



**University
of Manitoba**

Vidir Vertical Solutions Vertical Farm

BIOE 4950

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EXECUTIVE SUMMARY

Vidir Vertical Solutions is a company that specializes in designing and producing vertical carousel shelving systems. They are hoping to produce a vertical farming system that will be adapted from their existing carousel design. Team 4 has been tasked with continuing development of a solution for conversion of an existing product from work conducted by a biosystems capstone group from 2021-22. The previous team confirmed the effectiveness of utilizing hydroponic growth systems with intermittent watering for use in a static system, and through discussions with the client during the fall 2022 school term Team 4 have been tasked with developing a full-scale single shelf unit which could be used as a test rig for lighting configuration and timing of a watering system.

Team 4's solution (Figure 1) to this problem consists of a modified shelf unit based on an existing shelf unit from Vidir systems, mounted on a stand unit over a static basin, in which the nutrient solution is pumped into to water plants in cups mounted in the shelf. Watering is accomplished by raising and lowering the basin water level to the height of shelf unit simulating a watering cycle in a full system. Lighting for the plants was accomplished by three led panels, with a control section mounted in a top-down position, and two mounted in a side position, with alternating on periods which simulate the movement of the shelf around the carousel unit.

Testing was done with the shelf divided in two halves with one half being used as a control for effects of lighting position, with the LED panel mounted in the top position. The other side was lit by side mounted panels, and the effects of external light were eliminated by black-out fabric. From testing it was determined that the effects of side lighting negatively affected the plants, with leaves of the lettuce looking less full than that of top lighting. The intermittent watering schedule had no effect on either the control or test crop, which falls in line with the findings of the previous capstone team's work.

Team 4 would recommend that further research be conducted on the effects of lighting angle for side mounted lighting on plants, automation of the pumping system with regards to water levels and testing of the system within a full-scale system.

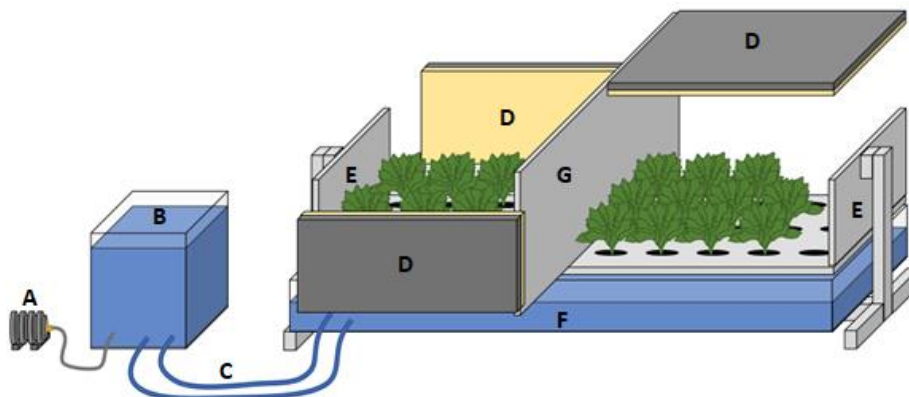


Figure 1 - Conceptual Drawing of Prototype

A: Air pump and air-line, B: Reservoir, C: Water pump/lines, D: Lighting, E: Shelf and stand, F: Nutrient basin, G: Light Impermeable Divider

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1.0 Introduction

As the global population increases at an exponential rate pressure placed on the agricultural industry also increases. An increase in population results in the need for more food production. With the need of the agriculture industry to improve its production the pressure on the environment has increased. The farmland that is still available to be farmed is being overused. To meet the food production requirements the world would need an additional 2.1 billion acres of farmland (Despommier 2009). This land space is not available without degrading natural ecosystems.

Vertical farms are at the fore front to combat this issue. Vertical farms are a controlled environment agriculture practice (CEA), meaning that all aspects affecting the crop are controlled. The water, nutrients, temperature, and lighting are all controlled to best meet the needs of the plants. Due to the controlled environment the efficiency of growing in a vertical farm can be greater than that of standard agricultural practices, as the weather, and pests are not a concern (Despommier 2019). Vertical farms also help fix the space issue that farming is facing. Vertical farms stack plant shelves on top of each other, storing and growing the plants in a vertical shelving system (Despommier 2019). Therefore, a smaller footprint is needed to grow a large number of crops which increases yield density.

Many companies are looking at developing new technologies within the vertical farming industry, attempting to grow more efficiently and have a higher production of plants. Vidir is among these companies. Vidir primarily develops and manufactures vertical rotating carousel shelves that house dry stock. These carousels have shelves within the unit that are able to rotate around the unit. Figure 1 shows a model of a Vidir product. Vidir is looking to move into the vertical farming industry using their carousel design.



Figure 2 - Vidir's vertical carousel shelving unit

1.1 Background

Background information on any subject is essential to the ability to understand what one is reading through. In the following, all background information needed to understand the project at hand will be discussed.

1.1.1 Problem

Vidir has tasked the design team to develop a vertical farming carousel system. The design will be able to grow plants within one of Vidir's already existing carousels. All requirements to keep the crops alive must be present within the carousel such as, nutrients required of the crop, water, and light. The hope of the developed design is to be able to grow and store plants efficiently within Vidir's shelves. The potential of this design is that crops can be grown in little space, in a controlled design and can be easily accessed due to the rotating shelf function.

1.1.2 SCOPE

Due to the complexity of the project the design team will be limiting the areas worked on due to time constraints. Rather than creating a full-scale prototype a scaled down version will be created instead. The focus will be on having one shelf inside the carousel survive and grow lettuce. The design will be responsible for delivering lighting, nutrients, the substrate the plants sit in and water to one tray of plants. The tray that was designed by the biosystems team in 2021 will be used, it is a smaller size than the carousel that Vidir makes.

The list below shows the areas that the design team has determined are within the scope of the project.

- Lighting system
- Irrigation system
- Growth medium of plants
- Nutrient requirements
- Delivery of water to plants
- Tray of carousel
- Safety concerns of design

The main concern of the design team is to develop a prototype that is able to grow and sustain one tray of plants. This design will be a proof of concept that could then be expanded on by Vidir to develop a full-scale vertical farming system with multiple shelves.

As previously mentioned, due to time constraints there are certain aspects of the design that are out of scope for the project. The list below shows the areas that are not in scope for this project.

- Temperature control
- Programming of carousel
- Multiple trays moving within carousel
- Full scale mockup
- Moisture control
- Powering system of carousel
- Waterproofing trays and carousel
- Harvesting and planting plants

By limiting the scope of the project, it is believed the design team will be more successful as more focus can be applied on specific areas of the design and making those areas successfully work. The goal is to create a proof-of-concept that Vidir is able to build on and create a full-scale vertical farming system using their carousel design.

1.1.3 HYDROPONICS

Soil is the traditional growing medium for plants. However, soil has many drawbacks when it comes to diseases, soil degradation and compression, as well as requiring a large area to grow on. Hydroponics uses a water based mineral nutrient solution to supply plants with nutrients which eliminates the need for soil. These plants can either be directly submerged in water for a period, then exposed to air, or be planted in a substrate that is regularly exposed to water (Sardare 2013). It is essential that plants are exposed to adequate light, clean water and air for their best performance. Ebb and flow hydroponics uses a substrate that is flooded and drained at a regular rate to provide the plant roots with nutrients, water, and air. These methods may lead to more efficient plant growth compared to conventional agriculture (Wortman 2015).

1.1.3.1 Substrate

The purpose of a substrate is to retain water while not submerged and keep it available for the plant, as well as have a high enough porosity to allow for some air to be retained around the root system while submerged. This substrate is held within a mesh netting that has enough room for the plant roots to grow in. It is also important for the substrate to not affect the electroconductivity or pH of the water, as this can alter the cation exchange capacity of the plant (Goddek 2019). Two main hydroponic substrates exist: organic, and inorganic. Some organic substrates include peat moss, coir (coconut fiber), sawdust, or other plant fibers (Jensen 1997). Inorganics can include stone wool, pumice, sand, perlite, vermiculite, and air expanded clay pebbles (hydroton) (Goddek 2019). Some synthetic substrates do exist, such as expanded polystyrene, but have a very low water retention capacity.

The findings of Enzo et al. (2001) show that out of all substrates tested, expanded clay has the highest potential for a low pH, with a range between 4.5-9.0 depending on the type used. Ideally a type that has a pH below 7 would be used in hydroponics, as plants tend to favour the take up of acidic nutrients, which raises the pH of the solution. This system will utilize a mixture of hydroton and peat moss. This will allow for a controlled balance between water retention and drying.

1.1.3.2 Water Pump

Water circulation is not technically required within a hydroponic system, however Nurhasan (2018) suggests that by automatically circulating water can be effective in nutrient circulation. as well as a reduction in algal and bacterial growth. In a larger system a reservoir and basin are used. The basin directly feeds the plants, while the reservoir is used to store water and act as a

point of application for nutrient solutions (Dubey & Nain 2020). The water pump is submerged within the reservoir.

1.1.3.3 Air Stone

The primary purpose of the air stone is to create bubbles that “ensure the supply of oxygen to the nutrient solution and nutrient solution does not get stagnant” (Dubey & Nain 2020). This will oxygenate the water and help prevent algae and microbial growth which can inhibit plant health.

1.1.3.4 Nutrients Required

Bruce (2016) describes the relation between the addition and subtraction of nutrients and their impact on electroconductivity and pH. As nutrients are added, such as calcium, they dissociate into their ions and can increase the EC of the solution. Additionally, if more anions get absorbed than cations, then the pH of the solution will increase. These two metrics, pH and EC are vital to monitoring the suitability of the solution. Another way for this to affect pH is the addition of a certain type of needed nutrient, such as nitrogen. If supplied as nitric nitrogen (NO_3^-) the pH may be increased through an increase in hydroxide (OH^-) which increases pH. Conversely if ammonium nitrogen (NH_4^+) is supplied there will be a release in hydrogen ions (H^+), lowering pH.

1.1.3 Lighting Requirements

Lighting is an extremely important part of agriculture and horticulture as light is where plants receive their energy to be able to perform photosynthesis. In the following is an explanation of the lighting requirements for the system.

1.1.3.1 Distance from Plants

The previous biosystems capstone team completed an experiment on the distance that the lights should be placed from the lettuce. Since this design is building on the previous work done, Team 4 will use their recommendation from their research completed. The team initially placed the lights 8 inches from the plants, this resulted in the lettuce getting burned from the lights. The lights were then moved 18 inches from the plants. This resulted in no damage to the lettuce and a strong dense yield, thus the biosystems team recommend placing the lights 18 inches from the tray.

One area of the lighting that is unknown is if the orientation of the lights will affect the growth of the plants. Due to the design the client wants the lights will likely have to be positioned to

the side of the plant. Often lighting not coming from directly above the plant can cause the plant to not grow straight, as plants grow towards the source of energy. An experiment will need to be conducted to assess if this design will impact the yield of the lettuce substantially.

1.1.3.2 Spectrum of Lights

Light-emitting diodes (LED) will be used for this project as they are able to reach a specific light spectrum with more accuracy all while having a lower energy consumption (Loconsole et al. 2019)

When selecting the lighting requirements for lettuce there are two areas that need to be taken into account: the Photosynthetically Active Radiation (PAR) and the Photosynthetic Photon Flux Density (PPFD). The PAR is the waveband of light that plants are able to use for photosynthesis (LumiGrow, 2019). Within the light spectrum there is only a fraction that plants can harvest energy from, therefore, it is crucial that the lights chosen emit this spectrum. PPFD is the rate at which PAR is landing on a square meter (LumiGrow, 2019). The units of this measurement are micromoles per meter squared per second. Knowing the PPFD of a lighting fixture allows the user to know how much energy the plants are gathering.

