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Recirculating Hydroponic System with Automated Nutrient Sensing and Control

BREE 495 – DESIGN III

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Abstract

This report outlines a design for a recirculating hydroponic system with automated nutrient sensing and control for the client Urban Barns Foods Inc., a Canadian food producer dedicated to producing fresh leafy vegetables without the use of pesticides and herbicides. Urbans Barns has set a goal to further decrease their environmental impact by recycling up to 90% of the water used in their hydroponic units. The proposed design recirculates the water and includes an array of ion selective electrodes for the detection of the macronutrients calcium, nitrate, and potassium as well as electric conductivity and pH in the effluent solution from the hydroponic unit. The proposed nutrient sensing and control system accurately detect the depleted nutrients in the effluent of the system and sends a signal to a series of peristaltic pumps to dispense the appropriate levels of nutrient concentrate in order to replenish the nutrient depleted water prior to redistribution to the plant. The optimal nutrient levels, to which the system aims to maintain, is determined daily by recirculating Hoagland solution through the automated recalibration loop. The proposed system was prototyped and tested for structural inadequacies and accurate sensor readings. Proof of concept of the nutrient sensing and calibration loop highlighted the particularly slow speed at which the calcium sensor read the concentration in the solution as well as reinforced the necessity for regular calibration to ensure accurate readings of the nutrient levels. The design was optimized through further testing and risk analysis, and the proper safety measures implemented to ensure a well-functioning and safe system. After consideration of all the final design specifications, cost analysis was performed and the total cost of building one automatic recirculating hydroponic unit came to $2348.85.

Introduction

This report outlines a design for a recirculating hydroponic system with automated nutrient sensing and control for the client Urban Barns Foods Inc., a company dedicated to producing fresh leafy vegetables in an indoor, controlled environment that uses no pesticides or herbicides. The company grows the vegetables in hydroponic units that make use of vertical space that conventional agriculture techniques do not. Urban Barns has partnered with McGill University to improve upon and optimize the technology currently used in production. As the company expands, there is a desire to move towards increased automation in the system. Additionally, Urbans Barns has set a goal to further decrease their environmental impact by recycling up to 90% of the water used in the hydroponic units.

The Urban Barns facility, located in Mirabel, QC, obtains its water supply from a nearby groundwater well. The water is then mixed with stock solutions of nutrients to form a nutrient solution that is to be circulated to the plants through the hydroponic unit. Each hydroponic unit is composed of 108 trays, each holding 340 mL of water, and plants as they travel on a conveyor belt through the unit (Figure 1). The water is delivered to the trays in a batch system, and once the water has been added to a tray, it remains in that tray for 1.65 hours before being dumped into a collection tank, and refilled with new, nutrient rich water.

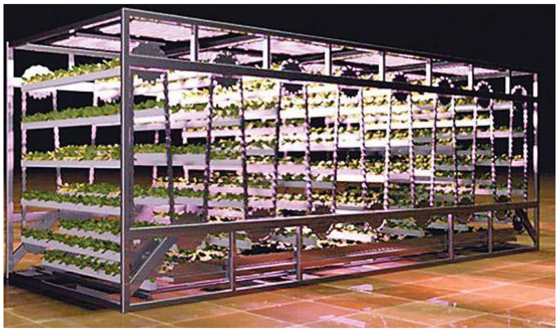

Figure 1 Hydroponic unit with trays and conveyor belt (Urban Barns Inc., 2014)

The nutrient solution currently in practice follows the recipe developed by Hoagland (Hoagland et al., 1938). The nutrients found in the Hoagland solution and their corresponding concentrations are listed in Table 1.

Table 1 Hoagland solution

Nutrient	Concentration (ppm)
Nitrogen	210
Calcium	200
Potassium	235

Since the water is to be recirculated, the amount of nutrients following uptake must be accurately detected to enable precise replenishment of nutrients prior to its return to the hydroponic units. The proposed design makes use of ion selective electrodes (ISEs) for the detection of the macronutrients calcium, nitrate, and potassium as well as electric conductivity and pH. The proposed control system monitors these ions and aims to maintain the levels of each at an optimum concentration determined daily by recirculating the Hoagland solution through the recalibration loop. For each nutrient, once the concentration is detected to be below the desired level, a signal is sent to turn on each of the peristaltic pumps which dispense nutrient concentrates of potassium nitrate (KNO_3), calcium chloride ($CaCl_2$), and potassium phosphate (K_2PO_4), supplementing for nitrate, calcium, and potassium respectively. Lastly, a fourth peristaltic pump is used to inject hydrochloric acid (HCl) for pH control which must be kept between 5.5 and 6.5.

The constraints and criteria that were critical in developing the design solution included durability/reliability, safety, capital cost, low energy consumption, minimal maintenance, and compatibility with the existing system. The nutrient levels of nitrate, calcium, and potassium must be monitored and maintained at the aforementioned Hoagland solution concentrations (Table 1). Additional parameters that were considered included pH, temperature, accurate sensor readings (i.e. eliminate air bubble formation on ISEs), as well as automated nutrient injections and recalibration.

The Initial Design

Discharged water from the plant trays in the hydroponic unit is first dumped into a collection tank, which is located underneath each hydroponic unit (Figure 2). The collection tank facilitates future upscale of this design. The collection tanks would collect the water from each plant unit and redirect the water to a centralized water holding tank. While there is constant mixing occurring within the tank, discussed below, it is referred to as the holding tank for sake of clarity. A peristaltic pump is used to pump the water from the collection tank to the holding tank. A screen filter is added to the top of the collection tank to ensure that no large particles are introduced into the tank and interfere with the peristaltic pump. The centralized water holding tank holds the nutrient balanced water solution, but for the sake of clarity, the contained fluid will be referred to as water.

