Addressing Challenges in Controlled Environment Agriculture to Grow Food in Northern Canada

By

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Abstract

Food insecurity is a main concern of our time, which affects various regions of the world. With the increasing population and natural disasters linked to climate change, agricultural yields are at risk which may lead to an increase of food price, deepening the issue of worldwide food insecurity. Promoting local food production is one of the various ways to mitigate this worldwide issue. However, conventional agriculture is not suited to the conditions of the remote locations often faced with food insecurity, such as northern Canada, where the high cost of transportation is a critical factor that contributes to the inaccessibility of fresh produce.

Growing food in a remote location is a complex problem that must be solved via inclusive and innovative solutions having long term positive impacts. Agricultural practices to allow food production in northern Canada exists and northern agriculture has seen a rise in the past few years. One of these solutions is the use of Control Environment Agriculture (CEA), via the use of indoor agricultural systems using soilless growing methods, such as hydroponics, and the use of electrical lighting. Even with years of research and production experience, they still come with challenges. This thesis proposes three solution to three different issues facing CEA for remote food production, heat and energy efficiency, labor requirements and fertilizer demand.

This thesis presents three studies. The first focuses on the Canadian Integrated Northern Greenhouse (CING), a hybrid in between a growth chamber and a northern greenhouse designed to use natural resources to reduce energy requirements for northern food production. To reduce the use of electrical lighting and benefit from the Sun's natural light and heat, the CING was designed and prototyped by McGill students. Lettuce was grown during the four-season test of this food production unit it. The greatest yield obtained in the CING was in March 2019, where the plants grown achieved 72% of the dry mass of the plants grown in the research greenhouse. The CING relied on supplemental heating to successfully grow plants but demonstrated the potential for northern and remote applications.

The second study focuses on the comparative test of innovative vertical hydroponic configurations for shipping-container plant factories. Specifically, three systems were designed based on aeroponics, nutrient film technique (NFT), stagnant shallow water culture and flowing shallow water culture. Lettuce was grown in all systems and the performance of each system was assessed in terms of biomass yield, uniformity and ease of use. During the test, a metal ion contamination occurred, causing a bias on the results. However, the stagnant shallow water culture was the technique preferred by the industrial partner, for its larger yield resulting from the ability to be independent of the continuous nutrient solution distribution.

The third study focuses on the optimization of an organic nutrient solution, brewed using fresh chicken manure extracts and vermicompost leachate. The goal of this study was to produce an organic nutrient solution with a similar nutrient ratio to a conventional hydroponic nutrient solution. The preliminary experiment of this study occurred during the four-season testing of the CING, where a nutrient solution prepared with vermicompost leachate was compared to an inorganic solution. By mixing the concentrated vermicompost leachate with chicken manure extracts within a bioreactor, Biojuice was brewed and compared to an inorganic nutrient solution by growing lettuce in hydroponic conditions. The N-P-K ratio of the Biojuice

and the inorganic nutrient solution were comparable, respectively 4.6-1-7.9 and 7-1-7.5. The Biojuice yielded lettuce with fresh mass 15% higher than the inorganic nutrient solution at an electrical conductivity of 1.1 $mS.cm^{-1}$. At higher electrical conductivity of 1.5 and 1.6 $mS.cm^{-1}$, the Biojuice lettuce yield were respectively 44 % and 69 % lower than the inorganic nutrient solution. This result is explained by a calcium deficiency in the plants caused by a nutrient ratio in-balanced mixed with a high sodium content.

Résumé

L'insécurité alimentaire est une préoccupation majeure de notre époque, affectant diverses régions du monde. Avec l'augmentation de la population et les catastrophes naturelles liées aux changements climatiques, les rendements agricoles sont menacés, pouvant entraîner une augmentation des prix des denrées alimentaires, aggravant le problème de l'insécurité alimentaire dans certaines régions du monde. La production alimentaire locale est l'un des différents moyens d'atténuer ce problème mondial. Cependant, l'agriculture conventionnelle n'est pas adaptée aux conditions des régions éloignées souvent confrontées à l'insécurité alimentaire, comme le nord du Canada, où le coût élevé du transport est un facteur critique qui contribue à l'inaccessibilité de produits frais.

Cultiver des aliments dans un endroit éloigné est un problème complexe qui doit être résolu par des solutions innovantes et socialement inclusive ayant des impacts positifs à long terme. Il existe des pratiques agricoles permettant la production alimentaire dans le nord du Canada et l'agriculture nordique a connu une augmentation au cours des dernières années. L'une de ces solutions est l'utilisation de l'agriculture en environnement contrôlé, via l'utilisation de systèmes agricoles intérieurs utilisant des méthodes de culture hors sol, comme la culture hydroponique, et l'utilisation d'éclairage électrique. Même après plusieurs années d'expérience en recherche et en développement, l’agriculture en environnement contrôlé présente encore des défis. Cette thèse propose trois solutions à trois problématiques différentes auxquelles l’agriculture en environnement contrôlé est confrontée pour la production alimentaire en région éloignée : l'efficacité énergétique, les besoins en main-d'œuvre et la demande en fertilisants.

Cette thèse présente trois études. La première concerne le test quatre saison de la serre nordique intégrée canadienne, en anglais le «Canadian Integrated Northern Greenhouse (CING)», un hybride entre une chambre de croissance et une serre nordique conçue pour utiliser les ressources naturelles afin de réduire les besoins énergétiques pour la production alimentaire nordique. Pour réduire l’utilisation de l’éclairage électrique et profiter de la lumière et de la chaleur naturelles du soleil, le CING a été conçu et prototypé par des étudiants de McGill. La laitue a été cultivée pendant le test de quatre saisons de cette unité de production alimentaire. Le plus grand rendement obtenu dans le CING a eu lieu en mars 2019, où les plantes cultivées ont atteint 72% de la masse sèche des plantes cultivées dans la serre de recherche. Le CING s'est appuyé sur un chauffage d'appoint pour faire pousser des plantes avec succès, mais a démontré le potentiel pour les applications nordiques et éloignées.

La deuxième étude concerne un test comparatif de configurations hydroponiques verticales innovantes pour les usines de plantes en conteneurs d'expédition. Plus précisément, trois systèmes ont été conçus sur la base de l'aéroponie, de la technique du film nutritif, de la culture en eau peu profonde stagnante et de la culture en eau peu profonde. La laitue a été cultivée simultanément dans tous les systèmes et la performance de chaque système a été évaluée en termes de rendement en biomasse, d'uniformité et de facilité d'utilisation. Au cours du test, une contamination par des ions métalliques s'est produite, entraînant un biais sur les résultats. Cependant, la culture en eau peu profonde stagnante était la technique préférée par le partenaire industriel, pour son plus grand rendement résultant de la capacité à être indépendant de la distribution continue de la solution nutritive.

La troisième étude se concentre sur l'optimisation d'une solution nutritive organique, brassée à partir d'extraits de fumier de poulet frais et de lixiviat de vermicompost. Le but de cette étude était de produire une solution nutritive organique avec un rapport nutritif similaire à une solution nutritive hydroponique conventionnelle. L'expérience préliminaire de cette étude a eu lieu pendant les essais de quatre saisons du CING, où une solution nutritive préparée avec du lixiviat de vermicompost a été comparée à une solution inorganique. En mélangeant le lixiviat concentré de vermicompost avec des extraits de fumier de poulet dans un bioréacteur, une solution nutritive organique liquide a été brassés, nommé Biojuice, puis comparée à une solution nutritive inorganique en cultivant de la laitue dans des conditions hydroponiques. Le rapport NPK du Biojuice et de la solution nutritive inorganique était comparable, respectivement 4,6-1-7,9 et 7-1-7,5. La laitue nourrie par du Biojuice a atteint une masse fraîche 15% plus élevée que la solution nutritive inorganique à une conductivité électrique de 1,1 mS / cm. À une conductivité électrique supérieure de 1,5 et 1,6 mS / cm, le rendement de la laitue obtenue par le Biojuice était respectivement de 44% et 69% inférieur à celle obtenue par la solution nutritive inorganique. Ce résultat s'explique par une carence en calcium des plantes causée par un rapport nutritionnel déséquilibré combiné à une forte teneur en sodium.

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Thanks to Julien Loiseau and Richard Giunta, founders of La Boîte Maraîchère, for funding part of my research within their business. Working with passionate and experienced industrial partners was an amazing opportunity and shaped the path of my future projects. Dr. Grant Clark, my committee member for his help and guidance to include waste management into biomass production. Hélène Lalande, laboratory coordinator of the soil testing service, for her help analysing all my samples and tolerating an unusual smell during some of theses analyses. Sarah MacPherson, research associate and professional scientific writer, for her invaluable help reviewing my writings and applying to multiple grants.

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Format of thesis

This thesis explores three different topics to address in northern food production involving hydroponic cultures in controlled environment agriculture. The second chapter was published as a conference paper at the American Society of Agricultural and Biological Engineers (ASABE) 2019 conference in Boston. The third chapter was written as a technical report submitted to La Boîte Maraîchère, the industrial partner part of a Mitacs Accelerate internship. The fourth chapter was written as a manuscript in the intent of publishing it within the Canadian Society for Bioengineering (CSBE), as it was presented to the CSBE 2019 conference in Vancouver.

Table of Content

Abstract i
Résumé iii
Acknowledgement v
Format of thesis vi
List of Tables xi
List of Figures xii
Chapter 0. Introduction 1
0.1. General context behind the problem 1
0.2. Factors causing food insecurity in northern Canada 1
0.3. Paths towards food security 1
0.4. Local food production 1
0.5. Environmental challenges in northern agriculture 1
0.6. Controlled environment agriculture 2
0.7. Challenges in CEA for Northern Canada 2
0.8. Research Goals 2
0.8.1 Energy use in northern Canada for CEA 2
0.8.2 Labor in CEA 3
0.8.3 Fertilizer inputs in remote CEA 4
0.9. Hypothesis 4
Chapter 1. Literature review 5
1.1. Plant factories 5
1.2. Shipping-containers for plant factories 5
1.3. Hydroponic configurations in plant factories 5
1.3.1. Drip irrigation 6
1.3.2. Deep flow technique 6
1.3.3. Nutrient film technique 6
1.3.4. Aeroponics 6
1.3.5. Vertical Towers 7
1.4. Automation in plant factories. 7

1.4.1. Automation in Container Plant Factories 7
1.4.2. Environmental control automation 8
1.4.3. Nutrient management 8
1.4.4. Specific nutrient monitoring 8
1.4.5. Machine-learning in nutrient management 9
1.5. Fertilizer in plant factories 9
1.6. Alternative fertilizers 9
1.6.1. Fresh chicken manure in hydroponics 10
1.6.2. Vermicompost in hydroponics 10
Connecting text to Chapter 2 11
Chapter 2. The Canadian Integrated Northern Greenhouse 12
2.1. Abstract 12
2.2. Introduction 13
2.2.1 Container farming 13
2.3 Materials and Methods 15
2.3.1 Design of the CING 15
2.3.2 Energy Usage 18
2.3.3 Thermal curtain parameters 18
2.3.4 Growth experiments 19
2.3.5 Biological nutrient solution testing 19
2.3.6 Hydroponic systems parameters 20
2.3.7 Parameters 22
2.3.8 Monitoring of systems 23
2.4 Data Analysis 23
2.5 Results 24
2.6 Discussion 26
2.6.1 Summary of results 26
2.6.2 Environmental and growing parameters differences 27
2.6.3 Cold weather trials 27
2.6.4 Feasibility of the CING 31
2.7 Conclusion 32
2.7.1 Recommendations 32
2.7.2 Future opportunities 33

Connecting text to Chapter 3 34
Chapter 3. Multistage Hydroponic Configuration testing in Container Plant Factory 35
3.1. Abstract 35
3.2. Introduction 35
3.2.1. Issues addressed with this research 35
3.3. Methods 36
3.3.1. Dimension of the experimental tests 36
3.3.2. First configuration: Aeroponics with raised NFT trays 37
3.3.3. Second configuration: Flowing shallow water culture 38
3.3.4. Third configuration: Stagnant shallow water culture 39
3.3.5. Monitoring 40
3.4. Results 40
3.4.1. Notes on trials 40
3.4.2. Light mapping of systems 44
3.4.3. Summary of nutrient solution monitoring 45
3.5. Discussion 45
3.5.1. Summary of results 45
3.5.2. Aeroponic System 45
3.5.3. Flowing water 46
3.5.4. Stagnant Water 46
3.5.5. Pros and cons of each systems 47
3.5.6. Future research 47
3.5.7. Other Recommendations 48
3.6. Conclusion 48
Connecting text to Chapter 4 49
Chapter 4. Optimizing an organic hydroponic solution brewed from a combination of chicken manure extracts and vermicompost leachate 50
4.1. Abstract 50
4.2. Introduction 50
4.3. Methods 51
4.3.1. Proof-of-concept and experimental installation 51
4.3.2. Vermicompost leachate 52
4.3.3. Chicken manure extract 53

4.3.4. Brewing 53
4.3.5. Nutrient analysis 54
4.3.6. Hydroponic setup 55
4.3.7. Nutrient solution parameters 55
4.4. Results 56
4.4.1. Preliminary tests results 56
4.4.2. Brewing and bioreactor performance 58
4.4.3. Hydroponic growth trials 59
4.4.4. Nutrient content comparisons 60
4.5. Discussion 63
4.5.1. Nitrification using the bioreactor 63
4.5.2. Growth trials 63
4.5.3. Difference in between tests 63
4.5.4. Nutrient contents 68
4.5.5. Nutrient ratio 68
4.5.6. Apparent nutrient uptake 68
4.5.7. Sodium salt stress 69
4.6. Conclusion 69
Chapter 5. General conclusion 70
5.1. The Canadian Integrated Northern Greenhouse 70
5.2. Multistage Hydroponic Configuration Testing in Container Plant Factory 70
5.3. Optimizing an organic hydroponic solution brewed from a combination of chicken manure extracts and vermicompost leachate 70
5.4. Future Work 71
References 72
Appendix A. 76
Monitoring of systems 76
Temperature monitoring of the CING 77
Humidity monitoring of the CING 79
Light mapping of systems 81
Thermal curtain heat transfer rate calculation 86
Appendix B 87

List of Tables

Table 2-1 Summary of Annual Energy Consumption in kWh/m2 14
Table 2-2 Electrical current and voltage consumption of the CING environment control system components 18
Table 2-3 Averages of monitored nutrient solution parameters for all trials 23
Table 2-4 - Average fresh mass with Standard Error for all treatments, greenhouse and CING, with Vermicompost and Hoagland nutrient solutions at harvest 24
Table 2-5 - Summary of Table 2.3 and 2.4 for Cold condition trials of the CING 27
Table 3-1 – Average fresh mass of plants at harvest 43
Table 3-2 - Average parameters of nutrient solution in each test, from October 27th to November 30th 2018 45
Table 4-1 Nutrient analysis of the initial vermicompost leachate starting March 14th 2018.......... 56
Table 4-2 Comparison of organic vermicompost leachate and 0.25X Hoagland solution 57
Table 4-3 Electroconductivity and pH of organic vermicompost leachate solution and 0.25x Hoagland solution (H) and dry masses obtained for each treatment and location during Summer 2018. 57
Table 4-4 Nutrient content of chicken manure extracts at different concentrations.......... 57
Table 4-5 Average nutrient solution parameters of 0.25x Hoagland's and Biojuice 59
Table 4-6 Comparison of nutrient content and commonly recommended ranges for hydroponic solutions. Element concentrations lower than recommended ranges are highlighted in yellow. 68
Table A-1 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Spring trial 76
Table A-2 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Summer trial 76
Table A-3 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Fall trial 76
Table A-4 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Winter trial 77
Table A-5 - Light mapping, Summer trial.......... 81
Table A-6 - Light mapping, Summer trial.......... 81
Table A-7 - Light mapping, Summer trial.......... 82
Table A-8 - Light mapping, Fall trial, only supplemental light in the greenhouse.......... 82
Table A-9 - Light mapping, Fall trial only 83
Table A-10 - Light mapping, Fall trial, supplemental light in the CING 83
Table A-11 - Light mapping, Fall trial.......... 84
Table A-12 - Light mapping, Greenhouse Winter trial 84
Table A-13 - Light mapping, CINGWinter trial.......... 85
Table A-14 - Parameters for heat transfer rate calculations.......... 86
Table A-15 - Heat transfer rate calculation results 86
Table B-1 Monitoring of the water at La Boîte Maraîchère 87

List of Figures

Figure 0.1 Side view of a northern greenhouse using passive heating and thermal blanket 3
Figure 2.1 Outside of the CING, December 2017 13
Figure 2.2 A module for the Minimally Structured & Modular Vertical Farm 14
Figure 2.3 Original design of the CING 15
Figure 2.4 Representation of the opening and closing of the outside panels 15
Figure 2.5 Opening and closing of the CING insulating panels........ 16
Figure 2.6 Opening and closing of the CING rooftop panels 16
Figure 2.7 Original design of the CING growth tower, side-view and solution tank, pictures by Thanh Jutras, 2016. 17
Figure 2.8 Comparative growth tower in the research greenhouse, Summer 2018........ 17
Figure 2.9 Inside the CING, on the right is the closed thermal curtain, Winter 2019 19
Figure 2.10 Growing system prototype design described previously 20
Figure 2.11 The hydroponic growing tower system for the research greenhouse and growing system in the CING 21
Figure 2.12 - Average fresh mass of lettuce for all treatments at harvest 24
Figure 2.13 Lettuce grown in the CING before harvest, Winter 2019........ 25
Figure 2.14 Inside the CING, on top left is an opened roof panel, Summer 2018 26
Figure 2.15 - Outside temperature, inside temperature and outside PAR of the CING, December 10th to December 12th 2018 28
Figure 2.16 - Outside temperature, Inside temperature and outside PAR of the CING, March 4th to March 6th 2019........ 29
Figure 2.17 - Temperature Inside vs Temperature Outside of CING, Fall trial, December 10th to 12th 2018 30
Figure 2.18 - Temperature Inside vs Temperature Outside of CING, Winter trial, March 4th to 6th 2019........ 30
Figure 2.19 - Temperature Inside vs Temperature Outside of CING, Fall trial, December 1st to December 22nd 2018........ 30
Figure 2.20 - Temperature Inside vs Temperature Outside of CING, Winter trial, March 1st to March 23rd 2019 31
Figure 3.1 NFT tubes installation at la Boîte Maraîchère 35
Figure 3.2 Current installation for the floating bed in flowing shallow water experiment 36
Figure 3.3 Experimental design of the aeroponic and NFT hybrid........ 37
Figure 3.4 Experimental design of a floating bed in flowing shallow water 38
Figure 3.5 Experimental design of a floating bed in stagnant shallow water 39
Figure 3.6 – Shoots and roots of 1st and 2nd aeroponic experiment at harvest 41
Figure 3.7 – Shoots and roots of 1st and 2nd flowing water experiment at harvest 42
Figure 3.8 - Shoots and roots of 1st and 2nd stagnant water experiment at harvest........ 43
Figure 3.9 Light mapping of the aeroponic pool 44
Figure 3.10 Light mapping of the flowing water pool 44
Figure 3.11 Light mapping of the stagnant water pool 44
Figure 4.1 Growth Tower in Research Greenhouse during preliminary test, vermicompost nutrient solution and Hoagland nutrient solution, June 2018........ 52
Figure 4.2 Bioreactor linked to vermicompost installation for brewing 54

Figure 4.3 Measurement of ammonia and nitrates using an API test kit of fresh manure extract and biojuice once nitrification is complete 55
Figure 4.4 Average fresh mass of lettuce in proof-of-concept experiment comparing VL and 0.25x Hoagland nutrient solution. 58
Figure 4.5 Variation of nutrient content in the solution in the bioreactor 59
Figure 4.6 Average Fresh Mass of hydroponic growth comparative tests................................. 60
Figure 4.7 Comparison of seven major elements present in nutrient solutions at the start of each hydroponic growth trial. Data represent average values ± S. E. of the three growth trials. 60
Figure 4.8 Comparison of three minor elements present in nutrient solutions at the start of each growth trial. Data represent average values ± S. E. of the three growth trials........................... 61
Figure 4.9 Nutrient concentration in Hoagland’s over time, growth trial 2................................ 61
Figure 4.10 Nutrient concentrations in Biojuice over time, growth trial 2 62
Figure 4.11 Nutrient concentrations in Hoagland’s solution over time, growth trial 3 62
Figure 4.12 Nutrient concentrations in Biojuice over time, growth trial 3 63
Figure 4.13 Lettuce at Harvest, Hoagland Nutrient Solution and Biojuice Nutrient Solution Trial 2 64
Figure 4.14 Top view at harvest of the second trial, Hoagland nutrient solution and Biojuice nutrient solution... 65
Figure 4.15 Side view at harvest of the second trial, Hoagland nutrient solution and Biojuice nutrient solution... 66
Figure 4.16 Top view at week 2 of the third trial, Hoagland nutrient solution and Biojuice nutrient solution... 67
Figure 4.17 Side view at harvest of the third trial, Hoagland nutrient solution and Biojuice nutrient solution... 67
Figure A.1 - Temperature monitoring outside and inside the CING, Spring trial, corresponding averages : 19.3°C and 21.2°C.. 77
Figure A.2 - Temperature monitoring outside and inside the CING, Summer trial, corresponding averages: 24.7°C and 25.4°C... 77
Figure A.3 - Temperature monitoring outside and inside the CING, Fall trial, corresponding averages: -3.4°C and 11.0°C 78
Figure A.4 - Temperature monitoring outside and inside the CING, Winter trial, corresponding averages: -2.4°C and 14.8°C 78
Figure A.5 - Humidity and temperature monitoring inside the CING, Spring trial, average relative humidity: 49.2 %.. 79
Figure A.6 - Humidity and temperature monitoring inside the CING, Summer trial, average relative humidity: 59.1 %.. 79
Figure A.7 - Humidity and temperature monitoring inside the CING, Fall trial, average relative humidity: 42.2 %.. 80
Figure A.8 - Humidity and temperature monitoring inside the CING, Winter trial, average relative humidity: 35.1 %.. 80
Figure A.9 - Representation of the thermal resistance of the different layers of the CING window 86
Figure B.1 Temperature and Relative Humidity, 2018-10-30 to 2018-11-30............................... 89
Figure B.2 Temperature and Relative Humidity, 2018-11-30 to 2018-12-21............................... 89

Chapter 0. Introduction

0.1. General context behind the problem

Food insecurity is described as a lack of ''physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life''(FAO, 2018). In Canada, food insecurity affects over 4 million individuals per year especially women, children and Indigenous people from northern communities (Leblanc-Laurendeau, 2019).

0.2. Factors causing food insecurity in northern Canada

Northern communities are faced with multiple challenges to meet their food needs through traditional harvesting and hunting activities, including the decline in plant and animal populations, higher levels of contaminants in some country food, population increases, hunting restrictions, increasing cost of hunting equipment and transportation. The remote location of many northern communities, the harsh climate and negative impacts caused by climate change can contribute to their food insecurity. Poverty is another major factor in food insecurity, low nutrition rates being strongly correlated to low incomes. Market food is significantly more expensive in northern communities because of the high costs of transportation and distribution, paired with low incomes and high unemployment rates, this can lead to unhealthy diets (Canada's Public Policy Forum, 2015).

0.3. Paths towards food security

Food insecurity is a complex issue that requires made-to-measure and integrated approaches. Various policies and programs funded by federal government have been established. Two examples are Nutrition North Canada and Anti-poverty Strategic Framework. The Nutrition North Canada program began in 2011, it was implemented to improve access to perishable, nutritious food in isolated communities in the North. The Anti-Poverty Strategic Framework began in 2013, providing school-based breakfast programs to encourage healthy eating, and prenatal nutrition program focusing on education, counselling and support (Canada's Public Policy Forum, 2015).

0.4. Local food production

Local food production is a key contributor to provide fresh and healthy foods to these communities. Various programs such as the Inuit Fisheries, established in 2012, help to increase the level of Inuit ownership and participation in the offshore fishing industry. Measures were established in 2014 to promote an economically viable commercial northern agriculture system. Funds were received by the Northern Farm Training Institute (NFTI) , an experiential farm school, to establish a permanent campus in the Northwest Territories and the Northern Greenhouse Initiative, to increase the amount of locally grown food in greenhouses (Canada's Public Policy Forum, 2015).

0.5. Environmental challenges in northern agriculture

The major difficulties with crop production in northern Canada are the very short growing season, typically less than 60 days between frosts; very long summer days with up to 24-h daylight; and cold, dark winters with up to 24-h nighttime periods (Humphries & Landry-Cuerrier, 2013). Outdoor field production is limited to crops that can handle the very short growing season and long days, and not be impacted by the winters (Dearborn, 1979).

0.6. Controlled environment agriculture

To overcome the challenges of northern agriculture, many types of pilot greenhouse projects combining different technologies have occur in northern Canada. The use of technology to provide a stable growing environment, regardless of outdoor conditions, is known as Controlled Environment Agriculture (CEA). The use of electrical lighting with light emitting diodes (LED), heating, ventilating and cooling systems (HVAC), soil-less growing methods, thermal insulation and passive heating are all technologies studied for CEA in northern Canada (McCartney & Lefsrud, 2018). The use of solar energy with insulation can provide enough lighting and heating to extend the growing season using northern greenhouses, but during winter's shorter days and lower temperature, they suffer larger heat losses and rely on supplemental heating, which greatly increase the cost of the operation cost of northern greenhouses (Beshada, Zhang, & Boris, 2006). Another potential option of controlled environment for northern agriculture are fully indoor plant factories, using only electrical lighting. These systems require rigid environmental control, but heating produced by electrical lighting can replace part of the heat needed in a cold climate to operate. Plant factories are relatively new and come with higher start-up costs and operational cost, mainly due to labor needs and energy consumption, there is no consensus on the best controlled environment to produce local fresh crops in remote regions with cold climate (Fang, 2019).

0.7. Challenges in CEA for Northern Canada

To produce crops with economic viability requires performant installation. The remote location of crop production facilities in northern Canada bring extra challenges when it comes to resource utilization, either in greenhouses or plant factories, as pilot projects have shown feasibility to produce high quality crops in high latitude (Humphries & Landry-Cuerrier, 2013). The major challenge is to increase the scale, efficiency, and sustainability of these projects, which requires CEA facilities designed to fit the needs of each local polar climate. The 3 major costs in greenhouses and indoor farms, are energy, for heating, cooling and lighting, labour and fertilizer inputs (Eaves & Eaves, 2018). These main costs are recurrent in most CEA facilities, and can be optimized to increase feasibility of CEA.

