
Market for tractor, 4-wheel, agricultural	0.00E+00	2.24E-04	Peat moss production, horticultural use	1.44E+00	1.31E-01	1.64E+00	2.20E-01
Outdoor Horticultural practice	7.26E+00	1.05E+00	Market for nylon 6 | nylon 6 | Cutoff, U - RER	7.80E-01	7.06E-02	8.90E-01	1.20E-01
Outdoor fertilizing	5.83E+00	8.44E-01	irrigation, sprinkler | irrigation | Cutoff, U - CA-QC	6.60E-01	5.95E-02	7.50E-01	1.00E-01
Transport and molding	2.45E+00	3.55E-01	Limestone production, crushed, washed	2.00E-02	1.50E-03	2.00E-02	0.00E+00
Market for process-specific burdens, sanitary landfill	3.50E-01	5.13E-02	Transport and molding	2.50E+01	2.25E+00	2.77E+01	3.68E+00
Tomato seedling production, in unheated greenhouse,	1.10E-01	1.53E-02	Outdoor fertilizing	9.34E+00	8.44E-01	3.03E+00	4.00E-01
Market for shed | shed | Cutoff, U - GLO	3.43E+00	0.49709	Market for process-specific burdens, sanitary landfill	4.53E+00	4.10E-01	5.05E+00	6.70E-01
Market for electricity, low voltage	2.30E+00	3.33E-01	Tomato seedling production, in unheated greenhouse	1.70E-01	1.53E-02	1.90E-01	3.00E-02
			Outdoor tractor and steamer production and use	7.00E-02	6.40E-03	8.00E-02	1.00E-02
			Market for shed | shed | Cutoff, U - GLO	5.50E+00	4.97E-01	3.16E+00	4.20E-01
			Market for electricity, low voltage |	3.68E+00	3.33E-01	2.11E+00	2.80E-01

Table S3.7: Main processes contribution to terrestrial acidification of outdoor cannabis plant with or without on-site potting media reuse

Terrestrial acidification, FU: 100g THC, on-site reuse of potting media	H-		Terrestrial acidification, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg SO_2-Eq]	Process	Contribution [%]	Total result [kg SO_2-Eq]	Contribution [%]	Total result [kg SO_2-Eq]
Full outdoor production	1.00E+02	3.16E-01	Full outdoor production	1.00E+02	1.82E-01	1.00E+02	2.33E-01
Outdoor drying of fresh cannabis flower	1.00E+02	3.16E-01	Outdoor drying of fresh cannabis flower	1.00E+02	1.82E-01	1.00E+02	2.33E-01
Outdoor growing of fresh cannabis flower	9.40E+01	2.97E-01	Outdoor growing of fresh cannabis flower	8.96E+01	1.63E-01	9.32E+01	2.17E-01
Outdoor tractor and steamer production and use	7.45E+01	2.35E-01	Outdoor Horticultural practice	5.17E+01	9.38E-02	6.71E+01	1.56E-01
Diesel, burned in agricultural machinery	7.40E+01	2.34E-01	Expanded perlite production | expanded perlite	4.75E+01	8.61E-02	6.16E+01	1.43E-01
Market for agricultural machinery, unspecified	5.10E-01	1.61E-03	Polyethylene production, low density, granulate	1.98E+00	3.60E-03	2.57E+00	5.98E-03
Market for tractor, 4-wheel, agricultural	0.00E+00	3.48E-06	Peat moss production, horticultural use	1.32E+00	2.40E-03	1.71E+00	3.99E-03
Outdoor fertilizing	1.37E+01	4.34E-02	Irrigation, sprinkler | irrigation | Cutoff, U - CA-QC	5.50E-01	1.00E-03	7.20E-01	1.67E-03
Outdoor Horticultural practice	4.07E+00	1.29E-02	Market for nylon 6 | nylon 6 | Cutoff, U - RER	3.60E-01	6.53E-04	4.70E-01	1.09E-03
Transport and molding	1.34E+00	4.25E-03	Limestone production, crushed, washed	2.00E-02	3.63E-05	3.00E-02	7.30E-05
Market for process-specific burdens, sanitary landfill	3.60E-01	1.12E-03	Outdoor fertilizing	2.39E+01	4.34E-02	8.60E+00	2.00E-02
Tomato seedling production, in unheated greenhouse	7.00E-02	2.33E-04	Transport and molding	8.89E+00	1.61E-02	1.10E+01	2.56E-02
Market for shed | shed | Cutoff, U - GLO	3.41E+00	1.08E-02	Market for process-specific burdens, sanitary landfill	4.95E+00	8.98E-03	6.30E+00	1.47E-02
Market for electricity, low voltage	2.56E+00	8.08E-03	Tomato seedling production, in unheated greenhouse	1.30E-01	2.36E-04	1.70E-01	3.89E-04
			Outdoor tractor and steamer production and use	7.00E-02	1.27E-04	9.00E-02	2.16E-04
			Market for shed | shed | Cutoff, U - GLO	5.94E+00	1.08E-02	3.90E+00	9.07E-03
			Market for electricity, low voltage	4.45E+00	8.10E-03	2.92E+00	6.81E-03

Table S3.8: Main processes contribution to marine and freshwater eutrophication potential of outdoor cannabis plant with or without on-site potting media reuse (1/2)

Freshwater eutrophication potential, FU: 100g THC, on-site reuse of potting media	H-		Freshwater eutrophication potential, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg P-Eq]	Process	Contribution [%]	Total result [kg P-Eq]	Contribution [%]	Total result [kg P-Eq]
Full outdoor production	1.00E+02	2.00E-02	Full outdoor production	1.00E+02	1.90E-02	1.00E+02	1.50E-02
Outdoor drying of fresh cannabis flower	1.00E+02	2.00E-02	Outdoor drying of fresh cannabis flower	1.00E+02	1.90E-02	1.00E+02	1.50E-02
Outdoor growing of fresh cannabis flower	9.40E+01	1.88E-02	Outdoor growing of fresh cannabis flower	9.36E+01	1.80E-02	9.33E+01	1.40E-02
Outdoor fertilizing	6.22E+01	1.24E-02	Outdoor fertilizing	6.64E+01	1.20E-02	3.77E+01	6.00E-03
Outdoor tractor and steamer production and use	2.80E+01	5.60E-03	Outdoor Horticultural practice	2.36E+01	4.00E-03	4.86E+01	7.00E-03
Outdoor Horticultural practice	3.16E+00	6.32E-04	Transport and molding	2.57E+00	0.00E+00	5.13E+00	1.00E-03
Transport and molding	3.90E-01	7.88E-05	Market for process-specific burdens, sanitary landfill	8.20E-01	0.00E+00	1.65E+00	0.00E+00
Market for process-specific burdens, sanitary landfill	1.00E-01	1.92E-05	Tomato seedling production, in unheated greenhouse	1.00E-01	0.00E+00	2.00E-01	0.00E+00
Tomato seedling production, in unheated greenhouse, for planting	9.00E-02	1.85E-05	Outdoor tractor and steamer production and use	2.00E-02	0.00E+00	4.00E-02	0.00E+00
Market for shed | shed | Cutoff, U - GLO	3.94E+00	7.87E-04	Market for shed | shed | Cutoff, U - GLO	4.21E+00	1.00E-03	4.38E+00	1.00E-03
Market for electricity, low voltage	2.08E+00	4.17E-04	Market for electricity, low voltage	2.23E+00	0.00E+00	2.32E+00	0.00E+00

Table S3.8: Main processes contribution to marine and freshwater eutrophication potential of outdoor cannabis plant with or without on-site potting media reuse (2/2)