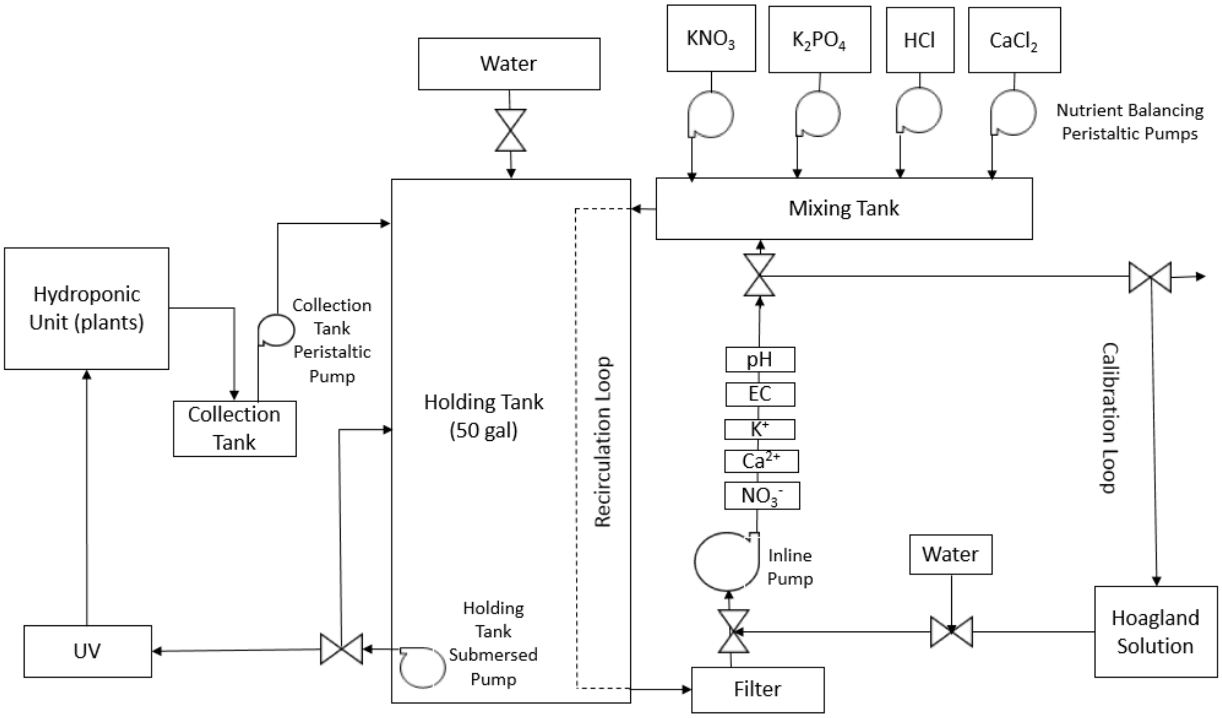

Figure 2 Initial proposed design

To achieve optimal nutrient balance and replenish the nutrient depleted water, a side loop is used to monitor, adjust and recalibrate nutrient levels. As part of the recirculation loop, water is pulled by the inline pump, first through a filter, then past the five sensors. The five sensors are used to measure nitrate, calcium, potassium, electro-conductivity and pH, in that order, and are secured into a rigid PVC pipe of 1" diameter to allow adequate space for the depths of the inserted sensors. 1" tubing was chosen based on the constraint of 1" PVC piping in an effort to limit variations in flows which could have a negative effect on sensor readings. Sensed water then continues to the mixing tank where nutrient injection occurs. The mixing tank is considerably smaller than the water holding tank for the purpose of achieving a pre-mixed solution prior to entering the centralized water holding tank. Nutrients are added by constant rate peristaltic pumps and are labelled in Figure 2 as nutrient balancing peristaltic pumps. The sensing and nutrient injection operates as a hysteresis controller, where the sensors indicate above or a below the concentration level determined during calibration and the pumps will turn on or off accordingly. Lastly, the nutrient balanced water is discharged back into the water holding tank. A secondary part of this section is the calibration loop. The sensors require recalibration periodically, which can be done via a one-point calibration by recirculating Hoagland solution past the sensors. Valves for the circulation loop are closed and opened for the calibration loop. The water from the initial step in the calibration loop where water is circulated to flush the sensor region prior to the Hoagland solution is drained. This step removes any buildups of nutrients from the sensor region. After flushing with water, the Hoagland solution is circulated past the sensors for re-calibration.

In the centralized water holding tank, a submersed pump transfers water to the disinfection stage, where it later flows into the plant trays. A diversion from the pump is used to induce mixing within the water holding tank. Additionally, water is regularly added to the water holding tank due to depletion from plant uptake and evaporation.

Analysis

Each tray of the current 180 tray unit holds approximately 340mL of water and remains in the tray for 1.65hrs. The water is delivered to the tray from the holding tank as a batch system.

Sizing inline pump

All the pipes used for the recalibration loop, connecting the PVC pipe with the sensors to the Hoagland solution, as well as water recirculation loop, connecting the PVC pipe to the mixing tank, was kept with a consistent diameter of 1". (Note that 1" PVC diameter was necessary in order to accommodate the depths of the sensors). In sizing the pump, the flow rate was calculated using the Reynolds number for flow in a pipe with a diameter of 1".

$$Re = \frac{VD}{\nu} = \frac{{}^{Q}/_{A} * D}{\nu}$$

Isolating for Q,

$$Q = \frac{Re * \upsilon * A}{D}$$

Re = Reynolds number
Re = 2000 for a laminar flow
Re = 4000 for a turbulent flow
D= hydraulic diameter = 1in = 0.025m
v=kinematic viscosity of water = 10^{-6} m^2/s
A = cross sectional area of pipe

Calculating the cross sectional area of pipe A,

$$A = \frac{\pi * d^2}{4} = \frac{\pi * 0.025^2}{4} = 4.9 * 10^{-4} m^2$$

Now calculating for the volumetric flow rate Q in (m^3/s),

For laminar flow,

$$Q = \frac{2000 * 10^{-6}\, {}^{m^2}/_{s} * 4.9 * 10^{-4} m^2}{0.025m} = 3.9 * 10^{-5}\, {}^{m^3}/_{s}$$

$$Q = \frac{3.9 * 10^{-5} m^3}{s} * \frac{15852gpm}{1\, {}^{m^3}/_{s}} = 0.62gpm$$

For turbulent flow,

$$Q = \frac{4000 * 10^{-6}\, {}^{m^2}/_{s} * 4.9 * 10^{-4} m^2}{0.025m} = 7.8 * 10^{-5}\, {}^{m^3}/_{s}$$

$$Q = \frac{7.8 * 10^{-5} m^3}{s} * \frac{15852gpm}{1\, {}^{m^3}/_{s}} = 1.24gpm$$

Thus to achieve laminar or turbulent flows, the inline pump must have a flow of 0.62 gpm or 1.24 gpm, respectively. Laminar flow was initially assumed to be optimal for accurate sensor readings. The calculated laminar flow was found unfeasible as it is too low for any practical pumps. Thus a low flow, non-submersible pump was chosen.

Pump chosen: 7.8 gpm max flow at 3ft, intake ½ NPT Female, discharge ½ NPT Male, height 4 3/8", width 4" and depth 8 ½".

Rate of returning water

The rate of returning water from the plants into the collection tank must be considered in selecting the inline pump as the rate of output from the collection tank must be equivalent to the rate of input to the collection tank in order to avoid nutrient accumulation. Calculating for the time required for water to return,

$$returing\ water = \frac{1.65hrs}{108\ trays} * \frac{60\ min}{1hr} * \frac{60\ sec}{1\ min} = 55sec$$

Rounding the returning rate of 55sec to 1 min, the nutrient addition and thorough mixing must be executed within 1 min to reach an equilibrium of well nutritionally balanced water in the tank before water is redistributed to the plants.

Sizing holding tank

A minimum amount of water is required at all times in the mixing tank to dilute the nutrient depleted incoming water. Having a large mixing tank volume compared to the small incoming nutrient depleted water volume induces a buffering effect thus improving the stability of the overall nutrient concentration in the holding tank. There is little time between the incoming water and redistribution of the nutrient balanced water, thus this dilution in the mixing tank prior to entering the holding tank will allow the system to more accurately control the nutrient concentrations by balancing the incoming depleted water with minimal volumes of nutrient concentrates. Since water is required in the mixing tank at all time, a submersible circulating pump was chosen for the design. One crucial requirement of the submersible pump is to have enough solution available in the tank for the pump to remain completely submersed. Since the volume required as a buffer is arbitrary, the volume need in the tank for accurately balanced water recirculation purposes will be assumed to be equivalent to the water required to submerse the pump.

$$minimum\ volume\ of\ water\ required =\ area\ of\ tank * height\ of\ pump$$

Height of pump= 4 ¼"

Area of tank= $\frac{\pi d^2}{4} = \frac{\pi(23.5in)^2}{4}$ = 433.74 in^2

$$minimum\ volume\ required =\ 4\tfrac{1}{4}'' * 433.74in2 =\ 1843.38in3 =\ 30.21L =\ 7.89gal$$

Thus the volume of water retained in the tank must be greater than 7.89 gal to ensure the pump is always fully submersed. Furthermore, the tanks must be capable in accommodating additional water in the case of excess nutrient concentration in the incoming water which can occur with low nutrient uptake by plants and high evaporation. In this case, there is a risk of overflow of the mixing tank as large volumes of additional water is added. Thus, a safety factor of 2 is integrated on the mixing tank.

$$7.89gal * 2 = 15.78gal$$

In the case of contamination or failure of the system, the tank should also be able to accommodate all the solution from the entire hydroponic system.

$$Total\ volume\ of\ water\ in\ hyroponic\ unit: 108\ trays\ *\ 340ml\ =\ 36.72L\ =\ 9.7gal$$

$$Total\ tank\ volume = \ minimum\ volume\ required\ +\ total\ volume\ in\ unit$$

$$=\ 15.78gal\ +\ 9.7gal\ =\ 25.48gal$$

For reasons of cost and availability, a tank of 23.5" in diameter, 34.75" in height, and capacity of 50 gal was chosen for the holding tank. These tanks are commercially available, cost effective, and recyclable.