Pennisi et al. (2020) conducted research on the PPFD required to optimize the yield of lettuce while sustainably using electricity. It was determined that lettuce had the highest yield when grown under lights with a PPFD of $250 \mu\text{mol}/\text{m}^2\text{s}$. This PPFD allowed the plant to improve its water, energy and light use efficiencies. Therefore, it is recommended that for this project LED lights that emit light with a PPFD of $250 \mu\text{mol}/\text{m}^2\text{s}$ be used. Pennisi et al. (2020) also looked at the photoperiod of lettuce, meaning the optimal length the lights should be on. It was found that 16 hours of light per day was sufficient to allow the plants to have a high yield.

1.1.4 Shelving Design

The design of the shelf to be used will be a modification of the current shelf that is being used in the Vidir carousels. Thus, many constraints of the current shelves will be acting on the design, from there a design needs to be created to support hydroponic growth.

1.1.4.1 Material

Upon recommendation from the client, the previous design team designed their prototype utilizing powder coated carbon steel. This was selected due to the protective nature of the powder coating, as well as the client's desire to use materials commonly utilized in their existing production lines. The previous team found however, that the powder coating of the previous

design was susceptible to damage and wear, which allowed for the formation of rust. This was deemed to be unacceptable, as the rust decreases the effectiveness of the nutrient solution of the system and affects plant growth. Recommendations were then made to use either aluminum or 304 Stainless Steel. Through research, it was determined that use of aluminum is unacceptable, as interactions between the nutrient solution and metal could cause aluminum poisoning within the crop's roots. The reaction between the potentially acidic solution of $\text{pH} < 5$ can cause the release of aluminum ions, which when uptakes by the root system results in a decrease in nutrient uptake of the plant (Delhaize and Ryan 1995).

1.1.4.2 Plant Spacing

Plant spacing can affect plant growth, as competition between individual crops can cause decreases in plant height and leaf growth. The previous design used by the previous team utilized a spacing of 6 in center to center, which seemed to provide positive results during testing. Further research provides a more specific value of 50 plants/ m^2 (Maboko and du Plooy 2013), which was shown to provide optimal growth for leafy greens in a hydroponic system, as well as intra-row spacing of 20 cm and interrow spacing of 10 cm. (Maboko and du Plooy 2013)

1.1.5 Existing Solutions

Current market solutions for vertical farming focus on stationary shelving, as well as movable whole units. One company that proposes a similar solution to the one proposed is the Vertical farming system by Sky Greens Canada. This system utilizes a carousel design of rotating shelves, provides nutrients using a hydroponic system, and provides water directly into each growth shelf. Other vertical farming systems use fixed shelving units, with stationary cells supplied from a central supply basin, such as systems created by Montel, which also utilize a tracked flooring system allow for side-to-side movement of whole units. Current market solutions tend to focus stationary shelving units, with only one similar product being produced.

1.2 Problem Definition

Vidir needs a vertical farming solution capable of supporting favorable conditions for multiple types of plants through their growth cycles. Optimal farmland is limited so indoor vertical space should be utilized fully.

1.2.1 Design Requirements

When creating a design there are always requirements desired from the client and/or stakeholders. These requirements describe what is objectively needed from the design and not necessarily what is to be expected from it. The design requirements come in three categories, Design Functions, Design Objectives, and Design Constraints; all three of which are described below.

Table 1: Design Functions, Objectives, and Constraints

Design Functions	Design Objectives	Design Constraints
Support plant growth by providing light, water, and nutrients for healthy growth.	Keep all plants alive during their entire growth cycle.	25 – 30 Watts/ft ² of light must be provided to the plants.
Farm will be stored vertically indoors, utilizing vertical space.	Design should be manufactured with at least 75% of parts made by Vidir.	The new design must integrate with the existing Vidir carousel.
Shelves storing plants will rotate within the vertical carousel based on timed intervals.	Have a timer run the rotation of the carousel and lifting of basin to allow autonomy of the carousel.	The carousel and auxiliary equipment must be powered by an external source.
	Maintain the pH of the water between 5.5 – 6.0.	pH of the water must be kept between 5 – 6.5.
	Plants will be harvested by one user without the aid of anyone else.	
		Weight of each shelf must not exceed 1000 lb.

2.0 Design Solution

The hydroponic system used for this project has three main components: the growth shelf, the nutrient basin, and the storage reservoir. Together, along with the subcomponents providing light, water circulation and aeration, they create an ebb and flow hydroponic system.

2.1 Growth Shelf

The growth shelf is a direct adaptation from the existing carousel shelves that can be found in Vidir carousels. The shelf was modified from the original by adding holes through the bottom surface to carry the hydroponic baskets. The changes from the original shelf and the shelf used for this project can be seen in Figures two, three, and four. Modifications for the shelf were the removal of the rear wall, alteration of the lips of rim of the shelf unit to make it symmetrical, and use of stainless steel as the material.

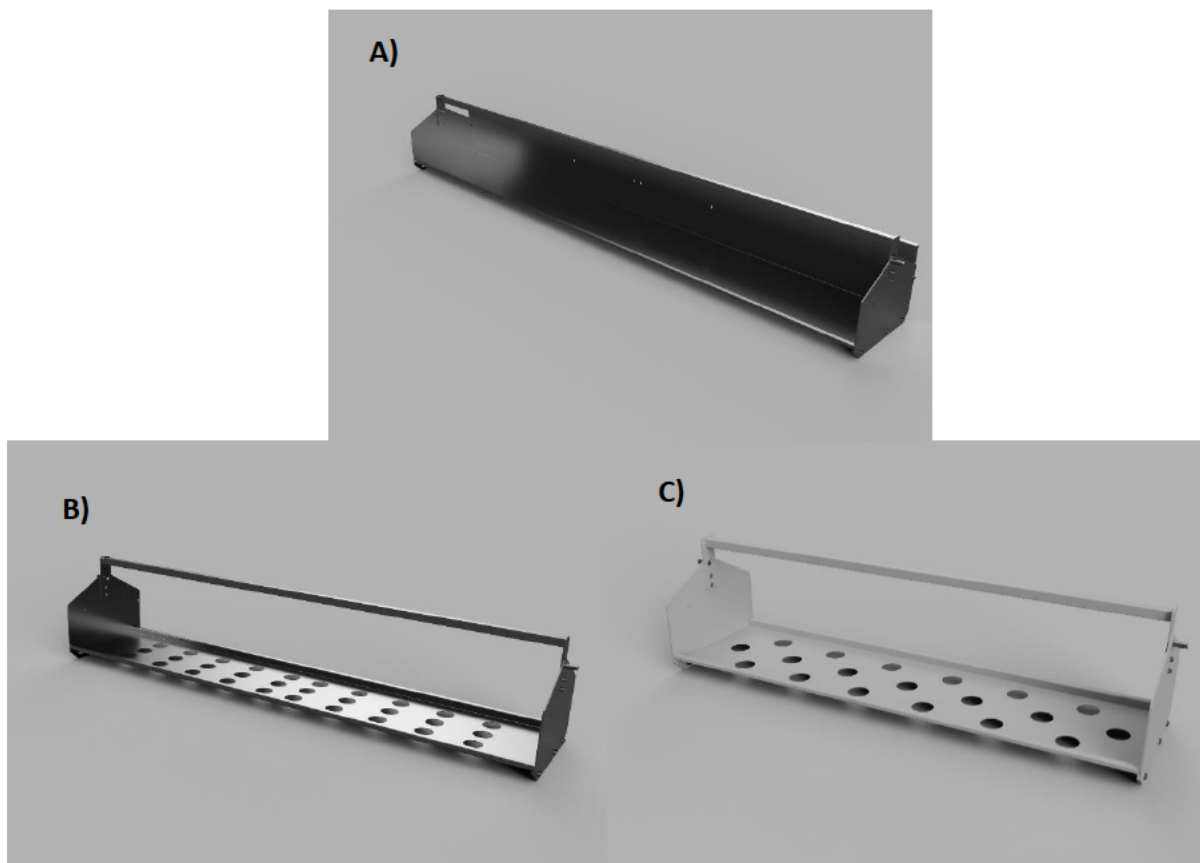


Figure 3 - A) Vidir's original shelf, B) First modification of shelf, C) Final test version of shelf

The hole spacing in the initial design creates a growth density of 30 plants/m², which is under the ideal density of 50 plants/m² for lettuce but provides adequate space to alleviate crowding. During the team's design review, it was suggested to offset the hole pattern to increase the density of plants while maintaining appropriate row spacing. The test model used had an offset pattern with a growth density of 21.42 plants/m². Painted steel was used instead of stainless steel due to cost considerations. Equipment limitations in manufacturing the shelf required a reduction in length from 108-1/2 to 84-1/5 inches. The generic plastic hydroponic baskets that are held by the growth shelf are perforated at the bottom and lower sides, filled with clay beads, and hold the lettuce seeds; these can be seen in Figure 5.



Figure 4 – Hydroton filled hydroponic basket

Every six hours the basin fills with a nutrient rich solution which the substrate surrounding the seeds is submerged into and then absorbs the solution. After the basin is left filled for fifteen minutes, and the solution is absorbed, the solution level is lowered, and the seeds can draw from the moisture and nutrients that the substrate has absorbed. The basin is then left at its lowered level until the next watering time six hours later.

The shelf itself is suspended using mounting plates and pins manufactured by Vidir, and a custom stand was designed to allow the mounting system to be connected to and hang the shelf inside of the nutrient basin. The complete assembly of the shelf and stand can be seen in Figure 6.

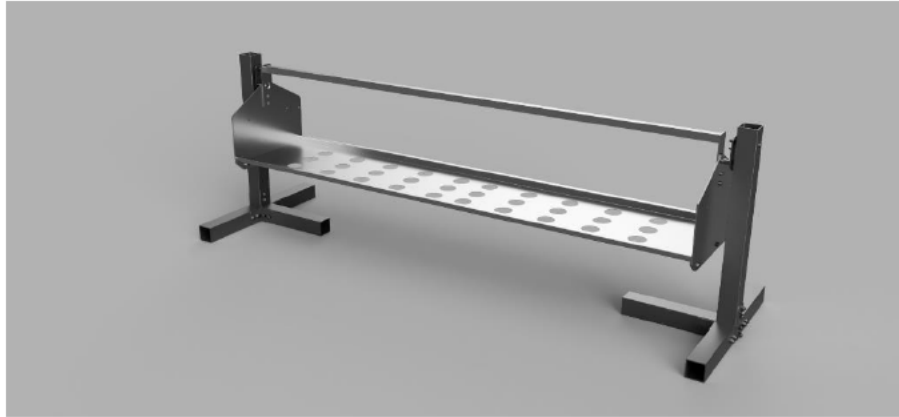


Figure 5 - Complete assembly of shelf unit and stand

2.2 Nutrient Basin

The nutrient basin is a key component of the system as it holds and provides the nutrient solution to the lettuce. It is made from 14-gauge sheet metal which was bent and welded to create an 85 x 35 x 12 inch nutrient basin. This allows the growth shelf to be nested inside of it; seen in Figure 7. The basin is painted to prevent rusting of the metal. Powder coating or stainless steel are both options to improve rust resistance if needed.



Figure 6 - Shelf unit hanging inside of nutrient basin

The nutrient basin will be filled with a nutrient solution to a level below the hanging hydroponic baskets. At this “drained” point the substrate will not be in contact with the solution. The solution level is raised by pumping stored solution from the reservoir into the basin. The level will rise until the baskets are submerged 75% submerged which allows the substrate to absorb the moisture. Once the absorption time is complete, a pump inside the basin will pump the nutrient solution back into the storage reservoir through a different tube, as shown in Figure 8. The nutrient solution level is lowered to the drained position below the hydroponic baskets. The water pumps, with an aeration kit, and an air pump that is connected to three air stones in the basin provides aeration. Air stones produce bubbles by forcing air through tiny pores in a rock, and the aeration kit takes in air after the water has left the pump turbine. This bubbling action aerates the nutrient solution and helps minimize stagnation of the solution in the basin.