0.8. Research Goals

The goal of this thesis was to explore pathways to solve current challenges in adopting CEA in northern Canada. The current identified challenges are the following:

0.8.1 Energy use in northern Canada for CEA

By opting for a strategy that utilizes solar energy, passive greenhouses can rely on low energy needs to extend their growing season. The use of thermal curtains and passive heating, as shown in Figure 1.1 was studied and showed its effectiveness to reduce heat loss at night and during dark cold days, while passively storing heating energy that can be released when outside temperatures drop (Beshada et al., 2006).

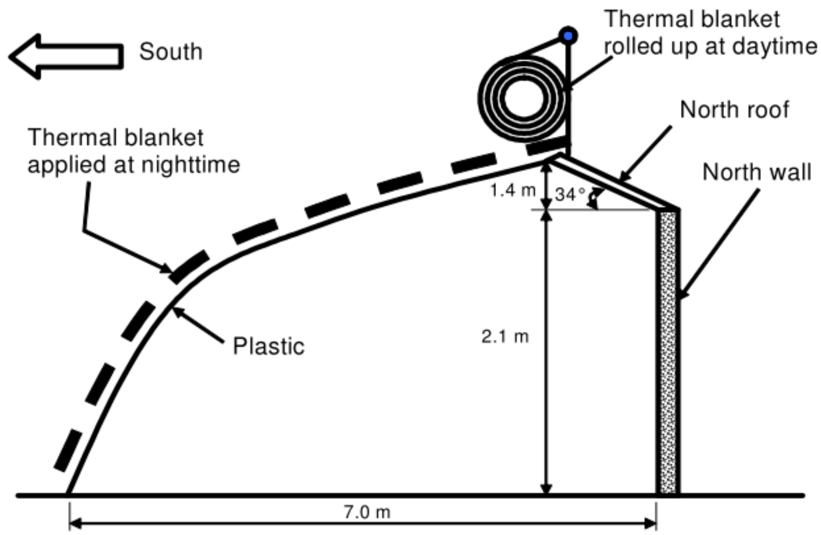

Figure 0.1 Side view of a northern greenhouse using passive heating and thermal blanket (Beshada et al., 2006)

To operate in the colder period of the year, this system still requires supplemental heating, increasing the energy needs to a peak of 152 $W.m^{-2}$ in February, with average energy requirement of 17 $W.m^{-2}$ (Beshada et al., 2006). In Québec in February, the average electrical energy need in a commercial greenhouse is 168 $W.m^{-2}$ including heat and lighting (Pelletier & Godbout, 2017). These metrics are different, one being from an experimental greenhouse in Southern Manitoba and the other from the average of commercial greenhouses in Québec but express the potential to use a heat energy saving strategy to save on energy costs in CEA.

When considering winter production of crops, fully indoor farms using electrical lighting and vertical farming, have the advantage of being better insulated than most greenhouses and have fully controllable parameters, thus they can produce crops year-long even in a cold climate. When comparing greenhouses with indoor farms using vertical farming in Québec, indoor farms require more energy for lighting than greenhouses, but less energy for heating (Eaves & Eaves, 2018). This is because the heat generated by the electrical lighting reduces the needs for heating. However, indoor farming typically comes with higher capital expenses, and their economic profitability has longer timeframes (Fang, 2019). The best strategy to implement CEA for northern Canada applications is not clear and needs further research.

0.8.2 Labor in CEA

In CEA, labor is the first or second expense, comparable to the energy requirements (Nakamura, 2019). To be successful, any type of CEA in northern Canada must take in account the intensive labour requirement, regardless of the season. Labour forces in northern Canada are variable according to various social factors, such as the practice of traditional activities including hunting and gathering seasons, which are essential to many native communities (Arriagada & Bleakney, 2019). This poses a challenge to CEA, which is highly dependant on labour and must be continuously run to maintain economic feasibility. To reduce the labour requirements in CEA, many large-scale plant factories rely on automation to replace or facilitate various tasks. However, automation is expensive and can greatly increase the capital expense of CEA facilities

(Shimizu, Fukuda, Nishida, & Ogura, 2016). Hydroponic cultivation of leafy crops on trays is common in greenhouses and plant factories, by allowing the plants to move in the production system according to its growth stage, reduces the manual handling of crops hence reducing labour costs (Nakamura, 2019). Low-cost semi-automated production methods could facilitate the tasks needed in CEA, hence palliate the challenge to fill the labour requirements in CEA for northern Canada.

0.8.3 Fertilizer inputs in remote CEA

Most plants grown in CEA required fertilizing inputs. Hydroponic cultures rely on synthetic molecules and mined minerals, to make water soluble nutrients available for plant uptake (Mattson & Lieth, 2019). Fertilizers are a main input costs in CEA, using them in remote communities where import of goods comes with high transport costs resulting in higher operational costs (Fellows & Tombe, 2018). Synthetic ammonia, which is a main fertilizer in CEA, comes with a high carbon footprint linked to its production (Woods, Williams, Hughes, Black, & Murphy, 2010). To improve the facilities sustainability, local organic sources of fertilizers to CEA are critical to reduce the carbon footprint related to their operation and reduce their operation expenses linked to imported fertilizers.

0.9. Hypothesis

a) Using a combination of natural and electrical lighting combined with insulation and thermal heating can optimize the energy efficiency of CEA in conditions.
b) Allowing movement of plants on trays in indoor agriculture with low-cost design strategies which can facilitate the labour for indoor vertical farming environments.
c) Using organic fertilizers than can be sourced in the local area of CEA facilities in northern Canada which can replace a large part of the unsustainable synthetic compounds and mined minerals used in remote CEA facilities.

Chapter 1. Literature review

1.1. Plant factories

The challenges classical soil agriculture are facing have created an increased interest in indoor agriculture practices, where advanced soilless culture techniques in self-contained systems, optimize the needs in water, nutrients and energy (Despommier, 2012). Greenhouse cultivation has evolved to highly sophisticated controlled environment agriculture (CEA) facilities with many components and subsystems to optimize growing parameters (Ramin Shamshiri et al., 2018). Plant factories (PF), are large scale closed growth environments, insulated, semi to fully automated and electrically illuminated designed to provide food production perspectives in urban environment or in regions where climate is not suitable for agriculture (Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018). PF regroup several types of installations, categorized based on their main light energy source for plants, with three current types: (1) greenhouses using sunlight (typical Dutch-type greenhouse), (2) greenhouses that supplement sunlight with artificial lighting, and (3) closed-growth rooms with fully electrical lighting. Plant factories using sunlight are inconsistent with sunlight to grow year-round. Therefore, some plant factories use electrical lighting to create a more consistent light environment for the plants (Brandon et al., 2016).

1.2. Shipping-containers for plant factories

Recycled shipping-containers are a great option to host small and mobile plant factories. They can be installed at any location with the concept that vegetable cultivation is possible as soon as electricity and water are available (Nakamura & Shimizu, 2019). Plant factories housed in shipping containers, or container plant factories (CPF), are proposed by emerging companies such as: *La Boîte Maraîchère, Freight Farms, Growtainers, Cubic Farms*, etc.

1.3. Hydroponic configurations in plant factories

Hydroponics is a soilless plant cultivation method. Many large-scale and commercial controlled agriculture systems such as greenhouses or plant factories rely on hydroponic systems. They allow for automation and control of irrigation and fertilization. This reduces labour and facilitates vertical farming, the latter of which leads to higher crop yield per volume of growing space (Wada, 2019). The favoured hydroponic configurations in PF are drip irrigation, deep flow technique, nutrient film technique, or aeroponics. These methods can allow for vertical production of crops, optimize land and reduce water consumption (Kalantari, Mohd Tahir, Akbari Joni, & Fatemi, 2017).

1.3.1. Drip irrigation

Drip irrigation is used in commercial greenhouses with soilless growing media such as sand, rock wool or coco-coir, to grow tomatoes, peppers and cucumbers. Theses systems use barbed drip emitters on tubing to distribute nutrient rich water to the growing media held in pots. The watering cycle is few minutes per hour to provide oxygen to the growing media. This nutrient supply to the plants is known as fertigation (Waller & Yitayew, 2016).

1.3.2. Deep flow technique

Deep flow technique (DFT) uses floating beds in a pool of nutrient solution and can be divided in two categories depending on the depth of water needed: Deep water culture (DWC) or Shallow water culture (SWC). DWC is used in commercial greenhouses with soilless growing media held on a Styrofoam floating trays, to grow leafy greens such as lettuce, basil or kale. DWC requires large pools of depth over 30 cm depth, keeping the roots continuously exposed to moving water and nutrients and is suited for small to large greenhouse operations. The floating beds typically move from on side to the other in the pool from transplant to harvest (Brechner & Both, 2013). SWC requires less depth of water (<5 cm), hence it is possible to stack levels of cultures in a vertical manner, which is suited for vertical plant factories (Kozai & Niu, 2016). The large volume of nutrient solution used in DFT makes it considerably simpler to control the nutrient solution since only a small fraction of the water and nutrients are up taken by the plants (van Os, Gieling, & Lieth, 2019).

1.3.3. Nutrient film technique

Nutrient film technique (NFT) is where a thin film of nutrient solution is fed to roots in an inclined pipe holding the plants in a hydroponic substrate, usually rockwool held in a net pot. It uses gutters or pipes with diameters of 4 – 15 cm with holes of 3 – 10 cm depending on the crop grown. Pipe slopes varies from 0.3% - 2% with flow rates of 3 – 8 L m^{-2} h^{-1}. Most crops can be grown in NFT but since it lacks the ability to buffer small interruption in water and nutrient supply and there is a considerable risk of spreading root-borne diseases, this technique is not widespread in plant factories (van Os et al., 2019). The small space required for NFT is suited for vertical plant factories (Kozai & Niu, 2016).

1.3.4. Aeroponics

Aeroponics is a system where plants are suspended in a space similar to SWC in shape and dimension, where nozzles intermittently spray the roots with nutrient solution. Humidity is kept at 100 % but since there is no constant water layer at the surface of the roots, oxygen availability is optimized (van Os et al., 2019). Higher yield of lettuce was documented using aeroponics versus other hydroponic methods (Kratky, 2005). Like NFT, aeroponics lacks the ability to buffer small interruption in water and nutrient supply and there is a considerable risk of spreading root-borne diseases. This method is adapted and widely used in vertical plant factories (Kalantari et al., 2017).

1.3.5. Vertical Towers

Vertical towers are common in small scale plant factories. Various vertical hydroponic towers are available on the market. They are plastic structures allowing multiple plants to be stacked vertically, where nutrient solution is fed inside the towers, top to bottom percolating through the root zones of the plants. The ZipFarm technology used in *Modular Farms* is well adapted to CPF, making it an optimal use of space and better heat management in CPF (Modular Farms, 2018).

1.4. Automation in plant factories.

According to the *Osaka Prefecture University* in Japan, which studies one of the largest fully automated PF, these massive installations use moving parts to allow continuous high yield crop production. They require expensive systems which are not economically viable today (Park, Nakamura, Nishiura, & Murase, 2013).

The main operation to be considered in PF automation are seeding, transplanting, moving of cultivation panels, harvesting, weight checking, packaging, equipment inspection and cleaning. The full automation of PF is debatable, and it is suggested that human labor is needed at certain point in the process. There are no established preferred automation strategies in PF, since the size of the cultivation area and plant density differs between facilities. General automation equipment for PF are often made-to-order and the introduction cost is high. The Japanese PF previously cited, reduced by 40% its operation costs by introducing a seedling sorting robot system, an automated cultivation system and a LED lighting system. Multistage production is known for increasing production efficiency. Multistage production in large PF can be achieved using a 'Shuttle-Type Transfer Robot'. This system can move the cultivation from the beginning to the end of a lane until the crops are ready for harvest which includes changing shelf of the multistage production installation (Shimizu, Fukuda, Nishida, & Ogura, 2016).

1.4.1. Automation in Container Plant Factories

CPF all have different hydroponic configurations and are not automated. The smaller scale of CPF doesn't allow them to use the same hydroponic strategies as in large PF in terms of automation and environment control. CPF being mobile units, it is a priority that their hydroponic configuration can withstand transportation and maximise their production, promoting automation to optimize labor work. However, combining those two requirements in a limited space offers great challenges to ensure the economic viability of such systems (Shimizu et al., 2016).

1.4.2. Environmental control automation

The variety of choices offer by hydroponic culture in CPF lead to differences in production strategies. Nutrient solution concentration and heat management are two main issues to consider (Son, Kim, & Ahn, 2016). The presence of ionized nutrients increases the electrical current of a solution, electrical conductivity. It is the most common measurement of nutrient concentration for hydroponic solutions. Temperature control in CPF is accomplished by heating, ventilating and air conditioning (HVAC) systems (Modular Farms, 2018). Since CPF are small enclosed environments, temperature control is directly affected by the hydroponic configuration. To avoid heat problems related to lighting and evaporation, it is necessary to know the energetic behavior of the plants growing in the different hydroponic configurations (Graamans et al., 2018).

The internet of things (IoT) allows automation of environmental and production parameters for large hydroponic cultures (Balducci, Impedovo, & Pirlo, 2018). Monitoring of water level, pH, temperature, flow, air exchange, humidity and light intensity can be regulated using IoT, which allows for machine to machine interaction and intelligently controlling the hydroponic system with deep neural networks (Luna Maldonado et al., 2019).

1.4.3. Nutrient management

To ensure good nutrition of plants, open loop systems are adopted since nutrient uptake will be greater. However, a closed nutrient loop is more common in CPF as they reduce water needs and increase nutrient recycling. The information on the effectiveness to manage nutrients using different hydroponic configurations is limited and must be tested. Monitoring of growing factors in PF aims at nutrient concentration, pH, dissolved oxygen, temperature and electrical conductivity of the nutrient solution. The best practice would be to know the changes of each nutrient in real time. These high precision sensors are relatively expensive but hold great promise as the industry develops (Son et al., 2016).

In commercial inorganic hydroponic solutions, balancing of the recycled nutrients is typically performed via the dilution of two main stock solutions (Wada, 2019). Since nutrient requirements for optimal plant growth in a solution and plant nutrient uptake are different it is important to balance nutrient solution composition to optimize crop yield without compromising plant health or causing metal ion toxicity. Plant nutrient uptake can be estimated by monitoring nutrient solution composition.

1.4.4. Specific nutrient monitoring

Hydroponic solutions used in greenhouses or plant factories are usually evaluated based on their electrical conductivity (EC) and pH. However, EC and pH cannot provide enough information about ion imbalances present in hydroponic solutions which causes toxic or deficient nutrient levels thus leading to poor yields and loss of crops. Recent work has demonstrated the potential of using an on site-monitoring system outfitted with ion selective electrodes (ISEs) that automatically measure specific ions (e.g. NO_3^-, K^+, Ca^{2+}). This enables the farmer to better manage hydroponic solutions by detecting imbalances in nutrient ratios (Cho et al., 2018).

1.4.5. Machine-learning in nutrient management

Machine-learning algorithms have proven useful for managing nutrients in hydroponic solutions. They can increase crop yield by better preserving the ratios of specific nutrients that optimize their uptake by the plant. For instance, specific NO^{-}_{3} and NH_4^+ ratios can inhibit NO^{-}_{3} ion uptake and cause toxicity, leading to important differences in crop yield. This highlights the importance of maintaining ion balance and good control over nutrient solution composition (Sambo et al., 2019). Interpretation algorithms that use machine-learning logic to analyze such data can play a pivotal role in continuously monitoring and adapting hydroponic solution composition to achieve desired crop yield and quality. These technologies are not yet implemented in hydroponic cultures using organic fertilization. The reason for this is likely related to the smaller scale and limited investments that organic hydroponic operations allocate to such technologies. However, if large commercial producers are considering a change toward organic fertilisation, efficient and low-cost technologies that optimize nutrient management could facilitate this shift. Hence, tools and strategies that optimize the use of various sources of organic nutrients in commercial hydroponic cultures must be developed.

1.5. Fertilizer in plant factories

Fertilizer demand is increasing worldwide, and most hydroponic systems are dependent on inorganic chemicals that are either mined or synthetized. The production and extraction of these fertilizers come with a considerable environmental cost. Policies are starting to push for a shift from inorganic chemical fertilizers to more sustainable sources of fertilizers derived from organic waste matter. Examples include manure and compost (Chowdhury, Milne, & Chakraborty, 2019).

1.6. Alternative fertilizers

Alternatives to inorganic fertilizers in soilless cultures already exist. Aquaponics is a food production system that combines a recirculating aquaculture system with a hydroponic system. Fish are fed a commercial fish feed diet. Their waste accumulates in tanks which is then directed to a hydroponic system as a liquid fertilizer (Endo, 2019). Other agricultural residues and industrial wastes have been studied on an experimental scale. Supporting data indicates that this method has the potential to replace inorganic fertilizers in hydroponics (Phibunwatthanawong & Riddech, 2019).

1.6.1. Fresh chicken manure in hydroponics

Recent research at McGill University investigated the potential of poultry manure extracts in hydroponic crop production. These tests used ion activity monitoring to evaluate the nutrient value of these extracts in real-time. This proved the feasibility of using ion monitoring to quantify organic nutrient solutions. Further nutrient solution analyses indicated that some nutrients were not present in adequate amounts to promote plant growth. While the manure extracts were rich in ammonia and phosphorus, concentrations of potassium, iron and other micronutrients were lower than recommend for hydroponic cultivation (Tikasz, Macpherson, Adamchuk, & Lefsrud, 2019).

1.6.2. Vermicompost in hydroponics

Vermicompost, a method to degrade organic matter by the action of earthworms which result in castes and vermicompost leachate (VL). VL contains plant available nutrients and showed a positive effect on plant growth in soil, hence its potential as a hydroponic nutrient solution. Nutrient concentration of VL is dependant of the organic matter fed to vermicompost, with VL nutrient content and microbial community varying greatly (Donohoe, 2018). VL is very concentrated and alkaline, requiring dilution and pH buffering to bring the nutrient solution to an optimal nutrient concentration and pH for hydroponics. The nutrient content of VL from different sources of composted organic matter was studied and its effect on plant growth in different growing methods was studied (Churilova & Midmore, 2019). The effect of vermicompost leachate on plants in hydroponic conditions in different combinations of substrates and inorganic fertilizer ratio has been studied, higher plant height in *S. rebaudiana* were observed at a 1:3 ratio of inorganic fertilizer to vermicompost leachate (Bidabadi, Afazel, & Poodeh, 2016). Developing an equilibrated fertilization strategy that combines the proper ratios of inorganic fertilizer and VL could be justified for sustainable hydroponic cultivation, as vermicompost increases populations of beneficial microorganisms and the potential availability of plant growth-influencing-substances (Arancon, Edwards, Atiyeh, & Metzger, 2004).

Connecting text to Chapter 2

Chapter 2 concerns the Canadian Integrated Northern Greenhouse (CING) four season testing. The CING has been the topic of multiple undergraduate and graduate research projects at McGill Macdonald campus since 2013. Its different features allowed for testing under various growing conditions which provided an outlet for benchmark performance factors of CPF systems. Even if not all features were functional for the four-season test, crops were successfully grown in the CING. The best yields in cold conditions were achieved when the thermal curtain remained closed. This limited the heat losses at the expense of natural light exposure with 24h/24h of electrical lighting being provided during this trial.

Chapter 2. The Canadian Integrated Northern Greenhouse

2.1. Abstract

Food security has become a prominent issue in northern Canada. The high cost of transportation is a critical factor that contributes to the inaccessibility of fresh produce. Many constraints, including environmental, cultural and economic barriers to cause food insecurity in northern Canada where local food production is one proposed solution to the northern food crisis. Initiated at McGill University by the Biomass Production Laboratory, the Canadian Integrated Northern Greenhouse (CING) unit provides a completely integrative design solution that could allow northern Canadian communities to grow their own fresh and nutritious food year-round. The CING unit is a hybrid between a northern greenhouse and a growth chamber housed in a shipping container. It was designed to be adaptive by functioning as a typical solar greenhouse when solar light provides considerable heat and light, and as a closed growth chamber during the night and when colder, darker winter conditions prevail. Other components, such as a vertical hydroponic growing system, inter-canopy LED lighting, heating and ventilation, as well as a complete automation of the components have all been designed specifically to fit the CING unit's requirements.

The main objective of the tests performed in this CPF was to compare the fresh mass and plant health of lettuce grown in the CING subject to varying environmental conditions over 4 consecutive growing cycles to plants grown in a typical glass research greenhouse. The individual tests spanned 3 to 4 weeks. In addition, it was demonstrate that even with less energy consumption, growing conditions in the CING unit were comparable to those found in a typical research greenhouse. The secondary experiment concerned the comparison of a biological nutrient solution and an inorganic nutrient solution, in both growth environments. The first cold condition growing was a 3 weeks test trial (December 2018) performed when outside temperatures were below freezing point (0 °C). Consecutive tests were completed in Spring, Summer, Fall of 2018 and Winter 2019. In cold conditions, lettuce plants grew in the CING, but to a lesser extent than in the research greenhouse based on their average fresh and dry masses. In the research greenhouse, both nutrient solution treatments resulted in greater yields than in the CING. However, the difference between treatments in the CING was less obvious. In the greenhouse, the inorganic nutrient solution resulted in a greater yield than the biological nutrient solution for every test. The greatest yield obtained in the CING was in March 2019, where plants achieved 72 % of the fresh mass of the plants grown in the research greenhouse.

Being the first prototype of its kind, the CING needs multiple improvements to be a fully functional unit. Since different northern researchers have expressed interest in hosting such a unit, efforts are being made to implement a unit in northern Canada. However, designing a unit that would fit the needs of a community must be done in full communication with future owners and operators of this food production unit. Building a pilot unit in a northern region is the next clear step for this project.

Keywords. *Container Farming, Controlled Environment Agriculture, Northern Agriculture, Northern Greenhouse, Organic Fertilizer.*

2.2. Introduction

The CING is designed as a hybrid between a closed growth chamber and a greenhouse to optimize energy requirements related to the production of fresh produce throughout the year. The unit can open to allow sunlight to enter, utilizing the unit's greenhouse function, or be completely covered by an insulated thermal curtain, employing the unit's growth chamber function. Specific exterior and interior conditions dictate when the use of each mode is most efficient to promote the best interior conditions. To determine and predict these conditions, climatic and environmental data were recorded outside and inside the CING prototype situated at McGill University's Macdonald Campus in Sainte-Anne-de-Bellevue, QC, since summer 2015.

2.2.1 Container farming

Container farming (CF) is an indoor agricultural practice falling under the Controlled Environment Agriculture (CEA) category (Ramin Shamshiri et al., 2018). Plants are grown hydroponically in a shipping container with electrical lighting and most of the environmental

Figure 2.1 Outside of the CING, December 2017

parameters are controlled by the grower. Converting a shipping container into an indoor farm has many advantages. First, a shipping container is an inexpensive infrastructure. Buying a refurbished shipping container and modifying its structure by cutting through the walls is still considered cheaper than buying a new building. Second, transportation, if the structural components of a shipping container are intact (i.e. the four corner beams), the CF has a strong foundation that can be moved as a typical shipping container. In this way, it acts as a mobile agricultural unit. Third, a converted shipping container's internal environment is independent of environmental parameters. In an insulated environment comprising electrical lighting, soil-less cultures, and heating ventilating and air conditioning (HVAC) technologies, it is possible to grow crops in any climate. Finally, a converted shipping container offers high yield per square meter. Using vertical farming in which five levels of shallow water hydroponic cultures of lettuce are stacked, it is possible to grow 20 times more produce per square meter in a CF than field agriculture with corresponding yields of 1000 plants.m^{-2} (Touliatos, Dodd, & McAinsh, 2016).

CF is still a relatively new agricultural practice, and indoor farmers don't necessarily agree that this new agricultural practice is economically viable, still being considered an overhyped technology, with only 50% of container farms being profitable in the U.S. (Agrilyst, 2017). Yet CF has many different styles, with companies such as Freight Farms, Growtainers, and Cubic Farms offering similar options to grow crops in urban or remote areas (Benis, Reinhart, & Ferrão, 2017). According to case studies from companies like Bright Agrotech and independent reports from universities such as the University of Bonn in Germany and the Massachusetts Institute of Technology, vertical farming and CF can be economically profitable and viable depending on different economic parameters, such as market, labor and cheap energy availability (MIT, 2016).

The concept of a modified shipping container for controlled environment agriculture is not new (Figure 2.2). Strategies using modified shipping containers with natural lighting has been made for conditions comparable to those found in New York City and Los Angeles by the University of Arizona. From these simulations, it was determined that shipping containers with transparent walls have a much lower energy consumption than opaque and well-insulated walls (Table 2.1) (Liu, 2014).

Figure 2.2 A module for the Minimally Structured & Modular Vertical Farm, designed by Dr. Cuello from The University of Arizona (Liu, 2014)

Annual Energy Estimation (kWh/m^2)	Los Angeles		New York City	
	Transparent wall	Opaque wall	Transparent wall	Opaque wall
Tomato	240.06	381.30	557.65	325.34
Lettuce	418.38	1950.99	773.84	1640.85

Table 2-1 Summary of Annual Energy Consumption in kWh/m2 (Liu, 2014)

From these energy values, except for growing tomatoes in a transparent wall shipping container in New York City where the well-insulated opaque wall helped reduce heat loss in colder month, using transparent walls in a shipping container would reduce the energy needs to grow certain food crops in CF, even for Lettuce during cold months (Liu, 2014). Following these findings, the CING was not modeled for its energy use, rather, a design and experimental approach was chosen to test the use of natural lighting in CF in a cold climate.

2.3 Materials and Methods

2.3.1 Design of the CING

The CING was first designed in 2013 by Bioresource engineering students at McGill University (Figures 2.3 and 2.4). A shipping container was purchased in 2015. One of its walls and the roof were replaced by polycarbonate sheets to allow the shipping container to use natural light for growing purposes.