To ensure a better buffer action, volume greater than 15.78 gallons of water should be kept in the tank. Since the tank chosen permits a maximum volume of 50 gallons, a safety factor was considered in deciding on a volume of 25 gallons be kept in the tank at all times.

Chosen holding tank: 50 gallon steel drum

Sizing submersed pump in the holding tank

It will be assumed that the tank will be fully mixed if 1/10 of the 25 gallon volume in the holding tank is circulated every minute.

$$Q = \frac{V}{t}$$

Q= volumetric flow rate (gal/min)
V=volume (gal)
t=time (min)

$$Q = \frac{{}^{1}/_{10} * 25gal}{1min} = {}^{2.5gal}/_{min}$$

Chosen pump: 5gpm at 1ft, 4gpm at 5ft head. The maximum head is 12.2ft. 120VAC, 1/4NPT male discharged. Height is 4 ¼".

(Note that these calculations depend on the selected pump and mixing tank, therefore it is an iterative calculation. The amount of water needed and the pump chosen must be selected simultaneously).

Sizing collection tank pump

A pump is required to transfer the water from the collection tank to the holding tank. As previously determined, the rate of returning water is approximately 340ml every 55sec. This gives a total flow rate of 128gal/day. Since this is a very small flow, a peristaltic pump was chosen with a level float that will turn the pump on or off depending on the water level in the collection tank. This ensures the motor will not be running without purpose.

Chosen pumps: fix-flow peristaltic pump. 143.79gal/day 1/16" pipe. 120VAC 1.9Amps. Self-priming up to 29ft.

Sizing peristaltic pumps for nutrient balancing

The nutrient balancing time of 30 seconds was assumed since the water is redistributed every 1 min, thus balancing time of 30 seconds allows for two nutrient balancing opportunities.

Ideally, the volume of nutrients dispensed by the peristaltic pumps should be consistent and equivalent to the volume of the nutrients depleted. However, the volume of nutrients left in the water after plant uptake can significantly fluctuate depending on plant conditions and other variables. There can be a major nutrient depletion, no depletion, or possibly an accumulation of nutrient somewhere in the system due to simultaneous rapid evaporation and nutrient uptake by plants. Thus the flow rates of the peristaltic pumps must be able to supply the holding tank water with a volume of nutrients in the case of a maximum nutrient depletion as well as a minimum volume of zero in the case of no depletion.

The maximum flow rate required for the peristaltic pump in the case of maximum nutrient depletion is calculated using the dilution ratios of the premixed nutrient solutions currently used in Urban Barns.

Dilution ratios of the premixed nutrient solutions currently used in Urban Barns:

- 1.5ml/L Solution A 5-0-2
- 1.5ml/L Solution B 1-5-8
- 1.5ml/L Calcium-Magnesium additive
- 1.0ml/L Polydex (copper-based) solution

Solving for peristaltic pump flow Q,

$$Q = \frac{V}{t}$$

$$Q = \frac{1.5ml}{L} * 25gal * \frac{3.7854L}{1\ gal} * \frac{1}{30sec} = \frac{4.73mL}{s} = 115.2\ gal/day$$

Such a flow rate of nutrient concentrates would likely be necessary at the initial start-up or restart-up after flushing out the system for cleaning. Assuming a relatively large mixing tank volume of 30 L, significantly smaller flow rate will be required for maintaining optimal nutrient concentrations since a relatively small volume of 340mL will be diluted in the mixing tank holding a relatively large volume of balanced water at 1 minute intervals. (Note that a mixing tank volume of 30 L was assumed). Determining the appropriate flow rates for the nutrient dispensing peristaltic pumps is a major design consideration as both large and small flow rates are required for the system. Controlling the dispensed volumes from peristaltic pumps with high flow rates is difficult and inaccurate as even a fraction of a second will have a big impact on the dispensed volumes of nutrients. This potentially detrimental risk of inaccuracy can be easily avoided by selecting peristaltic pumps with lower flow rates, especially considering the system will usually require only minor volumes of nutrient injections. However, in using peristaltic pumps with low flow rates, the system will take much longer to reach equilibrium when large volumes of nutrients are required. In the case this time lag at start-up pose as a major problem, a strategic start-up process such as starting the inline pump prior to the submerged pump can be implemented. Nevertheless, a more pertinent approximation of the flow rate is required.

Assuming that the 340mL of incoming water will be completely depleted of nutrients thus requiring correction, a more relevant flow rate of the peristaltic pumps can be calculated.

$$\frac{1.5ml}{L} * 0.340L * \frac{1}{30\ sec} = 0.017ml/\sec = 0.388\ gal/day$$

It should be noted that the peristaltic pumps will not be running continuously. The flows of the peristaltic pumps will be controlled by the computer system as a function of time to account for the variations in required nutrient concentrations. A minimum flow of 0.388 gal/day is required for the peristaltic pumps since pumps with greater flows can adjust for both large volumes of nutrients as well as small volumes simply by manipulating run time, whereas those with smaller flows cannot accommodate for large volume without inducing a significant time lag. Nonetheless, peristaltic pumps with such reduced flow rates are commercially unavailable thus the pump with the lowest possible flow rate was chosen.

Pump chosen: 1.14 gal/day, Self-priming up to 29 ft. 120VAC, 0.37Amps

Sizing nutrient concentrate containers

One criteria of this project is minimal maintenance. Thus it will be assumed that an employee will monitor and prepare new nutrient mixes for the plants once a week.

Designing for the maximum nutrient uptake by the plants, the volume of water cycled in a week is calculated.

$$\frac{36.72L}{1.65hrs} * \frac{168hrs}{7\ days} = 534.1L$$

$$\frac{1.5ml}{L} * 534.1L = 801ml = 0.21gal$$

Thus a minimum of 0.21 gallons must be held in the nutrient containers. But due to practicality, commercial availability, and cost, 3.25 gallon nutrient contains were chosen for the design.

Chosen nutrient concentrate container: 3.25 gallons

Prototyping

A prototype of the water recirculation and nutrient sensing system was built in order to perform scalable tests on the design. The prototype was intended to be a rough version of the system that would include only essential components of the design for proof of concept. Various designs were considered in developing the prototype. The two final prototype designs are demonstrated in Figures 3 and 4. The initial prototype illustrated in Figure 3 was built first but required adjustments along the way which lead to the development of Prototype 2 (Figure 4).