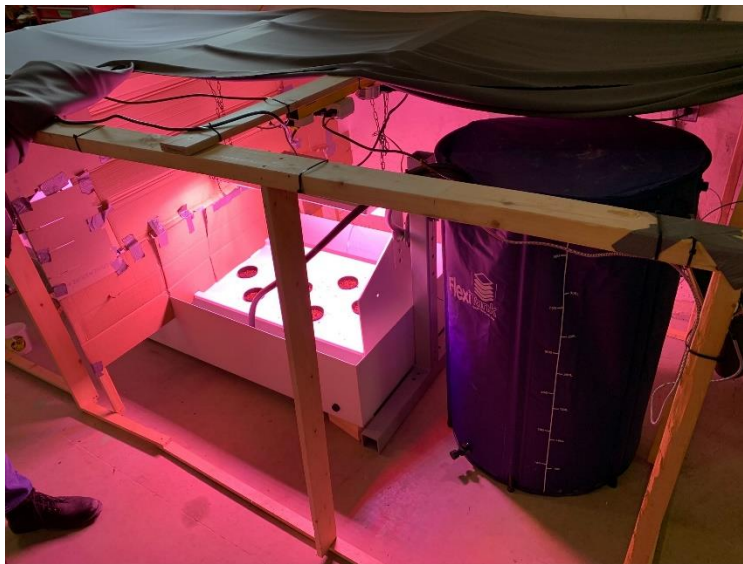


Figure 7 - Plumbing of pumps to and from nutrient basin

There are four watering cycles every day. A watering cycle is the raising and lowering of the nutrient solution in the basin. The first watering occurs at 8:00 AM. A timer will turn on the pump in the reservoir which forces water through a tube up out of the reservoir, and into the basin. As the tubing has to travel up 3 feet this would lead to a reduction in pump flow from 1000 to 825 gallons per hour (GPH), which results in the basin being filled from a drained state to filled state (4 to 11 inches) in under 6 minutes. At this point the reservoir pump would shut off and the substrate would be submerged. This is left for 15 minutes till 8:21 AM. The basin pump would turn on and begin draining the basin back to 4 inches of water. By 8:27 AM the pump is shut off and the basin would be back at its drained state. This would repeat 4 times per day. The next cycle would be at 2:00-2:27 PM, and again 6 and 12 hours later. This start time was chosen as at 2:00 PM the team would be available to work on the system. A 6-hour spacing was chosen as the pump timer used was limited to 8 on/off functions per day. This is acceptable for the chosen substrate, which is a mixture of mostly hydroton with some peat moss. The

hydroton provides the majority of structural support and allows the substrate mixture to dry, while the peat moss retains a smaller amount of long-term moisture. This ensures the substrate is never soggy, nor fully dried out after a 5.5 hour drying period.

As this system was designed to mimic conditions inside of a vertical carousel the amount of water used was kept to a minimum. This would save space inside of a carousel and require less energy. However, in this model the shelf is stationary. In a real carousel the shelf would rotate down to the bottom position, and not always remain fixed in place. Similarly, however in both the model and final product the solution level rises up to meet the substrate and lowers back down. This would allow for the substrate and nets to drip dry in place. Even if a carousel was at a maximum capacity of 7 shelves there would still be 24 minutes each cycle for each shelf to drip dry. This would help contain water in the basin and reduce the number of lettuces getting burnt from water droplets magnifying LED light.

2.3 Storage Reservoir

The storage reservoir holds excess nutrient solution for the system when the plants are not being watered. The reservoir is a 90 gallon (350 liter) soft side tank with hose connections at the bottom and top. A water pump is placed inside of the reservoir which will pump the nutrient solution out the top and into the basin when required. Once the watering time is complete, the pump in the basin will then pump the water back into the reservoir through the bottom of the reservoir. The hose connecting the basin pump to the reservoir empties through the top of the reservoir. This allows for the basin to empty into the reservoir and keep any solution flowing back into the basin through the hose from the reservoir. If the end of the hose was lower than the filled height of the reservoir the difference in head pressure would naturally push the solution in the reservoir back into the basin. The hose position prevents this back flow and allows complete control over the levels inside of the basin and the reservoir. This setup can be seen in Figure 8.

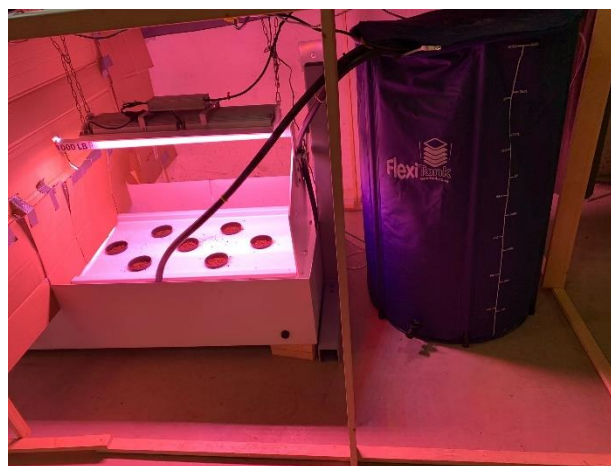


Figure 8 – Plumbing from basin to reservoir.

2.4 Lighting System

The lighting system is the focal point of this entire system since what is being tested first and foremost is the effect of side lighting on the growth of plants. In the lighting system there are several components and in the following all of these components are described.

2.4.1 Lighting Characteristics

To provide energy to the plants LED lights will be used. The lights chosen for the design were NODARK LED Biolights. Lettuce plants require a photosynthetic active radiation (PAR) of $200 \mu\text{Mol}/\text{m}^2/\text{s}$ (IGWorks 2019). The lights chosen emit a PAR within the required range of lettuce. The lights will require a voltage of 120 V. Therefore, they will be plugged into a standard outlet.

2.4.2 Light Positioning

To test the use of side lighting three lights will be used. The tray of lettuce will be split in half by an opaque divider, where one half has overhead lighting and the other has lighting from alternating sides (front and back). For the top lighting one light will be placed 18 inches above one half of the tray, facing downward. On the other half two lights will be placed 12 inches from the edge of the tray. A challenge of the side lighting is that the distance from the lights to each plant will be uneven. This will be studied to see if this negatively affects the growth rate of the lettuce.

2.4.3 Wood Frame

A wood frame surrounds the basin, this frame will be used to secure the lights. The top light will hang from chains that are secured on two wood planks. To secure the side lights, brackets will be used that connect the lights to the studs of the wood frame. This is shown in Figures 10 and 11. A) Left side light mount, B) Mounted light with full mounting system

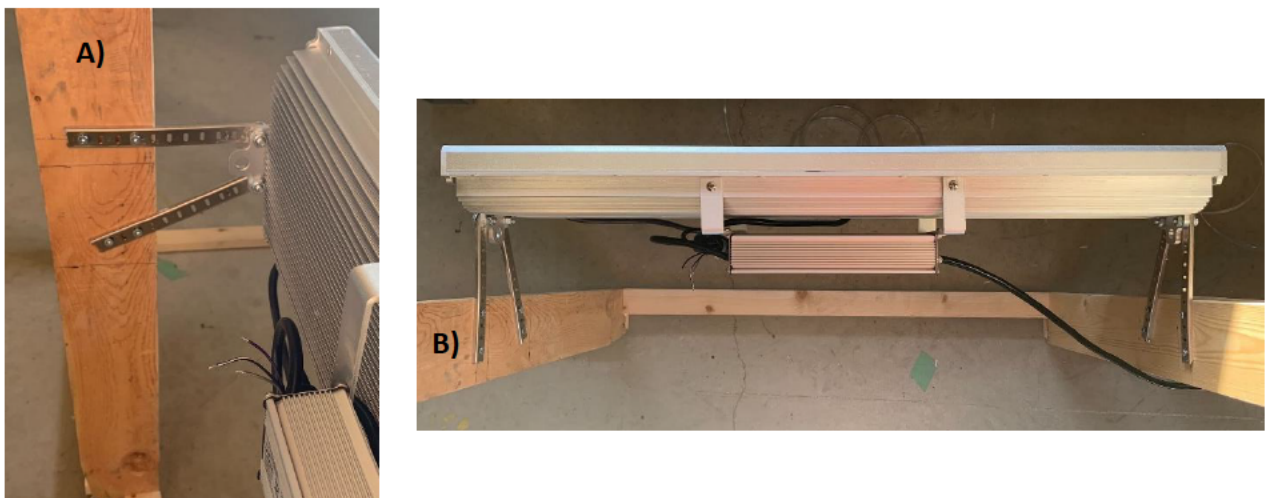


Figure 9 - A) Left side light mount, B) Mounted light with full mounting system

In order to block light any external light from the test, blackout fabric was placed on the frame. The brackets will keep the lights away from the blackout fabric, to reduce the risk of the fabric catching fire. Figure 12 shows the frame for the lights, where the bold black lines represent the mounts for the lights. The wood frame shown in Figure 12 was built before the basin size was changed therefore, it is longer than required. However, this extra space at one end is used to store the water reservoir.

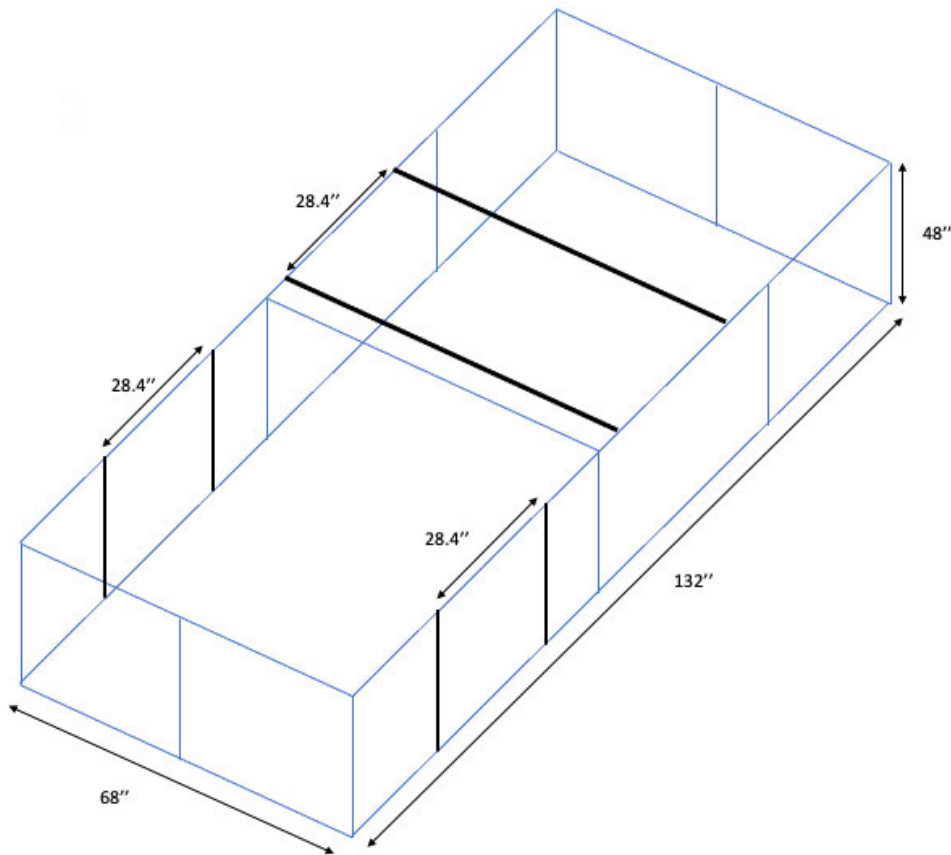


Figure 10 - Design of enclosure frame

2.4.4 Divider and Blackout Fabric

To ensure that the conditions inside the system are as controlled as possible, a divider was placed in between the two halves of the system, along with blackout fabric being draped on the frame around the entire system. The divider between the halves ensures that the light provided by the top lighting and side lighting doesn't penetrate to the opposite half and skewing any results. The blackout fabric around the whole system ensures that any light from the surroundings does not come into the system, ensuring that the only light that the plants get is the light that is being provided to them through the light panels.