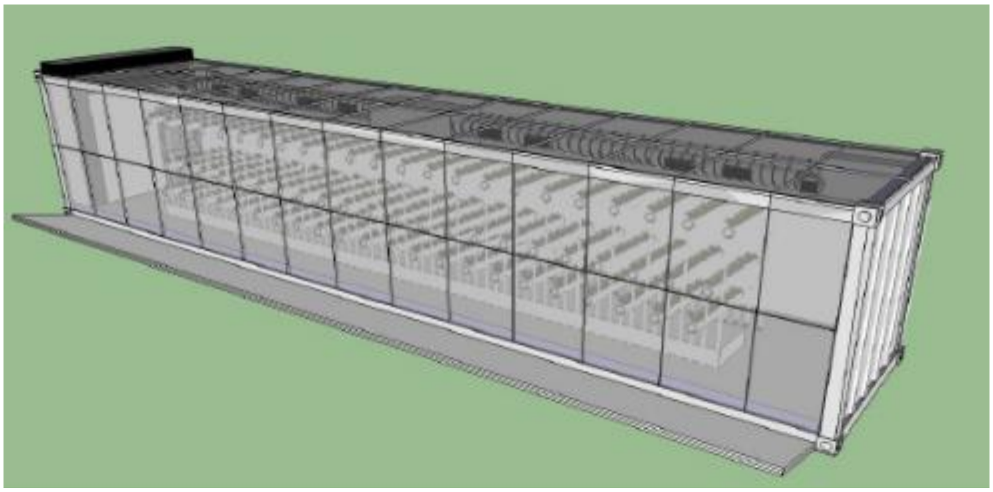

Figure 2.3 Original design of the CING (Fabien-Ouellet, Shodjaee-Zrudlo et al. 2013)

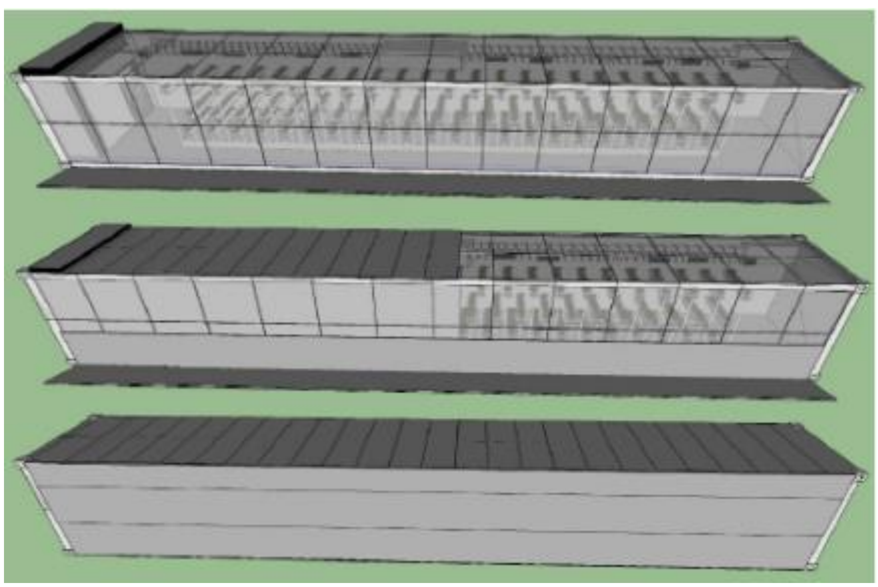

Figure 2.4 Representation of the opening and closing of the outside panels (Fabien-Ouellet, Shodjaee-Zrudlo et al. 2013)

Only half of the 40-foot shipping container was used for growing space. The CING design includes insulating panels that can open and close (added in 2015) to benefit from natural light when available (Figures 2.5 and 2.6). Their opening and closing was operated by 2000-lb winches controlled by an Arduino Mega (Adafruit Industries, US).

Figure 2.5 Opening (left) and closing (right) of the CING insulating panels

Figure 2.6 Opening (right) and closing (left) of the CING rooftop panels

A growth tower was designed to allow inter-canopy lighting of the crops, optimizing the use of the supplemental electrical light. The growth tower was originally designed for drip irrigation (Figure 2.7).

Figure 2.7 Original design of the CING growth tower (left), side-view (top right) and solution tank (bottom right), pictures by Thanh Jutras, 2016.

Figure 2.8 Comparative growth tower in the research greenhouse, Summer 2018

In 2017, the tower was converted to nutrient film technique (NFT). A comparative tower was built using a similar inter-canopy pattern for testing the CING's performance which was placed in a research greenhouse at McGill University's Macdonald Campus (Figure 2.8).

2.3.2 Energy Usage

One of the CING operational challenge was using minimal energy consumption. It was determined that the CING must be operational on a 30-Amp, 110 V-circuit year-round, for a maximum daily energy usage of 79.2 kWh.

$$Energy\ (kWh) = Current(A) * Voltage\ (V) * time\ (h)/1000$$

For this reason, supplemental lighting and heating is limited, but the use of natural light as a light and heat source for the growing environment was the main parameter studied to evaluate the CING's potential as an energy-efficient indoor growing system adapted for a northern climate.

Equipment	AC Current (amps)	Voltage (V)
Irrigation pump (4 pumps)	3.2	110
Heaters	13.8	110
LED lights	3.3	110
Automation control system	1*	110
Motor for thermal curtains	1*	110
Exhaust fans	2.12	110
Total	**24.42**	110

*Table 2-2 Electrical current and voltage consumption of the CING environment control system components.(Gaudet, 2017). *The estimated current was required for automation system and thermal curtains function*

Under cold weather conditions the exhaust fans were not used while in warm weather the heaters were not used resulting in maximum daily energy uses of 29.4 $kWh.m^{-2}$ and 14.0 $kWh.m^{-2}$ respectively. These values were obtained using only a small, representative growing area (2 m^2). The growing area of half of a 40-foot shipping is 14.4 m^2. More lighting, pumping capacity and air exchange would be needed if this growing area was used.

2.3.3 Thermal curtain parameters

A thermal curtain (TEMPA 7567 D FB, Svensson, North Carolina, U.S.), allowed a transition from greenhouse mode to growth chamber mode (Figure 2.9). The thermal curtain was functional and set to open when solar irradiation was above 12 $W.m^{-2}$ and close when irradiation went lower than the set value. This value was recommended in a previous report on recommended operation conditions of the CING (Gaudet, 2017).

2.3.4 Growth experiments

The CING ran for four consecutive seasons: Spring 2018 (May 7th to June 6th), Summer 2018 (June 8th to July 2nd), Fall 2018 (December 1st to December 22nd) and Winter 2019 (March 1st to March 23rd).

2.3.5 Biological nutrient solution testing

Since both growing systems had two independent pumps for the right and left sides, two nutrient solutions were tested in each system. The first was a one-quarter strength Hoagland solution (Fernandez, 2009) and the second comprised a biological nutrient solution based on vermicompost leachate. This solution was continuously prepared during the experiment using 10 L vermicompost, fed a constant diet of egg shells, banana peels, coffee grounds and cardboard. By flooding the vermicompost weekly with 1 L water, the leachate was collected and diluted to match the electrical conductivity (EC) of the Hoagland nutrient solution.

Figure 2.9 Inside the CING, on the right is the closed thermal curtain, Winter 2019

2.3.6 Hydroponic systems parameters

2.3.6.1 Design

The hydroponic growth systems were built as growing towers (Figure 2.10 and 2.11). The growing systems were 6-feet high (183 cm), each containing 16 42-inch (107 cm) long tubes, where six lettuce plants can grow using NFT, resulting in 96 lettuce plants total per system. Tube diameters were 2 inches (5 cm) diameter and lettuce heads were held in 2-inch (5 cm) net pots.

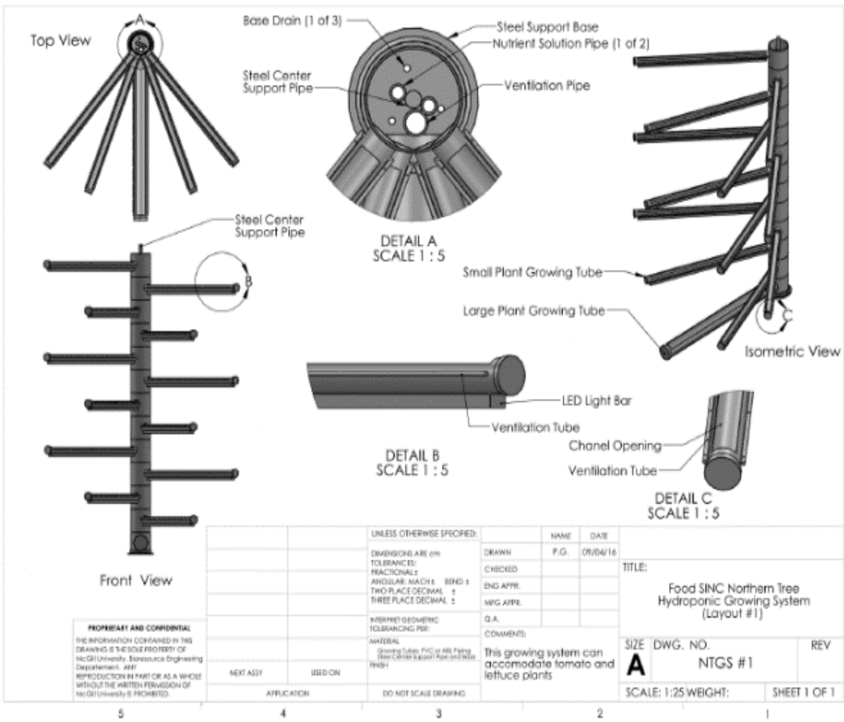

Figure 2.10 Growing system prototype design described previously (Gaudet, Hendry et al. 2017)

Figure 2.11 The hydroponic growing tower system for the research greenhouse (left) and growing system in the CING (right)

2.3.6.2 Flow in hydroponic systems

Each side of the growing systems has an independent pump. The nutrient solution is pumped by a magnetic drive submersible water pump (EcoPlus, Eco 396, US), delivering a flow of 1500 $L.h^{-1}$ (396 GPH), at a height of 2 m. A valve was used to control the flow in each tube, and a 1 $L.min^{-1}$ flow ensures a 3-mm level of nutrient solution in the 5 cm tubes (Lennard & Leonard, 2006). Four NFT tubes per experiment were tested, to ensure 0.6–1 $L.min^{-1}$ per tube.

2.3.6.3 Electrical conductivity (EC)

EC was monitored with a handheld EC-meter (HM Digital Meters COM-80 Electrical Conductivity and Total Dissolved Solids Hydro Tester, Seoul, Korea). The EC was kept between 115–125 mS/m (± 2.5 mS/m) above the greenhouse's irrigation water EC. The EC was adjusted by adding greenhouse irrigation water or concentrated nutrient solution (Brechner & Both, 2013).

2.3.6.4 pH

The pH of both nutrient solutions was maintained between 5.50 to 7.00 (±0.01). It was monitored with a handheld pH-meter (Dr. Meter PH100, China). Phosphoric acid (19.7% w/w) was used to lower pH to the desired value.

2.3.6.5 Light

Electrical light in the CING unit was provided by an LED installation. This comprised 10 light strips installed underneath the NFT tubes and six vertically hung light strips. When the thermal curtain was open, natural light was made available. In the Fall trial, the thermal curtain was only open when solar radiation was over 12 W/m^2 (Gaudet, 2017). The outside light was measured with a Solar Radiation Smart Sensor (ONSET, Massachusetts, US), with a range of 0 to 1280 W/m^2 ± 10 W/m^2. Light intensity to activate the thermal curtain was measured with a TSL2561 luminosity sensor, measuring Lux (Environmental Growth Chambers, 2018).

The natural lighting in the research greenhouse was supplemented with a high-pressure sodium (HPS) lamp lighting system. To ensure good growth, combined lighting is approximately 17 $mol/m^2/day$. The targeted instantaneous light intensity, measured with the LI-250A Quantum Radiometer Photometer, was estimated at 197 ± 1 $\mu mol/m^2/sec$. However, we expected that lighting would sometimes be lower than this targeted value, and the lowest light intensity value was estimated at 50 ± 1 µmol.m^{-2}.sec^{-1}. Light mapping of the system was made to determine the amount of light achievable in both systems (Appendix A Tables A-5 to A-13) (Brechner & Both, 2013).

2.3.6.6 Temperature and relative humidity

The internal CING temperature set point was 24 °C during the day and 19 °C during the nighttime. This temperature was maintained using an electric auxiliary heater connected to an electrical thermostat (LUX Win100, Philadelphia , Pennsylvania). For the fall and winter trials. Auxiliary electrical heating was necessary and almost constant.

The internal temperature in the CING was monitored with a 12-Bit Temperature/Relative Humidity sensor (± 0.2°C from 0° to 50°C ; ± 2.5% from 10% to 90%) compatible with the Hobo data logger (ONSET, Massachusetts, US). Humidity levels were not controlled.

The heating, ventilation and air-conditioning (HVAC) system was not functional for the test trials. However, exhaust fans were set on a thermostat, pulling fresh air into the CING, reducing temperature and relative humidity. A 9-inch 1100 CFM and a 16-inch 1435 CFM exhaust fan (Hessaire, Phoenix, Arizona, US) where mounted on the side wall, set on a electrical thermostat LUX Win100, Philadelphia , Pennsylvania) to cool the CING at 27 °C.

2.3.6.7 Crops

Romaine lettuce *(Lactuca sativa)* was cultivated for the first three trials (Spring 2018, Summer 2018 and Fall 2018), and Boston lettuce (*L. sativa)* was grown in Winter 2019 due to lack of available seeds.

2.3.7 Parameters

2.3.7.1 Light Mapping

Light mapping of the systems was made using a handheld Li-Cor Li-250A light sensor (LI-COR Biosciences, NE, US). To get the daily light integral (DLI) (mol.m^{-2}.d^{-1}), the photosynthetically active radiation (PAR) obtained at the brightest moment in the day was deducted from the PAR provided by the supplemental lights provided (PAR measurement after sundown), in the greenhouse and in the CING. PAR from the supplemental HPS lights in the greenhouse was 56.69 µmoles.m^{-2}.s^{-1} and PAR from the supplemental LED lights in the CING was 37.58 µmoles.m^{-2}.s^{-1}. Assuming that a quadratic function represents PAR versus the time of day for the length of the specified day, with the measured PAR value at its highest value during daytime, it was possible to evaluate the maximum daily light integral from the Sun light for a specific trial. By adding the DLI from the sun with the DLI of the supplemental light, a total maximum DLI was obtained.

For the Summer trial, PAR was measured on June 19th, 2018 under clear skies, assuming a 16-h day and 8-h night during the entirety of this trial. DLI in the greenhouse was evaluated at 29.4 mol/m^2/d and DLI in the CING was evaluated at 20.9 mol.m^{-2}.d^{-1}. For the Fall trial, PAR was measured on December 20th 2018 under clear skies, assuming a day length of 8 h 50 min during this trial. DLI in the Fall in the greenhouse was evaluated at 5.1 mol.m^{-2}.d^{-1} and 7.61 mol.m^{-2}.d^{-1}in the CING. For the Winter trial, PAR was measured on March 19th, 2019 under clear skies, with an average daytime of 12 h, assuming the same PAR from supplemental lighting in the greenhouse and the CING from previous experiments. DLI in Winter in the greenhouse was evaluated at 18.0 mol.m^{-2}.d^{-1}and in the CING was evaluated at 9.3 mol.m^{-2}.d^{-1}. PAR mapping of the systems is available in Appendix A.

2.3.8 Monitoring of systems

The EC, pH, temperature and volume of the nutrient solutions for both systems were measured manually. Full monitoring data is available in the appendices and mean values for each trial are available in Table 3.1.

	GREENHOUSE							
	Vermicompost Nutrient Solution				Hoagland Nutrient Solution			
Trial	**pH**	**EC (ms/m)**	**Temp. (°C)**	**Vol. (L)**	**pH**	**EC (ms/m)**	**Temp. (°C)**	**Vol. (L)**
1	9.1	129.9	31.7	13.8	7.9	160.2	30.3	12.2
2	6.4	140.8	26.4	15.0	6.5	146.8	26.4	15.5
3	6.9	109.5	22.6	12.9	6.6	118.4	21.9	12.4
4	5.1	146.7	24.0	14.5	4.9	84.5	23.1	11.3

	CING							
	Vermicompost Nutrient Solution				Hoagland Nutrient Solution			
Trial	**pH**	**EC (ms/m)**	**Temp. (°C)**	**Vol. (L)**	**pH**	**EC (ms/m)**	**Temp. (°C)**	**Vol. (L)**
1	8.9	117.2	20.0	14.9	8.0	119.5	19.5	15.1
2	6.4	128.5	26.3	22.0	6.3	132.3	26.0	23.5
3	6.9	68.2	10.7	10.3	6.6	128.2	10.2	18.7
4	7.4	123.2	19.6	16.3	7.3	114.5	19.3	14.1

Table 2-3 Averages of monitored nutrient solution parameters for all trials (Trial 1, 2, 3 and 4 respectively correspond to Spring 2018, Summer 2018, Fall 2018 and Winter 2019)

2.4 Data Analysis

Independent samples t-tests were performed using Excel to assess the statistical difference of the yields of fresh and dry masses of lettuce obtained in between growing environment for each trial.

2.5 Results

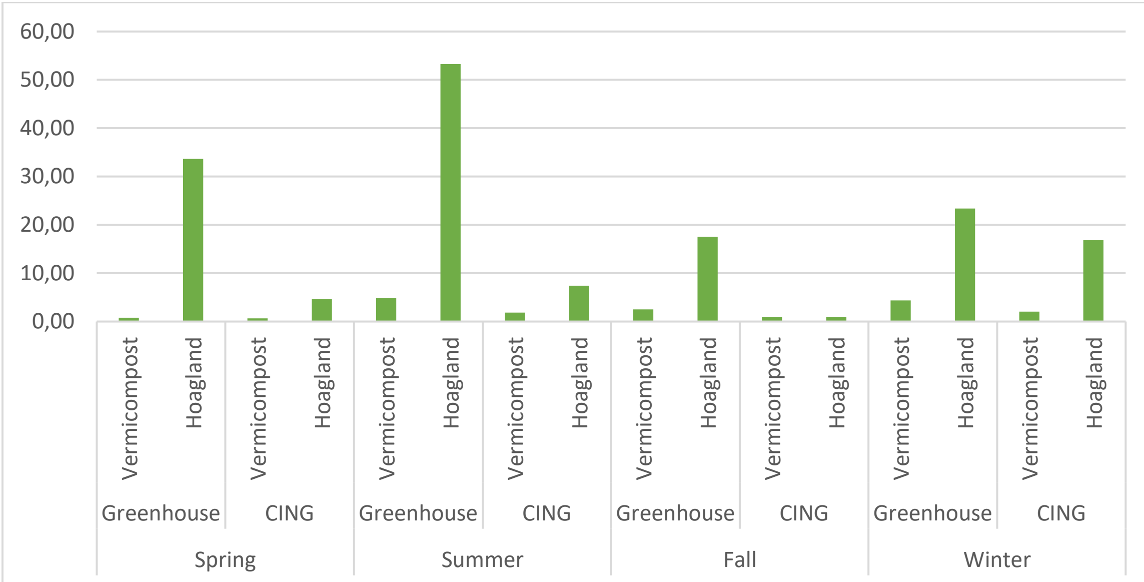

Figure 2.12 - Average fresh mass (g) of lettuce for all treatments at harvest

Season test Run	Spring				Summer			
Growth environment	GH		CING		GH		CING	
Treatment	V	H	V	H	V	H	V	H
Average fresh mass of lettuce (g)	0.82	33.63	0.64	4.60	4.81	53.25	1.86	7.41
S.E.	0.11	5.05	0.14	1.33	0.16	4.75	0.27	0.70
Season test Run	Fall				Winter			
Growth environment	GH		CING		GH		CING	
Treatment	V	H	V	H	V	H	V	H
Average fresh mass of lettuce (g)	2.51	17.54	0.99	0.97	4.38	23.40	2.07	16.79
S.E.	0.17	2.15	0.06	0.08	0.34	2.15	0.21	2.70

Table 2-4 Average fresh mass with Standard Error (S.E.) for all treatments, greenhouse (GH) and CING, with Vermicompost (V) and Hoagland (H) nutrient solutions at harvest

Figure 2.13 Lettuce grown in the CING before harvest, Winter 2019

2.6 Discussion

Figure 2.14 Inside the CING, on top left is an opened roof panel, Summer 2018

2.6.1 Summary of results

Plants grown in the research greenhouse with the Hoagland nutrient solution had the highest fresh and dry mass for all tests. Of all the CING trials, the fresh and dry mass of lettuce grown in the CING with the Hoagland nutrient solution during the Winter trial were the highest. The Vermicompost nutrient solution had lower fresh and dry mass compared to the Hoagland in a common growing environment.

During the Winter trial, the hydroponic system pumps quit unexpectedly 2 days before the harvest. As such, plants in the greenhouse were wilted and their fresh mass was affected. To make a comparison, with fresh mass of the plants in the greenhouse was estimated, the dry basis moisture content of the plants in the CING was determined with the following equation:

$$Dry\ basis\ moisture\ content = \frac{Mass_{fresh} - Mass_{dry}}{Mass_{dry}}$$

$$Estimated\ fresh\ mass = Dry\ basis\ moisture\ content * Mass_{dry} + Mass_{dry}$$

2.6.2 Environmental and growing parameters differences

Because of the climate difference between trials, the growth environment differed greatly in the CING. The lighting cycle for the Spring trial was 12 h day: 12 h night, the thermal curtain was active and roof panels were closed. In addition, pH was not controlled for this trial. The lighting cycle for the Summer trial was 12 h day: 12 h night, the thermal curtain was active and only one roof panel was open (Figure 12). The lighting cycle for the Fall trial was 16 h day: 8 h night, the thermal curtain was active and only one roof panel was open. The lighting cycle for the Winter trial was 24 h day 0 h night, the thermal curtain was not active and only one roof panel was open.

During the Spring trial, the pH in the vermicompost nutrient solution was over 8.5, pH was not controlled during the Spring trial and this may have limited nutrient availability and uptake.

During the Spring, Summer and Fall trials, plants in the CING grew very little when compared to plants grown in the greenhouse. During the Summer trial, average temperature was slightly higher (25.4 °C) than the suggested temperature for lettuce growth (25 °C), and in the Fall the average temperature was 11 °C, which is lower than the recommended minimum (15 °C) for lettuce growth. Relative humidity for all trials ranged between of 50 to 70 %, which is recommended for lettuce cultivation (Brechner & Both, 2013). The Hoagland nutrient solution for the Winter trial was added at the beginning of the trial but not during; this explains the lower EC observed in the greenhouse for the Winter trial.

2.6.3 Cold weather trials

The Fall and Winter trials were the first cold climate trials undertaken in the CING unit. The comparison of the average conditions in the CING during both trial is available in the next table.

Trial	Average Outside Temperature (°C)	Average Inside Temperature (°C)	Approximate DLI ($mol.m^{-2}.d^{-1}$)	Average Fresh Mass (g)
Fall 2018	-3.9	11.0	7.6	0.97
Winter 2019	-2.4	14.8	9.3	16.79

Table 2-5 Summary of Table 2.3 and 2.4 for Cold condition trials of the CING

For the Fall trial, the thermal curtain was set to open and close according to outdoor solar radiation. For the Winter trial, the thermal curtain remained closed, to help reduce thermal heat losses.

The curtain has an 80% shading level in diffused light PAR. The 20% of diffused light combined with the light from one opened roof panel, the constant supplemental lighting and the longer days allowed for greater DLI in the Winter Trial then the Fall trial. The average inside temperature in Fall was below the 15 °C recommended temperature for lettuce production (Brechner, 2013). This environmental difference explain the major difference in crop yield from the two cold conditions tests.

2.6.3.1 Thermal Curtain

The thermal curtain usage changed the internal conditions of the CING. By comparing a set of days during both trials with similar outdoor temperature changes and environmental conditions, it is possible to better assess the impact of the thermal curtain. From December 10th to 12th 2018, the average outdoor and indoor temperatures were respectively, -7.6°C and 12.3°C. From March 4th to 6th 2019, the average outdoor and indoor temperatures were respectively, -8.2°C and 7.5°C.

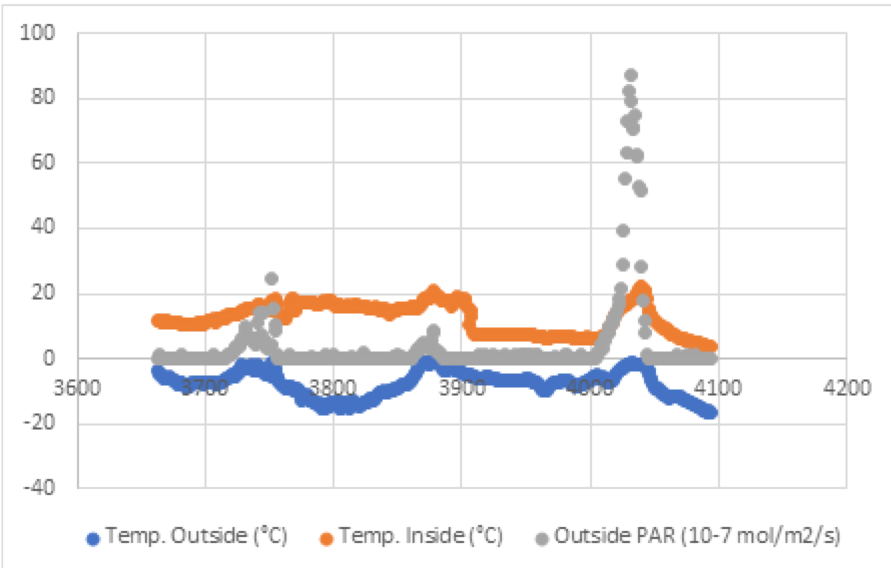

Figure 2.15 - Outside temperature, inside temperature and outside PAR of the CING, December 10th to December 12th 2018

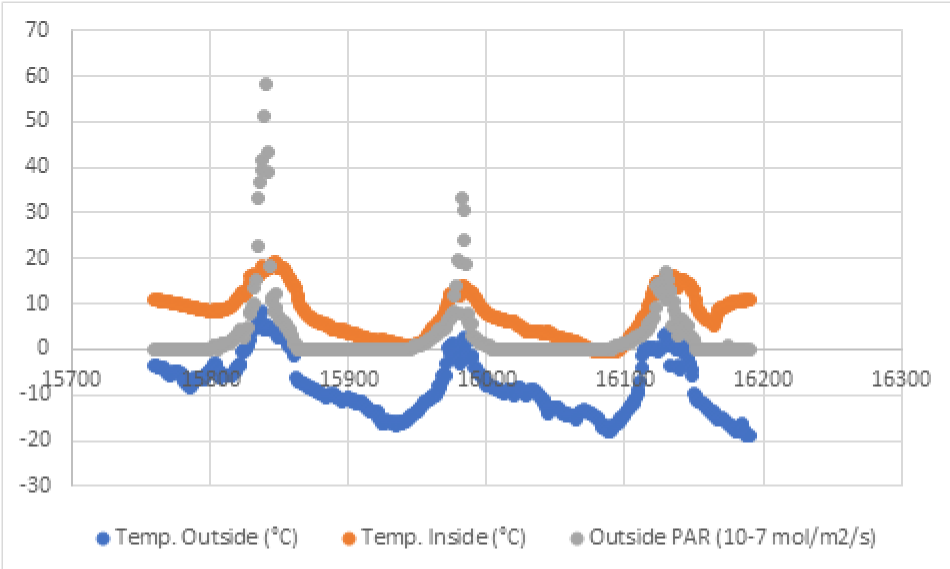

Figure 2.16 - Outside temperature, Inside temperature and outside PAR of the CING, March 4th to March 6th 2019

Considering the thermal properties of the polycarbonate sheet, the thermal curtain and the insulating layer of air kept in between the thermal curtain and the polycarbonate sheet, with a temperature gradient of 15 °C from the inside and the outside of the CING the thermal heat loss from the window would be 17 Watts with the curtain closed, and 282 Watts with the curtain open. See full heat transfer rate calculation in Appendix A.