Marine eutrophication potential, FU: 100g THC, on-site reuse of potting media	H-		Marine eutrophication potential, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg N-Eq]	Process	Contribution [%]	Total result [kg N-Eq]	Contribution [%]	Total result [kg N-Eq]
Full outdoor production	1.00E+02	1.92E-02	Full outdoor production	1.00E+02	9.30E-03	1.00E+02	1.01E-02
Outdoor drying of fresh cannabis flower	1.00E+02	1.92E-02	Outdoor drying of fresh cannabis flower	1.00E+02	9.30E-03	1.00E+02	1.01E-02
Outdoor growing of fresh cannabis flower	9.22E+01	1.77E-02	Outdoor growing of fresh cannabis flower	8.39E+01	7.80E-03	8.74E+01	8.81E-03
Outdoor tractor and steamer production and use	7.02E+01	1.35E-02	Outdoor fertilizing	3.68E+01	3.40E-03	1.57E+01	1.58E-03
Diesel, burned in agricultural machinery	6.97E+01	1.34E-02	Outdoor Horticultural practice	3.45E+01	3.20E-03	5.32E+01	5.36E-03
Market for agricultural machinery, unspecified	4.10E-01	7.96E-05	Expanded perlite production | expanded perlite	2.99E+01	2.80E-03	4.61E+01	4.64E-03
Market for tractor, 4-wheel, agricultural	0.00E+00	1.46E-07	Polyethylene production, low density, granulate	1.82E+00	1.69E-04	2.80E+00	2.83E-04
Outdoor fertilizing	1.79E+01	3.43E-03	Peat moss production, horticultural use	1.44E+00	1.34E-04	2.22E+00	2.24E-04
Outdoor Horticultural practice	2.75E+00	5.28E-04	Market for nylon 6 | nylon 6 | Cutoff, U - RER	8.80E-01	8.18E-05	1.36E+00	1.37E-04
Transport and molding	9.60E-01	1.84E-04	Irrigation, sprinkler | irrigation | Cutoff, U - CA-QC	4.60E-01	4.28E-05	7.10E-01	7.19E-05
Market for process-specific burdens, sanitary landfill	3.40E-01	6.59E-05	Limestone production, crushed, washed	3.00E-02	2.79E-06	4.00E-02	4.26E-06
Tomato seedling production, in unheated greenhouse	7.00E-02	1.40E-05	Transport and molding	6.73E+00	6.26E-04	9.66E+00	9.73E-04
Market for shed | shed | Cutoff, U - GLO	5.85E+00	1.12E-03	Market for process-specific burdens, sanitary landfill	5.64E+00	5.25E-04	8.55E+00	8.61E-04
Market for electricity, low voltage	2.00E+00	3.84E-04	Tomato seedling production, in unheated greenhouse	1.50E-01	1.40E-05	2.30E-01	2.33E-05
			Outdoor tractor and steamer production and use	8.00E-02	7.44E-06	1.20E-01	1.23E-05
			Market for shed | shed | Cutoff, U - GLO	1.20E+01	1.12E-03	9.38E+00	9.45E-04
			Market for electricity, low voltage	4.11E+00	3.82E-04	3.20E+00	3.23E-04

Table S3.9: Main processes contribution to metal depletion potential of outdoor cannabis plant with or without on-site potting media reuse

Metal depletion, FU: 100g THC, on-site reuse of potting media	H-		Metal depletion, FU 100g THC, without on-site reuse of potting media	H-		L+	
Process	Contribution [%]	Total result [kg Fe-Eq]	Process	Contribution [%]	Total result [kg Fe-Eq]	Contribution [%]	Total result [kg Fe-Eq]
Full outdoor production	1.00E+02	3.29E+00	Full outdoor production	1.00E+02	1.41E+00	1.00E+02	1.54E+00
Outdoor drying of fresh cannabis flower	1.00E+02	3.29E+00	Outdoor drying of fresh cannabis flower	1.00E+02	1.41E+00	1.00E+02	1.54E+00
Outdoor growing of fresh cannabis flower	7.77E+01	2.56E+00	Outdoor growing of fresh cannabis flower	4.80E+01	6.77E-01	5.99E+01	9.25E-01
Outdoor tractor and steamer production and use	6.89E+01	2.27E+00	Outdoor Horticultural practice	2.48E+01	3.50E-01	3.77E+01	5.82E-01
Diesel, burned in agricultural machinery	6.60E+01	2.17E+00	Outdoor fertilizing	1.18E+01	1.66E-01	5.61E+00	8.66E-02
Market for agricultural machinery, unspecified	2.93E+00	9.66E-02	Transport and molding	9.51E+00	1.34E-01	1.38E+01	2.12E-01
Market for tractor, 4-wheel, agricultural	0.00E+00	1.61E-04	Market for process-specific burdens, sanitary landfill	1.71E+00	2.41E-02	2.55E+00	3.94E-02
Outdoor fertilizing	5.05E+00	1.66E-01	Outdoor tractor and steamer production and use	1.00E-01	1.40E-03	1.40E-01	2.23E-03
Outdoor Horticultural practice	2.82E+00	9.27E-02	Tomato seedling production, in unheated greenhouse	9.00E-02	1.30E-03	1.40E-01	2.12E-03
Transport and molding	8.30E-01	2.73E-02	Market for shed | shed | Cutoff, U - GLO	3.01E+01	4.25E-01	2.32E+01	3.58E-01
Market for process-specific burdens, sanitary landfill	9.00E-02	3.01E-03	Market for electricity, low voltage	2.19E+01	3.09E-01	1.68E+01	2.60E-01
Tomato seedling production, in unheated greenhouse	4.00E-02	1.28E-03					
Market for shed | shed | Cutoff, U - GLO	1.29E+01	4.25E-01					
Market for electricity, low voltage	9.38E+00	3.09E-01					