Figure 11 - Frame with blackout fabric over it (left), and light divider between side and top lighting halves (right)

2.4.5 Lighting Schedule

Each light will also have an automatic timer. The lettuce requires 16 hours of light per day. The top light schedule will have the lights on for 16 hours and then off for 8 hours (6AM to 10PM). To mimic the growth conditions in the carousel the side lights will alternate on and off, the total light time for the 2 side lights will be 16 hours. Thus, one side light will be on for 8 hours (6AM to 2 PM), that light will then turn off and the other light will turn on for 8 hours (2PM to 10PM). Both side lights will then be off for 8 hours. Figure 13 shows the light schedule for the lighting system.



Figure 12 - System lighting schedule

2.5 Environmental Conditions of Site

The site used was the Sustainability in Action Facility (SIAF) located at 20 Service 2 St SW, Winnipeg, MB. This indoor location had a typical temperature range between 17°C to 22°C. Natural light is allowed in from a south facing window but was blocked by a blackout fabric that surrounded the hydroponic system. No supplementary ventilation was provided by the building's HVAC system. Light dust and dirt tended to collect on the floor, similar to the environment to a workshop but without sawdust or metal files.

With the design, building and implementation of these four main sections of the system: growth shelf, nutrient basin, storage reservoir, and lighting system. The will be a complete system that is able to grow lettuce hydroponically while also testing the effect of side lighting on plant growth.

3.0 Evaluation

Testing is nothing without being able to evaluate the data that is collected from the testing being conducted. In the following, the evaluation methods for the constructed system will be discussed.

The proposed design has many technical requirements to be considered functional. Each of these requirements have different testing methods to reach these goals. Table 2 shows the testing methods used for each of the requirements within the design.

Table 2: Testing Methods for each Requirements

Grouping	Requirement	Testing Method	Goal	Member Responsible
LEDs	Distance to Plant	Using a ruler measure the distance from the nearest leaf to the light source.	8+ inches, TBD	Allison
	Light Level	Photosynthetic Active Radiation (PAR) will be calculated based on the wavelength of light supplied and the relative spectral power distribution.	25 – 30 Watts/ft ²	Allison
Lettuce	Growth Rate	Lettuce must have grown over the course of 32 days. This will be monitored by taking a picture as often as possible from the same viewpoint. A ruler can be used to measure the height of the lettuce each time as well.	4 inches by 32 days	All
	Healthy Growth	Lettuce may exhibit symptoms of stress that stem from poor environmental conditions. The plants will be inspected visually with cameras and in-person inspection, as well as physically by feeling the plant. Table 2.1 details lettuce maladies, their causes, symptoms, and how to remedy them.	Crisp, mid-tone green lettuce without discolouration (See table 2.1)	Kevin
Solution	pH	A pH meter will measure the pH of the solution daily, as well as before and after the addition of nutrients. The temperature and time of recording will be noted.	5.5-6.0	Kevin
Shelf Design	Circulation	A one-gallon container will be used to make sure that the water pump is correctly set. The time it takes for the container to be filled will be recorded. The volume, one gallon, divided by the time will yield the flow rate.	> 600 GPH	Kevin
	Number of Lettuces per Shelf	The number of lettuces the shelf can hold will be counted.	>= 19	Josh

Shelf Design	Shelf Weight	A CAD model of the shelf will be created and will have its weight calculated by the program. The additional weight of the plants, substrate, water, and nets will be weighted manually.	< 1000 lbs	Josh
	Drip Drying Time	The substrate will be soaked for the intended 15-minute period. The solution will be lowered, and as soon as the solution no longer touches the substrate and nets a timer will start. The timer will stop once dripping occurs no more than once every 30 seconds.	30 sec	Kevin
Overall Design	Percent of System Composed of Vdir Made Parts	As measured by weight, the weight of the carousel with all additional components will be calculated. The weight of all components not designed by Vdir will be divided by the total weight.	75%	Patrick
Financials	Cost Per Unit	This will be calculated by summing the cost of the existing unit, the price of each shelf in material, the price of the hydroponic components, while factoring in the labor to design, produce, and assemble the unit	75%	Patrick
	Profit Margin	Using the formula of revenue per unit minus the cost of a unit, all divided by the revenue per shelf the profit margin can be determined.	TBD	Patrick

Many environmental aspects and diseases affect lettuce quality. Each of those possible impacts, their resulting symptoms, and treatment options are listed in Appendix A1.

3.1 Verification

Verification of all project systems is essential to determine if the design is operating in the intended way.

3.1.1 Lighting System

The lighting system is what simulates the sun and its rays that are used for plant growth, this system is essential to the healthy life of the plants. Thus, there are four tests conducted with the lighting system to ensure that an environment with controlled lighting is maintained.

1. Test of side lighting effectiveness
2. Test of divider effectiveness

3. Test of blackout fabric
4. Test of light timing

The methods of each test will be detailed.

3.1.1.1 Test of Side Lighting Effectiveness

To test if side lighting will negatively impact the growth of the plants two lighting arrangements were used. The tray was split in half with a cardboard divider in the middle to block the light from crossing each side, as shown in Figure 14 a. The left side of the tray was the experimental side which had side lighting, where lights were placed 18 inches from the edge of the basin. This is to mimic the distance the lights would be from the tray in a Vidor carousel. The right side was the control side, where one light was hung 18 inches above the tray which is conventional in hydroponic systems. The setup is shown in Figure 14. This allows a comparison of lettuce growth to determine the effects of growing plants with only alternating side lighting. The basin is not divided, so each side received the same nutrient solution.

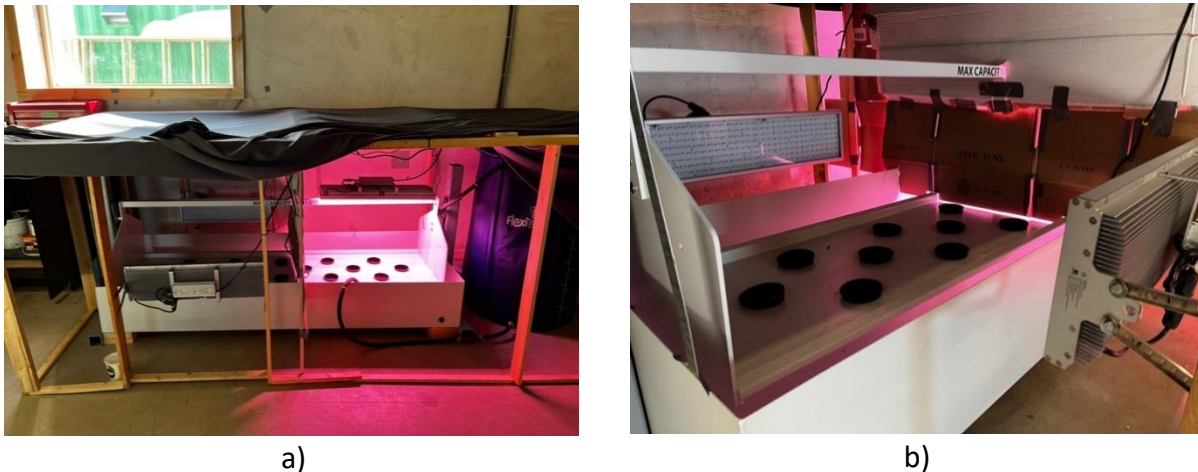


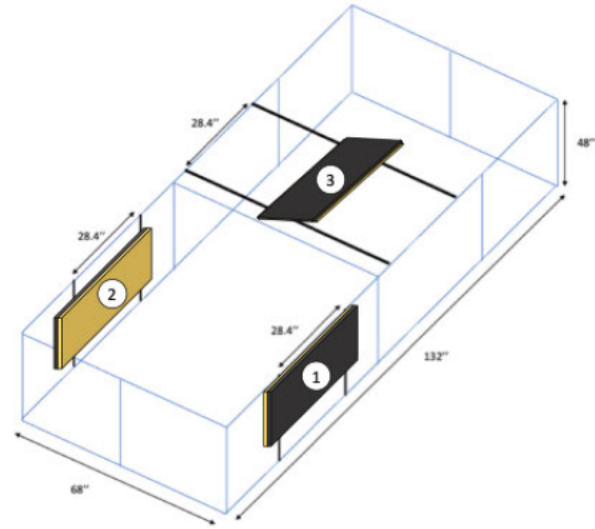
Figure 13. Lights and divider set up. a) entire system set up, control side (right) and experimental lighting (left) set up and b) side lighting set up.

3.1.1.2 Test of Divider Effectiveness

To determine if the divider was stopping the light from shining through to the other side a lux meter (Dr. Meter Digital Light Meter, 0-200,00 Lux ASIN:B005A0ETXY) was used. The lux reading was taken on the control side with all lights off, it was then taken with side light 1 on and again with side light 2 on this is shown in Table 2. The lux reading was then taken on the side lighting side with all lights off and then again with the top light on. The readings from this test are shown in Table 3. Due to the readings not changing with the addition of light from the other side it was determined the divider was successful at blocking light from each side, left and right.

Light #	Placement	Situation
1	Front	Side lighting
2	Back	Side lighting
3	Top	Top lighting

a)



b)

Figure 14 Light numbering for experiment. a) numbers defining lights and b) diagram of light placement

Tables 3 and 4 indicate the on / off state as 1 or 0. 1 refers to the light being on, while 0 indicates the light is off. All measurements are in lux.

Table 3 Lux values for side light side with alternating top light on and off (1= on and 0= off)

Side Lighting (Lights 1 & 2)					
Light On/Off			Distance		
1	2	3	Close (Lux)	Mid (Lux)	Far (Lux)
1	0	1	7800	3800	2800
1	0	0	7800	3800	2800
0	1	1	9500	5000	3100
0	1	0	9500	5000	3100

Table 4 Lux values for top light side with alternating side lights on and off (1=on and 0=off)

Top Lighting (Light 3)					
Light On/Off			Distance		
1	2	3	Close (Lux)	Mid (Lux)	Far (Lux)
1	0	1	16000	16000	16000
0	1	1	16000	16000	16000
0	0	1	16000	16000	16000

3.1.1.3 Test of Blackout Fabric

The only light supply that will be present within the Vidir made system will be light provided by internal LEDs. Therefore, blackout fabric was placed on the wood frame to block out natural

light so that the only light present for the plants was from the LEDs, emulating lighting inside of a carousel. The lux meter was used to assess whether the fabric successfully blocked out all other light. Lux meter readings were taken on both sides in numerous locations with all the lights off. Table 5 shows these results, which were negligible when all LED's were shut off at 2PM on February 17th. At 2PM the sun shines directly onto the system; however, no light can reach the lettuce. Therefore, no external light will impact the growth of the lettuce.

Table 5 Lux readings with all lights off and black out fabric

Tray #	Close (Lux)	Mid (Lux)	Far (Lux)
Tray 1	7	9	8
Tray 2	5	8	7

3.1.1.4 Test of Light Timing

The light timings are described in the proposed solution section. To ensure that lights were timed correctly the security cameras installed by the team were used. There are three times 6am, 2pm and 10pm where the lighting will change. These times were monitored using cameras to ensure the timers were working. Any lighting changes are alerted via the iPhone, ensuring the team was notified of any lighting changes. All light timers are working correctly.

3.2.1 Schedule of Monitoring

In order for the team to monitor the growth of the lettuce a schedule has been set to make observations and take pictures. At least one team member will go three times a week: Monday, Wednesday and Friday to take pictures of both sides and make observations on the success of lettuce growth. The height of selected lettuce plants can also be recorded at this time.

3.2.2 Growth Rate

Growth rate of the lettuce is an extremely strong verification of how healthy the plants are, as well as the suitability of the growing environment. Comparing the expected growth rate of lettuce, in ideal conditions, of a maximum of one Inch per week to the actual growth rate experienced by the lettuce will provide this verification. Further verification will be the comparison of the two separated growth sides in the chamber, one with top lighting and one with side lighting. The height of the plants will be measured in millimeters 3 times a week using a Lufkin 1" x 26' tape measure with 1 mm resolution. The measurements will be taken with three different plants of each side of the chamber and the average of these three measurements will be used to determine the growth rate. The comparison of the two sides together will provide a verification as to if the use of side lighting is viable compared to the conventional method of top lighting.