Using the thermal curtain, the solar heat gain (SHG) to the CING was reduced, proportionally to the sunlight blocked, 80% (Ludvig Svensson, 2020). This difference in SHG can be linked to the more stable temperature during the day, noticeable in Figure 2.15 during the Fall trial cold days testing. However, during the Winter trial, with the thermal curtain constantly closed, the inside temperature was more dependent of the outside temperature as observed in Figure 2.16 for a 3 days comparison with similar average temperatures.

This trend can be observed when comparing the relationship between the indoor and outdoor temperatures, during the 3 days comparison in Figure 2.17 and Figure 2.18 and the whole experiment data in Figure 2.19 and 2.20. Whereas the R^2=0.0656 for the Fall trial and R^2=0.702 for the Winter trial during the 3 days comparison and R^2=0.3114 for the Fall trial and R^2=0.5741 for the Winter trial during the full trials.

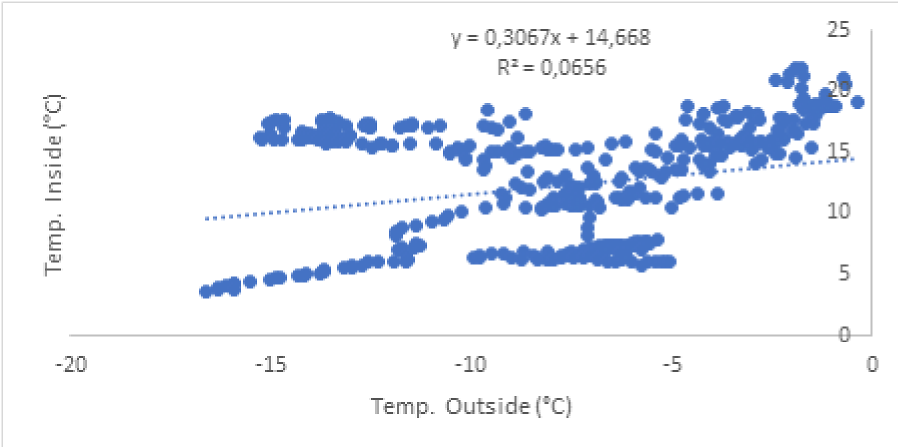

Figure 2.17 - Temperature Inside vs Temperature Outside of CING, Fall trial, December 10th to 12th 2018

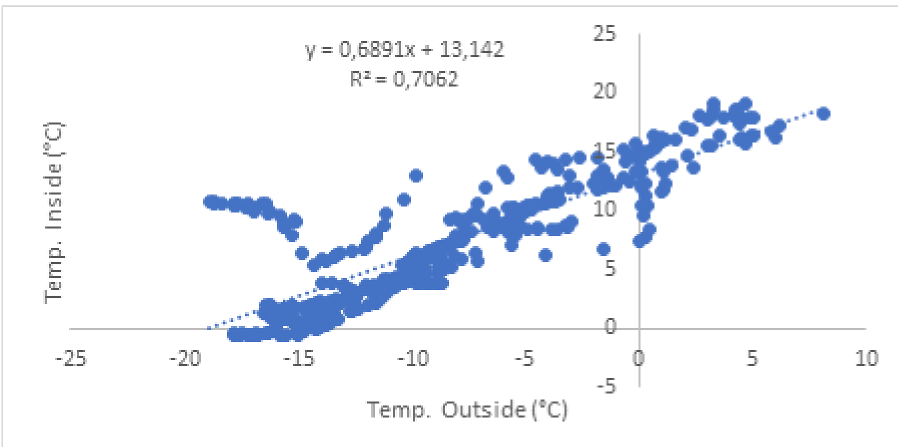

Figure 2.18 - Temperature Inside vs Temperature Outside of CING, Winter trial, March 4th to 6th 2019

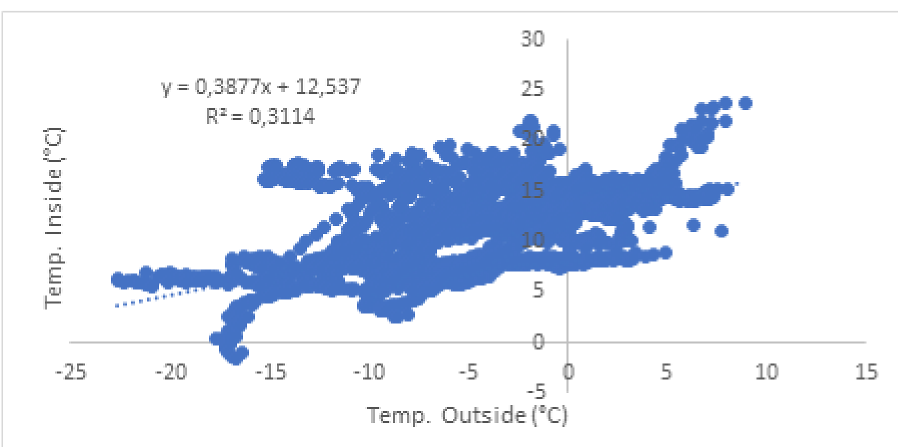

Figure 2.19 - Temperature Inside vs Temperature Outside of CING, Fall trial, December 1st to December 22nd 2018

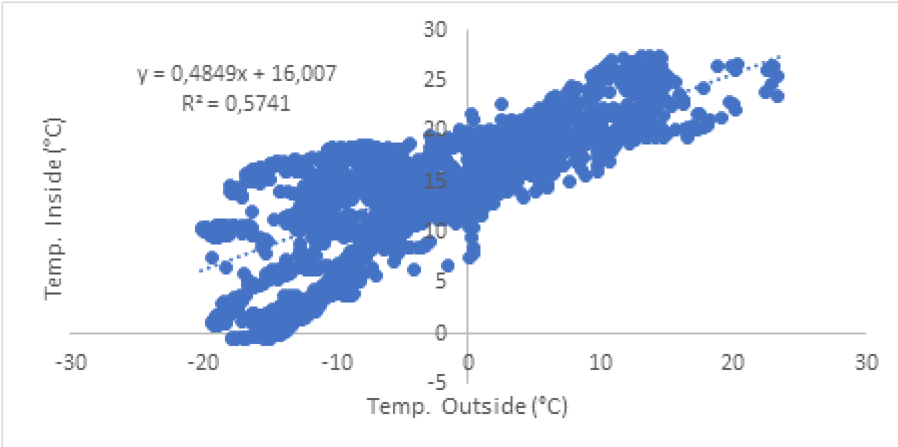

Figure 2.20 - Temperature Inside vs Temperature Outside of CING, Winter trial, March 1st to March 23rd 2019

2.6.3.2 Energy Usage

Considering that the average cold and warm weather maximum energy requirements of the CING are approximately 21.7 kWh.m^{-2}, the maximum yearly energy use of the CING would be 7920 kWh.m^{-2}. This is still considerably higher than the modified shipping container described by The University of Arizona and higher than the 711.91 kWh.m^{-2} average for 164 greenhouses occupying a total of 16444 m^2 operated by Cornell University's Agricultural Experiment Station (CUAES) in New York (Liu, 2014).

The use of the thermal curtain showed an effect on inside temperature, but the extra sunlight SHG did not provide enough light and heat to achieve growing parameters during the Fall trial. The use of electrical lights and heating however provided enough light and heat to achieve growing parameters during the Winter trial.

Heating was almost constant in cold conditions, with average indoor temperature for the Winter trial of 14.8°C. Heating was the most energy intensive parameter of the CING, representing 62% of the maximum daily energy requirement, but the achieved temperature was still lower than recommended temperature for lettuce growth (Brechner, 2013).

2.6.3.3 Other Considerations

The CING structure was strong enough to withstand the weight of snow accumulation.

Interestingly, we observed that highest lettuce yield for the CING-grown plants was during the Winter trial. This substantiates the potential of winter growth within the CING.

The vermicompost-based nutrient solution has seen an improvement from the beginning of the experiments but the nutrient profile is not yet complete and provides lower lettuce yields than the Hoagland nutrient solution.

2.6.4 Feasibility of the CING

Inspired by container farming, the CING was designed to operate in a cold and warm climate, exemplified by the short growing season in northern Canada. The environmental conditions surrounding the CING had a major impact on its interior environment, but the ability to insulate the CING unit using a thermal curtain helped manage heat and keep stable growing conditions.

If CF can successfully allow for food crop growth in cold climate as demonstrated by these CING trials, the prototype cannot yet be considered viable as heating demands are too high and environmental control is not adequate. However, the use of natural light has made it possible to cultivate plants in this growing environment with minimal supplemental lighting. The main issue with the CING is its capacity to keep a desired internal temperature under outdoor cold conditions. The opening of the thermal curtain did increase light intensity and allowed for a higher solar heat gain. Performance of the CING in terms of biomass production was higher when the thermal curtain remained closed during the Winter, but this result is mainly caused by the average inside temperature and DLI to be higher during this trial.

2.7 Conclusion

The CING unit was able to successfully grow lettuce plants in a cold climate during the Winter trial but energy demands were still very high because of heating. The dry mass of lettuce grown in the winter achieved 72% of the average fresh mass of lettuce grown at the same time in the greenhouse. In addition, the lettuce grown in the CING during the winter had the highest fresh and dry mass when compared to the other trials in the CING unit when using Hoagland nutrient solution. The vermicompost nutrient solution allowed for lettuce growth but at a much lower yield for all trials likely due to nitrogen deficiency. Continuous supplemental LED light provided the best results for lettuce growth in the CING. The thermal curtain opening according to an outdoor solar radiation threshold did allow for more light and heat in the CING unit, reducing the correlation of inside and outside temperature, under cold outdoor conditions.

2.7.1 Recommendations

The combination of natural and supplemental light in CF has the potential to reduce energy needs linked to lighting. However, heat loss analyses must be made to evaluate the energy efficiency of a single transparent wall, or part of a single transparent wall of a container farm in a northern Canada climate.

Secondly, trials performed in the CING only used a small part of the growing space. To decrease the energy needs per growth surface another hydroponic configuration could be used. Container farms often use stacked shallow water cultures to grow leafy greens, which allows the highest density of crop production. Considering the full growing area of the CING represents half of a 40-foot shipping container or 14.4 m^2, 75% of this the growing area or 10.8 m^2 could be used for plant growth, thus reducing energy requirements per square meter of production. More lighting and air exchange would be needed to use all the growing area, and heating energy requirements might be reduced by the addition of supplemental lighting. Modifying the CING for a better space usage could reduce energy demands per unit of crops produced.

Thirdly, a recommended modification to the CING unit would be a functional HVAC system; to increase the temperature and humidity control of the CING. An increase in the thermal mass of the northern CING wall; this would help reduce the heating requirements by increasing the passive heating of the CING (Beshada, Zhang, & Boris, 2006). A complete heat exchange simulation of the CING would be necessary to compare its performance as a northern growing unit.

2.7.2 Future opportunities

A northern industrial partner is needed to develop a pilot CING unit, and prospective partners in the Northwest Territories have expressed interest in indoor agriculture using electrical lighting. A feasibility study using the CING unit still must be completed.

Connecting text to Chapter 3

In Chapter 2, the Canadian Integrated Northern Greenhouse four-season testing results were presented. The unit showed potential to grow plants in cold conditions but is not yet energy efficient as it relied closely on supplemental heating. Exploring innovative growing environments to answer the challenges to grow food in northern Canada is a common research topic and some systems are already commercially available.

With the experience gained in shipping-container farming as the first part of this thesis, Chapter 3 was conducted in partnership with La Boîte Maraîchère, a commercial hydroponic lettuce producer, operating a plant factory housed in an array of shipping-containers. This project was funded by the Mitacs Accelerate program. The aim of the project was to design and test innovative vertical hydroponic configurations to improve the production methods at La Boîte Maraîchère.

Chapter 3. Multistage Hydroponic Configuration testing in Container Plant Factory

3.1. Abstract

The goal of this study was to develop hydroponic systems suited for vertical optimisation of space in a Container Plant Factory (CPF). Three experimental hydroponic systems were designed and tested: aeroponics with raised NFT trays, stagnant shallow water culture and flowing shallow water culture. The main differences between the systems were the root zone aeration and the nutrient distribution strategies. The impact of the hydroponic strategy was tested on Romaine lettuce (*Lactuca sativa*). The crop yields and ease of use of the systems were studied to compare the systems. The Stagnant shallow water culture yielded lettuce with fresh mass 2 to 3 times higher than the other methods. This yield difference was in part determined to be caused by a copper ion contamination in the aeroponics and flowing shallow water methods, whereas the stagnant shallow water culture was not affected. This result expresses the importance of contamination control in the nutrient solution to optimize plant growth in hydroponic conditions. The use of trays in stacked hydroponic systems did increase work efficiency and created a better way to transport grown plants.

3.2. Introduction

Vertical farming in indoor controlled environment is an increasingly popular practice of commercial indoor producers growing hydroponic crops. There are many different hydroponic strategies available to optimize space, energy and labour, but they come with various challenges. The goal of this research is to compare 3 vertical hydroponic configurations in a shipping-container plant factory at La Boîte Maraîchère, to evaluate the ease of use and performances in terms of system's work ergonomics, shoot mass of crop, crop losses percentage and crop uniformity. The crop studied is Romaine lettuce (*Lactuca sativa*). Currently, the main hydroponic configuration used at la Boîte Maraîchère is in NFT tubes (Figure 3.1).

Figure 3.1 NFT tubes installation at la Boîte Maraîchère

3.2.1. Issues addressed with this research

3.2.1.1. Issue 1

Current working methods are very tedious, demanding labor to move between all lanes to transplant and harvest all plants. It is hard to access the plants in the top and lower shelves of the systems and near the walls of the container. These hard to access plants are sometimes not visible during their growth making diseases hard to detect.

3.2.1.2. Main hypothesis 1

If plants were to be transplanted in trays and then placed in the systems, it could be easier to work with the lower and higher levels of the systems. Harvesting them by removing the trays could be an easier method, or at least harvesting without having to circulate along the isle of a container, because the trays could be pulled to the side of the system near the working area, where transplanting and harvest happens.

3.2.1.3. Issue 2

The production at la Boîte Maraîchère is not vey uniform. From system to system, there is a noticeable variability in the morphology of the plants, due in part by different lights, ventilation efficiency and temperatures, which can create large differences in humidity and temperature called “Hot-spots” in the system. The duration between transplant and harvest varies from one system to another, complicating production.

3.2.1.4. Main hypothesis 2

Movement of the plants according to their growth stage will allow them to spend less time at the same location, under the same condition. This could reduce risks of loosing crops and increases the uniformity of the crop production, since the plants will move between multiple locations before they are harvested, avoiding Hot-spots.

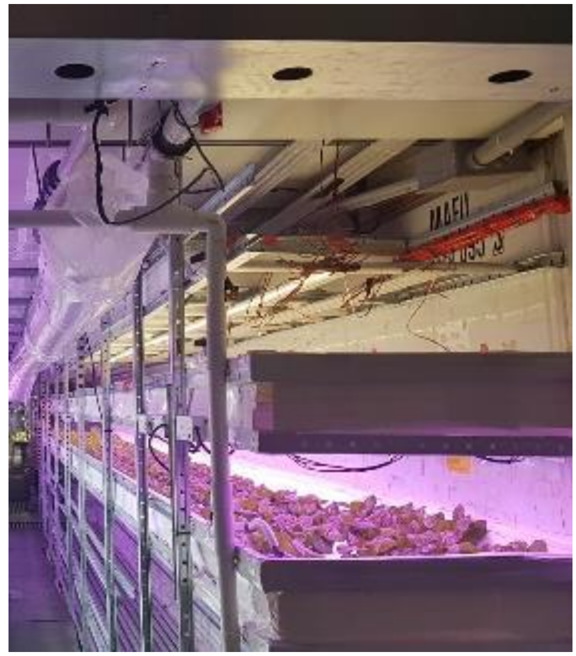

Figure 3.2 Current installation for the floating bed in flowing shallow water experiment

3.3. Methods

Three experimental designs were proposed, based on different hydroponic techniques, aeroponics with raised NFT trays, stagnant shallow water culture and flowing shallow water culture.

3.3.1. Dimension of the experimental tests

The three hydroponic systems consist in pools 11.9 m x 0.76 m (39 ft x 30 in). The trays are 0.61m x 0.76m (24 in x 3 in) and can hold 24 plants each. The test was done in 4 trays of each configuration, for a total of 194 plants seeded per experiment. The crop density of each experiment was 51.67 plant.m^{-2}.

3.3.2. First configuration: Aeroponics with raised NFT trays

The first experimental design to be tested is a hybrid between a NFT system and an aeroponic system. The idea is to have trays holding the plants that are not floating but laying on the sides of the pool. The raft with the young transplant will be placed at point A in Figure 3.3, where the substrate of the plants will be sprayed by aeroponic nozzles, allowing the roots to develop quickly in the beginning of the system. When the roots are long enough to reach to bottom of the pool, the raft can be moved from point A to point B of the system, where there are no more aeroponic nozzles. The roots can take up nutrient from the solution and be able to develop without getting entangled in the aeroponic nozzles. In a 40 feet container, the aeroponics system would only cover the first 10 feet of the system, after a week sprayed by the nozzles, the roots will be more than 10 cm long, hence they are able to uptake nutrient via the film of nutrient in the bottom of the pool, similar to the NFT system.

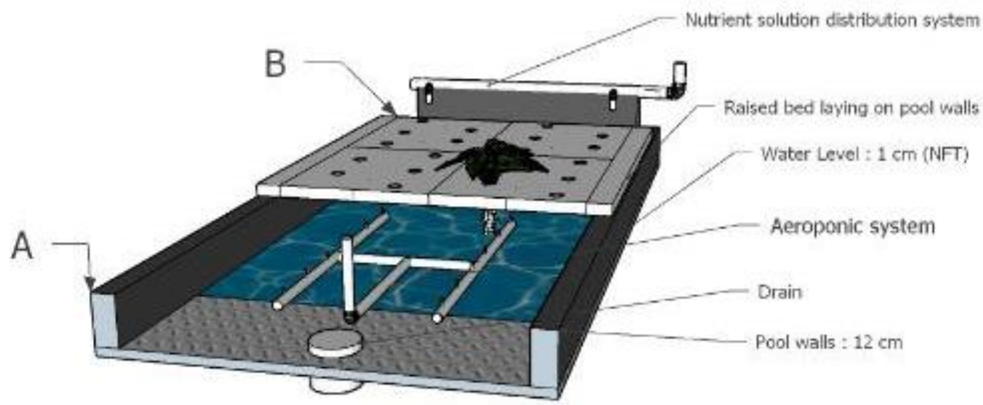

Figure 3.3 Experimental design of the aeroponic and NFT hybrid

Pros :

- Plants can move together within a single raised tray.
- Trays can easily be taken off the system.
- Rapid root growth due to aeroponic culture.
- Maximum oxygen content in root zone.
- Lower water load for system, about 85 L for 40 feet of system.

Cons :

- More complex nutrient delivery system requires a booster pump, pressure accumulating tank and pressure regulator for the aeroponic system.
- Plant movement must be done according to root development.
- Crop might die if spray distribution is not adequate.
- Different size of trays.

3.3.3. Second configuration: Flowing shallow water culture

The second configuration was a floating bed technology in a shallow pool of nutrient solution as it can be seen in Figure 3.4 Rafts holding the plants will be placed at point A of the system, and they will be harvested at point B. Aerated nutrient solution will flow continuously in the system the level of nutrient solution being determined by the height of the drain, which is kept between 8 and 12 cm, to allow roots to grow underneath the trays with enough water circulation.

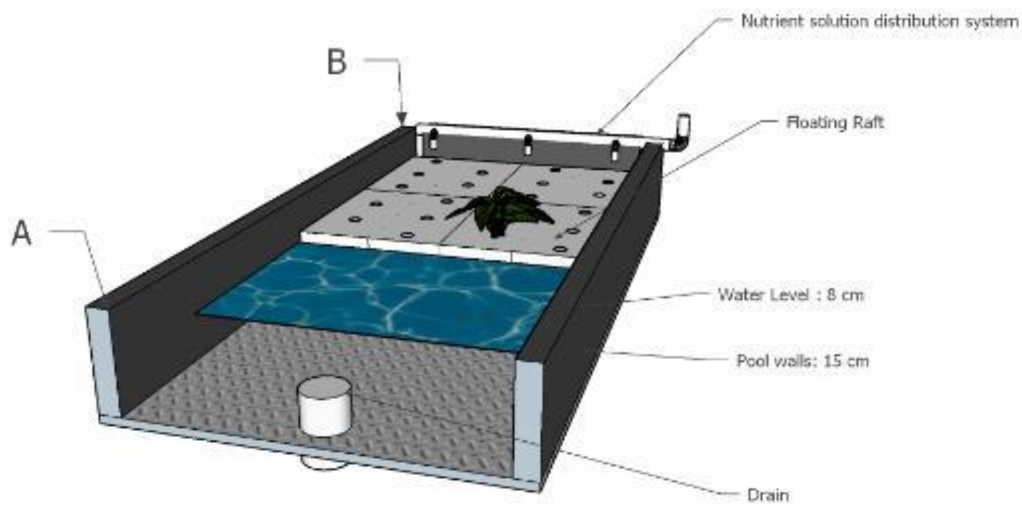

Figure 3.4 Experimental design of a floating bed in flowing shallow water

Pros :

- Plants can move together within a single floating raft.
- The water level can be adjusted with the drain height.
- Simple nutrient distribution system.
- Floating rafts can easily be taken off the system.

Cons :

- Oxygen in the water must be added by ozone directly into the nutrient solution, prior to being fed to the plants.
- When filled between 8 to 12 cm of nutrient solution, about 850 to 1240 liters of water is held in the system, with 100 g mature fresh plants, the total maximum load is 1300 kg.

3.3.4. Third configuration: Stagnant shallow water culture

The third experimental hydroponic strategy was similar to the first configuration, but instead of having a continuous flow of water, the pool was filled once, and the same water was used for the whole growing period. Since this test was performed in a closed system, an array of air stones was laid at the bottom of the pool providing aeration to the nutrient solution. A total of 18 air stones where needed, with two air pumps, in the figure only one air stone is shown.

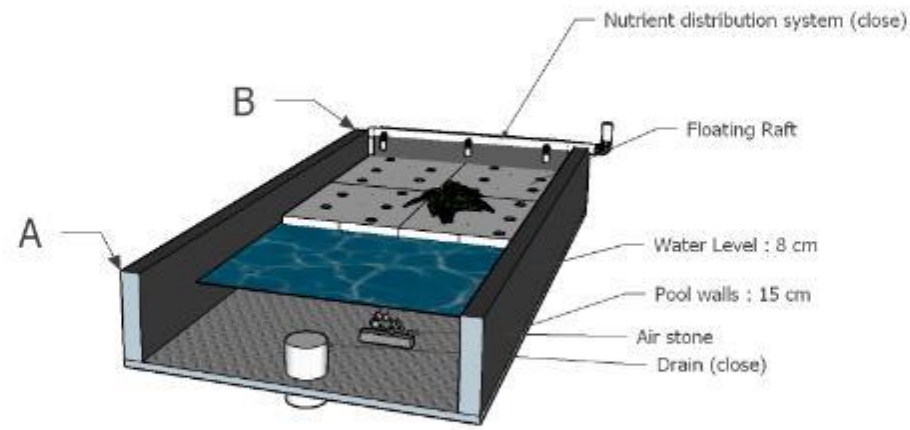

Figure 3.5 Experimental design of a floating bed in stagnant shallow water

Pros :

- System in stagnant water, does not require continuous feed of nutrient solution.
- Movement of the trays can be very easy to remove from the system.
- Extra aeration by the air stones.
- Nutrient solution in closed loop is isolated from potential contamination

Cons :

- Uniformity of aeration depends on the air pumps efficiency and the air stone configuration.
- Potential decrease in nutrient solution concentration.
- Air stone arrangement might interfere with movement of the trays.

3.3.5. Monitoring

Temperature and relative humidity of all three experimental systems were monitored using an Arduino Uno board (Adafruit Industries, US) and DHT22 sensors (Adafruit Industries, US). Electrical conductivity, pH and temperature of the water in the systems was measured daily with the GroLine HI 9814 handheld meter (Hanna Instruments, US). The full monitoring of the experiment can be found in Appendix B. Lighting of each system was mapped before the tests using a handheld Li-Cor Li-250A light meter (LI-COR Biosciences, NE, US).

3.4. Results

3.4.1. Notes on trials

For the first trial of the experiments the nutrient solution used at la Boîte Maraîchère suffered a contamination of copper ions, which led to a slower formation of roots. Hence the results of this first experiment are not fully representative of the reality at La Boîte Maraîchère. Moreover, when the growth test was launched, the pool of the stagnant water experiment (Experiment 3) was filled with freshly mixed nutrient solution, which only showed traces of the contaminant. For the two other experiments, the nutrient solution came from the main nutrient solution tank at la Boîte Maraîchère, in which the concentration of the contaminant increased gradually during the tests. Seedlings were transplanted in the systems two weeks after seeding. This trial lasted from October 26th to November 30th, 2018, during which the plants remained 5 weeks in the systems. Figure 3.6 show shoots and roots of a single tray per experiment.

For the second trial, the copper ion contamination was less noticeable, but still affected the growth of the plants. This second trial lasted from November 30th to December 19th 2018. Seedlings were transplanted in the systems two weeks after seeding. Note that the total time of growth in the systems for the 2nd trial of experiment was only 3 weeks.

The irradiance level of the aeroponic pool received an average of 159.1 $\mu mol.s^{-1}.m^{-2}$, the flowing water pool had an average of 154.6 $\mu mol.s^{-1}.m^{-2}$ and the stagnant water pool 138.1 $\mu mol.s^{-1}.m^{-2}$.