Conceptualization

Prototype 1

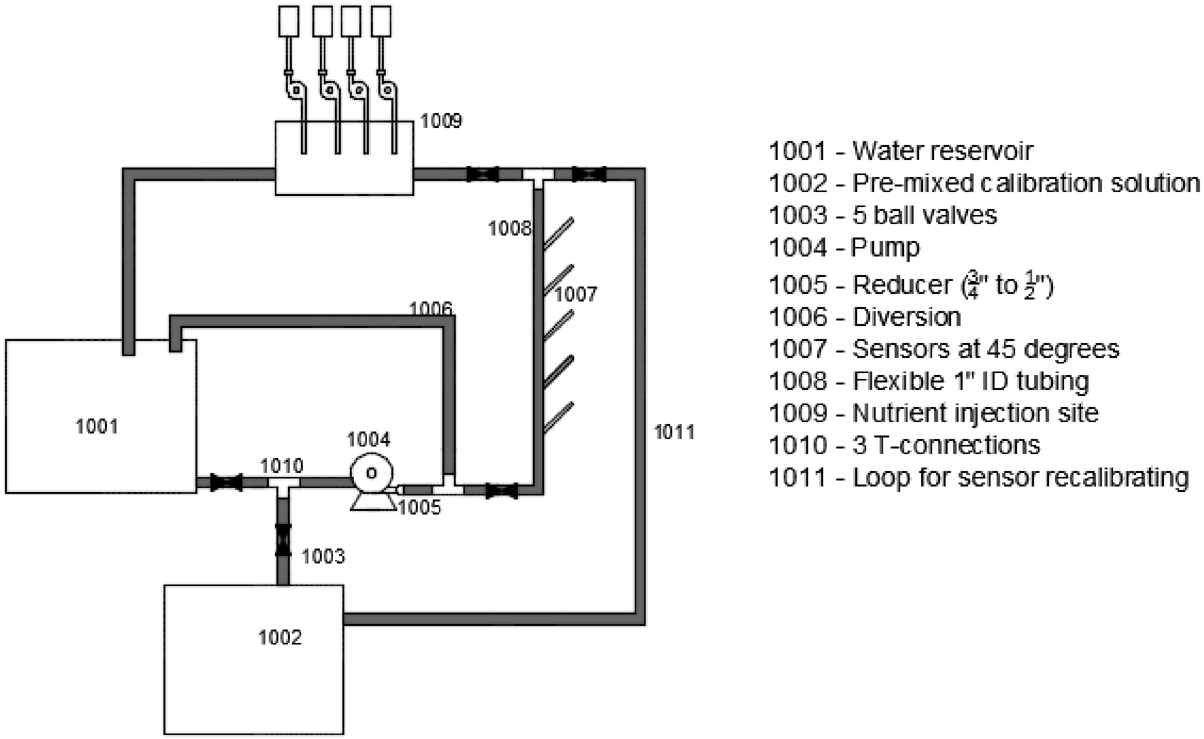

Figure 3 Design of Prototype 1

When designing the first prototype, a list of design constraints was compiled as follows:

- Tubing size of 1 inch ID
- Sensors at 45 degree angles
- Laminar flow by sensors
- Diversion to redirect excessive flows from sensors
- System to recalibrate sensors (one point calibration)

A tubing size of 1 inch ID was required to allow sufficient room for water to flow by the sensors which would be inserted directly into the tube. It was noted in conceptualization that the presence of oxygen bubbles in the form of air voids interfere with sensor readings. Since the voltages produced by the sensors normally flow through water as a medium, the presence of air will change the properties of the medium therefore falsifying the readings. This can be mediated by placing the sensors at a 45 degree angles so that any voids can easily slip off the sensors instead of hitting them head on when the sensors are at 90 degrees. Flows that are too high would predictably disrupt sensor readings and since the manufacturers of the sensors did not provide specifications for water flows, laminar flow was safely assumed to be ideal in the first prototype. A diversion with a ball valve was used to redirect and vary the flow of water from the pump to the sensors. This addition makes it possible to vary flows during testing to determine the optimal conditions for the sensors. The computer is programmed to compute the difference between nutrient levels in the water read by the sensors and the reference point derived from optimal plant conditions. After continuous use, the sensors require a recalibration to reset the reference point which can be achieved via one point calibration. To accommodate for automated recalibration, the recalibration loop was implemented where a premixed solution of ideal nutrient concentrations, in this case the Hoagland solution, is circulated through the sensors. The recalibration loop can be blocked off by using ball valves under regular circumstances but when recalibrating, the water recirculation loop would be closed off using ball valves instead.

Prototype 2

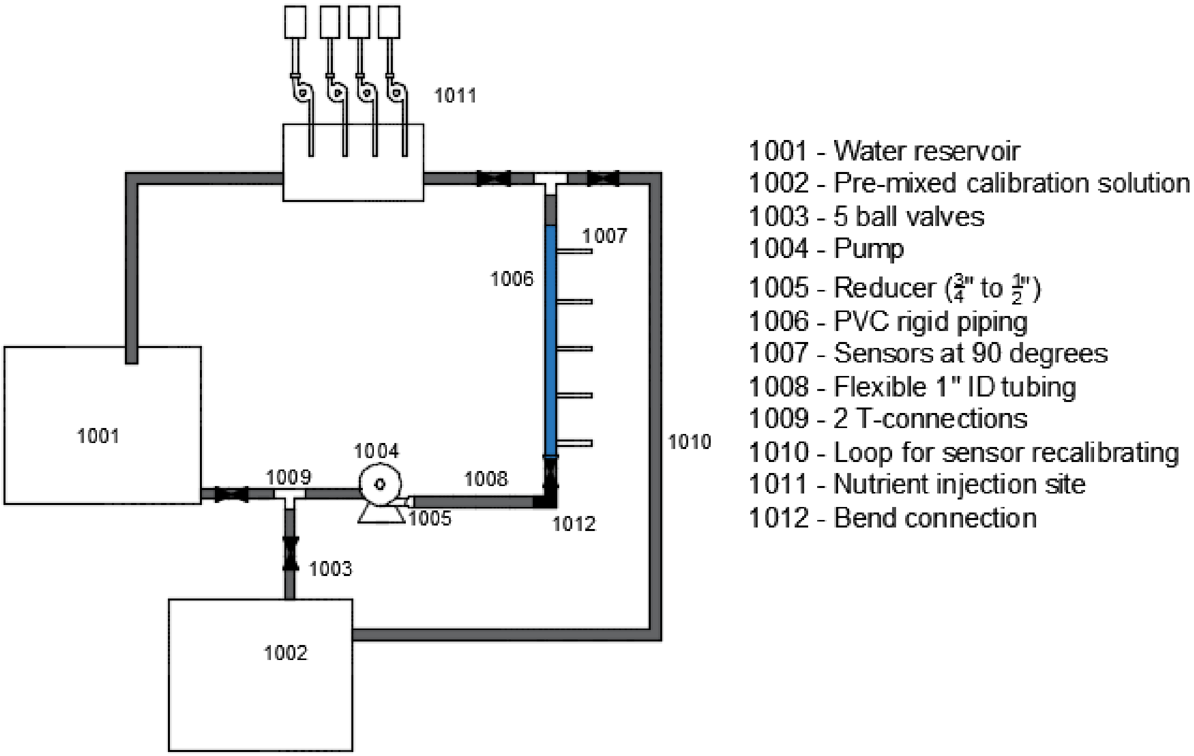

Figure 4 Design of Prototype 2

As the project progressed, it was decided that Prototype 1 needed to be adjusted to include a rigid pipe for the sensing section of the system and that a diversion to reduce flows was not necessary. Turbulent flows would be inevitable as purely laminar flows were infeasible. Nonetheless, the flow could be varied using the ball valve and the effects of flow on the sensors could be tested. Prototype 2 was devised to include a rigid PVC pipe of 1 inch ID while replacing the diversion between the pump and sensors with an additional ball valve to roughly vary the flow if necessary. With the use of flexible tubing along the sensing region, there was a risk that water would warp the tubing and sealing around the sensors and result in a sensor popping out of its placement. The use of PVC piping limited the ability to drill holes at 45 degree angles and so the sensors could only be placed at 90 degrees. This alteration enabled the use of grommets to securely hold the sensors in place instead of the silicone sealant. Considering the value of the sensors being used, the security of the sensors was prioritized over their 45 degree angles placements (it was more important to ensure secure insertion and sealing in the sensor region than their placement at 45 degree angles). Nonetheless, if full-pipe flow is achieved in the PVC piping, then the PVC piping can be rotated 45 degrees for an equivalent effect.