-

Supplementary Figure

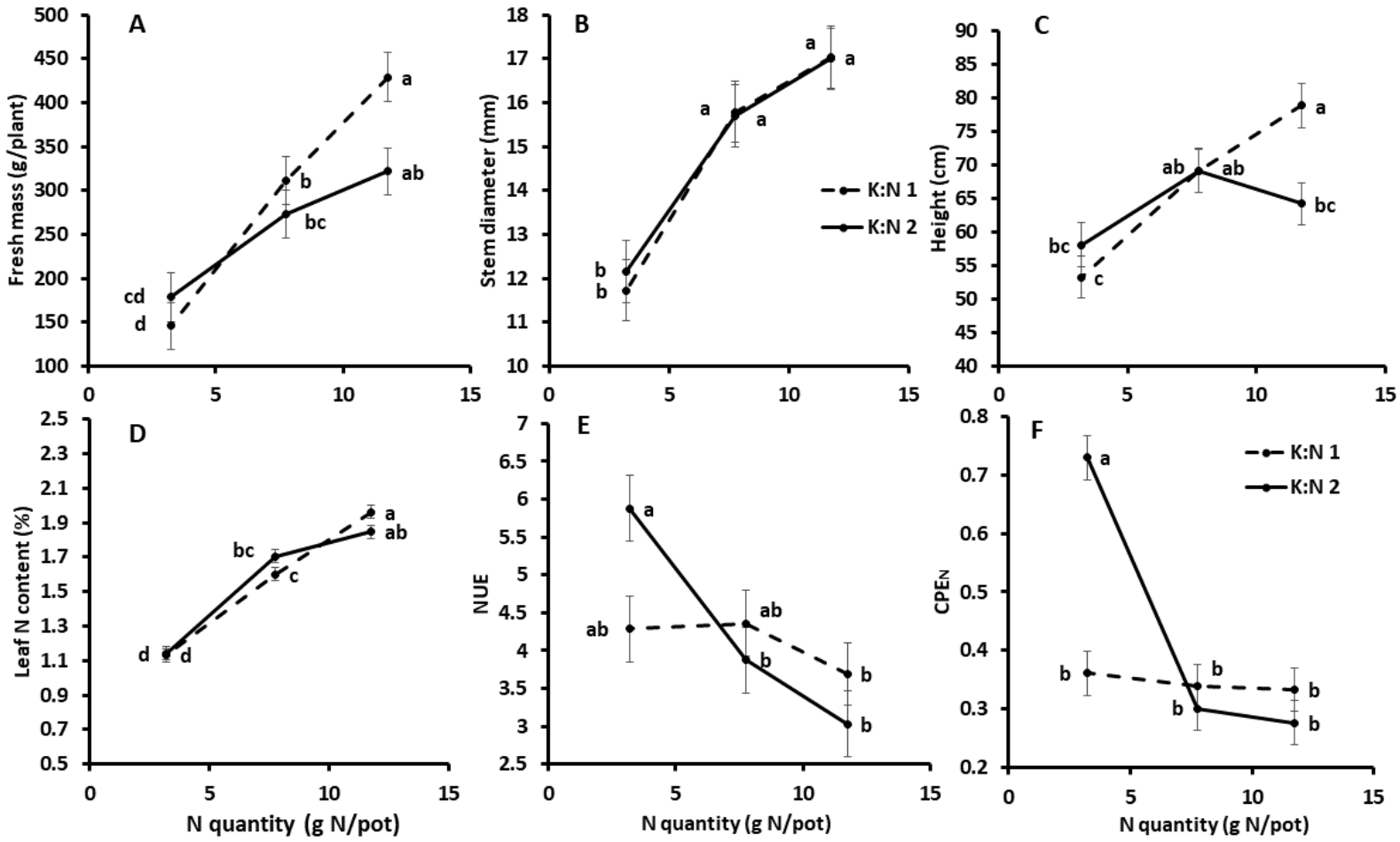


Figure S3.1: Effect of fertilizer N-level and K:N ratio on cannabis plants.
Cannabis fresh mass (A), stem diameter (B), height (C), leaf N content (D), plant nitrogen use efficiency (NUE) as dry flower yield over N-input (E) and cannabinoid production efficiency of nitrogen (CPE_N) (F). Dashed lines are for treatment with a K:N ratio of 1 and continuous lines are for treatment with a K:N ratio of 2. Data are presented as LSmeans ± SE of plants harvested between 2020-2022 for A-B-C (n=15-16). ± SE of plants harvested between 2021-2022 for D-E-F (n=10-11). Different letters represent significant difference between treatment by Tukey HSD at α=0.05

Appendix-B: Supplementary Material Chapter – 4 - Supplementary Methods

Greenhouse experiment parameters

Relative humidity was not controlled and fluctuate daily between ~25-65%. Sun irradiance was the main source of lighting and T-5 fluorescent light bulbs (SunBlaster Holdings ULC, Langley, Canada) were set to provide an 18:6 photoperiod throughout the experiment. Sunlight intensity fluctuated between the 3 time-separated blocks. Average PPFD measured at noon were equal to 200 ± 25, 104 ± 10 and 55 ± 5 μmol m^{-2} s^{-1}. PPFD values were measured similarly to the CE experiment with a spherical underwater quantum sensor (LI-193, LI-COR, Lincoln, USA).

Basil seed germination

During this period, light for seedling germination and early growth was provided by LED lights (UV 13W V-01 RoHS 20-12) placed above seed trays. After this period, seedlings were transplanted into 4-inch mesh pots filled with clay pebbles that were pre-soaked in a 1M KOH solution (pH = 5.5) for a 24-h period prior to experimentation.

Inorganic fertilizer solution preparation

At each location, the inorganic fertilizer solution was prepared by mixing macronutrient fertilizer salt ($CaNO_3$, KNO_3, $MgSO_4$ and K_2PO_4) with water available on-site: municipal treated water in the controlled environment (CE) and untreated well water in the greenhouse (GH) location. The targeted electrical conductivity (EC) for the CE location was 1.8 and 2.4 for the GH location. Difference in EC in the GH location was to accommodate the on-going economical operations.

Each location would first prepare 180L of fertilizer solution. When preparing 180L of inorganic fertilizer solution in the CE location, masses of fertilizer salts dissolved in water were 68.2g of KNO_3, 159.4g of $CaNO_3$, 66.6g $MgSO_4$ and 18.4g of KH_2PO_4 (targeted EC 1.8 mS cm^{-1}). When preparing 180L of inorganic fertilizer solution in the GH location, masses of fertilizer salts dissolved in water were 91.0 of KNO_3, 212.5g of $CaNO_3$, 88.7g $MgSO_4$ and 24.5g of KH_2PO_4. (targeted EC 2.4 mS cm^{-1}). Once macronutrient fertilizer salts were completely dissolved, micronutrient solution containing 2.86 mg L^{-1} H_3BO_3, 2.17 mg L^{-1} $MnSO_4$, 0.13 mg L^{-1} ZnS, 0.08 mg L^{-1} $CuSO_4$, 0.12 mg L^{-1} Na_2MoO_4, 5.57 mg L^{-1} $FeSO_4$ and 7.45 mg L^{-1} of NaEDTA added at a rate of 0.75 mL L^{-1} or 135 mL for the whole 180L. After that, pH was adjusted to 6.2-6.3 using 17% H_3PO_4 solution with exact volume depending on initial pH which was monitored with a handheld pH/EC meter (HI 9813-61, Hanna, Laval, QC, Canada).

From the 180L of freshly prepared solution, 60L would be transferred to another reservoir for the OLF+ treatment: a half and half mixture of inorganic nutrient solution and organic liquid fertilizer (OLF).

ISE monitoring

Additionally, ion-selective electrodes (ISE) were used to monitor NH_3/NH_4^+, NO_3^-, electrical conductivity (EC) and pH fluctuations during the process (NH_4^+ ISE BNC, Vernier, ON, Canada; NO_3 ISE BNC, Vernier, ON, Canada; pH probe ENV-40-pH, Atlas Scientific, NY, US; Conductivity Probe K 10, ENV-40-EC-K10, Atlas Scientific, NY, US). ISE readings were amplified, processed, and compiled using Arduino Uno boards (Adafruit, New York, USA), Raspberry Pi 3 B+ (Raspberry Pi Foundation, UK) and Tentacle Shields (Atlas Scientific, NY, US). Calibration solution was used to increase NH_3/NH_4^+, and NO_3 concentration calculation accuracy.

Controlled environment experiment nutrient solutions

OLF was brewed on-site using insect frass from a local insect producer with the same method described in section 2.3.3. All solutions had a pH of 5.5–6.5, controlled by the addition of

phosphoric acid (17% H_3PO_4). EC at the start of the experiment was 1.8-1.9 mS cm^{-1} for all 3 solutions. EC and pH were monitored with a handheld pH/EC meter (HI 9813-61, Hanna, Laval, QC, Canada). Nutrient solution volume was maintained by adding tap water.

Elemental analysis

Freshly made nutrient solution, bioreactor solutions, spent fertilizer solution, representative samples of manure input and aerial biomass samples for each treatment were analyzed for elemental composition. Samples were sent to a third-party lab (A&L Laboratory, London, ON, Canada) for elemental analysis. Metals were analyzed by acid digestion (ICP-OES Ref. EPA3050B/EPA6010B). NO_3^+ was measured by colorimetric dosage (Standard Methods 4500-NO3-F automated cadmium reduction method), total N by combustion/thermal conductivity (Dumas method), and chloride by K2SO4 extraction with the standard method 4500-Cl-G mercuric thiocyanate flow injection analysis. Samples were collected from 2020 to 2021.

Statistical analysis

All data analyses were carried out with the JMP software Version 14.1 (SAS Institute, Cary, NC, US). Assumption for normal distribution and homoscedasticity were tested using Shapiro-Wilk test and Levene's test respectively. Data collected was first scanned for outliers using the extreme studentized deviate (ESD) method to exclude significant outliers. One outlier was detected in the GH experiment. Outliers were not included in subsequent tests.

For nutrient solution Tukey's Honestly Significant Difference (HSD) post-hoc test was used to group significantly different least-square means (LSmeans). If a value was below limit of quantification (LOQ), it was substituted by half of the LOQ value.

For CE harvest data if a significant effect was observed, Tukey HSD test ($\alpha = 0.05$) was performed for multiple comparisons among nutrient solution treatment. Averages for treatments were reported as LSMeans with 95% confidence intervals calculated from linear models.

For GH harvest data the model had 3 fixed effects: nutrient solution, harvest month and cut number. One random effect was added: individual plant. Harvest month was classified as a fixed parameter because in a semi-controlled environment greenhouse, environmental parameters should be similar at the same time of year: warmer months will produce higher yields, colder months induce lower yields. Parameter estimate was done using the restricted maximum likelihood (REML) method. Averages for treatments were reported as least-square means (LSMeans) with 95% confidence intervals calculated from linear models.

LCA Details

The OpenLCA software tool v1.11 (GreenDelta, Berlin, Germany) modeled and computed the scenarios and CO_2 emissions using the EcoInvent v3.8 database. The ReCiPe midpoint impact assessment method (hierarchist version) was used (Huijbregts et al., 2017). Only data from the CE environment was used as it did not violate functional equivalence.