3.2.3 Nutrient and pH Monitoring

To ensure that the system maintains the specified pH of 5.0 – 6.5, as well as maintaining the electroconductivity of the solution, testing of the nutrient solution was required. pH testing was conducted using an in-situ method, with measurements taken in both the basin and reservoir using a handheld pH monitor (HM DIGITAL PH-80). Measurements were taken three times per week, and both the basin and reservoir were measured three times per session. The pH meter was immersed for approximately 30 secs to allow for stabilization of the reading, and then the pH and temperature was recorded. If the pH reading is above 7, a pH reduction solution can be added, and measurements taken after a mixing period of 5 minutes where both pumps run simultaneously to circulate the solution.

Simple nutrient monitoring was accomplished using a commercial soil testing kit (Panacea Soil Test Kit). Tests were done according to the kits instructions and provided a range indication of nutrient levels within the basin and reservoir. The commercial test kit did not provide measurements of EC or specific ranges of nutrient concentrations and was only useful for monitoring the need for additional nutrient solution. Nutrient level testing occurred during the same session as the pH monitoring and was conducted after pH reading was taken.

3.2.4 Plant Health Monitoring

Growing plants hydroponically provides all the benefits of a controlled environment; however, it is still possible for unexpected issues to occur. These issues are laid out in Table 2.1. Each issue negatively impacts lettuce in some way, whether it be aesthetics, growth rate, or yield percentage. By visually inspecting the lettuce plants in person at least three times per week these problems can be mitigated. As photos of the lettuce are taken three times per week a reference database can be created to compare current lettuce conditions to previous. This allows the team to monitor the effectiveness of a certain treatment by monitoring visual changes in the lettuce. For example, if the lettuce is suspected of being overexposed to UV light then the cycle can be adjusted to reduce UV exposure. Initially the lettuce may be pale or turning brown at the leaf tips, but after a reduction in light exposure it would be expected that the lettuce would regain colour. By photographing this process, the team can identify if a treatment option is working by visually monitoring and comparing the lettuce progress.

4.0 Results

From the experiment the team was able to draw many conclusions. Results regarding the effect of the side lighting and the water and nutrient schedule will be detailed in this section.

4.1 Effect of Side lighting

One of the main goals of this project was to determine if only using side lighting for a plant would negatively impact the plant growth. Therefore, a control side with top lighting and an experimental side with side lighting were used to grow lettuce. The results from the experiment are detailed below.

4.1.1 Germination

The seeds were planted on Feb 17th. On Feb 22nd each side had sprouts, by Feb 27th all pods had sprouted. The sprouts looked the same on both sides. Therefore, it was concluded from the test that side lighting did not affect the germination. Figure 17 shows the initial sprouts for the top and side lighting.

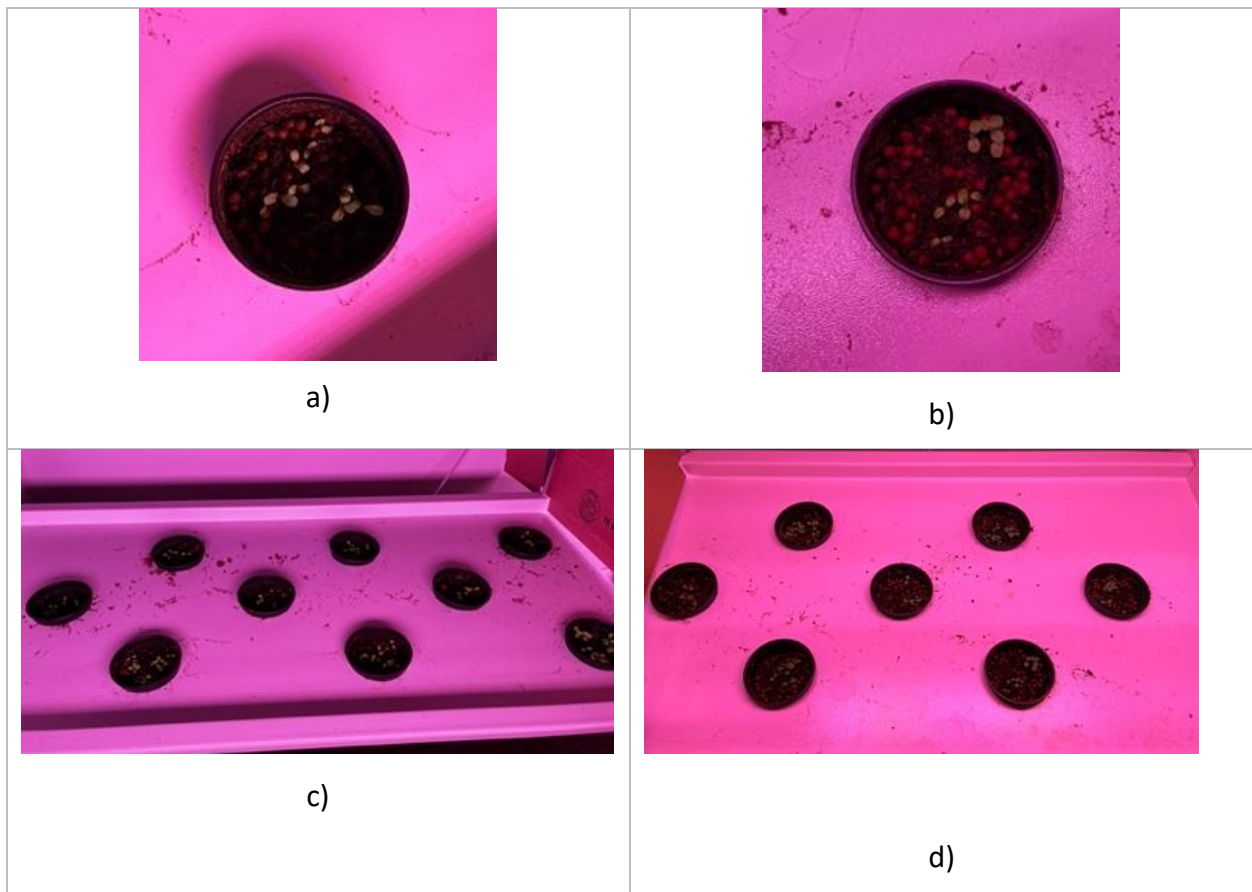


Figure 15 - Germination of the lettuce. a) one pod for side lighting, b) one pod for top lighting, c) all pods for side lighting, and d) all pods for top lighting.

4.1.2 Lettuce Growth Rate

The growth of the lettuce was then monitored for 30 days (minimum time required for lettuce to mature). Over this period the height, color and thickness of lettuce was monitored for both sides. Table 6 shows a timeline comparing the side and top growth.

Table 6: Lettuce growth for both top and side lighting over the course of the 30-day growth period







Date	Side Lighting	Top Lighting
March 1 st	 A small lettuce seedling in a black pot, showing minimal growth. A small white tag with the letter 'A' is placed in front of the pot. The background is a light blue surface.	 A small lettuce seedling in a black pot, showing minimal growth. A small white tag with the number '1' is placed in front of the pot. The background is a light blue surface.
March 8 th	 The lettuce seedling has grown slightly taller and has more leaves. A small white tag with the letter 'A' is placed in front of the pot. The background is a light blue surface.	 The lettuce seedling has grown significantly taller and has more leaves. A small white tag with the number '1' is placed in front of the pot. The background is a light blue surface.
March 15 th	 The lettuce seedling has grown much taller and has many leaves. A small white tag with the letter 'A' is placed in front of the pot. The background is a light blue surface.	 The lettuce seedling has grown much taller and has many leaves. A small white tag with the number '1' is placed in front of the pot. The background is a light blue surface.

Table 6 continued: Lettuce growth for both top and side lighting over the course of the 30-day growth period



The height of the lettuce was also measured during the course of the growth cycle. Table 7 shows the results of the plant height.

Table 7: Height of lettuce throughout the growth cycle for top and side lighting

		HEIGHT (MM)					
		SIDE			TOP		
DATE	A	B	C	1	2	3	
2023-03-01	16	20	20	10	12	12	
2023-03-04	23	22	20	16	16	18	
2023-03-08	21.5	27	30	26	28	32	
2023-03-15	78	80	78	90	84	100	
2023-03-22	90	92	95	98	120	105	

Finally, the final wet biomass of the lettuce was taken at the 30-day mark. Three plants from each side were measured. Table 8 shows the results of the biomass.

Table 8 Final Wet Lettuce Biomass for top and side light

	Right (g)	Left (g)	B (g)	Average (g)
SIDE	9.8	14.5	15.4	13.23
TOP	48.7	32.8	33.7	38.4

From the observations taken it is clear that the plants grew better with top lighting. Overall, the leaves were larger and a darker green color, whereas the side light plants were a pale green and did not have full leaves. The difference was first noticed on March 8th and continued throughout the 30-day growth cycle. Table 7 also shows this difference as from March 8th the height of all plants with top lighting were higher than all the plants grown with side lighting, this continued throughout the growth cycle. Finally, the final wet plant biomass shows that the top lighting allowed the leaves of the lettuce to be more full as the final average mass of the lettuce was more than double the average mass of the side light lettuce. This shows that strictly growing plants by side lighting will negatively impact the growth of the plants. Ways to address this issue will be discussed in the recommendations section.

4.1.3 Side Lighting Effect Throughout the Tray

One main area of concern regarding side lighting was that the plants were not at an even distance from the lights. From observing the plants throughout the growth cycle and the final biomass of the plants, this did not affect the growth of the lettuce. Figure 16 shows the side lighting tray on day 30. Although there is a difference in size between plants, there was not a pattern to this difference. Therefore, the side lighting did not affect the evenness at which the lettuce on the tray had.



Figure 16 - Side lighting tray of lettuce on day 30 of the growth cycle

4.2 Effect of Water and Nutrient Schedule

The control plants were pivotal in informing the team if the watering and nutrient schedule were sufficient to grow the plants. All plants germinated and no plants died throughout the 30-day growth cycle. This shows that the schedule used was sufficient to keep the plants alive. Figure 19 shows control side of the shelf at the 30-day mark.



Figure 17 - Top light tray on day 30 of the growth cycle. Lettuce is ready to harvest at this point

Figure 17 shows that all the lettuce plants are large and healthy with broad leaves. The lettuce was harvested by pulling the root bundle out of the pod. The root system is shown in Figure 18. The large root system of the lettuce also indicates that the lettuce was healthy as it was able to develop large roots in the 30-day growth period. Additionally, the roots did not extend through the pod but stayed contained within the pod. This indicates the roots would be easy to control and would not interact with any external systems, such as the driving mechanism or lights.