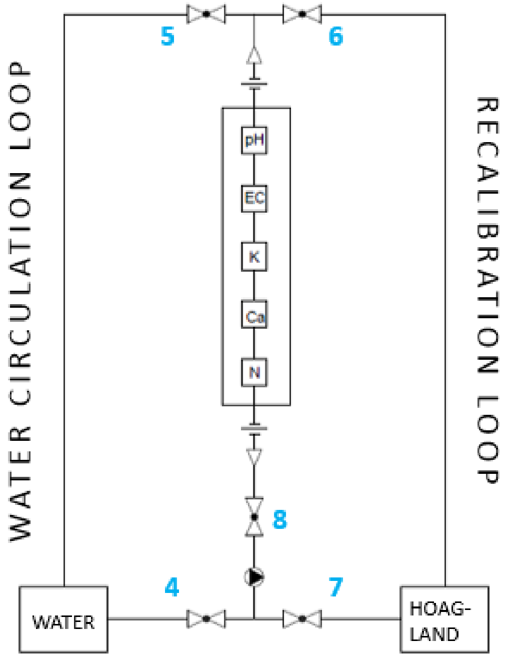

Figure 5 Schematic of Prototype 2

Prototype 2 functions as follows:

Using Figure 5 as a reference, water from the plant tray enters the water tank, at which ball valves 4, 5 and 8 are opened and ball valves 6 and 7 are closed. The water is then pumped up towards the sensing region where the entering flow is controlled by ball valve 8. Water then flows to the nutrient injection site and later falls by gravity back into the water tank. During recalibration, ball valves 4 and 5 are closed and ball valves 6, 7 and 8 are opened. Premixed Hoagland solution in the Hoagland tank is pumped up towards the sensors and flows back into the Hoagland tank. To achieve accurate recalibration, this process is left to circulate for a few minutes in order to rinse out any accumulation of nutrients within the tubing. Prototype 1 functions in the same way as Prototype 2 with the exception that some water is diverted from between the pump and ball valve 8 back into the water tank as well as that flexible tubing is used in the sensor region rather than PVC piping.

Construction

The construction phase provided insight on the designs of both the prototype and final design. Figures 6 and 7 are the constructed versions of Prototype 1 and Prototype 2. While building Prototype 2, it was decided that for the purpose of this prototype to test nutrient sensing and injection, nutrient addition would occur in the water tank rather than in a mixing tank as proposed in conceptualization. This decision was made because the size of the water tank was small enough to assume complete mixing of the incoming flow with the nutrient injections.

Figure 6 Incomplete construction of Prototype 1

Figure 7 Constructed prototype 2

Prototype 2 Construction

Figures 8, 10, and 11 are close ups of the pump connections and sensing region connections. Figure 8 and 9 illustrates the connecting components used in connecting the pump inlets and outlets of ½ inch ID to the tubing of 1 inch ID. The connections between the PVC piping and the flexible tubing in the sensor region, illustrated in Figures 10 and 11, are sources of potential leakage and could have been substituted by machining threads into the PVC pipe and using two 1 inch threaded connectors. Figure 12 illustrates the design details of the sensing region including the inline pump and the PVC pipe with the sensors. Through-wall fittings and generous amount of silicone sealant were used to securely seal the holes made in both water and Hoagland tanks.

Figure 8 Picture of pump connections

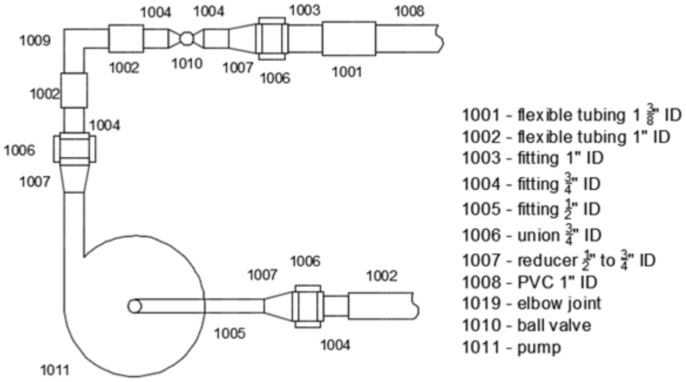

Figure 9 Design of pump connections

Figure 10 Sensing region (1)

Figure 11 Sensing region (2)

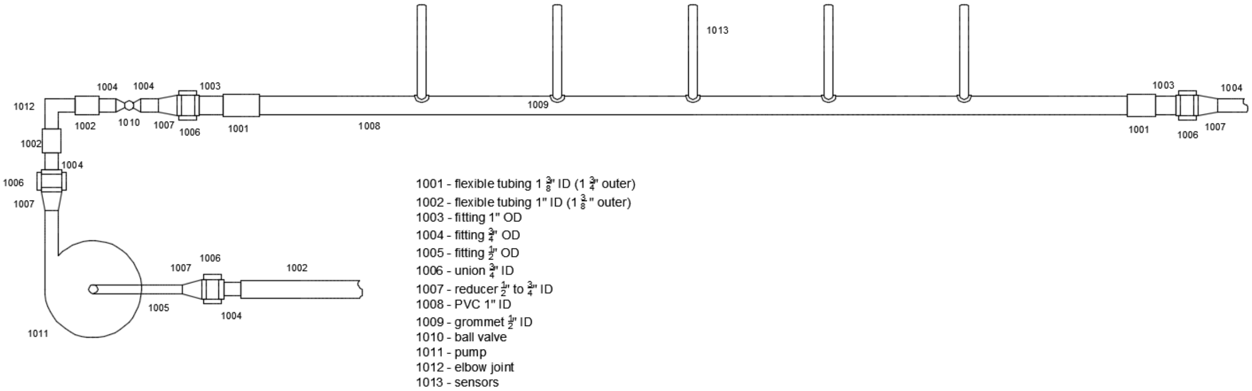

Figure 12 Design of sensing region

Nutrient Injection

Figure 13 Nutrient injection site

Components for nutrient injection (Figure 13) included four peristaltic pumps, four nutrient containers, tubing, and one stand for the pumps. Four 1 gallon jugs were used as containers for the nutrients and labelled accordingly as potassium phosphate, potassium nitrate, calcium chloride and hydrochloric acid. A small hole was retrofitted in the cap of each container. Lastly, a table was built out of two 2x4s to support the pumps.

Materials

All materials for prototyping were bought from Patrick Morin, Reno Depot and McMastercarr.com

Table 2 Materials used for prototyping

Materials Prototype 1		Materials Prototype 2	
Material	Amount	Material	Amount
Pump (12 gph)	1	Pump (12 gph)	1
Flexible tubing (1" ID)	18 ft	Flexible tubing (1" ID)	~12 ft
Ball valves	6	Flexible tubing (3/8" ID)	1 ft
Rubbermaid reservoir (40 L)	2	Ball valves	6
T-joints	3	Rubbermaid reservoirs (40 L)	2
Elbow joints	2	T-joints	2
Teflon tape	1	Elbow joints	1
Trident screw clamps	25	Teflon tape	1
Tubing connectors (1")	12	Trident screw clamps	30
Tubing connectors (1/2")	1	Tubing connectors (3/4")	12
Reducers	2	Tubing connectors (1/2")	1
Unions	2	Tubing connectors (1")	2
Silicone sealant	1 tube	Through wall fittings	2
		Reducers	4
		Unions	4
		Grommets	5
		Nutrient jugs	4
		Peristaltic pumps	4
		2x4s (for table)	2
		Silicone sealant	1 tube

Prototype Component Details

Tubing

Flexible, transparent tubing with an ID of 1 inch was chosen for the prototype. The prototype was subjected to many on-the-spot alterations and so flexibility was important for ease of bending, particularly when linking the tubing back to the reservoirs from the sensing region. An inside diameter of 1 inch was chosen to provide adequate room for water to flow past the sensors. Transparency was an asset when testing for bubbles and flow behavior, especially in proximity to the sensors.

Pump

A low flow, non-submersible pump was chosen based on previous flow calculations and requirements for the design. Specifications for the pump are stated below. Intake was ½ NPT female which lead to one single reducer to decrease the diameter from 1 inch tubing to the ½ inch intake of the pump. The same applies for the connection at the discharge connection. The pump's impellers are turned by magnets. This was a strategic choice that eliminates the risk of oil leaking into the water, which in this application, would be unacceptable.

Pump chosen: 7.8 gpm max flow at 3ft, intake ½ NPT Female, discharge ½ NPT Male, height 4 3/8", width 4" and depth 8 ½".

Through-wall fitting

Two through wall-fittings, as shown below were use to plug the two holes and act as outlets for each of the two reservoir tanks. Both were installed with a generous amount of silicone sealant. A ¾" fitting was used to connect the plugs to the tubing.

Through-wall fitting chosen: pipe size ¾", hole size 1 5/8", length 2 7/8", temperature range 40 – 140 degrees Fahrenheit, Female NPT threaded ends.