LCA Transportation

Data on the transportation of raw materials and finished products, including distance traveled, mode of transportation, and fuel consumption were calculated using the EcoInvent v3.8 database. Distances were assumed to be 1100 km of travel by train from the chemical producers to the train station (Lima, OH, US to Montréal, QC, CAN), and 20 km by light commercial vehicle from the train station to the urban farm location as well as from the urban farm location to composting center. The inorganic "business-as-usual" scenario assumes the insect frass that is not used in the OLF treatment needs to be sent to a composting facility, 20km away, by light vehicle. In the OLF scenario, this insect frass was modeled to be used on-site, requiring no vehicle for transport. Modeled solid output of the bioreaction was modeled to be sent out to the composting facility.

Supplementary Tables
Life-cycle inventory results

Table S4.1: Life-cycle inventory results for fertilizer-associated process for inorganic treatment

Input	Amount per FU	Unit
Boric acid	2.03E-01	g
Calcium nitrate	8.10E+01	g
Compost	4.05E+02	g
Copper sulfate	5.70E-03	g
Edta	4.63E-01	g
Inorganic phosphorous fert	4.86E+00	g
Iron sulfate	3.95E-01	g
Magnesium sulfate	3.38E+01	g
Manganese sulfate	1.54E-01	g
Molybdenum	3.90E-03	g
Na (so4)4	7.31E-01	g
Pot nitrate	3.58E+01	g
Potassium sulfate	4.73E+00	g
Transport, freigh, light	1.15E-02	t*km
Transport, freight train	1.89E-01	t*km
Zinc sulfide	9.30E-03	g
Output		
Dinitrogen monoxide (0.31 or 1% EF scenario)	0.092 – 0.296	g

Table S4.2: Life-cycle inventory results for fertilizer-associated process for organic liquid fertilizer treatment

Input	Amount per FU	Unit
Boric acid	2.03E-01	g
Compost	1.01E+02	g
Container	1.95E-04	unit
Copper sulfate	5.67E-03	g
Electricity	1.17E+00	kWh
Iron sulfate	3.95E-01	g
Manganese sulfate	1.54E-01	g
Molybdenum	3.94E-03	g
Pump	3.89E-04	unit
Transport, freight	1.96E-02	t*km
Zinc sulfide	9.31E-03	g
Output		
Dinitrogen monoxide (0-100 %N_2O of BioRx gas loss)	0.113 – 15.584	g

Table S4.3.1: Average nutrient content of all solutions from the CE experiment. Different letters stand for significant differences as determined by Tukey HSD (α=0.05)

Nutrient content	Unit	CE			
		Hoagland (n=3)	OLF (n=3)	OLF+ (n=3)	LOQ
pH	pH	6.3 ± 0.2	6.2 ± 0.1	6.1 ± 0.1	0.1
Conductivity (mS cm^{-1})	ms/cm	1.80 ± 0.06	1.91 ± 0.04	1.89 ± 0.04	0.02
NH3/NH4-N	ug/ml	0.27 ± 0.09	12.23 ± 9.1	16.33 ± 14.13	0.01
NO3- N	ug/ml	142 ± 5.46	103.67 ± 9.94	110.87 ± 6.69	1
P **	ug/ml	59.89 ± 9.58 abc	114.86 ± 21.91 a	107.32 ± 18.74 ab	0.1
K **	ug/ml	178.77 ± 11.29 b	374.87 ± 41.33 a	317 ± 13.44 ab	0.1
Ca ***	ug/ml	168.27 ± 11.09 b	56.75 ± 19.25 c	78.55 ± 18.69 bc	0.1
Mg **	ug/ml	47.91 ± 0.62 ab	22.79 ± 3.5 b	26.87 ± 5.33 b	0.1
S *	ug/ml	61.52 ± 6.42 a	45.09 ± 6.58 ab	46.21 ± 5.36 ab	0.1
Cl	ug/ml	19.7 ± 9.64	71.7 ± 36.62	27.5 ± 27	1
Mn	ug/ml	0.36 ± 0.02	0.34 ± 0.05	0.35 ± 0.05	0.02
Mo	ug/ml	0.04 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.02
Na **	ug/ml	18.84 ± 0.32 b	60.7 ± 8.48 a	54.88 ± 6.52 a	0.1
Zn	ug/ml	0.07 ± 0.04	0.12 ± 0.03	0.17 ± 0.11	0.02
B **	ug/ml	0.32 ± 0.01 ab	0.39 ± 0.03 a	0.37 ± 0.02 a	0.02
Cu *	ug/ml	0.12 ± 0 abc	0.2 ± 0.03 a	0.19 ± 0.05 ab	0.02
Fe ***	ug/ml	0.57 ± 0.02 ab	0.99 ± 0.1 a	1.11 ± 0.28 a	0.1

Table S4.3.2: Average nutrient content of all solutions from the GH experiment. Different letters stand for significant differences as determined by Tukey HSD (α=0.05)

Nutrient content	Unit	GH				
		Hoagland (n=3)	OLF (n=9)	OLF+ (n=3)	Tea (n=6)	LOQ
pH	pH	6.2 ± 0.9	5.9 ± 0.4	6.9 ± 0.2	7.6 ± 0.1	0.1
Conductivity (mS cm^{-1})	ms/cm	2.37 ± 0.18	1.6 ± 0.12	1.63 ± 0.35	1.8 ± 0.2	0.02
NH3/NH4-N	ug/ml	1.5 ± 0.31	3.32 ± 1.53	0.57 ± 0.32	201.9 ± 33.5	0.01
NO3- N	ug/ml	185.33 ± 8.11	111.29 ± 13.82	107.67 ± 36.37	0 ± 0	1
P **	ug/ml	41.77 ± 3.58 c	56.49 ± 8.43 bc	22.17 ± 9.51 c	33 ± 3.2	0.1
K **	ug/ml	244.37 ± 13.24 ab	217.71 ± 22.32 b	213 ± 34.42 b	212.6 ± 43.5	0.1
Ca ***	ug/ml	272.23 ± 21.02 a	111.68 ± 14.44 bc	124.3 ± 27.31 bc	50 ± 10.6	0.1
Mg **	ug/ml	77.3 ± 17.77 a	50.22 ± 4.19 ab	60.6 ± 11.91 ab	37.5 ± 6.2	0.1
S *	ug/ml	73.97 ± 10.06 ab	42.47 ± 4.76 b	63.1 ± 8.04 ab	34 ± 6.6	0.1
Cl	ug/ml	0.5 ± 0 BDL	56.09 ± 12.66	11.93 ± 5.76	63 ± 21.1	1
Mn	ug/ml	0.17 ± 0.16	0.21 ± 0.09	0.01 ± 0 BDL	0.08 ± 0.01	0.02
Mo	ug/ml	0.01 ± 0 BDL	0.08 ± 0.04	0.07 ± 0.06	0.01 ± 0.01	0.02
Na **	ug/ml	19.5 ± 8.6 b	48.99 ± 3.95 a	54.73 ± 5.83 a	40.66 ± 3.37	0.1
Zn	ug/ml	0.01 ± 0 BDL	0.25 ± 0.12	0.23 ± 0.03	0.04 ± 0.02	0.02
B **	ug/ml	0.4 ± 0 a	0.13 ± 0.04 b	0.2 ± 0.1 ab	0.08 ± 0.01	0.02
Cu *	ug/ml	0.01 ± 0 c BDL	0.07 ± 0.02 ab	0.07 ± 0.06 abc	0.03 ± 0.01	0.02
Fe ***	ug/ml	0.05 ± 0 b BDL	0.2 ± 0.08 b	0.05 ± 0 b BDL	0.24 ± 0.06	0.1

Additional Tables – Chapter 4

Table S4.4: Nitrogen content and masses of input used for bioreaction of manure into organic liquid fertilizer.