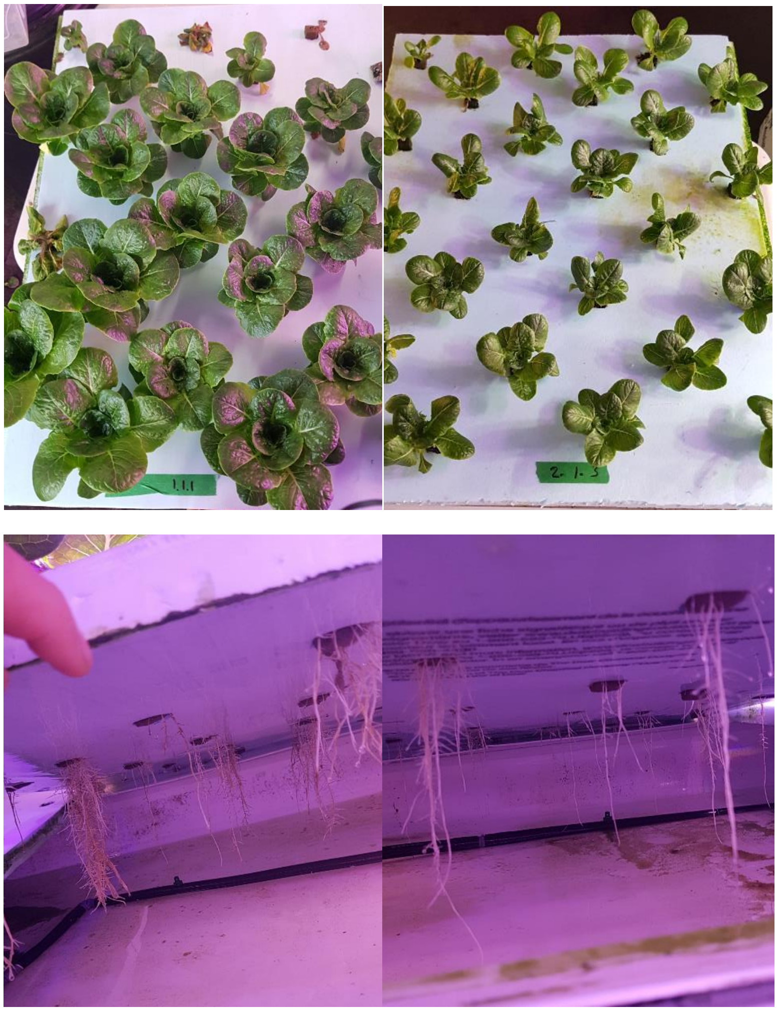

Figure 3.6 – Shoots and roots of 1st and 2nd aeroponic experiment at harvest

Shoots are visible at the top and roots at the bottom, 1st trial is on the left and 2nd trial is on the right of Figure 3.6 for the aeroponic experiment.

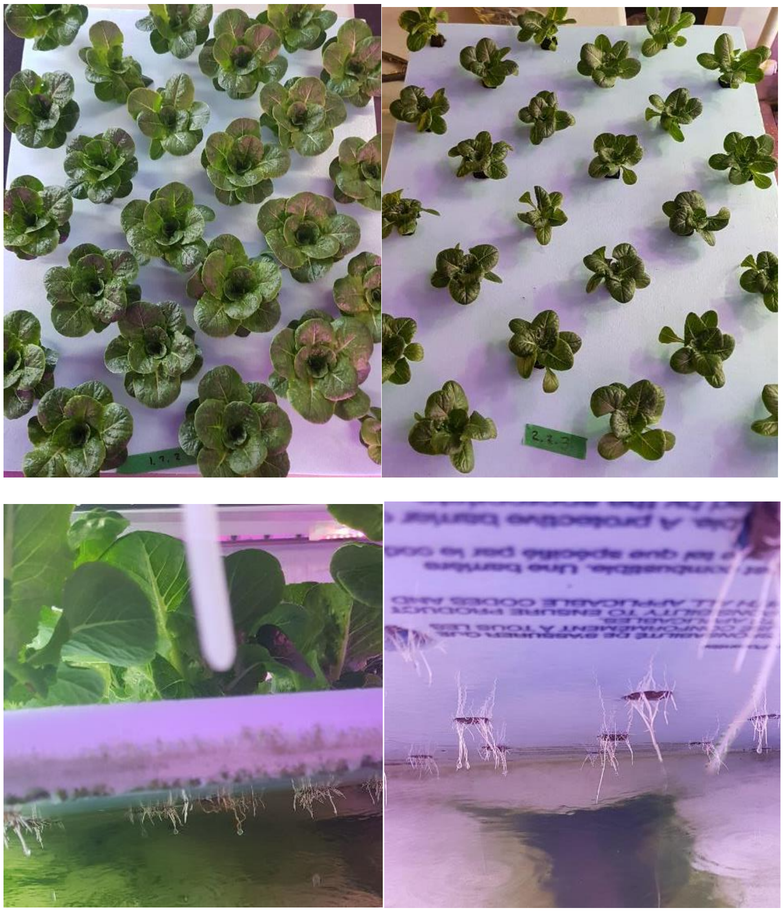

Figure 3.7 – Shoots and roots of 1st and 2nd flowing water experiment at harvest

Shoots are visible at the top and roots at the bottom, 1st trial is on the left and 2nd trial is on the right of Figure 3.7 for the flowing water experiment.

Figure 3.8 - Shoots and roots of 1st and 2nd stagnant water experiment at harvest

Shoots are visible at the top and roots at the bottom, 1st trial is on the left and 2nd trial is on the right of Figure 3.8 for the stagnant water experiment.

Experiment	1st trial (5 weeks in systems)	2nd trial (3 weeks in systems)
Aeroponic	35.7	4.9
Flowing water	26.0	4.6
Stagnant water	72.0	14.2

Table 3-1 Average fresh mass of plants (g) at harvest

3.4.2. Light mapping of systems

All systems were mapped to compare the light intensity they received during the hydroponic tests.

105.37	168.34	165.76	143.85	97.18
125.23	269.6	212.8	187.73	112.65
106.16	206	223.1	193.43	133.44
124.77	221.9	235.6	224	145.28
121.77	199.73	220.7	194.34	131.98
127.38	201.1	226.3	194.23	121.29
140.61	211.4	232.25	180.64	110.84
109.92	197.95	227.4	161.96	100.58
42.77	73.41	89.88	76.88	62.08

Figure 3.9 Light mapping of the aeroponic pool

Top left is left end of system, average light intensity is 159.1 umol.s^{-1}.m^{-2}.

138.62	157.16	160.85	148.64	123.84
141.75	176.17	186.1	173.8	136.3
138.75	170.07	194.15	188.76	143.63
134.04	172.46	202.8	194.49	151.72
125.81	166.23	183.34	179.02	144.14
132.21	178.34	188.15	181.23	149.88
138.3	172.78	184.55	179.8	148.95
117.05	159.22	175.14	161.29	136.7
71.1	111.18	130.98	116.9	89.28

Figure 3.10 Light mapping of the flowing water pool

Top left is left end of system, average light intensity is 154.6 umol.s^{-1}.m^{-2}.

90.67	121.71	137.17	134.82	97.12
122.21	167.54	180.08	174.01	124.99
116.46	162.37	186.84	185.26	132.77
121.95	164.34	194.98	192.98	156.59
98.68	144.92	169.93	165.82	123.49
108.22	153.88	179.93	171.72	122.04
120.34	165.52	190.51	179.6	128.42
112.59	164.72	198.62	187.11	123.37
38.94	53.48	56.74	51.14	38.11

Figure 3.11 Light mapping of the stagnant water pool

Top left is left end of system, average light intensity is 138.1 umol.s^{-1}.m^{-2}.

3.4.3. Summary of nutrient solution monitoring

	Aeroponics	S.E.	Flowing Water	S.E.	Stagnant Water	S.E.
pH	5.91	0.05	5.79	0.04	6.64	0.09
EC	1.07	0.01	1.08	0.01	1.01	0.03
Temperature	17.65	0.20	17.40	0.18	20.07	0.33

Table 3-2 Average parameters of nutrient solution in each test, from October 27th to November 30th 2018

3.5. Discussion

3.5.1. Summary of results

The plants of the stagnant water experiment had the largest yield, followed by the aeroponic and then the flowing water. For the 1st trial, the stagnant water experiment yielded lettuce 2.0 times larger than the aeroponic tested and 2.8 times larger than the flowing water experiment. For the 2nd trial, the stagnant water experiment yielded lettuce 2.9 times larger than the aeroponic tested and 3.1 times larger than the flowing water experiment.

However, the results of this experiment can only tell how the hydroponic strategy performs under a contamination. Before choosing which strategy has the best potential, it is important to run the tests without the presence of a contaminant.

3.5.1.1. Hypothesis validation

The first hypothesis concerning a improved work ergonomics has been confirmed. The transplanting and harvest methods could be optimized opting for a hydroponic configuration with trays. In the current installation, the worker needs to circulate within the rows of culture to plant and harvest every single lettuce growing, also requiring to often work in a crouched position and reach areas of the system with full extension of their arms, without having a clear visual of the plant they are trying to reach. Instead, the worker will be able to do all the transplant and harvest at a workstation, in a much more ergonomic position, without having to circulate in the rows of culture. It will ease and accelerate the most common tasks in their growing environment.

Between the 3 different hydroponic systems tested, there was a difference in yield and uniformity. Depending which of these parameters is the most valuable, the stagnant water pool achieved a higher yield, but the flowing water pool had a better uniformity in between plants.

3.5.1.2. Parametric differences

There was a slight difference in lighting intensity between systems, it can be considered that this difference had a limited impact on the yields since the stagnant water pool had the lowest light intensity but the largest yield.

3.5.2. Aeroponic System

3.5.2.1. 1st trial

The effect of the contaminant on root growth was easily observed, as it was shown by the thickness of the roots in the aeroponic treatment. There was a great variability between the root size of the plants. This was caused by the dispersion of nutrient solution by the nozzles at the bottom of the pool.

The aeroponic lettuce grew well, but the uniformity of the harvest was directly correlated to the roots that grew less. A few plant losses per tray occurred. With less contamination and a better dispersion of nutrient solution, the average shoot mass would be higher.

3.5.2.2. 2nd trial

The roots of the 2nd aeroponic experiment were healthier than the previous trial. The uniformity was better and they grew faster than in the previous aeroponic trials.

Shoots of the aeroponic experiment were more uniform than the previous trial. Algae formation on the trays was caused by the sprays of nutrient solution that occurred between the trays. This phenomenon was the cause of algae formation on the side of the pool.

3.5.3. Flowing water

3.5.3.1. 1st trial

In flowing water, the roots were the most affected by the contaminant and had limited growth. However, the plants that did grow had good uniformity, but at the slowest rate.

3.5.3.2. 2nd trial

The roots in the 2nd trial of the flowing water experiment were again the smallest as they were still affected the most by the copper ion contamination. However, they were a bit bigger than the previous trial.

The uniformity in the flowing water experiment was good, but the test was not long enough to observe clear differences between the aeroponic treatment. The average mass was still the smallest.

3.5.4. Stagnant Water

3.5.4.1. 1st trial

For the stagnant water experiment, when the pool was initially filled with nutrient solution, the contaminant level was at its lowest. Hence, the contaminant level for this experiment did not influence the growth of the roots, which grew the most.

The stagnant water experiment had the highest growth. However, relative humidity in the environment was high during the last week of the experiment, which led to the formation of mold killing the plants. This was caused by insufficient aeration and dehumidification performance on the highest level of culture in the vertical system. A harvest a week earlier, would have showed healthier plants. The rise of relative humidity can be observed in the monitoring data available in Appendix B.

3.5.4.2. 2^{nd} trial

The roots of the stagnant water experiment were again the healthier ones. However, it is possible to notice that some roots did not grow. This could be caused by the lack of uniformity in the aeration of the water.

The stagnant water experiment again achieved the highest average mass, without any losses compared to the previous trial. However, uniformity was poor.

3.5.5. Pros and cons of each systems

3.5.5.1. Aeroponic system

Pros : Fastest potential root growth, minimum water load on structure, constant nutrient feed, maximum oxygenation level.

Cons : Lowest uniformity, most expensive installation, movement of the plants to the nutrient film technique failed, continuous feed leads to exposure to potential contaminant in nutrient solution.

3.5.5.2. Flowing shallow water

Pros : Good uniformity, constant nutrient feed, simplest and cheapest configuration.

Cons : Lowest average mass, lowest dissolved oxygen level, continuous feed leads to exposure to potential contaminant in nutrient solution

3.5.5.3. Stagnant shallow water

Pros : Largest shoot and root yield, highest dissolved oxygen level, lowest exposure to potential contaminants in nutrient solution.

Cons : Requires an aeration line in the pool, aeration is not uniform, second most expensive installation, nutrient content in stagnant solution will decrease, nutrient solution needs to be drained and replaced periodically.

3.5.6. Future research

Since there was an environmental difference between the experiments according to their level in the racking, the first relevant test would be to interchange the hydroponic strategy between the levels. This would make sure that the environmental difference is only due to ventilation issues and not the hydroponic strategy.

Moreover, concerning the stagnant shallow water culture, to increase the aeration uniformity, it would be interesting to try to run a submersible pump within the pool, to create water circulation, which could uniform dissolved oxygen level in the water. Aeration was performed using an array of air stones, however different air distribution systems could be tried, such as holes or nozzles on the air line, which could be a cheaper alternative to provide aeration in the stagnant shallow water culture. These alternative methods could also be prone to lack of uniformity and would require testing.

Finally, trying a culture strategy in their new installation with a linear movement of the plants according to their growth stage within a single pool would be interesting, since it could increase the uniformity of the crop harvest. This test did not occur since the current test was focus on 4 trays in each pool, while the other trays in the pool were used for production in facility and where moved but not monitored. It was easier to keep track of the trays by keeping them in place during a test. The plant movement test will be done at La Boîte Maraîchère outside of the scope of this research project, as a continuation of the research done in their facility.

3.5.7. Other Recommendations

Reducing the depth of the pool walls from 6 to 4 inches by keeping a level of water in the system, of 3 to 4 inches, allows the plants in the trays to have better aeration, because the walls of the pool don't block the air flow in the system. Increased aeration enhances growth and reduces the chance of mold to develop at the base of a plant, leading to its death. Less water in the system means less load applied to the structure holding the different pools one over each other. A level of 3 inches instead of 5 inches represents a 40% load reduction on the structure, which is important to consider while designing vertical hydroponic systems.

The current pool linings are white, leading to light diffusion in the pool through the membrane itself. This encourages algae growth, which can be a problem in the hydroponic systems as the algae grows bigger, leading into more cleaning duties. With a black liner, algae growth would be much slower, reducing maintenance needs of the systems.

3.6. Conclusion

This research provided knowledge on alternative hydroponic methods for shipping-container plant factories, allowing movement of plants with a vertical usage of space with no mechanical parts. Testing different possible configurations lead to clear differences in yields, increased knowledge on aeration methods and allowed better working conditions to complete the transplanting, harvesting and cleaning tasks, increasing their efficiency. This research will help design the new installations at La Boîte Maraîchère and eventually increase their potential revenue.

Connecting text to Chapter 4

Chapter 4 is a follow-up to previous experiments on vermicompost leachate and manure extracts that were initiated within the study explored in Chapter 2. David Leroux studied the use of vermicompost leachate to brew organic nutrient solution and Peter Tikasz studied manure extracts for hydroponics (Tikasz et al., 2019). In the preliminary proof-of-concept experiment which occurred during the four season testing of the CING (Chapter 2), the vermicompost leachate (VL) derived from a vermicompost installation fed with a fixed organic diet, using highly nutritious food waste such as egg shells, coffee grounds, banana peels and inkless cardboard, showed potential to provide continuous nutrients for hydroponic plant production.

In light of recent findings that highlighted the nutrient content of chicken manure extracts when used as an organic hydroponic solution, Leroux and Tikasz hypothesized that brewing a combination of organic VL solution and a chicken manure extract would result in a balanced nutrient solution for plants growing in a hydroponic setup, and that this combined nutrient solution, referred as Biojuice, would be comparable to a chemical-based nutrient solution derived from Hoagland's recipe (Hoagland & Arnon, 1950).

Chapter 4. Optimizing an organic hydroponic solution brewed from a combination of chicken manure extracts and vermicompost leachate

4.1. Abstract

The goal of this study was to produce an organic nutrient solution with similar nutrient ratio of a conventional hydroponic nutrient solution. The use of a bioreactor, vermicompost leachate and fresh chicken manure extracts were studied to brew an organic nutrient solution referred as Biojuice. The impact of the Biojuice on Romaine Lettuce (*Lactuca sativa*) in hydroponic conditions were studied during three consecutive growing tests. The preliminary experiment of this study occurred during the four-season testing of the CING, an experimental northern greenhouse, where a nutrient solution prepared with vermicompost leachate was compared to an inorganic solution. The N-P-K ratio of the Biojuice and the inorganic nutrient solution were respectively 4.6-1-7.9 and 7-1-7.5. The Biojuice yielded lettuce with fresh mass 15 % higher than the inorganic nutrient solution at an electrical conductivity of 1.1 $mS.cm^{-1}$. At higher electrical conductivity of 1.5 and 1.6 $mS.cm^{-1}$, the Biojuice lettuce yields were respectively 44% and 69% lower than the inorganic nutrient solution. This result is explained by a calcium deficiency in the plants caused by a Ca:Mg nutrient ratio imbalanced mixed with a high sodium content.

4.2. Introduction

Hydroponics is an agricultural method that doesn't require soil, wherein all required nutrients for plant growth are delivered via water. Because commercial organic hydroponic approaches to food production are still in the early stages of development this plant production method relies heavily on chemical fertilizer. Organic sources of macronutrients and micronutrients must be provided in adequate quantities to provide an organic nutrient solution suitable for plant growth. Hydroponic crop production has become an increasingly popular practice in innovative and urban farming. However, chemical and inorganic fertilizers pose threats to the future of agriculture, since they are either mined or synthetized using energy derived from fossil fuels. Organic nutrient solutions in hydroponics have garnered increasing interest, but they are not widely commercially used, due to inconsistencies in the nutrient value of the solution used and lower concentrations, which can lead to lower biomass yields.

Aquaponics are the most recognized form of organic hydroponics. Nutrients for plant growth are mainly provided from fish waste that is processed by a biofilter. The fish waste hosts ammonia-oxidizing bacteria (AOB), nitrifying ammonia to nitrites, and then to nitrates (Endo, 2019). For organic fertilization derived from other sources (e.g. manure and vermicompost) to be feasible in commercial hydroponics operations, current nutrient management strategies must be modified. Brewing the nutrient solution prior to use may be a possible solution, but the nutrient profile of the organic solution must be consistent and comparable to chemical fertilizers with respect to biomass yield. Tikasz *et al*. (2019) used fresh chicken, cow and turkey manure to study their effects on hydroponically grown leafy greens. The highest biomass yields were obtained with turkey manure at a concentration of 50 g/L, this turkey manure outperformed chicken and cow manure because the manure source was composted 1–6 months before its use in hydroponics. Hence, the ammonia present was transformed in nitrates via the action of nitrifying bacteria. For the chicken manure experiment, the ammonia concentration at 50g/L was over the toxicity limit for plant growth (Tikasz et al., 2019). In a vermicompost bin, earthworms ingest, grind, and digest organic waste using bacterial activity present in their gut. As a result, rapid mineralization and humification begins, converting unstable organic matter into relatively stable and microbially active material (Ali et al., 2015). This nutrient-rich compost leaches a liquid called vermicompost leachate (VL), which is very rich in nutrients. According to a recent study on the effect of earthworms on ammonia and nitrification, vermicompost exhibits elevated numbers of ammonia-oxidizing archaea and bacteria (AOA and AOB) that can accelerate the nitrification process (Huang, Xia, Cui, & Li, 2017).

Using fresh manure extracts in hydroponics would require a pre-processing step of biofiltration to allow bacteria to convert the ammonia into nitrates. Knowing vermicompost is rich in AOB, the VL would also contain a significant amount of AOB that could nitrify the ammonia present in fresh chicken manure. By inoculating a biofilter with VL and mixing the VL with chicken manure extracts in a recirculating biofilter, it may be possible to nitrify ammonia present in a relatively short amount of time. This work investigated a method aimed at developing an organic hydroponic solution comprising two organic sources of nutrients, VL and chicken manure extracts, that were combined in a brewing phase prior to use in a hydroponic plant production system.

4.3. Methods

4.3.1. Proof-of-concept and experimental installation

A preliminary proof-of concept experiment was performed in two growing environments: the Canadian Integrated Northern Greenhouse (CING) and a research greenhouse, both located at McGill University (Macdonald campus, Sainte-Anne-de-Bellevue, QC). The CING is a hybrid between a northern greenhouse and a growth chamber, housed in a shipping container. It was designed to be adaptive, functioning as a typical solar greenhouse when solar light provides considerable heat and light, and as a closed growth chamber during the night and colder, darker winter conditions (Patricia Gaudet, 2017). The growing test occurred in the CING and in the research greenhouse simultaneously, over the duration of four different seasons. The test made use of a vertical hydroponic system comprising two towers, which were installed at both locations.

Figure 4.1 Growth Tower in Research Greenhouse during preliminary test, vermicompost nutrient solution (Left) and Hoagland nutrient solution (Right), June 2018

Since both vertical hydroponic systems had two independent pumps for the right and left sides of the growing towers, two nutrient solutions were tested in each system. The first nutrient solution was a 0.25x Hoagland solution described previously (Hoagland & Arnon, 1950) and the second nutrient solution was an organic nutrient solution containing only diluted VL. This VL was derived from 10 L vermicompost fed a constant diet of egg shells, banana peels, coffee grounds and inkless cardboard. By flooding the vermicompost weekly with 1 L water, VL was collected and diluted to match the electrical conductivity (EC) of the 0.25x Hoagland solution that was delivered to the other tower.

4.3.2. Vermicompost leachate

Red wiggler worms (*Eisenia fetida*) were used in the vermicompost. The quantities of organic matter inputs were adjusted during the experiment, to achieve complete degradation of inputs within two weeks of composting. The vermicompost was fed weekly according to these criteria, with the following readily available food waste items: one shredded organic banana peel (70 g), one tablespoon of fragmented and rinsed eggshell (14 g) and one cup of used coffee grounds (160 g). The vermicompost was fed weekly, alternatively feeding each half of the vermicompost bin, leaving the matter to be composted for 2 weeks. Food waste was placed at a depth of 3 to 5 cm from the top of the vermicompost, and then covered by vermicompost. Cardboard was added to adjust the humidity level of the vermicompost and increase its aeration by providing a structural component. Every week, 1 L of tap water was poured over the vermicompost to keep it moist and to increase leaching of nutrients. VL was collected via a drain at the bottom of the vermicomposting bin.

4.3.3. Chicken manure extract

Chicken manure was sourced from the Macdonald Campus farm (McGill University, Sainte-Anne-de-Bellevue, QC, Canada) and infused following the “Bucket-Bubbler Method” (Ingham, 2005) . Briefly, 1 kg of fresh chicken manure was infused into 20 L of tap water for 24 to 30 h. The manure was placed in a 400-micron compost tea filter bag (Compost TeaLab, California, U.S.), that was hung in a 20 L bucket. An air pump aerated the solution via an air stone for the whole duration of the infusion. This method allows for the extraction of nutrients and compounds from fresh chicken manure, such as ammonia, phosphorous and calcium, while reducing the amounts of particulate matter in the solution (Ingham, 2005).

4.3.4. Brewing

The VL and chicken manure tea were combined and brewed in a bioreactor designed and constructed for this study. At the end of the infusion, the chicken manure tea was transferred to the bottom of the bioreactor (Figure 4.2). The bioreactor was linked to the vermicompost installation drain so that the VL could mix with the chicken manure tea, while inoculating the bioreactor with bacteria present in the vermicompost. The porous media used in the trickle bed reactor to host bacterial activity was ¾ inch expanded clay; this is recommended in aquaponics, since it is light and has a large specific surface area ranging from 100,000 to 1,000,000 m^2 m^{-3} (Lekang & Kleppe, 2000). The submersible pump in the bioreactor liquid reservoir allowed to circulate liquid from the bottom part of the vermicompost through the bioreactor.

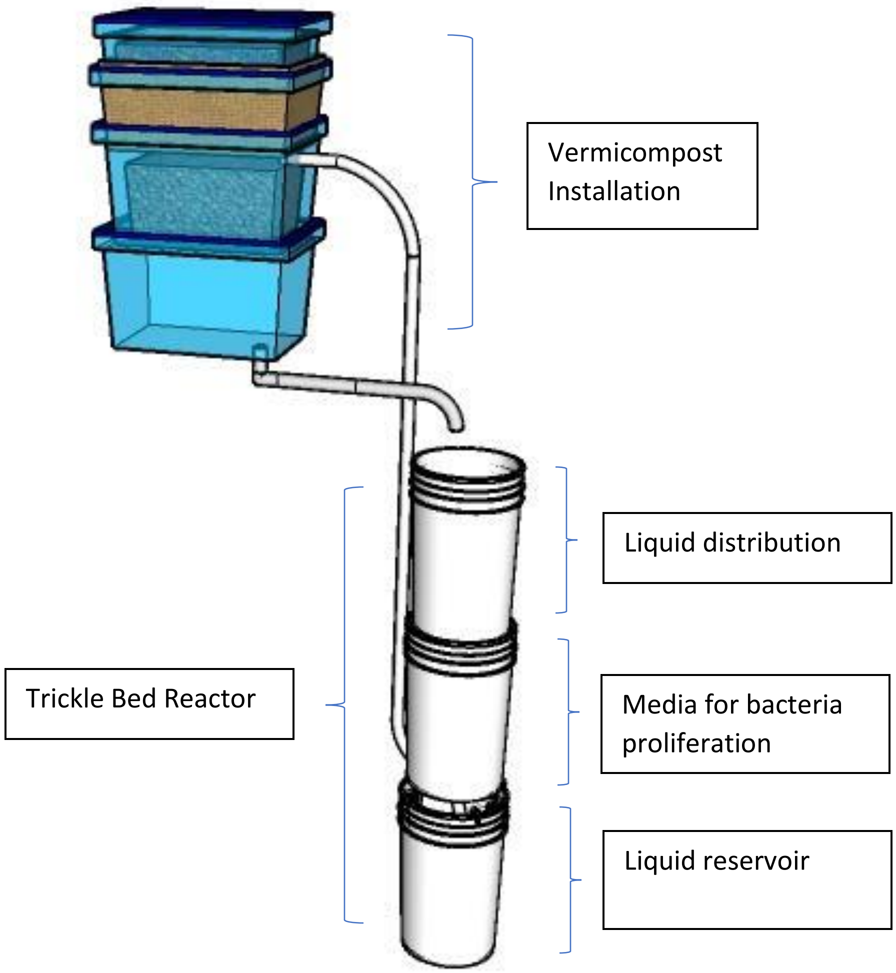

Figure 4.2 Bioreactor linked to vermicompost installation for brewing

4.3.5. Nutrient analysis

API freshwater test kits (Mars Fishcare, Chalfont, Pennsylvania, US) were used to estimate nutrient concentrations of ammonia, nitrites and nitrates during the brewing process. The nutrient solution was used only when the nitrification was completed, which was determine by the level ammonia dropping to almost 0 and the level of nitrates reaching a concentration of over 80 ppm.