Testing

Two tests were performed on the final prototype and sensors to locate major leaks, to test the security of the sensors in the pipe, and to test the effect of flow on the accuracy of the sensors.

Test 1 - Leakage

The first test was conducted to identify major leaks and to ensure security of the sensors in the PVC pipe. Ball valves 4, 5 and 8 were opened and ball valves 6 and 7 were closed in order to open the water circulation loop. Initially sensors at locations 1 and 2 (Figure 14) were leaky. The grommet and sensor at location 2 were adjusted and further leaking was avoided while minor leaks were still observed at location 1. It was noted that the grommets were sufficient in keeping the sensors secured in place.

The recalibration loop was then opened by opening ball valves 6 and 7 and closing ball valves 4 and 5. Minor leaks were identified at location 7 and 8 (Figure 14). More Teflon tape was added and connections were tightened to successfully prevent leakage. Prior to testing, location 3, at the Hoagland tank outlet, was predicted to be leaky between the through-wall connections because the hole in the plastic tank was not ideal and had a cut that reached outside the circumference of the hole. The cut was within the area covered by the through-wall fittings but extra silicone sealant was applied. Surprisingly, these measures seemed sufficient in preventing leakage. During the testing of the recalibration loop, ball valve 6 was accidentally left closed which resulted in the pump pulling in air for a short period of time before the valve was opened. The air had to be sucked out prior to restarting the pump which raised concerns about priming that would be addressed in the optimization of the design.

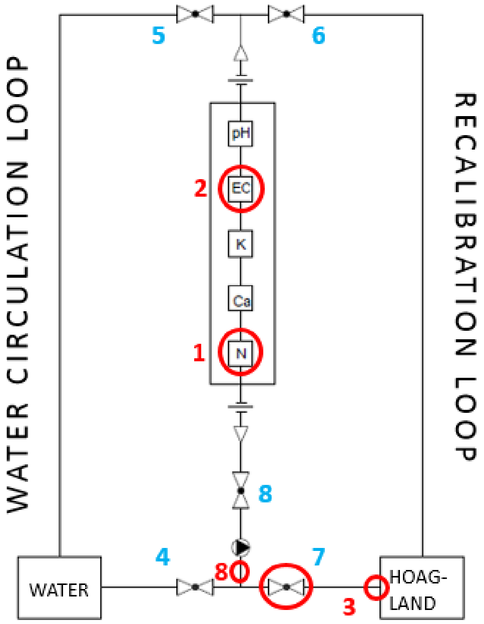

Figure 14 Location of leaks

Test 2 – Sensors and flows

The second test was conducted to test the effect of flow on the accuracy of the sensor readings. Five sensors were used for the testing. The calcium, nitrate and potassium sensors were used to give real-time readings whereas the pH and EC sensors were substituted for two dummy sensors. There was initial concern that full flow from the pump would be turbulent and would interfere with the sensor readings. Hoagland solution was circulated at four different flows which were varied by turning ball valve 8 to four different positions: 2/3rds, closed, 1/3rd closed, fully open and fully closed (trapped water). Flows were determined by measuring the volume of output water and recording the time required for the water to reach that volume. Lastly, water was circulated to see the difference in sensor readings between water and Hoagland solution. Figure 15 is a plot of the real-time results.

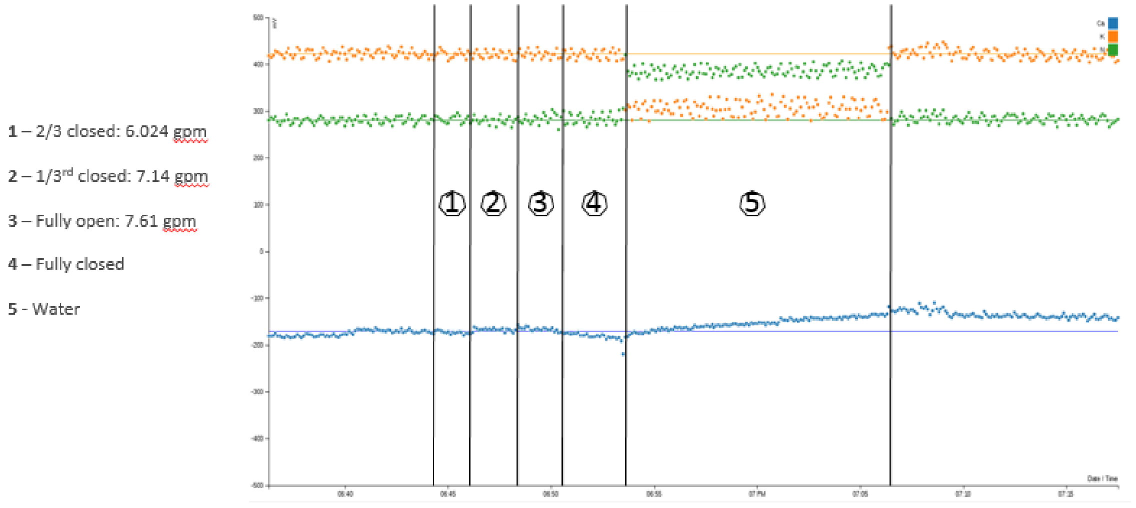

Figure 15 Sensor readings in Hoagland with varied flows and water

Each dot appears every couple of seconds and represents the average mV readings of 1000 samples. There was no change between intervals 1, 2 and 3 and all remained very close to the reference lines for each nutrient. The 4th interval produced slightly more error which can be attributed to the fact that the attempt to trap Hoagland in the sensing region failed as most of the Hoagland left the region. The sensors were able to produce readings from the little solution that were present in the pipe and the residuals on sensors. Although the readings were still relatively close to the reference line, they were deemed erroneous. When water was circulated, potassium levels decreased, nitrate levels increased, and calcium levels increased. The Hoagland was circulated again after the water trial. It was noted that the calcium sensor was very slow at responding when compared to the potassium and nitrate sensors. A voltmeter was used to determine the readings at the terminals of the sensors to confirm that the computer readings were accurate. From these results, it was concluded that flow does not affect the accuracy of sensors.

Risk Analysis

Observations made during testing supplemented by external analysis, identified several hazards associated with the system and their impact was assessed. Such potential failures include: leaking and/or flooding, malfunction of the nutrient sensing and control system, obstruction of flow due to accumulation of debris, accumulation of undesirable nutrients, power failure, contaminated incoming water, as well as warming of the recirculated water. Each of these problems was assessed in terms of consequences to management at Urbans Barns Inc., consequences to the public, and a measure for prevention of each of these identified risks.

As with any plumbing system, there is an inherent risk for leaks and/or flooding to occur as a result of possible faulty sealing, or automated valve failure. Specifically in this design, a failure in the bleeding valve under the tank, or of the inflow water solenoid valve could pose problems, especially as they are automated and electrically controlled (i.e. the solenoid valve). Failure of these components would result in a cost of repair to the management, as well as an economic loss due to plant death associated with the lack of recirculating water. In the case of flooding, this excess nutrient rich water enter the municipal water system, putting stress on the municipal water treatment facilities, thus having wider societal consequences beyond Urban Barns. Water volumes used in the facility are of a small enough magnitude such that flooding of nearby population does not pose as a risk. Leaks or sudden depreciation in water levels in the holding tank can be monitored by installing a float in the holding tank as well as installing a pressure valve in the calibration loop where the sensors are located. The float would also serve the purpose of ensuring adequate water level in the storage tank such that the submersible pumps do not run dry. If the pump does run dry, it would have to be replaced, therefore a replacement pump should be kept on location so that it can be exchanged quickly in the case of pump failure, minimizing damage to the plants.

Malfunction of the nutrient sensing and control system could occur as a result of a faulty calibration, non-uniform mixing, failure of the pump to deliver a sample of the nutrient depleted water to the sensors, and/or failure of the check valve. This would result in an unbalanced nutrient solution delivery to the plant unit. High levels of certain nutrients could be toxic to the plants, where as insufficient levels of nutrients would slow plant growth, both of which would results in a dying or slowing of plant production, translating to an economic loss for Urban Barns. Consequences to the general public are minimal in this case with the major consequence being a possible reduction in supply to Urban Barns customers.