Bioreactor step		Greenhouse bioreaction			
	n	N-content	Quantity	N quantity (g)	% Extraction of total N-input
Fresh manure	6	2.09% total-N	2000 g	41.8 total-N	100.0%
Spent manure	3	0.48% total-N	2000 g	9.6 total-N	23.0%
Tea	6	201.9 mg N-NO3&NH4/L	160 L	32.3 N-NH4	77.3%
Undiluted bioreaction	9	116.6 mg N-NO3&NH4/L	160 L	18.7 N-NO3&NH4	44.7%
Gaseous loss	NA				32.3%

Bioreactor step		Controlled environment bioreaction			
	n	N-content	Quantity	N quantity (g)	% Extraction of total N-input
Fresh manure	1	7.02% total-N	4000 g	280.8 total N	100.0%
Spent manure	NA				
Tea	NA				
Undiluted bioreaction	1	559.3 mg N-NO3&NH4/L	200 L	111.86 N-NO3&NH4	39.8%

Table S4.5.1: Global warming potential contribution for processes of fertilizer production, transport and use in soil-less setting for the production of 1kg of fresh basil using inorganic fertilizer input and 1% of total N-input as N_2O emission.

Process	Contribution [%]	Total result [kg CO_2-Eq]
soil-less fresh basil production	1.00E+02	7.88E-01
Transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | cutoff, u - row	4.59E+01	3.62E-01
Calcium nitrate production | calcium nitrate | cutoff, u - row	2.90E+01	2.29E-01
N_2O emission| soil-less plant production	1.12E+01	8.81E-02
Potassium nitrate production | potassium nitrate | cutoff, u - row	9.43E+00	7.44E-02
Magnesium sulfate production | magnesium sulfate | cutoff, u - row	1.76E+00	1.39E-02
Market for inorganic phosphorus fertiliser, as p2o5 | inorganic phosphorus fertiliser, as p2o5 | cutoff, u - ca	1.58E+00	1.24E-02
Potassium sulfate production | potassium sulfate | cutoff, u - row	6.00E-01	4.70E-03
Edta production | edta, ethylenediaminetetraacetic acid | cutoff, u - row	2.50E-01	1.95E-03
Sodium persulfate production | sodium persulfate | cutoff, u - glo	1.40E-01	1.07E-03
Transport, freight train, diesel | transport, freight train | cutoff, u - row	7.46E-02	5.88E-04
Boric acid production, anhydrous, powder | boric acid, anhydrous, powder | cutoff, u - row	2.37E-02	1.87E-04
Manganese sulfate production | manganese sulfate | cutoff, u - glo	1.38E-02	1.08E-04
Molybdenum production | molybdenum | cutoff, u - row	8.21E-03	6.47E-05
Iron sulfate production | iron sulfate | cutoff, u - ca-qc	3.19E-03	2.52E-05
Copper sulfate production | copper sulfate | cutoff, u - glo	2.64E-03	2.08E-05
Zinc sulfide production | zinc sulfide | cutoff, u - row	2.40E-03	1.89E-05
Treatment of biowaste, industrial composting | compost | cutoff, u - row	-7.55E-11	-5.95E-13

Table S4.5.2: Global warming potential contribution for processes of fertilizer production, transport and use in soil-less setting for the production of 1kg of fresh basil using inorganic fertilizer input and 0.31% of total N-input as N_2O emission.

Process	Contribution [%]	Total result [kg CO_2-Eq]
soil-less fresh basil production	1.00E+02	7.27E-01
Transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | cutoff, u - row	4.98E+01	3.62E-01
Calcium nitrate production | calcium nitrate | cutoff, u - row	3.14E+01	2.29E-01
Potassium nitrate production | potassium nitrate | cutoff, u - row	1.02E+01	7.44E-02
N_2O emission| soil-less plant production	3.75E+00	2.73E-02
Magnesium sulfate production | magnesium sulfate | cutoff, u - row	1.91E+00	1.39E-02
Market for inorganic phosphorus fertiliser, as p2o5 | inorganic phosphorus fertiliser, as p2o5 | cutoff, u - ca	1.71E+00	1.24E-02
Potassium sulfate production | potassium sulfate | cutoff, u - row	6.50E-01	4.70E-03
Edta production | edta, ethylenediaminetetraacetic acid | cutoff, u - row	2.70E-01	1.95E-03
Sodium persulfate production | sodium persulfate | cutoff, u - glo	1.50E-01	1.07E-03
Transport, freight train, diesel | transport, freight train | cutoff, u - row	8.08E-02	5.88E-04
Boric acid production, anhydrous, powder | boric acid, anhydrous, powder | cutoff, u - row	2.57E-02	1.87E-04
Manganese sulfate production | manganese sulfate | cutoff, u - glo	1.49E-02	1.08E-04
Molybdenum production | molybdenum | cutoff, u - row	8.89E-03	6.47E-05
Iron sulfate production | iron sulfate | cutoff, u - ca-qc	3.46E-03	2.52E-05
Copper sulfate production | copper sulfate | cutoff, u - glo	2.86E-03	2.08E-05
Zinc sulfide production | zinc sulfide | cutoff, u - row	2.60E-03	1.89E-05
Treatment of biowaste, industrial composting | compost | cutoff, u - row	-8.18E-11	-5.95E-13

Table S4.5.3: Global warming potential contribution for processes of fertilizer production, transport and use in soil-less setting to produce 1kg of fresh basil using organic fertilizer via novel bioreaction where 100% of gaseous N-loss is N_2O and 1% of total N-input as N_2O emission.

Process	Contribution [%]	Direct contribution [kg CO_2-Eq]
OLF fresh basil production	1.00E+02	4.71E+00
N_2O emission from bioreactor and soil-less plant production	9.85E+01	4.64E+00
Transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | cutoff, u - row	8.00E-01	3.75E-02
Electricity voltage transformation from medium to low voltage | electricity, low voltage | cutoff, u - ca-qc	6.10E-01	2.88E-02
Pump production, 40w | pump, 40w | cutoff, u - row	7.29E-02	3.44E-03
Boric acid production, anhydrous, powder | boric acid, anhydrous, powder | cutoff, u - row	3.96E-03	1.87E-04
Manganese sulfate production | manganese sulfate | cutoff, u - glo	2.30E-03	1.08E-04
Molybdenum production | molybdenum | cutoff, u - row	1.38E-03	6.53E-05
Iron sulfate production | iron sulfate | cutoff, u - ca-qc	5.34E-04	2.52E-05
Copper sulfate production | copper sulfate | cutoff, u - glo	4.39E-04	2.07E-05
Zinc sulfide production | zinc sulfide | cutoff, u - row	4.02E-04	1.89E-05
Container production, for collection of post-consumer waste plastic for recycling |	2.88E-04	1.36E-05
Treatment of biowaste, industrial composting | compost | cutoff, u - row	4.53E-12	2.14E-13

Table S4.5.4: Global warming potential contribution for processes of fertilizer production, transport and use in soil-less setting to produce 1kg of fresh basil using organic fertilizer via novel bioreaction where 0% of gaseous N-loss is N_2O and 1% of total N-input as N_2O emission.

Process	Contribution [%]	Direct contribution [kg CO_2-Eq]
OLF fresh basil production - raf	1.00E+02	1.04E-01
Transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | cutoff, u - row	3.61E+01	3.75E-02
N_2O emission from bioreactor and soil-less plant production	3.25E+01	3.38E-02
Electricity voltage transformation from medium to low voltage | electricity, low voltage | cutoff, u - ca-qc	2.77E+01	2.88E-02
Pump production, 40w | pump, 40w | cutoff, u - row	3.31E+00	3.44E-03
Boric acid production, anhydrous, powder | boric acid, anhydrous, powder | cutoff, u - row	1.80E-01	1.87E-04
Manganese sulfate production | manganese sulfate | cutoff, u - glo	1.00E-01	1.08E-04
Molybdenum production | molybdenum | cutoff, u - row	6.28E-02	6.53E-05
Iron sulfate production | iron sulfate | cutoff, u - ca-qc	2.42E-02	2.52E-05
Copper sulfate production | copper sulfate | cutoff, u - glo	1.99E-02	2.07E-05
Zinc sulfide production | zinc sulfide | cutoff, u - row	1.82E-02	1.89E-05
Container production, for collection of post-consumer waste plastic for recycling | container, for collection of post-consumer waste plastic for recycling | cutoff, u - row	1.31E-02	1.36E-05
Treatment of biowaste, industrial composting | compost | cutoff, u - row	2.05E-10	2.14E-13

Supplementary Results

GH harvest results

Data from the GH experiment was fitted to a linear mixed model using REML for covariance estimates to predict yield based on nutrient solution, harvest month and cutting number. The model included individual plant as random effect. The model had R^2 value of 0.71. Individual plant random effect had no significant effect on yield ($p=0.483$). Nutrient solution effect on yield was not found to be statistically significant ($p=0.078$). A significant effect was observed for cutting number ($F=120.8$, $df=1$, $p<0.0001$) and harvest month ($F=28.1$, $df=2$, $p<0.0001$). Cutting number had a negative impact on yield with a parameter estimate for cutting #1 of -10.2. Harvest month of August-September had a negative impact on yield with a parameter estimate of -3.9. Harvest month of June-July had a positive impact on yield with a parameter estimate of 11.0.