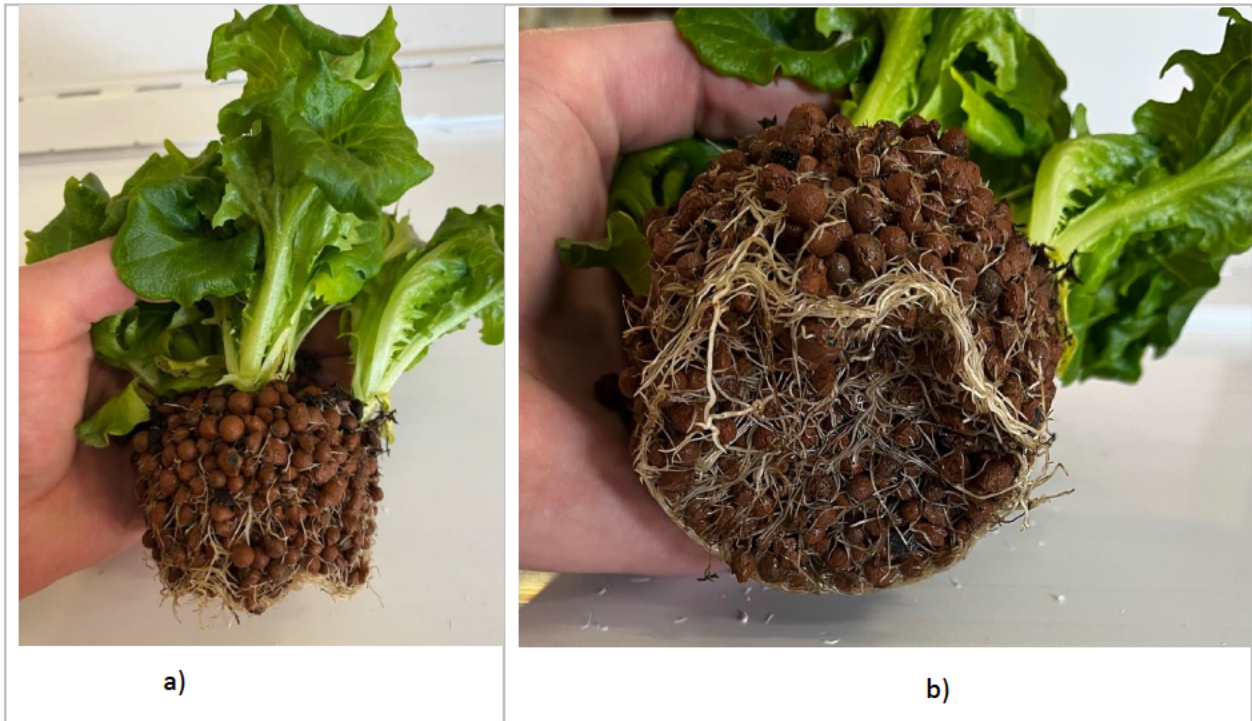


Figure 18 - Root growth of top light lettuce on day 30 of the growth cycle. a) side view of lettuce and b) bottom view of lettuce

Therefore, the team concluded that the watering and nutrient schedule used was sufficient in supporting lettuce growth. The watering schedule used is shown in Table 9. The first row shows the

basin is filled for 5 minutes instead of 4 like the other watering events. This was to counteract the small amount of flow imbalance that occurred throughout the day. Otherwise having a consistent flow regime would result in the basin flowing from 4" to 6" instead of 5" to 7" as expected. At 7" the nets holding the lettuce were approximately 75% submerged.

Table 9. Water pumping schedule. Reading from left to right the reservoir was drained to fill the basin, then all flow stopped to allow soaking of the hydroton, and lastly the basin was drained.

Reservoir pump (Fills basin)	Soaking	Basin pump (Drains basin)
1:00-1:05	1:05-1:19	1:19-1:24
7:00-7:04	7:04-7:19	7:19-7:24
13:00-13:04	13:04-13:19	13:19-13:24
19:00-19:04	19:04-19:19	19:19-19:24

5.0 Limitations

This prototype was designed to estimate the viability of a modified vertical carousel used to grow lettuce, however as time and space did not allow for a full-scale prototype this scaled down prototype was used. As this is a model there are associated limitations and assumptions made to simplify its assessment. The limitations within the design will be detailed in this section.

5.1 Lighting

For the testing of the lights the “worst-case” scenario was tested to determine the success of plant growth. In the test apparatus only one row of lights was used to assess the effectiveness of side lighting, this was due to the size limit of the test. In the Vidor carousel the plan is to have multiple lights on the side walls from top to bottom. The limitation of this is that it was assumed that plants will only get light from the light they are directly beside, however it is likely that the rays from one light would reach multiple trays at different elevations at the same time.

Another assumption made was there would be no reflection of light within the carousel therefore no reflective panels were used. In the carousel light will reflect around providing light at different angles to the plants.

Finally, it was assumed that a tray would only receive light from the side of the carousel it was on. This was tested by alternating the side lights on and off. In the carousel one tray would not block all of the light therefore, excess light would seep through to the trays on the other side.

All of these assumptions made would affect the success of the plant’s growth with side lighting conditions. A concern with side lighting is that the plants will not get any light from above, however if lights are at varying elevations this may limit the effect had on plant growth as some light will come down on to trays from lights at higher elevations. The reflection of light throughout the carousel could also make an impact as light could be reflected down onto the plants, creating a top lighting effect. Finally, the plants would get more lighting if light were seeping through the center of the carousel, more light would likely improve the growth of the lettuce. Overall, the assumptions made were so the worst-case scenario of side lighting could be tested to determine its effect on plant growth. If Vidor moves forward with side lighting a full-scale model should be tested to determine the side lighting effect in the full system.

5.2 Shelf and Basin

Due to the prototype nature of the project, there were limitations on what materials could be utilized and the dimensions that could be manufactured. This resulted in the use powder coated carbon steel rather than the recommended stainless steel as the cost of stainless steel

for the design was beyond the budget of the project. While Vidir was gracious enough to allow access to their facilities for building components, during the term of the project Vidir was burdened with many orders, meaning the project was limited to their smaller scale research and development department, which limited the dimensions of the components. As such, Vidir was able to produce a prototype shelf which was reduced in length from 108-1/2 to 84-1/5 inches. The basin was reduced to 85 in for the basin has been built. Therefore, the design is not a true full-scale prototype, and there may be unforeseen problems with the full-scale design.

Research conducted for this project suggested that plants be placed at a density of 50 per m² for optimal growing conditions, but due to placement of the planting cups in the design, a only density of 21.42 per m² was achieved. This decreased density was a limitation of the use of ideal intra and inter row spacing of the plants. This decreased density does not seem to impact the health of the plants during growth, rather this means that there is an improvement in yield per shelf to be found.

The use of carbon steel with a powder coating allowed for rusting to occur at areas where the coating was damaged and exposed to the nutrient solution. The effects of this rusting on plant growth were not measured and is unknown, but research suggests that it may decrease growth of plants. The current prototype had little rusting, and so it likely did not impact results.

5.3 Substrate

The substrate used was a base of hydroton with a thin layer of peat moss on top which just covered the hydroton. This was done to allow for extra moisture retention to keep the seeds moist while they were only days. No empirical method was used to add the peat moss, so exact moisture retention is unknown. Despite this the peat moss remained moist even after a 6-hour drying period. It is possible that additional nutrients were provided by the substrates used. This means that an unmeasured amount of additional nutrients was added. It is unlikely that this has a significant effect on the lettuce however in larger quantities, such as with more lettuce are added to each shelf, or multiple shelves are used in a full-scale system, there may be a compounded effect of this nutrient addition.

5.4 Lettuce

Only one type of lettuce was used in this experiment, Celinet lettuce. This is limiting as the results from this experiment cannot be extrapolated to other species of plants. As lettuce have similar environmental requirements it is likely that other types of lettuce would react similarly to this experiment. Other species may fair differently. An example would be potatoes and other root vegetables that tend to require less sunlight. In this case the side lighting used may not have a negative effect on growth. It could be expected that plants requiring plenty of sun such as peppers, tomatoes, or certain herbs like basil would fair poorer as the current setup lacks adequate sun exposure for even lettuce, which requires less light than these crops. No

phototropism was found during this experiment. It may still be possible that other plants will experience phototropism as lettuce tends to grow radially.

5.5 Solution and Pumps

The solution used was conventional to hydroponic systems, as was the watering cycle. The control side did grow adequately indicating that nutrient and water access was not an issue. However, the nutrient level could not be directly monitored, and only intermittent pH readings were conducted 2-3 times per week. This pH reading only acted as a proxy for nutrient content and was used to ensure that the lettuce received a solution at the correct pH. This pH never exceeded 7.0, however it was on occasion above 6.5, which can lead to less than optimal growth. The condition of the solution used cannot be accurately replicated in the future as turbidity, EC, nutrient content, temperature, and biological oxygen demand (BOD, a measure of oxygen used by life within a system) were not measured.

The circulation of solution was very intermittent, with the solution only being transferred between the basin and reservoir 4 times per day. Additional agitation was provided by bubbling air through three air stones, two of which were in the basin, and one was in the reservoir. This amount of oxygen addition and circulation was adequate to allow plant growth, however there was not enough agitation to prevent algae growth on the sides of the basin and reservoir. This algae could have inhibited plant growth by taking away nutrients from the lettuce, particularly phosphorus. The algae may have also produced cytotoxins which could negatively impact plant growth (Burton & Armstrong 2020). As there was no setting in which algae did not grow it cannot be determined what the true lettuce growth rate would have been.

6.0 Safety

Safety is an extremely important factor when it comes to the design of any system interacting with people. Safety is the first item listed in the Engineers and Geoscientists Manitoba's code of ethics, both the safety of the user, the safety of anyone in the vicinity of the system and for the safety of the system itself. Below is a list of potential safety concerns for the final system. Mitigation methods are listed in the recommendation section.

6.1 Tampering

The prototype had a camera monitoring system made from two old iPhones which provided a constant live video feed of the system. A similar strategy could be used with the full system as well, comprised of permanent cameras. A video monitoring system allows for notifications to be sent to the user if the cameras detect movement in the system that is not normal, such as an intruder tampering or plants falling. An alarm can then be sounded either manually by the user after checking to alert, or it can sound automatically to scare off the intruder and try to prevent any tampering or any safety hazards to the person and system such as have already been mentioned. At the very least if tampering should occur, the camera system will capture the exact time of the incident and images of the intruder.

Tampering of the full-scale system is not only a concern for the safety of the person tampering, but it also concerns the operation of the system itself. The carousel contains large and heavy shelves that carry plants. If the connections of the shelves become loose and fall, it could be devastating for not only the person tampering but other users as well. There are also moving mechanical parts and a chain as part of the drive system, if the drive system was to be turned on accidentally it could harm the person tampering in the system.

The full-scale system also has timed intervals which turn the growth lights on and off, rotate the shelves, and pump the solution. The prototype has all of these systems bar rotating the shelves. If any of these systems were to be tampered with and altered, it could prove to be devastating to the growth of the plants and ultimately kill them if left for a long enough period. The automated rotation of the shelves could catch or push a human that is servicing the machine.

6.2 Automatic and Manual Shutdown

A second safety concern is the ability of the full-scale system to be able to shut down either automatically or manually at any time. The need for an automatic shutdown of the system presents itself due to the many heavy moving components of the system. If a person nearby was to either intentionally or accidentally reach in or fall into the carousel they could easily be hurt by the movement of the shelves or the chain and drive system. A manual shut down is needed when maintenance is required on the system. Sudden operation while a technician is working on the system can cause serious harm to the technician.

An automatic shutdown could be easily implemented with the use of infrared sensors around the moving components of the system. If the beam between these sensors was to be broken at any point, the system would instantly shut off preventing harm to the person that broke the beam. A manual shut down system or procedure could be easily implemented by creating a “lockout – tagout” procedure. A “lockout – tagout” procedure is a procedure that is widely used in industrial applications. When a machine or system has maintenance required it is shut down and locked out in a way where it is obvious why the system is shut down. This prevents the accidental startup of components or systems when a technician is actively working on them.

6.3 Fire Monitoring

Fire safety is a massive concern as fire can be devastating to the carousel, the building the carousel is in, and most importantly, fire can take human lives. Thus, it is imperative that fire monitoring is provided in the system. Both the prototype and the full-scale system utilize powerful LED grow lights which create a significant amount of heat. Should anything flammable come in contact with the lights for an extended period of time it is possible that that object could catch fire.

The camera system mentioned before would be able to be utilized for fire monitoring. The motion sensing of the camera system would be able to detect if anything large fell onto the system and would send out an alert of this incident. In the case that the contact between a flammable material and the lights occurred subtly with no alert and a fire did start, the camera would be able to detect the fire and would again send out an alert of the situation. These alerts give advanced warning which can inform a technician to remove the object that is in contact with the lights. If a fire begins the cameras can alert a human who can start a fire alarm. If a fire is deemed to be likely enough to occur a fire suppression system could be installed within the carousel to extinguish a fire without the need of a human to physically approach the system. Current Vidir carousels have metal facing which will become too hot to touch in the event of a fire, so there is no guarantee that a human with a fire extinguisher can suppress a fire.

6.4 Fouling of Rotating Mechanism

Vidir carousels have a motor and gearbox assembly connected to a chain which drives the rotation of shelves around the carousel. A concern for this system could arise if excessive rust were to build up on the chain causing resistance to the drive motor or jamming of the chain and gearing mechanism. A further concern could be from plant debris clogging the chain and causing it to either jam or to skip a tooth on a drive gear.