Malfunction of the nutrient addition system could occur as a result of failure of the peristaltic pumps or a failure in communication between the sensors through the computing system to the pump. Any delays in communication would exaggerate any hysteresis occurring in the system, resulting in overshooting/undershooting of the nutrient levels being delivered to the plants. This would result in similar economic losses associated with slowing of plant growth and or/death discussed previously.

Provision of a favorable environment for plant growth (nutrient rich solution, water and light) is also a conducive environment for algae growth, which raises concern for obstruction of the system such as accumulation along the walls of the circulation system, as well as accumulation on the nutrient sensors, preventing accurate readings. There is also concern that if algae growth is uncontrolled, the nutrients in solution intended for the plants will be consumed by the algae instead. The current design uses ozone to treat the water before it is recirculated to the plants. While the ozone kills the algae, the cells are remain in the water, and accumulation on the filters could obstruct the pathway for circulation of the solution as well as prevent accurate readings by the sensors. Additionally, plant debris from the produce may also impede circulation and must be filtered out to prevent obstruction of the system as well as damage to the sensitive electrodes. Thus filters in place at the holding tank, collection tank, as well as after the ozone treatment must be replaced/cleaned regularly. An additional cleaning cycle could be implemented to flush the system at regular intervals to further prevent the build-up of debris in the system.

As the system is supplied with groundwater by a nearby well, there is a possibility of groundwater contamination that can introduce toxic substance to the plants. A method for prevention of this problem is to distil the water before administration to the plants. The cost of doing this however may not be proportional to the associated risk.

Recirculation of the water through moving parts involving electrical components such as pumps and high intensity LED lights in place, cause the water to heat up, possibly resulting in temperatures that are not ideal for plant growth. Addition of a heat exchanger in the system could lower the water to optimum temperatures before being returned to the plant unit.

Since the system is fully automated and electronically controlled, a power failure would result in a failure of the entire system. The plants would remain in water, and would likely survive until the power could be re-established. However, they would be depleted in nutrient levels, and their growth rate would have been slowed, resulting in economic loss for Urban Barns. Prevention of such an issue could be accomplished by implementing a backup generator in the case of power outage. A summary of the risks and consequences are discussed is provided in Table 3 below:

Table 3 Risk analysis.

Potential failure	Consequence to Management	Consequence to the public	Solution
Leaking/flooding Cause: Poor sealing Bleeding valve fails Inflow water solenoid valve fails	Cost of repair, Loss of plants due dysfunctional system (lack of water or diluted nutrients).	Increased environmental pollution, Increased volume of water to sewer system.	Installation of float in the holding tank and pressure gage in the calibration loop.
Dysfunctional sensory system Cause: dysfunctional calibration loop check valve fails improper mixing pump fails	Unbalanced nutrient solution circulated to plants which leads to reduced or loss of plant production.	N/A	Regular verification of calibration by an employee (in addition to computer system).
Dysfunctional nutrient addition system Cause: peristaltic pump fails computer system does not relay information	Unbalanced nutrient solution circulated to plants which leads to reduced or loss of plant production.	N/A	Quality assurance protocol (verification by employee) should be established to regularly monitor this.
Accumulation of debris Cause: dead plant material algae growth	Clogging of system, Pathogen growth, Decreased plant production, Cost associated with cleaning/changing system.	N/A	Filtration system. Integration of a cleaning cycle.
Submersible pump not submersed and running dry	Loss of plants, Replacing pump.	N/A	Add a water level gauge in tank.
Accumulation of undesired nutrients Cause: Inflow water solenoid valve fails Synchronization of bleeding valve and inflow water is bad	Loss of plants.	N/A	Quality assurance protocol (regular testing) should be established to monitor this.
Power failure	Plant death.	N/A	Add a back-up generator.
Contaminated incoming water	Plant death.	N/A	Connect to a distilled water supply.
Water heating up Cause: Too much energy added to systems from pumps, light	Plant death.	N/A	Add a heat exchanger.

Optimization and Final Design

The final design is completely automated and consists of a combination of 3 solenoid valves, 4 three-way valves, 6 pumps, filters, fittings, tubing, mixing tank, sensors and a computer system which orchestrates the process (Figure 16). Figure 17 illustrates the 3D rending of the final optimized design.