Organic liquid fertilizer in the greenhouse experiment caused nutrient deficiency symptoms.

Nutrient deficiency symptoms were observed in some basil plants in the OLF and OLF+ from the GH experiment. Around 50% of plants had interveinal chlorosis, but only after the first cut (Figure C.1). Interveinal chlorosis was seen on old and young leaves. Following this observation, representative plant tissue samples from healthy plants and deficient plants were sent for elemental analysis.

Elemental analysis showed that leaves with interveinal chlorosis had significantly lower P than healthy leaves from all other treatment: 0.79±0.22% versus 1.23±0.06% for inorganic (Figure C.2.A). Ca content varied between treatments, but the deficient plants did not show the lowest concentration (Figure C.2.A). The deficient plant had a significant increase in S and Na content ($p<0.05$ and $p<0.0001$ respectively) compared to the three treatments (Figure 4B). Cu content was similar between the control and the deficient individuals, but significantly higher in OLF and OLF+ treatment ($p<0.005$) (Figure C.2.B). Fe content was significantly different between treatment ($p<0.0001$), with the lowest concentration in the inorganic control. Highest Fe content was seen in the OLF treatment (Figure 4D).

Figure S4.1: Visual appearance of leaves showing interveinal chlorosis.
Data are means ± SEM with n=3. OLF stands for organic liquid fertilizer (OLF). Inorganic stands for inorganic control solution and OLF+ refers to a solution comprised of a 50:50 mixture of both inorganic and OLF. Dashed lines show sufficiency range has previously reported (Owen et al., 2018), maximum sufficiency range for B is reported to be 60 (out of range of the graph). No sufficiency range is reported for Na. Different small letters above means represent significant differences between treatments determined by Tukey HSD test at $\alpha = 0.05$. F-tests results of one-way ANOVA indicated as 'ns' for not significant, * for $p<0.05$, ** for $p<0.005$ and *** for $p<0.0001$. Values for all elements are presented in Table S4.

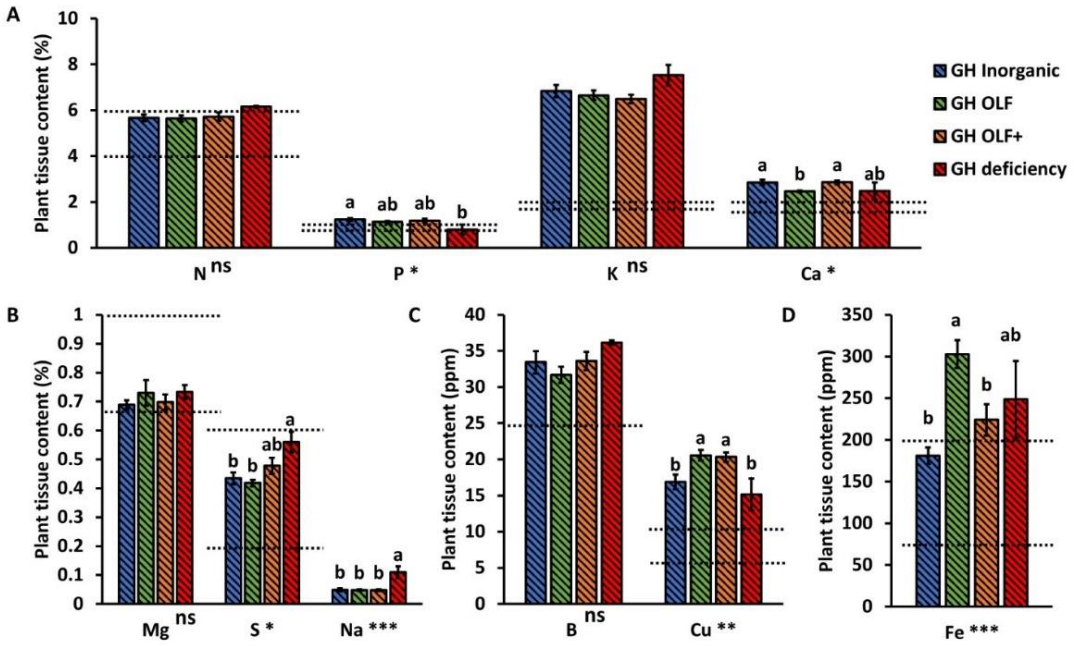


Figure S4.2: Plant tissue nutrient content from healthy plants affected by interveinal chlorosis

Appendix-C: Supplementary Material Chapter - 5

Supplementary Methods S5

HVAC energy demand: Humidification was done via NG when outdoor temperatures are below 42 °C and used electricity when outside temperatures were above 42 °C. (Summers et al., 2021)

Fertilizer input: Total water input was modeled as 3.8 L day^{-1} per plant. An additional daily 500 mL of liquid fertilizer was modeled. This solution had an assumed EC of 1.8 mS cm^{-1}. Inorganic fertilizer input was modified to align with optimal concentration recommended by fertilizer-response trials and had a N, P and K concentration of 140-23-205 ppm (Bevan et al., 2021; Saloner and Bernstein, 2022a, 2022b, 2021a, 2021b, 2020).

Transport modeling: The following transport distances were assumed: 805 kilometers from the point of manufacturing to distribution centers by train, 80 kilometers from distribution centers to small retail locations by lorry, and 15 kilometers in a passenger car for employees to the grow facility, which are the same distances used in a previous study (Summers et al., 2021)

Additional information, excel workbook and code can be found here: https://github.com/VinceDebile/LCannabis

Supplementary Tables

Table S5.1.1: Input quantity per functional unit (FU) for indoor model. See electronic supplementary material for more details