Figure 4.3 Measurement of ammonia and nitrates using an API test kit of fresh manure extract (left) and biojuice once nitrification is complete (right).

Nutrient analysis on the manure extracts, the VL and the Biojuice were carried out with flow injection analysis. The analysis on the Biojuice infusion, were done before and after brewing in the bioreactor, and during plant growth tests, to asses the different nutrient levels in the solution and potential deficiencies. The concentrations of ammonium (NH_4^+), nitrates (NO_3^-), phosphorous (PO_4^{3-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), iron (Fe^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}) of the studied solutions were determined using the Quickchem® method, as per the manufacturer's instructions (Lachat Instruments, Milwaukee, WI, US) (Lachat Intruments, 2010).

4.3.6. Hydroponic setup

Romaine lettuce (*L. sativa*) seeds were placed in rockwool cubes (Grodan, Ontario, Canada) soaked with tap water for one week, then soaked in a test nutrient solution (0.25x Hoagland's or Biojuice) for another week. Plants were then transplanted into the vertical hydroponic nutrient film technique (NFT) growing system installed in a research greenhouse at McGill Macdonald Campus (McGill University, Sainte-Anne-de-Bellevue, Canada). Each side of the vertical hydroponic growing system had an independent pump. The nutrient solution was circulated by a 400 GPH water pump and a valve controlled the flow in each tube. A 1 L/min flow ensured a 3-mm level of nutrient solution in the 2-inch tubes, as described previously (Lennard & Leonard, 2006). During testing pump flow was lower than expected. Only four NFT tubes per experiment were tested, to ensure 0.6–1 L/min per tube. For the five first tests, 24 plants were grown per experimental group (0.25x Hoagland solution and Biojuice). Because of space constraints in the research greenhouse, for the last two tests, only 2 NFT tubes were used, for a total of 12 lettuce plants per group.

4.3.7. Nutrient solution parameters

The EC of the 0.25x Hoagland and Biojuice hydroponic solutions was monitored with a handheld EC-meter (HM Digital Meters COM-80 Electrical Conductivity and Total Dissolved Solids Hydro Tester, Seoul, Korea). The EC of the nutrient solutions used to soak the rockwool cubes containing lettuce seeds was 0.8 $mS.cm^{-1}$. The EC of the nutrient solutions in the vertical hydroponic setup was kept between 1.15–1.25 $mS.cm^{-1}$ (± 0.025 $mS.cm^{-1}$) above the greenhouse's irrigation water EC. The EC was adjusted by adding irrigation water or concentrated nutrient solution as described previously to remain within range of desired EC

(Brechner & Both, 2013). The pH of both nutrient solutions was maintained between 5.50 to 7.00 (±0.01). It was monitored with a handheld pH-meter (Dr. Meter PH100, China). Phosphoric acid (19.7% w/w) was used to lower pH to within the desired range.

4.4. Results

4.4.1. Preliminary tests results

To test the feasibility of using VL as an organic hydroponic solution, VL samples were collected weekly for nutrient analysis to determine ranges of the macronutrient concentrations (Table 4.1), prior to testing the VL in hydroponic conditions.

Days of experiment	mg N/L	mg P/L	mg K / L	mg Ca / L	mg Mg / L
0	426	72.9	4260	244	92
7	345	69.8	3740	182	75
14	385	79.7	3700	186	84
21	382	74.9	5640	229	119
21	369	77.1	4960	213	107
28	655	121.2	6940	320	149

Table 4-1 Nutrient analysis of the initial vermicompost leachate starting March 14th 2018

As the VL showed elevated levels of potassium and nitrogen, the vermicompost was flooded with 1 L tap water weekly, then diluted to the desired EC. The initial EC of the VL ranged from 5 to 7.5 mS.cm^{-1}. Dilution ratios raged between 1: 10 and 1: 20 with irrigation water to reach an EC of 1.15–1.25 mS.cm^{-1} above that of irrigation water (0.1 mS.cm^{-1}), and these diluted VL solutions were circulated in vertical hydroponic setups installed in two different locations for growth trials: the CING research unit and a research greenhouse at McGill University's MacDonald Campus.

Nutrient analysis of both nutrient solutions (0.25x Hoagland's and VL) was performed after each growth trial at the two different locations. These data revealed that the nutrient content of the VL solution was constant. The initial analysis of the VL in Table 3.1 shows high total nitrogen content, but as the vermicompost was leached, nitrogen content remained lower in relation to other macronutrients. Table 4.2 shows the average nutrient content of the diluted VL nutrient solution at harvest for the experiment performed during Summer 2018 and Table 4.3 compares the electrical conductivity and pH of the solutions used in the two different growing environments (CING and research greenhouse).

	N as nitrate		N as ammonium		P as phosphate		K		Mg		Ca	
	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.
VL	-0.08	0.14	0.74	0.02	6.59	0.18	429.74	13.46	15.00	0.75	46.40	1.54
H	97.20	4.45	0.49	0.04	4.86	2.60	169.64	13.40	44.26	7.50	138.55	27.86

Table 4-2 Comparison of organic vermicompost leachate (VL) solution and 0.25X Hoagland solution (H). S.E.: standard error.

Location	Treatment	Average EC ($mS.cm^{-1}$)	Average test pH	Average dry mass (g)	S.E.
CING	H	1.41	6.44	1.23	0.14
GH	H	1.47	6.52	3.67	0.35
CING	V	1.29	6.36	0.75	0.18
GH	V	1.41	6.44	1.20	0.05

Table 4-3 Electroconductivity (EC) and pH of organic vermicompost leachate (VL) solution and 0.25x Hoagland solution (H) and dry masses obtained for each treatment and location during Summer 2018. S.E.: standard error

The following table presents nutrient concentration of fresh manure extracts, at different concentration, prepared according to Tikasz's method (Tikasz et al., 2019). 20 g, 50 g, and 100 g manure were separately diluted in 30 L tap water. Solutions were aerated with an air pump for 48 h then filtered through a 1-mm sieve to remove large fragments. The solutions were diluted with tap water to reach a final volume of 60 L with concentrations of 10 g/L, 25 g/L, and 50 g/L.

	N as Nitrates		N as ammonium		Na		Ca		Mg		Mn	
Conc. (g/L)	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.	mg/L	S.E.	ug/L	S.E.
10	0.5	0.4	100.1	14.5	12.1	0.7	16.7	1.3	5.9	0.9	112	27.6
25	2	1.1	221.9	11	30.6	6.2	21	0.4	13.4	1.6	217.5	68.6
50	2.7	0.9	366.6	28.9	50.2	2.4	44	0.6	20.6	1.6	91.9	19.9

Table 4-4 Nutrient content of chicken manure extracts at different concentrations (Tikasz, Macpherson et al. 2019)

4.4.1.1. Biomass yield at two locations

The fresh mass (FM) yield of lettuce plants grown with organic nutrient solution containing VL was lower than the FM of lettuce plants grown with 0.25x Hoagland solution (Figure 4.4).

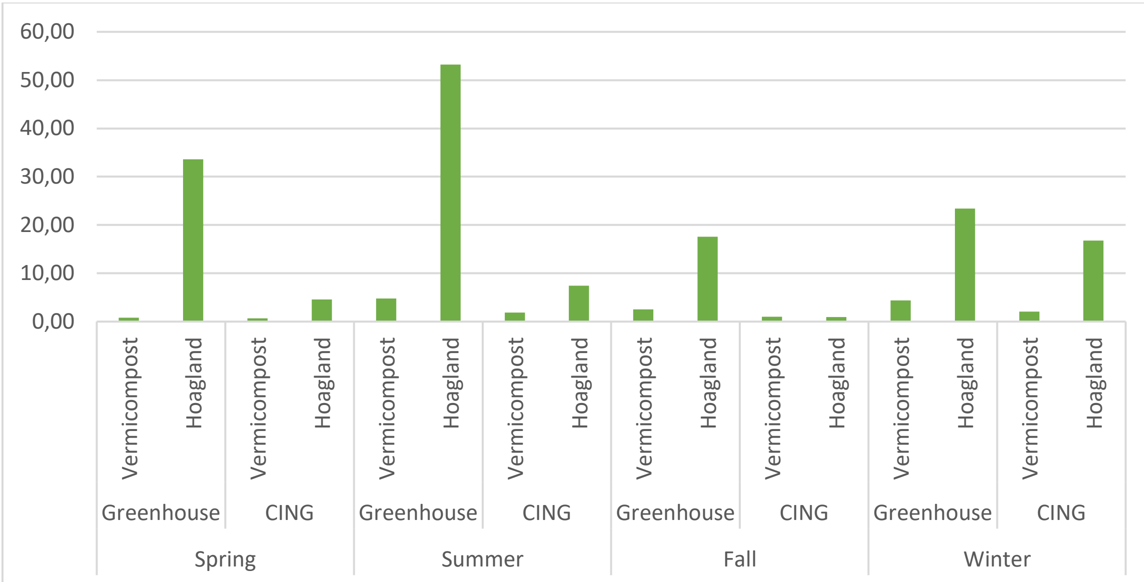

Figure 4.4 Average fresh mass (g) of lettuce in proof-of-concept experiment comparing VL and 0.25x Hoagland nutrient solution.

4.4.1.2. Vermicompost leachate nutrient content

A decrease in total nitrogen from the initial VL compared to the VL used later was observed and could be due to increases in forced water percolation from the vermicompost, likely leading to most of the nitrogen being leached out during the first VL collection. Nitrate is very mobile and easily leached because it has weak interactions with the negatively charged matrix of high humidity soil aggregates, such as vermicompost (Lehmann J, 2003). By feeding selected highly nutritious food waste to the vermicompost, a constant amount of macro- and micronutrients were degraded via the action of worms, bacteria and other microorganisms. Even if the nitrogen initially present in the vermicompost was lower over the duration of the experiment, the levels of the other nutrients remained stable.

4.4.2. Brewing and bioreactor performance

The purpose of the bioreactor is to provide an adequate environment for nitrifying bacteria (present in the VL) to thrive, proliferate, and accelerate nitrification of the ammonia present in the manure tea. Figure 4.5 shows the nutrient content of a chicken manure extract that was transferred into the bioreactor at day 0, with samples collected every 24 h for a 5-day period. After one week of brewing, the resulting nutrient solution (Biojuice) was circulated in a vertical hydroponic setup and compared to 0.25X Hoagland's solution.

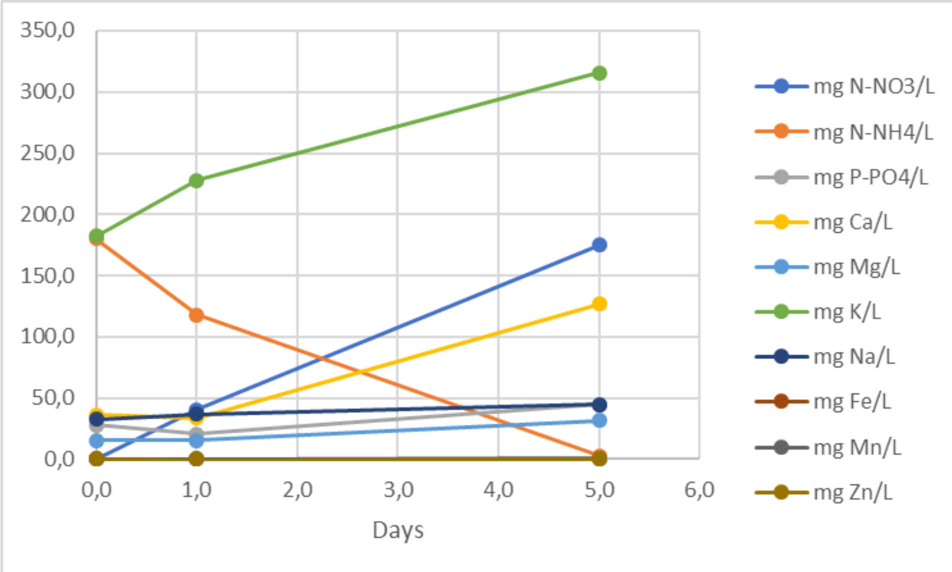

Figure 4.5 Variation of nutrient content in the solution in the bioreactor

4.4.3. Hydroponic growth trials

Average nutrient solution parameters and fresh mass yield of the lettuce plants for three hydroponic growth trials are presented in Table 4.5 and Figure 4.6.

	Trial 1 (33 Days)		Trial 2 (21 Days)		Trial 3 (23 days)	
	Biojuice	Hoagland	Biojuice	Hoagland	Biojuice	Hoagland
Average EC ($mS.cm^{-1}$)	1.07	1.08	1.52	1.47	1.55	1.61
Average pH	7.25	7.43	6.95	7.13	6.06	6.71

Table 4-5 Average nutrient solution parameters of 0.25x Hoagland's and Biojuice

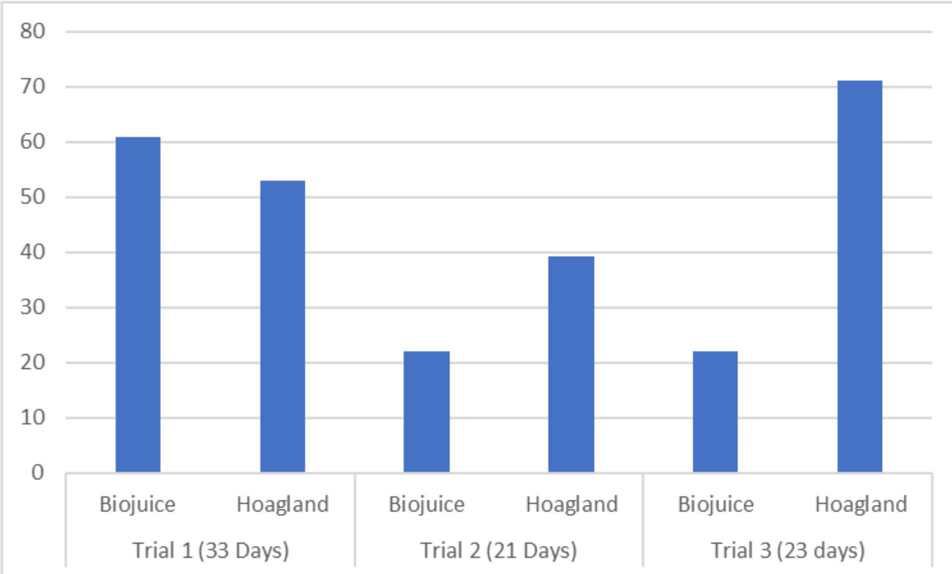

Figure 4.6 Average Fresh Mass (g) of hydroponic growth comparative tests

4.4.4. Nutrient content comparisons

Nutrient content of the different solutions used in the vertical hydroponic setup were analyzed for 10 essential elements. Macro- and micronutrient content of the initial solutions used in the growth trials are compared in Figures 4.7 and 4.8.

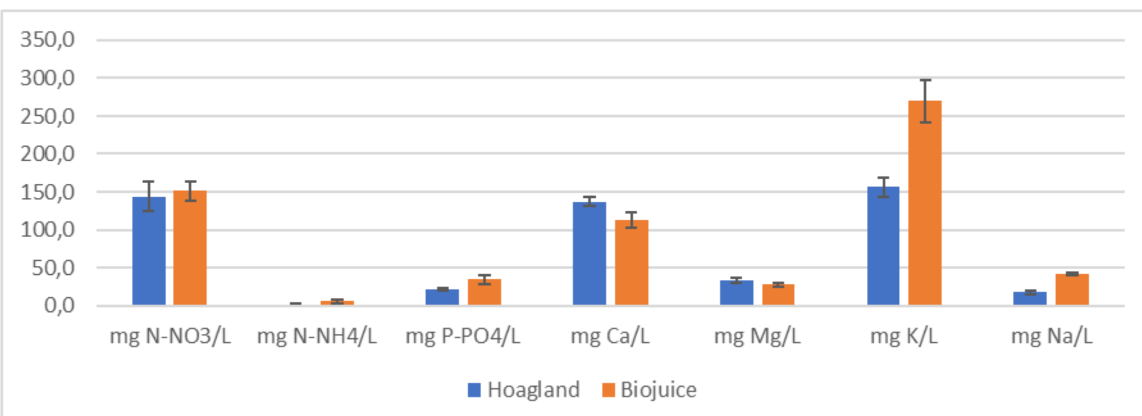

Figure 4.7 Comparison of seven major elements present in nutrient solutions at the start of each hydroponic growth trial. Data represent average values ± S. E. of the three growth trials.

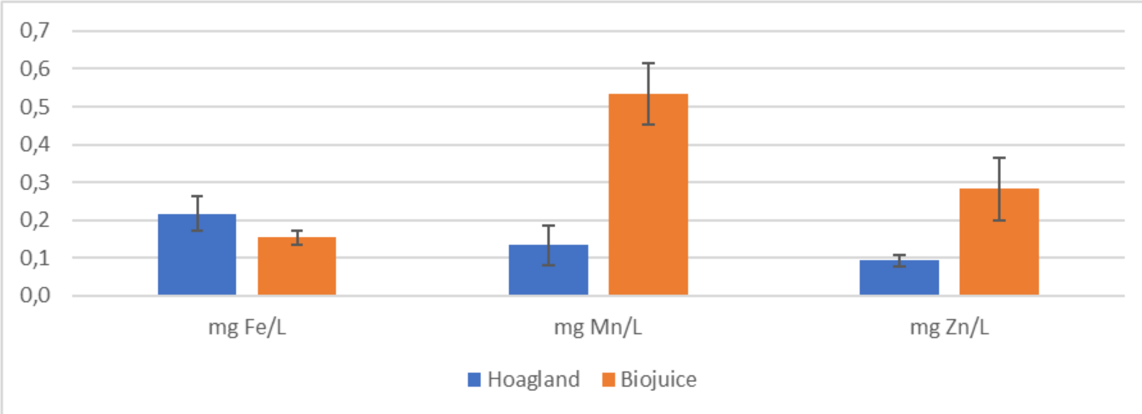

Figure 4.8 Comparison of three minor elements present in nutrient solutions at the start of each growth trial. Data represent average values ±/- S. E. of the three growth trials.

Differences in nutrient concentration over time, for 10 elements in 0.25x Hoagland's solution and Biojuice during the second and third hydroponic growth trials are shown in Figures 4.9, 4.10, 4.11 and 4.12.

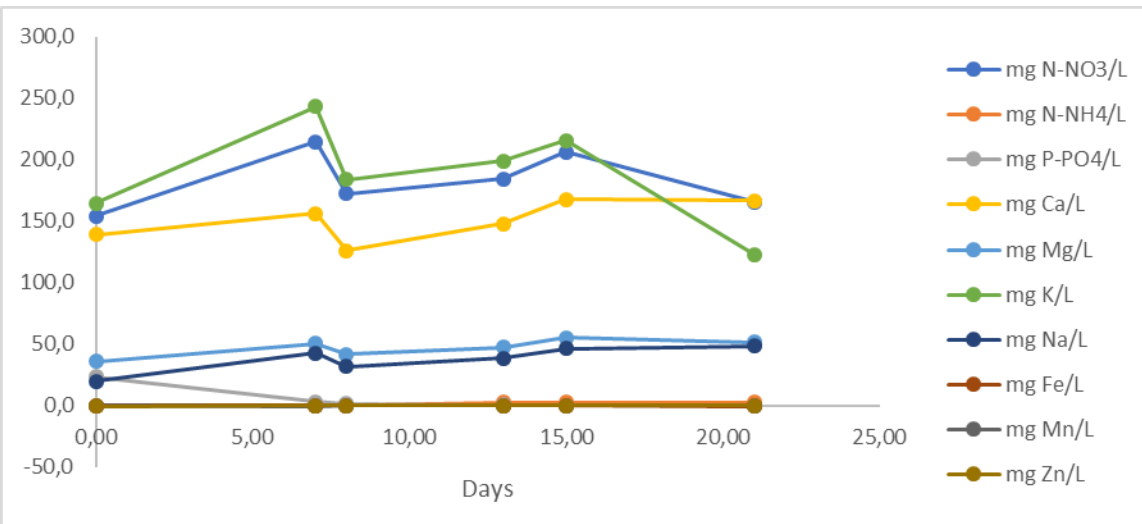

Figure 4.9 Nutrient concentration in Hoagland's over time, growth trial 2

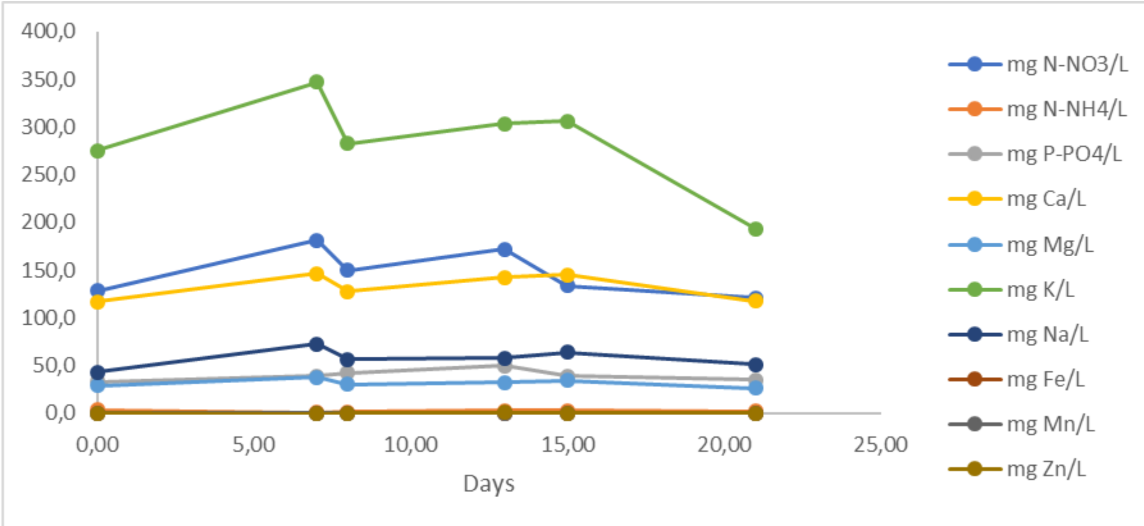

Figure 4.10 Nutrient concentrations in Biojuice over time, growth trial 2

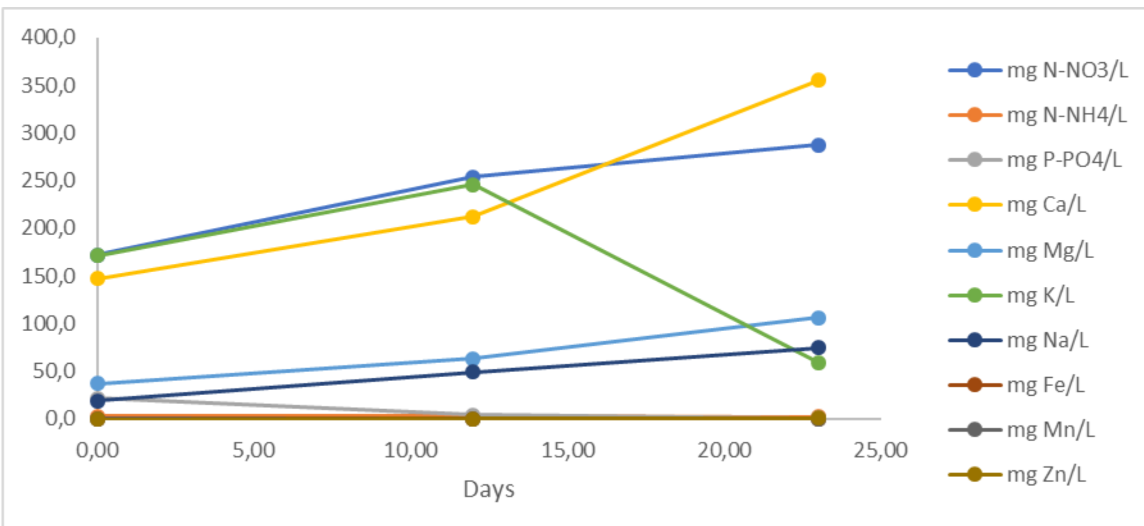

Figure 4.11 Nutrient concentrations in Hoagland's solution over time, growth trial 3

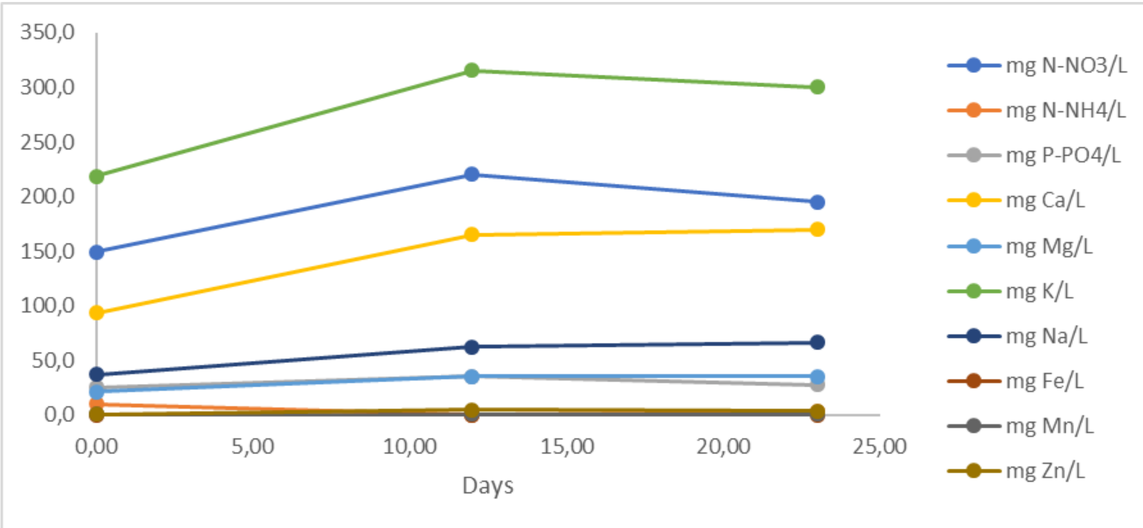

Figure 4.12 Nutrient concentrations in Biojuice over time, growth trial 3

4.5. Discussion

4.5.1. Nitrification using the bioreactor

The performance of the bioreactor was assessed using API test kits. Although these were not precise enough to indicate exact levels of nutrients, test values clearly showed if ammonia or nitrates were the main form of nitrogen present in the solution. This indicator was used to perform the three hydroponic growth trials, and the observed variation in nutrients over the time period in the bioreactor is confirmed in Figure 4.5, where the ammonia level drops at the same rate as increasing nitrate levels.