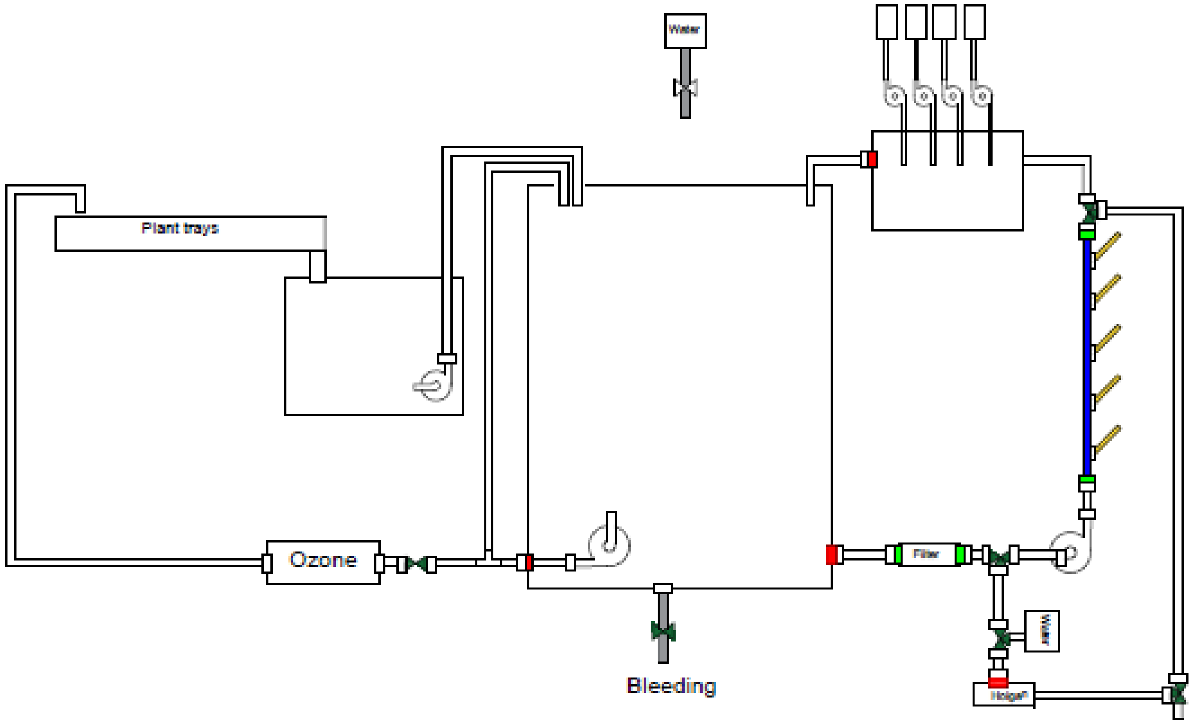

Figure 16 Overview of the final optimized design

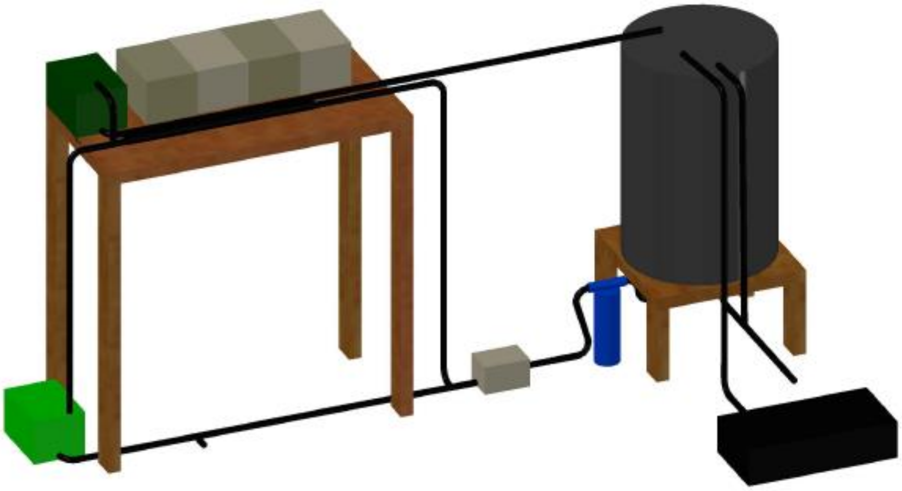

Figure 17 3D rendering of the final optimized design

Tests performed on the sensors revealed that the flow rate did not affect the sensor results. Although in the prototype the tubing was of 1" diameter was transparent, the optimized design will employ black, opaque tubing of ½" diameter. Tubing diameter of ½" is more favorable since most of the system components are more compatible with ½" tubing than 1" tubing. For example, all the pump outlets are either ½" or ¼" in diameter, the filter are ¾" in diameter, and the PVC pipe for the sensors is 1" in diameter. Using ½" tubing also limit the number of reducers required, thus reducing costs. Additionally, using ½" valves are more economical as the three-way valves with 1" tubing are not readily available on the market. ½" tubing is desirable also for maintenance purposes as it is important that all the components are easily accessible. The black opaque tubing is important in limiting light penetration through the tubing to minimize the growth of algae and cyanobacteria.

Although the prototype did not experience any structural weaknesses such as major leaks, the 1" PVC pipe used in the optimized design will be machined on both outlets to incorporate female NPT threading in order to allow for ¾" male NPT threaded fittings to more securely attach the piping to the rest of the tubing. In addition, reducers will be required to connect the ¾" threaded fittings to the ½" tubing.

Four three-way valves will be implemented in the optimized design along the recalibration loop as they are a major safety measure and an optimization consideration. Three-way valves will allow the system to choose either the circulation loop or the recalibration loop shown in Figure 14, while also acting as a preventative measure of pump failure by ensuring continuous liquid running through the pump. These valves play an imperative role in ensuring the separation of the Hoagland solution in the recalibration loop from the rest of the system. The Hoagland solution cannot contaminate the water being circulated to the plants as that will result in an imbalance of nutrient concentrations and consequently, plant death. Two of the four three-way valves placed directly before and after the sensors (Figure 16) are to be programmed together for simultaneous functioning.

Mixing in the holding tank will be achieved via a circulation loop from and to the plants using a submersible pump. To ensure that the pump remains submersed, an electrical float will be added to the tank. If the water levels are too low, the float will activate the incoming water solenoid valve to replenish the system. Since very little water is required for distribution to the plants, the same pump is used with a flow separator and a solenoid valve to control the water delivery to the plants. This additional functionality puts further emphasis on the importance of the submersible pump since failure or malfunctioning of the submersible pump will limit plants' water supply, resulting in plant death. An electrical cut-off float is also introduced in the collecting tank to ensure water levels are kept at a minimum so the pump does not run dry. If the float reads water level that are too low, the peristaltic pump will be shut off. A screen filter is added to the top of the collecting tank to ensure no large particle are introduced in the tank and interfere with the peristaltic pump.

A Bleeding valve (solenoid valve) is necessary to let the water out of the system in the case of excess nutrient concentration in the water or flushing is required for maintenance to cleaning.

Filters are added to the recirculation loop, specifically surrounding the PVC pipe with the sensors, to ensure no particles are introduced to the sensors and cause damage to the electrodes. This filter also help minimize algae growth in the sensing region to keep the sensor reading accurate.

With the current system for nutrient sensing and control, the peristaltic pumps to inject the nutrient concentrates are activated when the value is less than or greater than (depending on the sensor, the mV changes negatively or positively with increasing ppm) the desired ppm for each nutrient. Currently, the control system adds nutrients if the concentration falls below a hard limit, which was determined during the calibration that day. Tests are to be conducted to verify if this form of control is adequate. Eventually, a more sophisticated PID controller may be put in place to control the length of pump pulses based on the average error from the ideal millivolt level detected by the ISE.

Additionally, risk analysis helped to identify several modifications to be made to the design to increase the safety of the design and reduce the risks and costs associated with certain failures. Several of these optimizations have been mentioned previously, such as a float in the holding tank to prevent the pump from running dry, and filters in place to prevent obstruction in the circulation system, as well as damage to the electrodes. Potential leaks in the calibration loop are to be monitored and prevented using a pressure gage. Finally, the final design could also incorporate a heat exchanger in the case that water temperature rises too far above an optimum of 20°C.

Cost Analysis

Cost analysis of the optimized final design was calculated as seen in Table 4.

Table 4 Cost analysis

Item	Quantity	Cost per unit	Total cost
Solenoid valve	1	49.43	49.43
Concentrated nutrient tanks	4	6.32	25.28
Peristaltic pump	4	158.67	634.68
Pre-mixing tank	1	6.32	6.32
1/2" hose fittings	24	1.37	32.88
Cable ties	1	8.25	8.25
1/2"-3/4" reducer	4	0.5	2
3/4"-1" reducer	2	1.67	3.34
3 way valve	4	117.69	470.76
Grommets	5	5.53	27.65
Electrode PVC	4	15.83	63.32
PVC to tubing connector	2	12.37	24.74
1/2" tubing	25	0.7	17.5
Pump	1	156.82	156.82
Hoagland tank	1	48.34	48.34
Filter	1	75.51	75.51
Through wall fittings	3	18.24	54.72
Bleeding solenoid valve	1	49.43	49.43
Circulating pump	1	89.1	89.1
T-connector	1	7.42	7.42
Solenoid valve	1	49.43	49.43
Tubing	25	0.55	13.75
Holding tank	1	100.88	100.88
Pump to mixing tank	1	186.18	186.18
Floats	2	75.56	151.12
		total	2348.85

Thus initial investment for building this system is approximately $2348.85. It should be noted that the sensors will eventually need to be replaced depending on maintenance and care. Maintenance will be required for weekly nutrient container refills, cleaning, and overall supervision.

Conclusion

This report details the design for a recirculating hydroponic system compatible with the plant units currently in place at Urban Barns Foods Inc. It has incorporated an automated nutrient sensing and control system. Proof of concept of the nutrient sensing and calibration loop was demonstrated through prototyping and testing, which highlighted the particularly slow speed at which the calcium sensor read the concentration in the solution. It also reinforced the necessity for regular calibration to ensure accurate readings of the nutrient levels. The design was optimized through further testing and risk analysis and the proper safety measures were put in place to ensure a well-functioning and safe system. After consideration of all the final design specifications, the total cost came to $2348.85, which is the cost associated with building an automatic recirculating system for one plant unit, composed of 108 trays. Economies of scale are expected to be gained if this system is used for more than one plant unit, as only one central holding tank and submersible pump would be needed. There are however maintenance costs associated with the replacement of filters and ISEs as they eventually wear out. Note that the lifespan of the sensors can be greatly extended through effective calibration methods and proper care of the electrodes (~1 year) (Thermoscientific. 2013). Future tests are to be conducted with the nutrient sensing and control system installed on a full scale plant unit. Testing can be done to determine if the current system for nutrient control is adequate for healthy plant growth, or alternatively if the hysteresis associated with sensing and then addition of nutrients is too extreme for the plants, in which case the control system will need to be upgraded to a PID controller to control nutrient levels with higher accuracy.

Student Design Competition

This design project has been submitted to the 2015 G. B. Gunlogson Student Environmental Design Competition, which is an engineering competition for environmentally and biologically related design projects. The competition requires that an intent of participation be submitted by April 8th (done on March 27th, 2015) and a final design report be submitted by either of two deadlines: May 6th, 2015, or one week after the final deadline for a senior design report. The teams scoring among the top 3 best reports will participate in presentation competition at the ASABE Annual International Meeting (Jul 26-29, 2015).

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