OpenLCA indoor model input	Quantity	units	OpenLCA flows & processes
Electrical energy input	Depends on region	kWh/FU	Electricity, high voltage, production mix | electricity, high voltage | cutoff, u - ca-xx
Natural Gas energy input	Depends on region	MJ/FU (4.10 kg CO_2/kg NG)	Heat production, natural gas, at boiler condensing modulating <100kw | heat, central or small-scale, natural gas | cutoff, u - row
Fertilizer solution (water)	3.28E+02	l/FU	Tap water production, conventional treatment | tap water | cutoff, u - row
Ammonium nitrate	4.04E-02	kg per FU	Ammonium nitrate production | ammonium nitrate | cutoff, u - rna
Ammonium sulphate	7.71E-03	g per FU	Ammonium sulfate production | ammonium sulfate | cutoff, u - rer
Borax	2.81E-04	kg per FU	Borax production, anhydrous, powder | borax, anhydrous, powder | cutoff, u - row
Calcium nitrate	5.92E-02	kg per FU	Calcium nitrate production | calcium nitrate | cutoff, u - row
Copper sulphate	5.50E-04	g per FU	Copper sulfate production | copper sulfate | cutoff, u - glo
Iron EDTA	2.64E-03	kg per FU	Iron sulfate production | iron sulfate | cutoff, u - row
Magnesium sulphate	1.03E-01	g per FU	Magnesium sulfate production | magnesium sulfate | cutoff, u - row
Manganese sulphate	3.32E-05	kg per FU	Manganese sulfate production | manganese sulfate | cutoff, u - glo
Molybdenum	7.50E-06	g per FU	Molybdenum production | molybdenum | cutoff, u - row
Mono-ammonium phosphate	1.34E-02	kg per FU	Monoammonium phosphate production | monoammonium phosphate | cutoff, u - row
Potassium nitrate	1.30E-01	kg per FU	Market for potassium nitrate, agricultural grade | potassium nitrate, agricultural grade | cutoff, u - glo
Zinc sulfide	3.53E-04	g per FU	Zinc sulfide production | zinc sulfide | cutoff, u – row
g N_2O to air (1% total N)	4.59E-01	g per FU	Ecospold 2 elementary exchange, id = 20185046-64bb-4c09-a8e7-e8a9e144ca98
g NO_x to air (21% of N_2O)	9.64E-02	g per FU	Uuid d9d14565-ed4d-3ffb-b9e0-a4ebd2031b80
g NH_4 to air (4% total N)	1.84E+00	g per FU	Ecospold 2 elementary exchange, id = 87883a4e-1e3e-4c9d-90c0-f1bea36f8014
phosphate to water (12% total P)	5.78E-01	g per FU	Ecospold 2 elementary exchange, id = c8791f3c-3c4a-4278-91c0-483797d14da2
g N-Nitrate to water (1% total N)	4.59E-01	g per FU	Ecospold 2 elementary exchange, id = 5189de76-6bbb-44ba-8c42-5714f1b4371f
growth CO_2	6.53E+02	kg/FU	Carbon dioxide production, liquid | carbon dioxide, liquid | cutoff, u - row
Pesticide	1.79E+00	kg/FU	Pesticide production, unspecified | pesticide, unspecified | cutoff, u - row
Soil Amendments (Perlite)	2.70E+00	kg/FU	Expanded perlite production | expanded perlite | cutoff, u - row
Peat moss as soil	1.97E-01	m3/FU	Peat moss production, horticultural use | peat moss | cutoff, s
Neem oil (vegeTable oil)	1.26E+00	kg/FU	Soybean oil, refined, to generic market for vegeTable oil, refined | vegeTable oil, refined | cutoff, u - glo
Surfactant mixed with neem oil application	3.10E-01	kg/FU	Soap production | soap | cutoff, u - row
Water Amount	2.15E+03	l/FU	Tap water production, conventional treatment | tap water | cutoff, u - row
Landfill CH_4 emission	1.70E+01	kg/FU	Uuid 20408dd1-8534-11e0-9d78-0800200c9a66
Landfill CO_2 émission	1.61E+01	kg/FU	Uuid 7ae371aa-8532-11e0-9d78-0800200c9a66
product that is sequestered CO_2	1.09E-03	kg CO_2-FU	Uuid 7ae371aa-8532-11e0-9d78-0800200c9a66
landfill mass that is sequestered CO_2	1.21E+02	kg CO_2-FU	Uuid 7ae371aa-8532-11e0-9d78-0800200c9a66
Transport (train)	6.43E+02	t*km per FU	Transport, freight train, diesel | transport, freight train | cutoff, u - row
Transport (lorry)	7.46E+01	t*km per FU	Transport, freight, lorry 16-32 metric ton, euro5 | transport, freight, lorry 16-32 metric ton, euro5 | Cutoff, u - row
Transport (passenger car)	1.50E+01	km/FU	Transport, passenger car with internal combustion engine | Transport, passenger car with internal combustion engine | cutoff, u - row
HPS light energy	1.38E+03	kWh/FU	Electricity, high voltage, production mix | electricity, high voltage | cutoff, u - ca-xx
HPS light fixture	7.43E+02	h/FU	Custom, see openlca files and zhang (2017)

Table S5.1.2: Input quantity per functional unit (FU) for outdoor model. See electronic supplementary material for more details

OpenLCA outdoor model input	Quantity	units	OpenLCA flows & processes
Electrical energy input minus lighting	6.10E+01	kWh/FU	Electricity, high voltage, production mix | electricity, high voltage | cutoff, u - ca-xx
Natural Gas energy input	3.68E+03	MJ/FU (4.10 kg CO_2/kg NG)	Heat production, natural gas, at boiler condensing modulating <100kw | heat, central or small-scale, natural gas | cutoff, u - row
Fertilizer solution (water)	1.72E+02	l/FU	Tap water production, conventional treatment | tap water | cutoff, u - row
Ammonium nitrate	2.12E-02	kg/FU	Ammonium nitrate production | ammonium nitrate | cutoff, u - rna
Ammonium sulphate	4.04E-03	kg/FU	Ammonium sulfate production | ammonium sulfate | cutoff, u - rer
Borax	1.48E-04	g/FU	Borax production, anhydrous, powder | borax, anhydrous, powder | cutoff, u - row
Calcium nitrate	3.11E-02	kg/FU	Calcium nitrate production | calcium nitrate | cutoff, u - row
Copper sulphate	2.89E-04	g/FU	Copper sulfate production | copper sulfate | cutoff, u - glo
Iron EDTA	1.38E-03	g/FU	Iron sulfate production | iron sulfate | cutoff, u - row
Magnesium sulphate	2.44E-02	kg/FU	Magnesium sulfate production | magnesium sulfate | cutoff, u - row
Manganese sulphate	1.74E-05	g/FU	Manganese sulfate production | manganese sulfate | cutoff, u - glo
Mono-ammonium phosphate	7.02E-03	kg/FU	Monoammonium phosphate production | monoammonium phosphate | cutoff, u - row
Potassium nitrate	6.83E-02	kg/FU	Potassium nitrate production, agricultural grade | potassium nitrate, agricultural grade | cutoff, u - cl
Zinc sulfide	1.85E-04	g/FU	Zinc sulfide production | zinc sulfide | cutoff, u - row
Mo	3.90E-06	g/FU	Molybdenum production | molybdenum | cutoff, u - row
g N_2O to air (1% total N)	2.41E-01	g/FU	Ecospold 2 elementary exchange, id = 20185046-64bb-4c09-a8e7-e8a9e144ca98
g Nox to air (21% of N_2O)	5.05E-02	g/FU	Uuid d9d14565-ed4d-3ffb-b9e0-a4ebd2031b80
g NH4 to air (4% total N)	9.63E-01	g/FU	Ecospold 2 elementary exchange, id = 87883a4e-1e3e-4c9d-90c0-f1bea36f8014
phosphate to water (12% total P)	3.03E-01	g/FU	Ecospold 2 elementary exchange, id = c8791f3c-3c4a-4278-91c0-483797d14da2
g N-Nitrate to water (1% total N)	2.41E-01	g/FU	Ecospold 2 elementary exchange, id = 5189de76-6bbb-44ba-8c42-5714f1b4371f
Input		units	Openlca flows & processes
Electrical energy input minus lighting	6.10E+01	kWh/FU	Electricity, high voltage, production mix | electricity, high voltage | cutoff, u - ca-xx
Natural Gas energy input	3.68E+03	MJ/FU (4.10 kg CO2/kg NG)	Heat production, natural gas, at boiler condensing modulating <100kw | heat, central or small-scale, natural gas | cutoff, u - row
Fertilizer solution (water)	1.72E+02	l/FU	Tap water production, conventional treatment | tap water | cutoff, u - row
Ammonium nitrate	2.12E-02	kg/FU	Ammonium nitrate production | ammonium nitrate | cutoff, u - rna
Ammonium sulphate	4.04E-03	kg/FU	Ammonium sulfate production | ammonium sulfate | cutoff, u - rer
Borax	1.48E-04	g/FU	Borax production, anhydrous, powder | borax, anhydrous, powder | cutoff, u - row
Calcium nitrate	3.11E-02	kg/FU	Calcium nitrate production | calcium nitrate | cutoff, u - row
Copper sulphate	2.89E-04	g/FU	Copper sulfate production | copper sulfate | cutoff, u - glo
Iron EDTA	1.38E-03	g/FU	Iron sulfate production | iron sulfate | cutoff, u - row
Magnesium sulphate	2.44E-02	kg/FU	Magnesium sulfate production | magnesium sulfate | cutoff, u - row
Manganese sulphate	1.74E-05	g/FU	Manganese sulfate production | manganese sulfate | cutoff, u - glo
Mono-ammonium phosphate	7.02E-03	kg/FU	Monoammonium phosphate production | monoammonium phosphate | cutoff, u - row
Potassium nitrate	6.83E-02	kg/FU	Potassium nitrate production, agricultural grade | potassium nitrate, agricultural grade | cutoff, u - cl
Zinc sulfide	1.85E-04	g/FU	Zinc sulfide production | zinc sulfide | cutoff, u - row
Mo	3.90E-06	g/FU	Molybdenum production | molybdenum | cutoff, u - row

Table S5.2: Environmental parameters setpoints for indoor cannabis cultivation for each grow room depending on stage of growth, adapted from Summers et al., 2021

Parameter Name	Clone	Vegetative	Flower	Cure
Temperature High (°C)	26.7	23.9	29.4	23.9
Temperature Low (°C)	21.1	15.6	21.1	15.6
Relative Humidity High	70%	50%	50%	50%
Relative Humidity Low	40%	40%	40%	30%
CO2 (ppm)	400*	700	1400	400*

Additional Tables – Chapter 5

Table S5.3: Output from energy consumption model for all 80 Canadian locations.