4.5.2. Growth trials

The Biojuice and Hoagland nutrient solution comparison was completed three times. While the Biojuice brewing method remained constant throughout, growth trials differed slightly, and hence, they will be discussed individually.

4.5.3. Difference in between tests

Tests were completed from June 5th 2019 to October 27th 2019 in three subsequent growing trials. Natural light changed but the comparative tests were all simultaneous so the differences in crops grown can be associated with the different nutrient solution more than the environmental difference effect. The first Biojuice test was performed at an average EC of 1.07 $mS.cm^{-1}$, which was lower than the second and third tests, respectively at EC of 1.52 $mS.cm^{-1}$ and 1.55 $mS.cm^{-1}$. Nutrient solution was added during the first and second tests to adjust the nutrient content. The third test was performed with a single nutrient solution without any addition during the test.

4.5.3.1. First growth trial

The first growth trial was performed with an average nutrient solution of pH 7.25 and EC of 1.08 $mS.cm^{-1}$, compared with a 0.25x Hoagland solution with a pH of 7.43 and EC of 1.07 $mS.cm^{-1}$, with an irrigation water of pH 6.9 and EC 0.1 $mS.cm^{-1}$. Under these growth conditions, lettuce grown with Biojuice had a 15% yield higher than lettuce grown with Hoagland's.

Figure 4.13 Lettuce at Harvest, Hoagland Nutrient Solution (top) and Biojuice Nutrient Solution (bottom) Trial 2

This result was not observed in growth trials 2 and 3. The main reason for this result could be that the EC level during this test was lower than the recommended EC for inorganic hydroponic nutrient solutions 1.15-1.125 $mS.cm^{-1}$ above irrigation water recommended for lettuce, which may have caused lower nutrient uptakes. However, when measuring EC for organic nutrient solution, it is possible that the nutrients in the hydroponic solution are not all in ionic form, hence the EC reading may not have taken them in account. The actual nutrient levels in the Biojuice was then higher than in the Hoagland nutrient solution, while the nutrient uptake of the Hoagland was also not optimal because of a pH higher than 7 (Brechner & Both, 2013).

4.5.3.2. Second growth trial

The second trial Biojuice had a higher EC and pH from the previous trial, 1.52 $mS.cm^{-1}$ and pH 6.95, compared to the Hoagland nutrient solution (EC of 1.47 $mS.cm^{-1}$ and pH of 7.13). Nutrient solution was added during the test to maintain levels in the tank, which also added new nutrients into the systems during the experiment. Under these growth conditions, it was noted that the lettuce grown with Biojuice had a fresh mass yield 56% that of the lettuce grown with Hoagland's. The look of the plants were very similar during this test, which ca be observed in Figure 4.14, but it is possible to visually assess the size difference in between treatments in Figure 4.15 .

Figure 4.14 Top view at harvest of the second trial, Hoagland nutrient solution (row 1 and 3) and Biojuice nutrient solution (row 2 and 4)

Figure 4.15 Side view at harvest of the second trial, Hoagland nutrient solution (row 1 and 3) and Biojuice nutrient solution (row 2 and 4)

4.5.3.3. Third growth trial

The third growth trial was performed with similar conditions recorded for the second growth trial; the Biojuice had an EC of 1.55 mS.cm^{-1} and pH of 6.06, compared to a Hoagland nutrient solution with an EC of 1.61 mS.cm^{-1} and a pH of 6.71. For this trial, the nutrient solutions were filled at the beginning of the test and only tap water was added during the test to maintain the level in the tank and EC within the desired range. Under these conditions, lettuce grown with Biojuice had a fresh mass yield 31% that of the lettuce grown with Hoagland's. For the second and third trials, the Hoagland nutrient solution outperformed Biojuice. At higher EC, the plants were able to uptake nutrients faster, building more biomass. However, at these EC values the Biojuice did not perform as well as the test at lower EC, which can be caused by limited uptake due to potential toxicity levels of certain elements present in the nutrient solution, or imbalanced nutrient ratios. It is possible to notice yellowing of the plants grown in Biojuice in Figure 4.16, and visually assess the size difference at harvest in Figure 4.17.

Figure 4.16 Top view at week 2 of the third trial, Hoagland nutrient solution (row 1 and 3) and Biojuice nutrient solution (row 2 and 4)

Figure 4.17 Side view at harvest of the third trial, Hoagland nutrient solution (row 1 and 3) and Biojuice nutrient solution (row 2 and 4)

4.5.4. Nutrient contents

As observed in Figures 4.7 and 4.8, all elements compared were present in both the Hoagland's and Biojuice nutrient solutions. The initial concentrations were statistically different ($p > 0.05$), but most elements in the initial nutrient solutions were within the recommended ranges for hydroponic solutions, as demonstrated in Table 4.6.

Element (with form analyzed)	Hoagland Element Concentration (mg/L)	Biojuice elements concentration (mg/L)	Common range (mg/L)
N (NO3- and NH4+)	144.8	156.3	100 - 250
P (PO43+)	20.7	34.3	30-50
K (K+)	156.1	270.0	100-300
Ca (Ca2+)	137.2	112.3	80-140
Mg (Mg2+)	32.8	27.2	30-70
Fe (Fe3+)	0.2	0.2	1.0-5.0
Mn (Mn2+)	0.1	0.5	0.5-1.0
Zn (Zn2+)	0.1	0.3	0.3-0.6
Na (Na+)	17.1	41.6	<50 or TOXIC

Table 4-6 Comparison of nutrient content and commonly recommended ranges for hydroponic solutions. Element concentrations lower than recommended ranges are highlighted in yellow (Langenhoven, 2018).

4.5.5. Nutrient ratio

Nutrient ratios for both solutions were comparable. For instance, initial Hoagland's and Biojuice solutions N-P-K ratios were 7-1-7.5 and 4.6-1-7.9, respectively. Initial Ca-Mg ratios were 4:1 and 4.3:1, respectively. These ratios are very important for optimized nutrient uptake, since they have complex interactions, the mutual ratios in the nutrient solution of the ions will affect the uptake of a specific ion (Cees Sonneveld & Wim Voogt, 2009).

According to recommended nutrient ratios, calcium and magnesium ratios should be 3-5 $mg.L^{-1}$ calcium to 1 $mg.L^{-1}$ magnesium. If there is more calcium than this ratio, it can block the ability of the plant to take up magnesium, causing a magnesium deficiency. Conversely, if the ratio is less than 3-5 Ca: 1 Mg, the high magnesium proportion can block calcium uptake, causing a calcium deficiency (Langenhoven, 2018). It seems like in the case of Biojuice, the magnesium uptake blocked the calcium uptake.

4.5.6. Apparent nutrient uptake

The Yamazaki method can be used on the third growth trial to analyse apparent nutrient uptake, since no nutrient solution was added during this test (Wada, 2019). Using this method, it is possible to notice that the calcium uptake of the Biojuice during growth trial 3 appeared negative compared to a positive uptake in the Hoagland's solution: -6.85 mg Ca/g of dry mass in Biojuice and 19.09 mg Ca.g^{-1} of dry mass. However, apparent magnesium uptake in the Biojuice was larger than the uptake in the Hoagland's solution: 2.36 mg Mg.g^{-1} dry mass in Biojuice and 1.04 mg Mg.g^{-1} of dry mass in Hoagland.

4.5.7. Sodium salt stress

Even if sodium concentrations were lower than the recommended range to avoid toxicity, it was still much higher in the Biojuice than in the Hoagland nutrient solution, 17.1 mg.L^{-1} versus 41.6 mg.L^{-1}. It is possible that without causing toxicity, the sodium stress interfered with nutrient uptake of other elements, limiting plant growth. This phenomenon was observed in fada bean (*Vicia faba*), where higher concentration of Na^{2+} in soil interfered with K^{+} and Ca^{2+} nutrition and disturbed efficient stomatal regulation which results in a reduction of photosynthesis and growth (Tavakkoli, Rengasamy, & McDonald, 2010).

4.6. Conclusion

The main goal of this study was to optimize an organic nutrient solution combining VL with chicken manure extract that would be comparable in nutrient content to its inorganic counterpart. The Biojuice achieve higher yield than the 0.25x Hoagland's nutrient solution control at a low EC value (1.1 mS.cm^{-1}), but lower yields at higher EC (1.5 mS.cm^{-1}and 1.6 mS.cm^{-1}). It appears that the combined effect of higher nutrient concentration, unbalanced nutrient ratios and higher sodium concentration in the Biojuice led to a reduced uptake of calcium in the plants. This method requires improvement, but it demonstrates potential for replacing inorganic nutrient in hydroponic solution with nutrients derived from readily available organic waste. More research is required to optimize the recipe used in the nutrient solution brewing and research should be extended to other crops such as basil, tomato or cucumber, which have higher market value. Overall, this project opens the door to explore various combinations of local nutrient sources to brew organic nutrient solution, which allows remote food production systems to provide fertilizer to their crop from local inputs. Even if the yields of the inorganic nutrient solution outperform the Biojuice, the use of organic and local nutrients in innovative agriculture uses circular economy concepts, stimulating partnerships in between agricultural spheres, which is a requirement to achieve a sustainable food system able to tackle food insecurity.

Chapter 5. General conclusion

The objective of this research was to address challenges in controlled environment agriculture for northern applications. Energy efficiency, labor requirements and fertilizer supply were the three challenges addressed. Innovative agricultural systems such as shipping-container plant factories have the potential to increase food security in northern Canada. However, these systems are subjected to multiple modifications to overcome the challenges they face.

5.1. The Canadian Integrated Northern Greenhouse

To address the heat efficiency challenge, the Canadian Integrated Northern Greenhouse, a prototype hybrid between a growth chamber and a northern greenhouse housed in shipping container was tested and data was collected during a four-season experiment growing lettuce. The main result was that in cold conditions, keeping the thermal curtain closed and electrical lighting always on was the best production condition. It allowed for adequate temperature and lighting in the growing environment. Natural light was not used optimally but this way supplemental heating was less required.

Indoor agriculture facilities for northern applications must be designed according to local environmental conditions. Moreover, to thrive and have long term positive impacts, they must be operated and become an integral part of the communities they are meant for. With that mentality, the future projects on northern agriculture in the Biomass Production Laboratory will take the knowledge acquired from the present prototype testing results to work with northern communities in the design of adapted northern growing installations.

5.2. Multistage Hydroponic Configuration Testing in Container Plant Factory

Indoor agriculture being very labor dependant, with the limited labor force in northern Canada, the second study proposed hydroponic configurations that could reduce labor needs by allowing movement of plants and improve work ergonomics in indoor agriculture. This second study was conducted in partnership with La Boîte Maraîchère, indoor agriculture company, operating a container plant Factory in Laval, Québec. The project compared 3 different hydroponic configurations that allowed movement of plants held in trays. Of the strategies, the preferred one was the stagnant shallow water culture. It allowed a better control of nutrients, when the system was subjected to contaminants, increasing yield of fresh biomass.

These results were used to guide the industrial partner in the design of their future systems. By opting for plants in trays able to move in their growing system, they were able to reduce the labor workload. To push the optimisation of labor in plant factories, automation of plants manipulation is a main research perspective. It requires large investments but since labor is the main operational costs of these systems, when considering operating in remote locations where labor can be limited, automation to reduce the labor workload is a promising avenue to increase economic viability of plant factories.

5.3. Optimizing an organic hydroponic solution brewed from a combination of chicken manure extracts and vermicompost leachate

The remote locations of northern communities often have limited ability to import specific resources such as fertilizers at a viable cost. To be self-sufficient and economically viable, indoor northern agriculture could rely on local sources of nutrients. To do so, vermicompost leachate and chicken manure extracts were studied to brew an organic nutrient solution referred to as Biojuice, which was tested to grow lettuce in hydroponic conditions. The goal of this third study was to provide nutrients from a potential local source in remote communities. Plants successfully grew in hydroponic conditions and the solution brewed had nutrients ratios comparable to an inorganic control nutrient solution following the Hoagland recipe. The nutrient N-P-K ratios obtained this way for the Biojuice and the Hoagland recipes were respectively 4.6-1-7.9 and 7-1-7.5. The Biojuice yielded lettuce with fresh mass 15% higher than the inorganic nutrient solution at an electrical conductivity of 1.1 $mS.cm^{-1}$. At higher electrical conductivity of 1.5 and 1.6 $mS.cm^{-1}$, the Biojuice grown lettuce yield were respectively 44% and 69% lower than the inorganic nutrient solution. This study was successful but the process to brew the nutrient solution must be improved for the process to be scalable.

5.4. Future Work

The research projects conducted on organic nutrient solution where the inspiration to launch the Cannafish Startup in collaboration with Peter Tikasz and others. The goal of this Startup is to include manure and compost in liquid fertilization plan on a commercial scale. Ultimately, this project could replace large amounts of inorganic phosphorus and synthetic ammonia, which both have significant environmental impacts. Moreover, it creates value for a problematic manure generation from animal farming, especially from the aquaculture industry. Cannafish valorizes manure by transforming it into liquid organic fertilizers using a unique bioreactor technology and vermicompost. This waste management to fertilization service replaces unsustainable chemical fertilizers with locally sourced organic nutrients, while ecologically managing organic waste.

Cannafish participated in entrepreneurship contests, such as the 2019 McGill Dobson Cup where they won 3rd place in the Innovation Driven Enterprise track and the 2019 Coopérathon where they won an Agriculture grant offered by AU/Lab, proposing a project including circular economy in urban farming. Cannafish was also incubated at the Esplanade Impact 8 and recently got support from the Mitacs Accelerate Entrepreneurship program to perform a research project studying a specific ion monitoring strategy in organic hydroponics to allow the preparation of a nutrient solution that is rich in nutrients and optimal for hydroponic plant growth.

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Appendix A.

Monitoring of systems

Table A-1 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Spring trial

	GREENHOUSE											CING										
	Vermicompost Nutrient Solution					Hoagland Nutrient Solution						Vermicompost Nutrient Solution					Hoagland Nutrient Solution					
DATE	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)
2018-05-08	8.4	110.0	36.2			7.5	150.0	36.2			28.5	8.2	87.7	21.1			7.5	131.0	21.0			27.0
2018-05-09	8.4	106.7	34.6			7.3	154.5	33.0			31.0	8.3	89.2	22.3			7.5	134.2	21.4			25.0
2018-05-11	9.0	100.0	32.0			7.7	160.0	32.0			34.0	8.7	81.0	13.0			7.9	126.0	13.0			13.0
2018-05-14	9.2	100.0	32.0			7.7	160.0	32.0			34.0	8.7	81.0	13.0			7.9	126.0	13.0			13.0
2018-05-15	9.7	123.0	26.0	3.3	13.2	7.7	160.0	26.0	4.0	16.3	28.0	9.0	109.0	18.0	4.0	16.3	8.1	124.0	18.0	4.0	16.3	20.0
2018-05-16	9.2	134.0	35.0	3.0	12.2	7.9	168.0	34.0	3.5	14.2	35.0	8.9	112.0	14.0	3.8	15.4	8.1	126.0	14.0	3.8	15.4	22.0
2018-05-17	9.1	141.0	27.0	2.9	11.8	7.9	183.0	27.0	3.4	13.8	28.0	9.0	116.0	21.0	3.9	15.9	8.3	127.0	21.0	3.8	15.4	22.0
2018-05-18	9.3	134.0	33.0	3.5	14.2	8.2	172.0	32.0	3.5	14.2	27.0	9.1	126.0	24.0	3.6	14.6	8.4	123.0	23.5	4.3	17.3	28.0
2018-05-21	9.3	153.0	32.0	2.8	11.4	8.3	216.0	31.0	2.2	8.9	29.0	9.0	135.0	19.0	3.4	13.8	8.3	129.0	18.0	3.8	15.4	22.0
2018-05-22	9.2	131.0	28.0	3.7	15.0	8.3	133.0	26.0	4.0	16.3	28.0	9.1	135.0	24.0	3.5	14.2	7.7	100.0	22.0	5.0	20.3	20.0
2018-05-23	9.2	140.0	32.0	3.5	14.2	8.3	143.0	31.0	3.5	14.2	27.0	9.1	132.0	20.0	3.5	14.2	8.1	102.0	20.0	4.0	16.3	22.0
2018-05-24		147.0	32.0	3.5	14.2		162.0	30.0	2.5	10.2	28.0		142.0	24.0	3.3	13.2		105.0	24.0	2.8	11.2	24.0
2018-05-25		157.0	32.0	3.2	13.0	7.9	211.0	26.0	1.5	6.1	26.0	9.2	145.0	26.0	3.4	13.8	8.3	110.0	24.0	1.3	5.3	26.0
2018-05-28	9.0	131.0		4.0	16.3	7.7	110.0		3.0	12.2			131.0		4.3	17.3		115.0		4.5	18.3	24.0
2018-05-29		141.0	32.0	4.0	16.3		121.0	28.0	2.0	8.1	23.0		136.0					115.0				
AVERAGE	9.1	129.9	31.7	3.4	13.8	7.9	160.2	30.3	3.0	12.2	29.0	8.9	117.2	20.0	3.7	14.9	8.0	119.5	19.5	3.7	15.1	22.0

Table A-2 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Summer trial

	GREENHOUSE											CING										
	Vermicompost Nutrient Solution					Hoagland Nutrient Solution						Vermicompost Nutrient Solution					Hoagland Nutrient Solution					
DATE	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)
2018-06-12	7.1	176.0	26.8	2.5	10.2	7.3	191.0	27.3	2.0	8.1		6.8	127.0	24.0	5.5	22.4	6.7	138.0	24.0	5.3	21.3	
2018-06-13	6.9	144.0	27.1	4.3	17.3	7.1	158.0	27.1	4.6	18.7		6.8	131.0	27.0	5.0	20.3	6.8	141.0	27.0	4.9	19.9	
2018-06-19												6.2	135.0				6.4	134.0		5.3	21.3	
2018-06-21	6.1	131.0		4.0	16.3	6.1	135.0		4.0	16.3		6.1	134.0		5.5	22.4	5.9	136.0		6.0	24.4	
2018-06-26	6.2	142.0	25.2	3.8	15.2	6.2	141.0	24.9	4.0	16.3		6.3	133.0	27.1	4.8	19.3	6.1	136.0	26.3	5.5	22.4	
2018-06-28	5.9	111.0		4.0	16.3	5.9	109.0		4.5	18.3		6.0	111.0	26.9	6.3	25.4	5.9	109.0	26.5	7.8	31.5	
AVERAGE	6.4	140.8	26.4	3.7	15.0	6.5	146.8	26.4	3.8	15.5		6.4	128.5	26.3	5.4	22.0	6.3	132.3	26.0	5.8	23.5	

Table A-3 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Fall trial

	GREENHOUSE											CING										
	Vermicompost Nutrient Solution					Hoagland Nutrient Solution						Vermicompost Nutrient Solution					Hoagland Nutrient Solution					
DATE	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)
2018-12-01	6.9	95.0		3.5	14.2	6.6	123.0		4.0	16.3		6.8	80.0		2.0	8.1	6.5	130.0		2.5	10.2	
2018-12-04	8.1	105.0	22.8	3.0	12.2	6.9	133.0	22.7	3.5	14.2	22.0	7.4	47.0	11.9	4.5	18.3	7.1	63.0	11.6	6.0	24.4	13.9
2018-12-04	7.2	110.0	22.4	3.0	12.2					0.0						0.0	6.6	129.0	11.7	6.5	26.4	13.9
2018-12-05	7.0	117.0	22.2	3.0	12.2	7.0	128.0	22.9	3.0	12.2		7.0	58.0	8.5	5.0	20.3	7.0	130.0	8.4	6.0	24.4	10.0
2018-12-10	7.0	107.0	23.1	3.0	12.2	6.7	120.0	19.9	3.0	12.2		6.9	67.0	9.0	4.5	18.3	6.9	134.0	9.1	5.0	20.3	13.3
2018-12-11	7.5	117.0	21.6	2.5	10.2	7.2	130.0	21.9	2.5	10.2	20.2	7.7	73.0	7.0	4.8	19.3	7.0	137.0	7.4	6.0	24.4	8.9
2018-12-13	6.5	122.4		3.0	12.2	6.3	93.5		3.0	12.2		6.5	57.8	11.1		0.0	6.1	105.3	8.8	5.5	22.4	16.1
	6.5	125.0		3.0	12.2	6.0	125.8		4.0	16.3		6.6	71.8			0.0	6.0	136.4			0.0	
2018-12-17	6.6	93.9	21.3	4.0	16.3	6.5	105.5	19.2	4.0	16.3	18.8	6.7	74.1	13.3	4.0	16.3	6.2	151.6	11.9	5.0	20.3	15.6
2018-12-18	6.9	95.0	23.9	4.0	16.3	6.5	112.0	23.8	4.0	16.3						0.0				4.0	16.3	
2018-12-21	6.5	116.9	23.2	3.0	12.2	6.5	113.4	22.8	2.5	10.2		6.9	84.9	13.8	3.0	12.2	6.3	165.3	12.4	4.0	16.3	15.0
AVERAGE	6.9	109.5	22.6	3.2	12.9	6.6	118.4	21.9	3.4	12.4	20.3	6.9	68.2	10.7	4.0	10.3	6.6	128.2	10.2	5.1	18.7	13.3

Table A-4 - Monitoring of pH, EC, temperature and volume of nutrient solution for the Winter trial

GREENHOUSE	Vermicompost Nutrient Solution						Hoagland Nutrient Solution						
DATE	pH	Tds (ppm)	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	Tds (ppm)	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)
2019-03-02	5.6	737.0	140.0	22.7	3.0	12.2	5.6	676.0	128.4	22.1	3.0	12.2	
2019-03-05	4.2	783.0	148.8	26.0	2.8	11.2	2.5	805.0	153.0	25.2	2.0	8.1	
	4.3	674.0	128.1		3.5	14.2	4.3	680.0	129.2		2.5	10.2	
2019-03-06	4.3	599.0	113.8	23.7	5.0	20.3	4.7	515.0	97.9	24.2	3.5	14.2	
2019-03-11	5.3	671.0	127.5	21.4	4.8	19.5	4.8	362.0	68.8	18.6	3.5	14.2	
2019-03-14	5.1	923.0	175.4	25.8	2.3	9.1	4.9	348.0	66.1	24.9	2.0	8.1	
	5.0	770.0	146.3	22.1	4.5	18.3	4.8	269.0	51.1	23.4	4.0	16.3	
2019-03-19	4.5	889.0	168.9	24.3	2.8	11.2	5.0	168.0	31.9	21.3	2.5	10.2	
2019-03-25	7.8	901.0	171.2	26.0	3.5	14.2	8.0	180.0	34.2	25.2	2.0	8.1	
AVERAGE	5.1	771.9	146.7	24.0	3.6	14.5	4.9	444.8	84.5	23.1	2.8	11.3	

CING	Vermicompost Nutrient Solution						Hoagland Nutrient Solution						
DATE	pH	Tds (ppm)	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	pH	Tds (ppm)	EC (ms/m)	T_solution (°C)	Level (inch)	Volume (L)	T_amb (°C)
2019-03-02	7.6	705.0	134.0	15.0	3.0	12.2	7.2	602.0	114.4	14.6	3.0	12.2	
2019-03-05			0.0										
	6.1	567.0	107.7	5.3	2.5	10.2	6.6	546.0	103.7	6.6	2.8	11.2	11.1
2019-03-06	7.0	697.0	132.4	20.3	5.0	20.3	7.1	575.0	109.3	20.0	5.0	20.3	
2019-03-11	7.3	910.0	172.9	25.0	2.3	9.1	7.3	792.0	150.5	23.5	2.5	10.2	
	7.8	649.0	123.3		4.5	18.3	7.4	662.0	125.8		3.0	12.2	
2019-03-14	7.6	776.0	147.4	24.2	3.5	14.2	7.4	780.0	148.2	23.9	2.0	8.1	
	7.6	705.0	134.0	21.5	5.3	21.3	7.5	522.0	99.2	20.9	3.0	12.2	
2019-03-19	7.5	961.0	182.6	24.8	4.0	16.3	7.5	815.0	154.9	24.0	2.0	8.1	
	7.5	660.0	125.4	21.0	6.0	24.4	7.5	363.0	69.0	18.0	6.5	26.4	
2019-03-25	8.0	500.0	95.0	19.5	4.0	16.3	7.8	370.0	70.3	22.0	5.0	20.3	
AVERAGE	7.4	713.0	123.2	19.6	4.0	16.3	7.3	602.7	114.5	19.3	3.5	14.1	11.1

Temperature monitoring of the CING

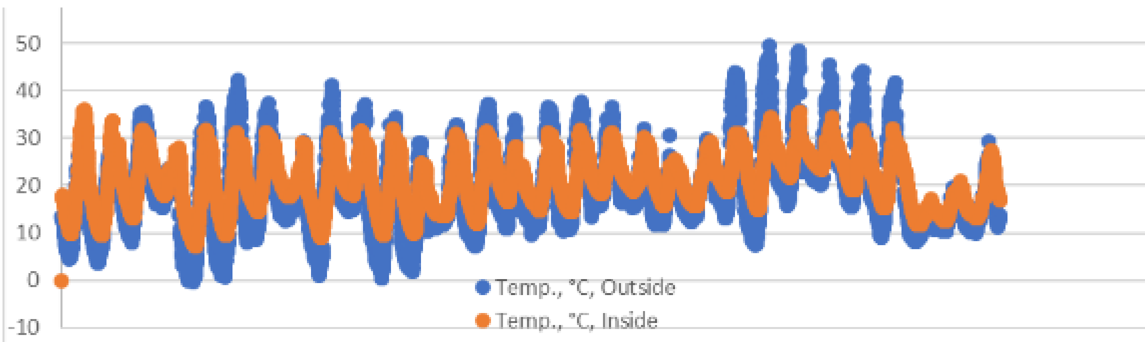

Figure A.1 - Temperature monitoring outside and inside the CING, Spring trial, corresponding averages : 19.3°C and 21.2°C