Rusting chains can be mitigated through the consistent lubrication and inspection of the chain and drive system. The issue of plant debris clogging the chain drive can again be mitigated by consistent inspection of the chain itself, as well as the selection of an appropriate plant to grow. Plants with long roots or stems may be unsuitable as they could reach out of the shelf.

6.5 Leak Detection

With a water system containing two separate containers of water with pumps and hoses running between the two there is always a risk of leakage from anywhere. Leaks pose a concern to the safety of people around because water on the floor makes it slippery posing the risk of slipping and falling. A second concern would be with the electronics controlling both the prototype and full-scale system. If water were to get into the controlling electronics of either system, it could damage or destroy components.

A way to mitigate the risks associated with leaks would be to utilize a moisture or leak detection device similar to what is used in home to detect basement flooding. The sensors would be able to detect leaks in the system and send an alert. This allows for immediate action to fix the leak and prevent damage.

6.6 Water Safety

When creating a system that involves open water basins there is concern around water safety. With the basin of both the prototype and then also the full-scale system being completely open to the surroundings with no lid, there becomes the concern of drowning from a possible accidental fall into the basin. The nutrient solution used is not meant for direct human consumption. It is also possible that mold, algae or bacteria can grow in the water that would be harmful to ingest directly and may be harmful or irritating if it comes in contact with the eyes or sensitive skin.

A way to mitigate the risk of drowning would be to have a guard rail around the basin to prevent anyone from falling in but allow it to be removable for ease of access for maintenance. To mitigate the risk of human consumption of the water and nutrient solution, signs could be put up on the system warning not to drink the water from the system. To protect people from biological threats growing in the carousel personal protective equipment is suggested when cleaning the system. This is likely not needed during routine use or when planting and harvesting.

6.6.1 Water Supply and Removal

Both the prototype system and full-scale system require a supply of water and water removal from the system. The reasoning for this is, other than the initial filling of the system, there needs to be a complete water replacement done every one to two weeks to help prevent bacteria and algae growth in the system.

In the prototype the only way to remove the water from the system was to use the systems pumps to pump the water out of the basin and into a 5-gallon pail which was then carried to a sink to drain. This repetitive action of lifting roughly 40 lb of water and carrying it 70 ft to the nearest drain poses a safety risk. The carrying of the bucket will cause repetitive strain on the

person carrying the bucket and has the possibility to injure the carrier, either from repetition or too heavy a weight. Slipping and falling could also have occurred while carrying these buckets. To mitigate these risks the team ensured three members were present when draining the system, and all walkways were kept dry and clear.

In the full-scale system, alterations should be made to the pump and plumbing layout to allow for the automatic exchange of water. If it is possible to rely on the pumps to empty and refill the basin and reservoir, then this will eliminate the need to move 5-gallon pails. This option also makes the water exchange extremely easy to complete.

6.7 Electrical Short Detection

Due to both the prototype system and the full-scale system having electrical operating controls near a water system there is always the risk of shorts caused by the water. A system to monitor and warn about water leaks has been discussed, but for redundancy, measures should be in place to prevent shorts in the case that water does come in contact with electrical components. Shorting of the system poses a risk to the system itself as it could potentially cause damage. But there are also risks posed to anyone nearby during the short and often shorts are accompanied by a shower of sparks which could potentially harm anyone nearby.

A way to mitigate shorts could be to use ground fault circuit interrupters (GFCI) throughout the system to detect any abnormalities, or a power surge in the system due to water being in contact with electrical components. When this abnormality is detected, the GFCI will trip, cutting power to the system.

7.0 Recommendations

From the developed prototype the team has developed recommendations for Vidir to help them continue to pursue vertical farming within their carousel shelving units. It would be suggested that Vidir use the prototype build for this report and continue modifying it until an acceptable configuration is found. This configuration would realistically model conditions within a vertical carousel more closely than the current configuration. It may also be used to introduce new variables such as lighting adjustments or plants used. Once an adequate configuration is found it is suggested that Vidir utilize an existing carousel that can be modified for research purposes. This carousel can be modified one shelf at a time to build a full-scale prototype.

7.1 Lighting

As previously mentioned, the side lighting did lead to a reduction of lettuce growth. Therefore, more tests must be run to assess the viability of side lighting in the Vidir carousel. The next test to be run should use the single shelf test system with the lights slightly angled. By having the lights at an angle, the plants may have enough top light so that plant growth is not impacted. A growth cycle of lettuce (30 days) should be completed, where lettuce grown with angled lights are compared to lettuce grown with top lighting. Figure 16 shows a diagram of the purposed change.



Figure 19 - Proposed lighting change. a) side lighting used for experiment b) proposed angled lighting for future testing

After this test is conducted another test should be run where the lights are back to their original position with, however, reflective panels are placed within the frame. These panels would reflect light down on to the plants, limiting the impact of side lighting. A growth cycle of lettuce (30 days) should be completed, where lettuce grown with side lights and reflective panels are compared to lettuce grown with top lighting.

Once both methods are tested separately a final test should be completed to compare lettuce grown with both angled lights and reflective paneling against lettuce grown with top lighting.

These tests would help understand if side lighting can be altered to increase the success of plant growth.

If after the tests Vidir still wants to pursue side lighting within the carousel a full-scale test should be run, with lights placed up the side of the carousel.

7.2 Shelf

For future evaluations, Team 4 recommends that there be testing of the effects of rust on plant growth in the system should be conducted. The use of rust proof materials such as stainless steel or aluminum for the shelf should also be researched.

7.3 Substrate

A peat moss and Hydroton mixture produced acceptable results for the control side of this prototype. It is expected that Hydroton is a suitable substrate for this application as it is lightweight, holds an adequate amount of moisture, and stops dripping in under a minute after being soaked. This is beneficial as each plant spends most of its time unsubmerged. So less dripping means that water is unlikely to continue dripping on other plants which can cause light burns. It would also contain the water in the carousel to the basin instead of dripping on the rest of the system. It is suggested that future prototypes use Hydroton without peat moss as peat moss can become overly moist and is not able to be produced sustainably. This additional moisture can cause mold growth, deny air to roots, and provide a suitable environment for insects. Additionally, Hydroton can be washed and reused if it is not broken too finely.

It is suggested that the moisture content of the chosen substrate be measured continuously in future tests. This would allow for more accurate detail on the rate of drying of each net regarding variables of interest. These variables include the type and amount of substrate used, the addition of air circulation, as well as type of plant used.

7.4 Lettuce

The Celinet lettuce used grows adequately in both conditions. However, the side lighting condition proved to not supply the lettuce with enough light as this lettuce was long but not full (Mattson 2018), leading to a lower leaf density and therefore a lower yield. As the main variable to change is the lighting condition it would be suggested that the same type of lettuce be used in future tests and planted in the same manner (3 seeds per net).

It is likely that owners of a vertical plant growth shelf would like to grow a larger variety of plants than just lettuce. It would be beneficial to test the growth of as many families of crops as possible. An example would be cauliflower, which does not require light during the growth of the edible part of the plant (Bodolan & Brătucu 2013). Cauliflower would be a beneficial crop to test as it does exhibit a growth efficiency increase when exposed to drought conditions (Kage et al. 004). This is created in the carousel using intermittent watering. If the results of this testing

show that cauliflower does not become stunted due to being root bound it would be useful to pursue further research.

Other plants that either require low light levels, or a similar spectrum of light, should be tested. This could prove to be useful as He et al. (2019) found that the exact ratio of red, green, and blue light produced by LED lights sources have a species dependent effect on productivity. This study specifically focused on leafy vegetables which include lettuce, broccoli, and basil. This information could also be informative on the design of a prototype that is configured to give a higher light intensity which would be beneficial for basil. It is unlikely that the current prototype would have a high enough light intensity to properly grow basil, so different lighting configurations should be used.

7.5 Solution and Pumps

The solution and pumps used proved to be adequate in providing water and nutrients to the lettuce. The primary issue of this system tended to be automation. The solution required weekly addition which was done manually by measuring out the correct volume and adding it in proportional parts to the basin and reservoir. In the future the addition of a nutrient solution should be automated. This can be achieved by either using or creating a system similar to the Intellidose™ product created by Autogrow (2023). This would be able to sense and adjust nutrient and pH levels of the system.

The pumps were on an open system, meaning they were activated based on the time of day. This caused water level drift, as the highest resolution of the timer used was one minute. So, every three days the water level would be about $\frac{1}{2}$ " to $\frac{3}{4}$ " lower than it should be. This is also due to water evapotranspiration and plant water uptake lowering the total amount of water in the system. It would be useful for the pumps to be a closed-loop system, meaning that they operate on a timed schedule, and would stop based on the water level height in the basin. It would also be useful for the prototype and final system to be connected to a clean water supply.

The prototype utilized Winnipeg's water supply, which was fine however still contains some chlorine content. It would be beneficial to see the performance of the prototype with and without chlorinated water as it is likely that this product will be used in urban settings. If chlorinated water has a negative impact on the growth of plants the water supply used could be filtered with an activated carbon filter. This could be a recurring source of income for Vidir as the filter would need to be replaced, likely every 1 to 3 months.

7.5.1 Cleaning

Algae growth was found in the current prototype after about 4 weeks. The team decided that algal growth was not beneficial in the current prototype and decided to get rid of it by flushing the system. Appendix 9.2.1 details the cleaning methods used.

7.5.2 Solution Disposal

The current prototype used a maximum of 110 gal of solution at a time. This is a low volume of solution and would not have a high impact when added to municipal wastewater treatment. It is suggested that when testing further prototypes this small amount of excess solution be diluted and added to potted plants not intended to be eaten. This will ensure that additional fertilizer does not runoff to groundwater or waterways.

For a final product there are two primary ways that the wastewater can be treated. The first would be to collect and concentrate phosphorus in the waste solution. The methods used by Arcas-Pilz et al. (2021) are currently being implemented in wastewater treatment plants worldwide. Phosphorus is a non-renewable resource and can supply the necessary nutrients to support algal blooms when added to lakes. Winnipeg has plans to add a wastewater nutrient removal system (City of Winnipeg, 2020), however if the same methods are applied at a small scale within the carousel, then the hydroponic wastewater produced could be less environmentally harmful. Owners of the carousel would benefit as they would retain some nutrients that can be reapplied. This would only be feasible if there is a high enough nutrient content in the solution that can be recovered.

The second option would be to remove all nutrients, solids, and particles as small as monovalent ions by reverse osmosis (RO). RO is extremely effective at removing impurities and leaving behind only water. This is however very expensive and energy intensive to implement and will likely be cost prohibitive to implement in each carousel. As an alternative to both recommendations the responsibility of solution disposal could be accepted by the owner of the carousel.

7.6 Basin and Reservoir

As mentioned in section 6.2, the use of rust proof materials is recommended for both the basin and reservoir in the next iteration of prototyping or for the final product. As well this could be combined with a thicker powder coating to reduce the possibility of it being scratched or damaged during transportation and assembly, reducing risk of rusting for non-rustproof materials.

7.7 Heating, Ventilation, and Air Conditioning

The prototype built made use of natural ventilation by allowing air to flow through gaps at the base and ceiling of the blackout fabric. Past Vidir vertical carousel models had no need for air circulation inside as moisture was not added to the system. It can be assumed that a future commercial model may require either heating or cooling, as well as proper ventilation. To emulate this in future iterations of this prototype the ambient air temperature, CO₂ and O₂ concentrations, and moisture content should be monitored. This data would be especially

informative in a full-scale prototype, as air would circulate less easily through it compared to the prototype used in this report.

HVAC requirements are also situational. If this were to be used inside of a commercial climate suitable for humans, such as a grocery, greenhouse, or big-box store, then there would be less of a need for heating or cooling as the environment would already be suitable for the plants. It is suggested that there still be some heating and cooling capabilities to account for various types of plants and their needs. There may also be a need to ventilate the system as there could be a buildup of heat or moisture. A potential HVAC design for a Vidor carousel can be found in a report by Capar et al. (2021). This was created as a final report for a University of Manitoba class titled MECH 4860 Engineering Design.