Lat	Lon	Site	State	carbon (kg CO_2-eq/kg-bud)	Electricity (kWh/kg-bud)	NG (MJ/kg-bud)
58.621	-117.165	CYOJ	AB	5229.7829	1854.6293	45320.9544
55.293	-114.777	CYZH	AB	4985.5211	1881.7183	40521.8843
54.405	-110.279	CYOD	AB	5001.4702	1887.3415	40728.7545
53.667	-113.467	CYED	AB	4929.5608	1874.2611	39619.2439
53.31	-113.58	CYEG	AB	5002.825	1896.3107	40624.003
53.309	-110.072	CYLL	AB	5033.9033	1895.311	41199.3571
51.114	-114.02	CYYC	AB	4783.6804	1853.5673	37284.2561
52.183	-113.9	CYQF	AB	4958.228	1860.682	40332.29
53.579	-116.465	CYET	AB	4961.3781	1849.4963	40550.2826
55.18	-118.885	CYQU	AB	4996.1656	1850.9424	41157.3548
53.25	-131.817	CYZP	BC	2756.3002	1895.8636	25258.2333
53.026	-122.51	CYQZ	BC	3284.2794	1857.6088	34831.1375
52.183	-122.054	CYWL	BC	3385.63	1843.0432	36676.8761
49.025	-122.363	CYXX	BC	2678.6631	1967.0366	23776.8009
50.681	-127.367	CYZT	BC	2796.128	1878.8851	25996.2224
48.647	-123.426	CYYJ	BC	2640.4581	1894.7948	23168.5276
50.702	-120.444	CYKA	BC	2930.3444	1889.4612	28406.8782
49.463	-119.602	CYYF	BC	2871.439	1890.8402	27342.1045
49.194	-123.184	CYVR	BC	2647.9499	1988.494	23198.2846
49.711	-124.887	CYQQ	BC	2645.9719	1917.6362	23242.3391
53.889	-122.679	CYXS	BC	3404.5248	1853.3281	37006.3436
54.283	-130.45	CYPR	BC	2868.7225	1879.889	27305.3983
56.238	-120.74	CYXJ	BC	3648.4102	1848.6199	41413.6903
58.833	-122.6	CYYE	BC	3853.4699	1844.4394	45119.6533
54.825	-127.183	CYYD	BC	3362.9051	1853.673	36254.7338
54.469	-128.576	CYXT	BC	3088.2738	1865.3052	31284.6403
56.864	-101.076	CYYL	MB	4058.8796	1843.0437	49175.1015
55.801	-97.864	CYTH	MB	4045.8442	1853.352	48930.152
49.917	-99.95	CYBR	MB	3624.0849	1991.8433	41187.68
49.91	-97.24	CYWG	MB	3548.5748	2021.7892	39796.6698
53.967	-101.1	CYQD	MB	3761.1606	1914.9654	43733.9369
56.35	-94.717	CYGX	MB	4122.8203	1847.2429	50325.2734
45.317	-65.883	CYSJ	NB	3887.0384	2031.1933	34286.7713
45.867	-66.533	CYFC	NB	3909.1879	2067.4517	34445.3114
46.112	-64.679	CYQM	NB	3902.3983	2073.1821	34284.6346
47.619	-52.752	CYYT	NL	3295.6398	1951.47	34232.7653
48.937	-54.568	CYQX	NL	3394.1438	1932.2098	36039.2938
49.217	-57.4	CYDF	NL	3418.7459	1948.4873	36459.2119
48.533	-58.55	CYJT	NL	3309.8854	1990.3825	34432.1817
53.317	-60.417	CYYR	NL	3833.4169	1850.9054	44088.6102
53.717	-57.033	CYCA	NL	3800.1633	1847.2379	43493.8332
52.922	-66.864	CYWK	NL	4114.123	1839.4649	49172.2274
44.881	-63.509	CYHZ	NS	4955.1957	2081.0672	31973.2709
44.984	-64.917	CYZX	NS	4916.2295	2115.0879	30696.0063
43.933	-60.017	CWSA	NS	4741.1382	2110.8509	27607.1477
43.827	-66.088	CYQI	NS	4846.0254	2093.3107	29796.2339
46.167	-60.05	CYQY	NS	4985.2777	2048.6036	33063.9124
42.276	-82.956	CYQG	ON	2980.9961	2288.8927	28718.6739
44.225	-76.597	CYGK	ON	3128.6105	2199.888	31489.1879
44.117	-77.533	CYTR	ON	3121.3444	2184.9008	31375.9084
43.036	-81.154	CYXU	ON	3103.2552	2195.4758	31036.7953
45.952	-77.319	CYWA	ON	3355.8573	2087.261	35725.2076
45.323	-75.669	CYOW	ON	3266.8632	2129.6018	34068.4094
44.75	-81.1	CYVV	ON	3180.5982	2107.8194	32537.3275
46.364	-79.423	CYYB	ON	3435.4397	2014.8876	37247.9371
48.57	-81.377	CYTS	ON	3637.6205	1917.3123	41013.5772
49.414	-82.467	CYYU	ON	3676.6382	1931.2608	41701.2012
49.767	-86.917	CYGQ	ON	3722.7982	1908.9077	42561.0271
50.117	-91.9	CYXL	ON	3660.5552	1949.8196	41388.7791
46.283	-63.133	CYYG	PE	3132.5043	2070.9222	33492.5055
48.775	-64.479	CYGP	QC	3383.1362	1968.0505	38169.6028
45.467	-73.733	CYUL	QC	3086.7084	2129.4414	32775.1661
55.283	-77.75	CYGW	QC	4019.1661	1833.6466	49686.3814
46.791	-71.393	CYQB	QC	3286.1879	2069.8774	36391.9472
48.6	-68.217	CYYY	QC	3336.1763	1958.906	37324.4867
48.053	-77.783	CYVO	QC	3486.769	1922.5065	40052.5601

Lat	Lon	Site	State	carbon (kg CO_2-eq/kg-bud)	Electricity (kWh/kg-bud)	NG (MJ/kg-bud)
48.206	-78.836	CYUY	QC	3525.7363	1929.8365	40753.9076
48.331	-70.996	CYBG	QC	3415.1444	1959.0897	38749.7829
48.517	-72.267	CYRJ	QC	3470.1916	1979.3239	39737.8489
50.217	-66.25	CYZV	QC	3564.8561	1893.6599	41469.8736
45.683	-74.033	CYMX	QC	3244.5561	2109.4377	35629.7181
58.1	-68.417	CYVP	QC	4189.4145	1829.1407	52760.5358
51.265	-102.462	CYQV	SK	4925.8338	1950.1756	41119.5111
50.433	-104.667	CYQR	SK	4866.55	1940.3433	40177.6821
53.214	-105.673	CYPA	SK	4994.7751	1935.28	42558.1309
52.769	-108.244	CYQW	SK	4873.0496	1913.9387	40639.3364
55.151	-105.262	CYVC	SK	5032.7117	1880.4228	43958.2586
60.116	-128.822	CYQH	YU	4160.3619	1828.1979	47876.001
60.71	-135.067	CYXY	YU	3998.8131	1832.0839	44949.773
63.616	-135.868	CYMA	YU	4206.743	1834.5268	48696.3433

Appendix-D: Supplementary Material Chapter - 6

Figure S6.1: Representative picture of cannabis plant grown outdoor during the experiment of Chapter 3. Notice difference in size between (A) the low N-input, high K:N ratio (L+) treatment and (B) high N-input, low K:N ratio (H-). Red and white bar is 30 cm.