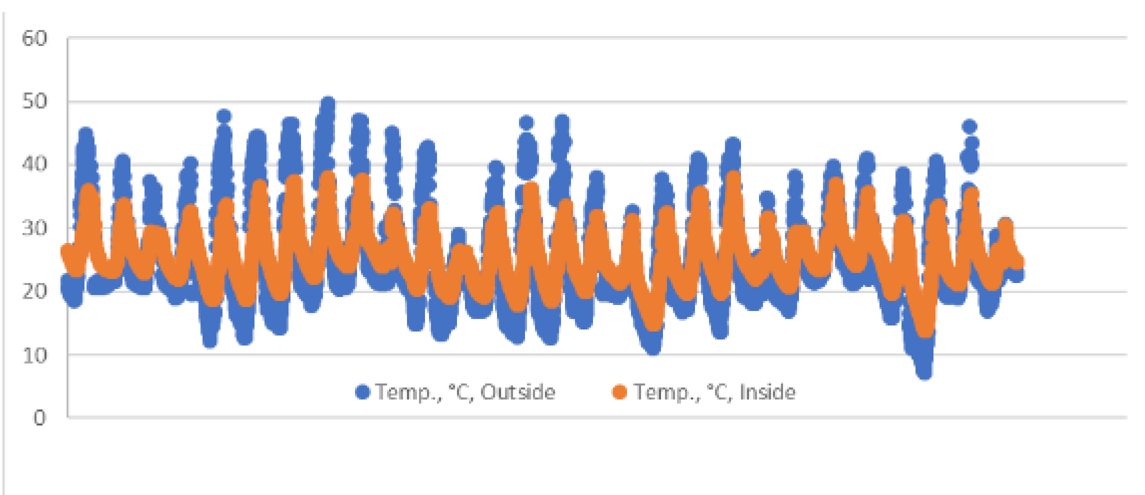

Figure A.2 - Temperature monitoring outside and inside the CING, Summer trial, corresponding averages: 24.7°C and 25.4°C

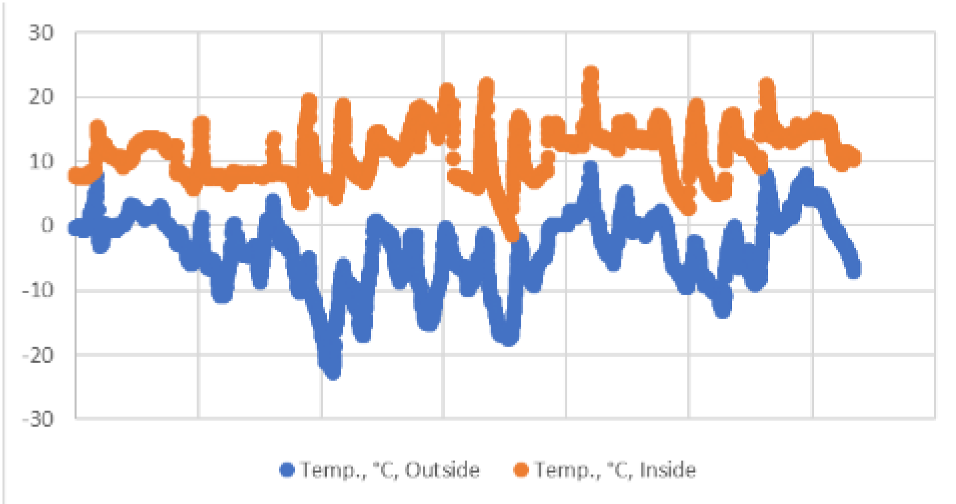

Figure A.3 - Temperature monitoring outside and inside the CING, Fall trial, corresponding averages: -3.4°C and 11.0°C

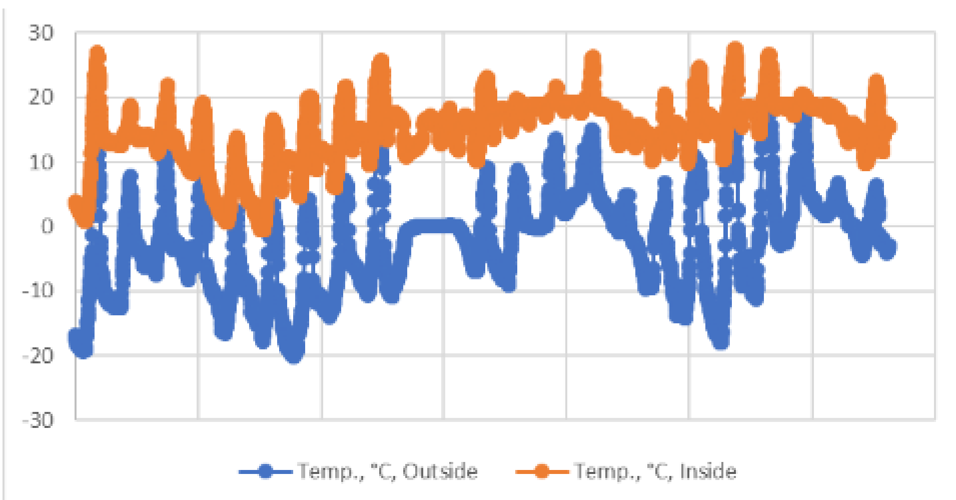

Figure A.4 - Temperature monitoring outside and inside the CING, Winter trial, corresponding averages: -2.4°C and 14.8°C

Humidity monitoring of the CING

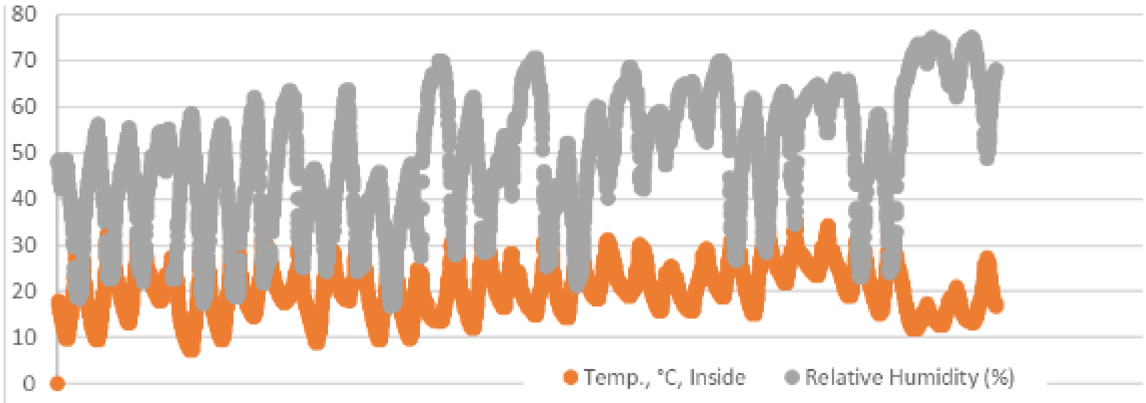

Figure A.5 - Humidity and temperature monitoring inside the CING, Spring trial, average relative humidity: 49.2 %

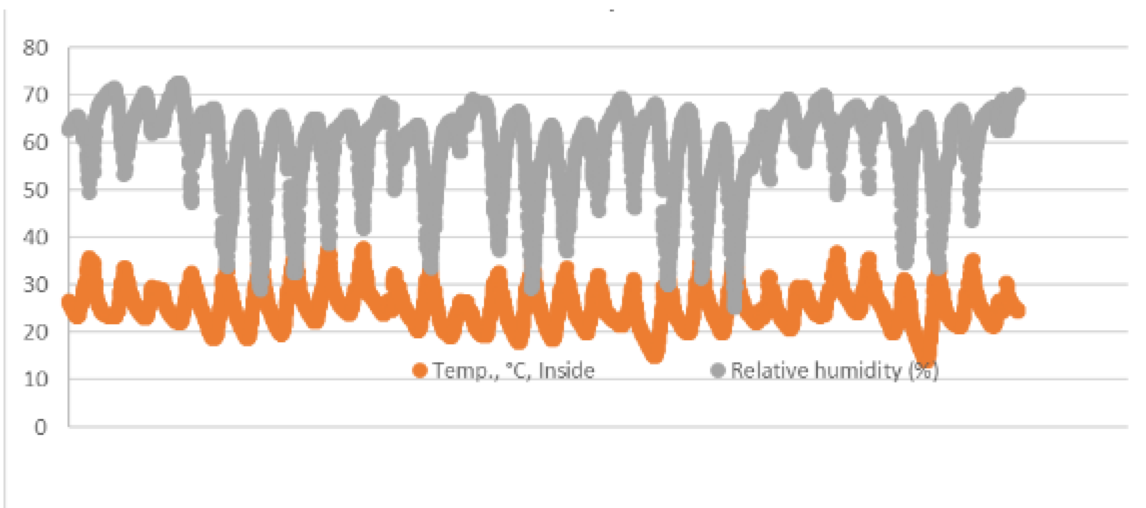

Figure A.6 - Humidity and temperature monitoring inside the CING, Summer trial, average relative humidity: 59.1 %

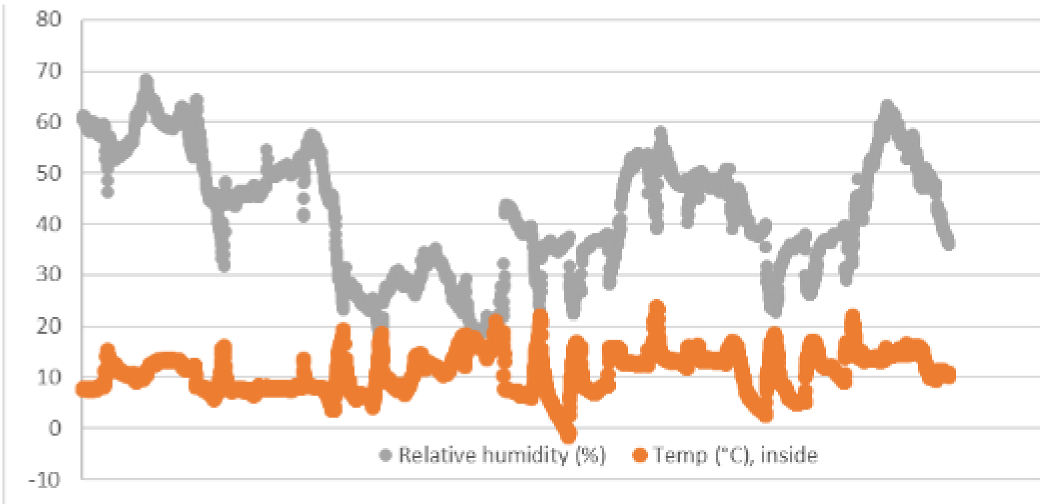

Figure A.7 - Humidity and temperature monitoring inside the CING, Fall trial, average relative humidity: 42.2 %

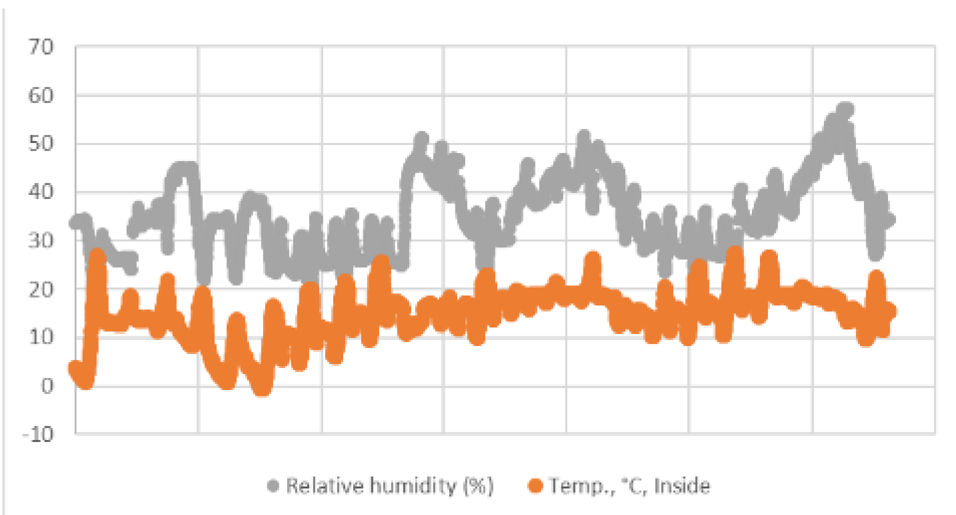

Figure A.8 - Humidity and temperature monitoring inside the CING, Winter trial, average relative humidity: 35.1 %

Light mapping of systems

Table A-5 Light mapping, Summer trial

Experiment	Greenhouse	
Date	2018-06-19	
Time	12:20	
Weather	Very sunny	
	PAR	µmoles/m^2/s
Row	Left	Right
1	322	962
2	669	681
3	709	1077
4	937	699
Average	659.25	854.75
Average PAR	757	

Table A-6 Light mapping, Summer trial

Experiment	CING	
Date	2018-06-19	
Time	12:20	
Weather	Very sunny	
	PAR	µmoles/m^2/s
	Left Row	Right rows
1	179	538
2	525	511
3	434	194
4	599	806
Average	434.25	512.25
Average PAR	473.25	

Table A-7 Light mapping, Summer trial

Experiment	CING	
Date	2018-06-19	
Time	14:20	
Weather	Very sunny	
	PAR	µmoles/m^2/s
	Left Row	Right row
1	276.5	259.3
2	523.2	356.7
3	802.9	531.7
4	832.6	781.1
Average	608.8	482.2
Average PAR	545.5	

Table A-8 Light mapping, Fall trial, only supplemental light in the greenhouse

Experiment	Greenhouse	
Date	2018-12-20	
Time	19:00	
Weather	Night	
	PAR	µmoles/m2/s
Row	Left	Right
1	51.6	29.14
2	43.68	43.65
3	65.87	51.87
4	86.31	81.37
Average	61.87	51.51
Average PAR	56.69	

Table A-9 Light mapping, Fall trial only

Experiment	Greenhouse	
Date	2018-12-20	
Time	14:30	
Weather	Very sunny	
	PAR	µmoles/m2/s
Row	Left	Right
1	76.14	76.2
2	66.27	73.3
3	88.2	98.53
4	114.92	112.23
Average	86.38	90.07
Average PAR	88.22	

Table A-10 Light mapping, Fall trial, supplemental light in the CING

Experiment	CING	
Date	2018-12-20	
Time	19:00	
Weather	Night	
	PAR	µmoles/m2/s
Row	Left	Right
1	48.09	63.52
2	57.23	59.76
3	12.57	20.52
4	20	18.94
Average	34.47	40.69
Average PAR	37.58	

Table A-11 Light mapping, Fall trial

Experiment	CING	
Date	2018-12-20	
Time	15:00	
Weather	Very Sunny	
	PAR	µmoles/m2/s
Row	Left	Right
1	53.5	278
2	145.08	509
3	166.34	506.4
4	187.46	523.3
Average	138.10	454.18
Average PAR	296.14	

Table A-12 Light mapping, Greenhouse Winter trial

Experiment	Greenhouse	
Date	2019-03-19	
Time	13:00	
Weather	Clear sky	
	PAR	µmoles/m2/s
Row	Left	Right
1	348.10	685.70
2	598.00	536.90
3	498.50	580.60
4	638.90	670.20
Average	520.88	618.35
Average PAR	569.61	

Table A-13 Light mapping, CINGWinter trial

Experiment	CING	
Date	2019-03-19	
Time	13:30	
Weather	Clear sky	
	PAR	µmoles/m2/s
Row	Left	Right
1	110.96	174.20
2	261.50	257.80
3	59.44	197.55
4	475.30	452.10
Average	226.80	270.41
Average PAR	248.61	

Thermal curtain heat transfer rate calculation

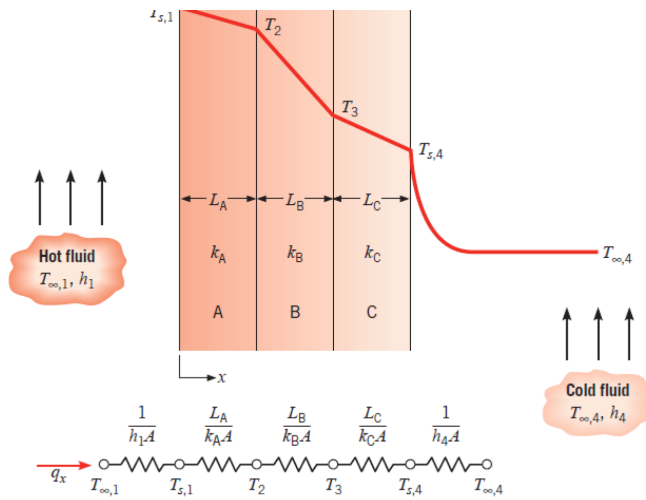

Figure A.9 - Representation of the thermal resistance of the different layers of the CING window (Bergman, Lavine, Incropera, & Dewitt, 2011)

Heat transfer rate calculation

$$q_x = \frac{T_{\infty,1} - T_{\infty,4}}{[(1/h_1A) + (L_A/k_AA) + (L_B/k_BA) + (L_C/k_CA) + (1/h_4A)]}$$

Parameters	Value
Convective heat transfer coefficient of air inside CING, h_1 (W/(m^2.K)	20 (EngineeringToolBox, 2020)
Convective heat transfer coefficient of air outside CING h_4 (W/ m^2 .K)	30 (EngineeringToolBox, 2020)
Thermal conductivity of thermal curtain, k_A (W/m.K)	0.104 (AZOMaterials, 2020) and (Ludvig Svensson, 2020)
Thermal conductivity of air layer, k_B (W/m.K)	25.3x10^{-3} (Bergman, Lavine, Incropera, & Dewitt, 2011)
Thermal conductivity of Twin-Wall polycarbonate Sheet, k_C (W/m.K)	37.86 (PALRAM, 2010)
Thickness of Curtain, L_A (m)	0.001
Thickness of air Layer, L_B (m)	0.15
Thickness of Twin Wall polyecarbonate sheet, L_C (m)	0.008
Area of Window (m^2)	7.27
Temperature gradient, $T_{\infty,1}$ -$T_{\infty,A}$ (K)	15.0

Table A-14 Parameters for heat transfer rate calculations

Heat transfer rate, qx (Watts) without curtain and stagnant air layer	282.4
Heat transfer rate, qx (Watts) with curtain and stagnant air layer	17.2

Table A-15 Heat transfer rate calculation results

Appendix B.

Table B-1 Monitoring of the water at La Boîte Maraîchère

	Aeroponic			Flowing shallow water			Stagnant shallow water			Other Comments		
Date	pH	EC (S/cm)	Temp (°C)	pH	EC (S/cm)	Temp (°C)	pH	EC (S/cm)	Temp (°C)	Aer	Flow	Stag
27-oct	6.17	1.09	18.3	5.79	1.13	17.5	5.87	1.15	19.1			
28-oct	5.8	1.08	16.9	5.64	1.1	18.1	5.3	1.05	19.73			
29-oct	6.49	1.12	19.5	5.47	1.13	17.4	5.66	1.2	20.1			
30-oct	6.33	1.12	20.1	5.43	1.14	17.4	5.85	1.14	20.4		Cu 0.7 O3 0.05 O2 >10	Cu 0.1 O3 0.05 O2 9
31-oct	5.47	1.12	17	5.54	1.12	16.2	5.99	1.19	19.7			
01-nov	5.41	1.13	17.3	5.53	1.12	16.8	6.11	1.15	19.7			
02-nov	5.65	1.11	17.7	5.68	1.11	17.7	6.2	1.17	20			
03-nov	5.83	1.17	15.6	5.83	1.29	14.4	6.92	1.22	29.4			
04-nov	5.88	1.21	17.2	5.81	1.19	17.8	6.99	1.2	21.7			
06-nov	6.23	1.15	19.9	5.83	1.02	19.5	6.56	0.76	18.2			
07-nov	5.77	1	16.8	5.74	1	17.2	6.26	1.13	20			
08-nov	6.22	1	17.5	6.21	1.02	17.7	6.33	1	19.9	General water shortage		
09-nov	5.73	1	17	5.72	0.99	17.1	6.37	1.15	20.6			
10-nov	6.52	1.14	20	5.82	1.06	16.8	5.8	1.05	16.7			
11-nov	5.7	1.05	17.5	5.74	1.16	18.8	6.72	0.1	19.8			
12-nov	5.58	1.07	16	5.63	1.06	15.9	6.77	1.08	19.5			
13-nov	5.75	1.05	16.8	5.8	1.05	16.7	6.85	1.06	19.8			

14-nov	5.61	1.08	16.2	5.58	1.07	16	6.92	1.04	19.5		O2 10	02 9.5
15-nov	6.54	0.9	17.1	6.11	0.92	17	7.09	1.05	19.5			
16-nov	6.2	0.98	17.4	6.03	0.99	17.2	6.03	1.05	18			
17-nov	5.9	1.06	17.5	5.9	1.1	18.9	6.73	1.05	18.9			
18-nov	5.81	1.08	17.1	5.78	1.04	17.4	6.7	1.09	18.7			
19-nov	5.61	1.03	17.3	5.61	1.01	17	7.01	1	20.8			
20-nov	5.81	1.08	18.1	5.83	1.09	18.1	7.03	0.97	20.4			
21-nov	5.55	1.06	18.4	5.45	1.07	18	7.09	0.95	21			
22-nov	5.63	1.08	16.4	5.72	1.08	16.3	7.12	0.94	20.6			
23-nov	5.73	1.12	16.8	5.77	1.14	16.5	7.12	0.95	20.2			
24-nov	5.9	1.14	20.1	5.88	1.08	19.1	7.19	0.96	21.5			
25-nov	5.98	1.09	18.1	5.88	1.12	17.9	7.11	0.97	21			
26-nov	6.03	0.84	18.1	6.16	1.08	16.8	7.2	0.92	19.9			
27-nov	6.3	1.11	18.9	6.19	1.01	19.4	7.08	1.04	20	O2 11	O2 12	O2 9.3
28-nov	5.99	1.13	17.2	6.18	0.94	18.6	7.25	0.9	19.6			
29-nov	5.92	1.07	17.1	5.92	1.07	17.2	7.27	0.88	19			
30-nov	5.75	1.07	17.1	5.78	1.08	17.1	7.32	0.88	19.5			

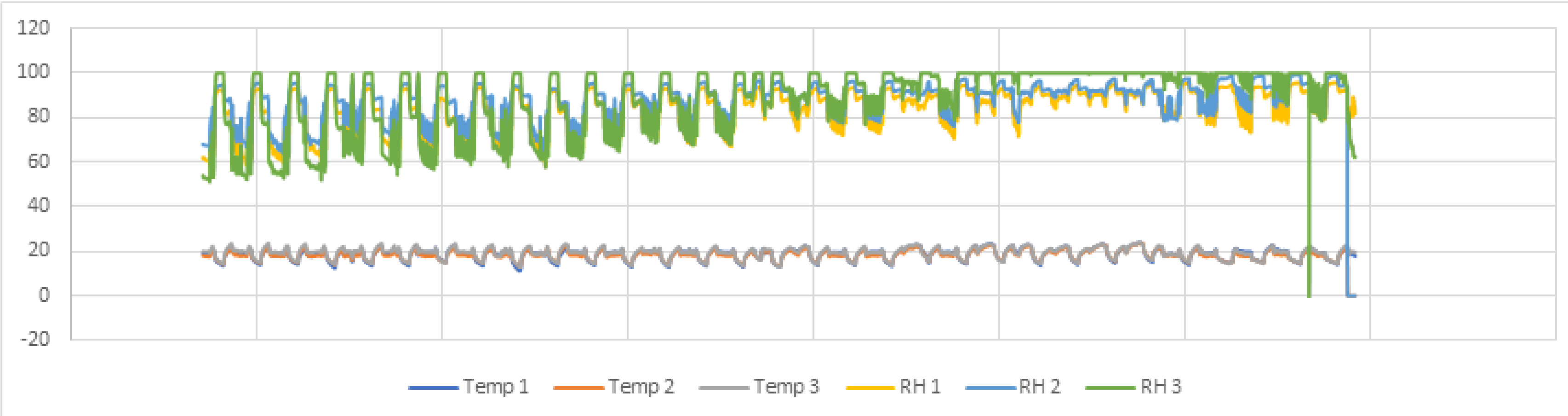

Figure B.1 Temperature (°C) and Relative Humidity (%), 2018-10-30 to 2018-11-30

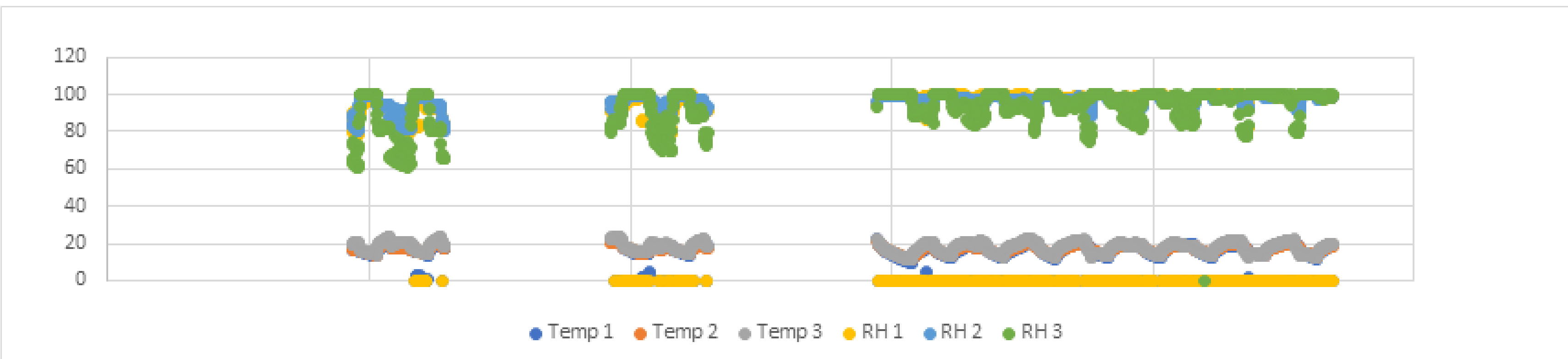

Figure B.2 Temperature (°C) and Relative Humidity (%), 2018-11-30 to 2018-12-21

* The points at zero are reading errors, ''Not a Number'' values caused by sensors errors

** The absence of points means no data was logged during these periods, probably because of a power outage of the data logger