7.8 System Housing

Current Vidor vertical carousels have either a solid opaque wall or a fence that surrounds the carousel. In traditional carousels this would serve to protect inventory and ensure upper levels of inventory are not accessed. Additionally, in the unlikely event that an item was to fall from an upper shelf it would not be able to hit a human. The prototype used in this report only used an opaque blackout fabric which still allowed for natural air flow. It is advisable that a future prototype be designed out of an impermeable material to better replicate air flow conditions within a carousel with solid walls. It

8.0 Conclusion

In conclusion, a single shelf prototype designed to simulate the hydroponic growth conditions in a full sized Vidir carousel was designed, built, and tested. The system consisted of four major parts: the growth shelf, nutrient basin, storage reservoir, and lighting system. All four of these systems worked in harmony to achieve controlled growth of lettuce using hydroponics.

The goal of the project was first, as a proof-of-concept that a Vidir carousel can be converted into a hydroponic vertical farm, and second, to assess the effect of side lighting on plant growth. The use of side lighting was required to allow all shelves to be lit in the carousel rather than have lighting from the top and have the first shelves block all the light from the plants below. The system was divided into two identical halves, save for the lighting configuration, one half was top lighting and the other was side lighting. This allowed for a controlled test with only one variable between the two halves.

After growing lettuce for 30 days it was found that the system was capable of allowing the lettuce to germinate and grow fully for the 30 days. Although growth was successful in both halves of the system there was a clear difference in the performance between them. The top lighting half ended with a biomass per growth net of 38.4 g compared to the side lighting half that only achieved 13.2 g. There were also visible differences between the halves in overall size of the plants as well as how densely the plants filled the nets.

Team 4 recommends further testing with the created prototype along with some changes to the system. The first change is to trial angled side lighting with the light panels. Tilting the panels downward instead of completely vertical will allow more of the light to be focused on the plants giving them their needed light energy for growth. A further trial could be conducted utilizing light reflection. This could be done with reflective panels in the system or just by having all materials inside the system painted white. Utilizing reflection will allow for any light that missed the plants to be able to be reflected and redirected back to the plants in the prototype. Finally, the use of a closed system for pumping the nutrient solution should be used. An open system using timers was used in the current prototype and this led to consistency errors in pumping times. From these consistency errors, the level in the basin needed to be reset every week to the required level. If a closed system utilizing a float for the pumps was used, this would eliminate the consistency errors.

Finally, Team 4 found that this proof-of-concept prototype was a success, and shows that creating a full scale, vertical hydroponic farm from existing Vidir carousels is possible. Further testing with the designed prototype is required, but Team 4 recommends pursuing further research into this vertical farming method.

9.0 Appendix

Text

9.1 General Materials

A1.1: Plant Related Issues, Identifying Information, Effects, and Treatment Options

Problem Type	Problem Name	Symptoms	Causes and Treatment
Infection	Bacterial	Brown slimy biofilm forms on surfaces (roots, tubing, basin, etc.)	Contaminated substrate, water, insects, or other material is brought in. The moisture content of the substrate should be decreased by decreasing watering lengths. A plant-safe bactericide could also be used on the entire system, flushing it clean with new water.
	Fungal	Fuzzy coloured growth (white, grey, blue, or green) on roots, leaves, or moist surfaces.	Typically caused by transmission via air. Dust and stale air entering the system should be reduced. An air filter and controlled air flow system would be ideal.
	Pythium (Root rot)	Roots will become black or brown, slimy and swollen, and emit an unpleasant odour. Stunted growth may also occur.	Caused by a soggy root bed that has contact with an outdoor environment. Increase DO content to mitigate root damage, and increase substrate drainage. Hydrogen peroxide can be applied to treat rot (3 mL/gal at 35% concentration). In the unlikely event this does not help, a restart will be required. Substrate and plants should be thrown out with the entire system being flushed. Only sterile substrates should be used.
	Viral	Stunted growth, chlorosis (yellowing due to a lack of chlorophyll) in outer leaves, dark inner leaves, brown spots (necrosis), root rot.	Rare occurrence. Plants need to be infected by other infected plants or insects. Can be treated by increasing DO content and drainage to increase root strength. Otherwise the substrate and plants should be thrown out with the entire system being flushed. Only sterile substrates should be used.
	Algae	Green or blue murky film, may stick to surfaces.	Brought in by contaminated water or material. Can be treated by increasing air circulation in water and flushing the system.
Nutrient Deficiency	Phosphorus	Initially: dark green new leaves, reduced growth rate (smaller leaves and thin stems), necrosis spots in outer leaves,	Lack of nutrient available. First check if pH is low enough. If not, lower pH. If it is, increase nutrient availability by adding nutrient solution.

		long primary roots with short secondary roots	
	Nitrogen	Stunted growth, fewer but longer primary roots, lighter green leaves, chlorosis of older leaves, tough leaves and roots	Lack of nutrient available. First check if pH is low enough. If not, lower pH. If it is, increase nutrient availability by adding nutrient solution.
	Calcium	Reduced growth, necrosis spots (black) on mid-leaf, leaves curl upwards, root necrosis	Lack of nutrient available. First check if pH is low enough. If not, lower pH. If it is, increase nutrient availability by adding nutrient solution.
	Magnesium	Chlorosis in older leaves at edges, then into veins, leaves curl downwards	Lack of nutrient available. First check if pH is low enough. If not, lower pH. If it is, increase nutrient availability by adding nutrient solution.
UV Light Imbalance	UV Light Over-exposure	Pale sun-bleached leaves that eventually turn brown and crisp.	Lighting schedule is too long, or too intense. A solution would be to decrease lighting duration by 2 hours per day (or depending on severity of overexposure). The lights could be moved further from the plants as well.
	UV Light Under-Exposure	Pale leaves eventually turn yellow. Stunted growth, node spacing increases, excessive phototropism	Lighting schedule is too short, or not intense enough. A solution would be to increase the lighting duration by 2 hours per day (or depending on severity of underexposure). The lights could be brought closer to the plants as well.

Nutrient Surplus	Nutrient Burn	Rusting (browning, yellowing, or blackening) occurs at the leaf tips then spreads to the rest of the leaf. Slow plant growth, dark green leaves, leaf tip curling, wilting, spotted necrosis.	Can be caused by underwatering, overwatering, or too high of a nutrient concentration. The system should be accessed to see if the plants are being adequately watered, and the pumping system should be modified to correct this. Any dead spots should be trimmed. Afterwards the solution should be drained and replaced with a lesser concentrated solution. Optionally, root stimulators can be added to the solution.
pH	High pH	Nutrient lockout (see “nutrient burn” above)	A pH above 7 will reduce nutrient uptake, effectively causing a nutrient lockout. pH down solution can be added to reduce pH. A pH below 6 is unlikely, as nutrient uptake always increases pH over time.

Additional nutrient related issues such as deficiencies, interactions, and pH imbalance can be found from Berghage et al. (2020).

9.2 Project Specific Materials

Methods and materials that are specifically used in this prototype.

9.2.1 Cleaning Method

To rid the system of algae the system was drained from approximately 105 gal to 20 gal. There was a residual amount of water as the pumps used could only drain water to about 4" before they started to run dry which would cause pump damage. To lower the basin to about 1" in depth the pump was manually held at a 90° angle so the intake could suck out 3 extra inches of water (38.64 gal). The water was pumped into 5 gal pails and then poured into an industrial sink connected to Winnipeg's sewer system. Next the algae buildup was wiped away with paper towel. No disinfectants were used as there was no noticeable effect on the lettuce. The system was refilled with water to 105 gal and nutrient solutions A & B were added.

9.2.2 pH Testing Method

The pH meter used was turned on with the power button. After a number appeared on the screen it was submerged in the solution and moved around to create eddies around the pH meter. This was done for approximately 30 seconds which gave a stable reading. The pH reading and temperature were recorded. Then another location on the approximate other side of the basin was chosen and the procedure was repeated.

9.2.3 pH Lowering Method

If the pH was measured to be above 6.0 and nutrient solution was added within a week, then the pH was lowered with "pH down" solution. Approximately 100 mL of this solution was added to the basin and reservoir while both pumps were running to circulate the solution. A metal meter stick was used to stir the solution as well. This was allowed to mix for 5 minutes, and the pH was read again. Once the pH was at or below 5.9 no more pH down solution was added.

9.2.4 Nutrient Addition Method

The volume of nutrient solution is based on the volume of water in the full system. The height of water in the basin was taken and multiplied by the basin area. This was also done for the reservoir to get the total volume of water. Next nutrient solution was added in proportion to this total volume as per the nutrient solution manufacturer's instructions.

9.2.5 Timer Programming Method

The BN-Link timers were programmed by first setting the day of the week and time by pressing and holding each until the display began to flash. The buttons were repeatedly pressed until the day of the week and time were both correct. To program when the timer would turn on the program button was held. The new screen allows for programming of up to 8 functions (on or

off). As the pumps and lights are on daily the timer was shown to select Monday to Sunday. The time was corrected by pressing and holding the time button.

9.3 Bill of Materials

All materials purchased are included in this table. The cost of the shelf and basin are not included.

A3.1 Bill of materials. All materials are purchased by Vidir, unless specified under ID column.

Name	ID	Source / Hyperlink	Cost Per Unit	Amount	Total Cost CAD
Water pump	SKU: AAPW1000	Hydro Farm	95.03 USD	2	262.28
Water tubing (3/4" ID)	SKU: HGC708245-F	Growers House	0.89 USD	40	49.13
Check valve (3/4")	SKU: CVPVC007-SW-SXS	Ponds Online	19.99 USD	2	55.17
Lettuce seeds	SKU: LT546	West Coast Seeds	3.29 USD	1	4.54
Nutrient solution A (4L)	SKU: 124-6201-15	Indoor Growing Canada	52.45 CAD	2	104.9
Nutrient solution B (4L)	SKU: 124-6251-15	Indoor Growing Canada	52.45 CAD	2	104.9
Nets (3.5" Diameter)	SKU: FUT414-0430	Incredigrow	0.95 CAD	52	49.4
Substrate, volcanic clay	SKU: MMP401-2247	Incredigrow	9.99 CAD	6	59.94
Air pump for air stone	SKU: 210000006386	Indoor Farmer	89.95 CAD	1	89.95
Air stone (Medium size)	SKU: 210000006598	Indoor Farmer	4.45 CAD	2	8.9
Air tubing (100')	SKU: 210000004560	Indoor Farmer	25.95 CAD	1	25.95
pH meter	ASIN: B01M5IASHD	Amazon	20.00 CAD	1	20
pH meter buffer (Calibration)	SKU: UZ-05942-10	Cole-Parmer	53.41 CAD	1	53.41
pH reduction solution (Solution)	-	Hydro Lite	44.95 USD	1	44.95
Light meter	ASIN: B005A0ETXY	Amazon	67.00 CAD	1	67
Reflective sheets	ASIN: B099PQNCBX	Amazon	20.00 CAD	1	20
Autopilot Timer	SKU: TM011715D	Hydro Farm	29.07 USD	1	38.66
Water reservoir	SKU: DC-900100-1.2	The Tank Depot	346.00 USD	1	300
Light timer	-	Canadian Tire	10.49 CAD	1	10.49
LED lights (Used)	Model #: ND-PGHxy-zz-FA240	WZL Neo-EcoTech Co.	240 USD	3	720
Blackout fabric	(UofM purchase)	Fabric Land	129.02 CAD	1	129.02
Hose clamps	(UofM purchase)	Home Depot	13.33 CAD	4	13.33
Hose ends	(UofM purchase)	Home Depot	7.82 CAD	2	7.82
Power bar	(UofM purchase)	Home Depot	33.57 CAD	1	33.57
Rubber stoppers	(UofM purchase)	Home Depot	8.94 CAD	2	8.94
Valve hose ends	(UofM purchase)	Princess Auto	25.73 CAD	2	25.73
Total					2307.98

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